BLINC: Designing Bicycle Path Protection for Accessible Transportation Networks

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Masters Thesis

By Blair A. Benson

Submitted for Acceptance of Partial Degree Requirements for Master of Architecture Degree from the Department of Architecture in the Golisano Institute for Sustainability at Rochester Institute of Technology

by

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on
08 May 2019
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The City of Rochester is defined by both poverty and renewed development in its center city. Often overlooked, access to transportation systems plays an important role in the prevalence of poverty. Accessing areas of Rochester that offer higher paying jobs, better schools, and a greater variety of services is directly related to car ownership, a luxury that Rochester’s poorest cannot afford. This transportation inequality is considered a contributing factor to Rochester’s poverty rate.

In addition, the discontinuous urban fabric of downtown Rochester is designed for automobile, not pedestrian or bicycle traffic. Safe and continuous pedestrian and cycling pathways are often absent, though Rochester contains major employment districts, academic institutions, cultural and entertainment venues, public spaces, and basic amenities. Wide streets, city-bisecting highways, and large areas of surface parking contribute to continued use of automobiles, restricting efforts to develop Rochester into a sustainable, accessible, human-scale, and lively city.

Bicycle transportation offers a viable alternative to automobile ownership and bus transportation, filling in the gap between accessibility and efficiency in Rochester’s transportation network. However, ridership deterrents such as the risk of inclement weather and lack of cycling-specific infrastructure must be addressed. A bicycle lane canopy is a potential solution for fulfilling these goals.

Projects in London and Berlin have shown that investment in cycling infrastructure is effective at promoting cycling as a mode of transportation. Tensile fabric architecture and textile projects in Boston, Detroit, Denver, and New Zealand have shown that tensile structures are able to define urban spaces in expressive ways.

In order to encourage bicycling as a mode of transportation by protecting cyclists and pedestrians from weather events and automobile traffic, a canopy structure was proposed. This Bicycle Lane Intelligent Network Canopy (BLINC) consists of a connected series of individual tensile fabric structures that interact to create an urban network of bike lane coverings. Potential tensile fabrics, designs and routes were analyzed to meet the needs of the tensile fabric structure; a PTFE triangular tee structure was determined to best fulfill the design intent.

A BLINC route network was proposed along several existing roadways that provide access to the urban fabric of employment, education, amenity, and recreational opportunities in the city. It is designed to provide efficient, convenient, and continuous cyclist access to the core and extents of Rochester, while enhancing the sense of place that the urban framework provides.

By encouraging cycling as a mode of transportation, the tensile fabric BLINC structure and proposed BLINC route network also improve community health, increase cyclist safety, lower greenhouse gas emissions, promote the local economy, and contribute to Rochester’s innovation in urban renewal.
Problem Statement
II. PROBLEM STATEMENT

The City of Rochester is defined by both poverty and renewed development in its center city. Though projects focused on bringing new economic, social, and environmental life into the city often aim to support anti-poverty initiatives, Rochester’s poverty rate continues to increase.

Often overlooked, transportation systems play an important role in the prevalence of poverty by restricting or promoting access to areas of economic and educational opportunity, social services, and essential resources. In Rochester, automobile highways divide prosperous and impoverished areas and promote the unnecessary use of automobiles in a compact urban center. These highways create an urban framework that is discontinuous, catering only to automobiles, not pedestrians or cyclists. Automobile ownership is often out of reach for the majority of the city’s low-income residents. However, Rochester’s alternative transportation option, the transit bus system, is inefficient and less comprehensive when compared to automobile travel. Accessing areas of Rochester that offer higher paying jobs, better schools, and a greater variety of services is directly related to car ownership. This transportation inequality can be considered a contributing factor to Rochester’s poverty rate.

The truly effective alternative to automobile transportation, bicycling as a mode of transportation, is not widely adopted in Rochester for several reasons. Transportation routes often lack infrastructure to make roadways safe for cyclists and pedestrians, weather conditions may discourage ridership, and too few commuting cyclists impart the impression that cycling is unsafe.

However, bicycle transportation offers a viable alternative to automobile ownership and bus transportation, filling in the gap between accessibility and efficiency in Rochester’s transportation network. By reimagining existing transportation routes to be designed for pedestrians and cyclists, the urban framework of Rochester could be reunited. A continuous network of streets with cycling and pedestrian focused infrastructure would help all members of the urban population access the city.

The following research seeks to determine the plausibility of utilizing tensile fabric structures to protect cyclists and pedestrians on Rochester’s transportation network in order to promote cycling as a mode of transportation, to expand equal access to efficient transportation, and to better connect the urban framework of the city.
Figure 1. Poverty rate in Rochester, NY, 2013.\textsuperscript{i}

\textsuperscript{i} “Neighborhood Data Base Maps,” City of Rochester, last updated 2014, https://www.cityofrochester.gov/neighborhooddatamap/
1. TRANSPORTATION IN ROCHESTER

1A. ROCHESTER, TRANSPORTATION AND POVERTY

As one of the poorest medium-sized cities in the nation, Rochester, NY has the dubious distinction of ranking first in extreme poverty and childhood poverty in the United States.¹ Though a variety of factors contribute to these alarming statistics, an equally vast array of strategies exist to help alleviate the plight of Rochester’s poorest citizens. Larger initiatives such as job-seeking assistance, educational quality and equality, and healthy lifestyle options are the major focus of Rochester’s city-wide anti-poverty efforts.² However, small steps in indirect areas of major initiatives are also important to ensure the success of overall anti-poverty plans. Transportation is just such an area.

Like many cities in America, the economic boom of the 1950s and the following 60 years led to an exodus of middle income citizens leaving Rochester’s center-city for the suburbs.³ In addition, as Figure 2 shows, the urban flight of the late-20th century also took jobs to the farther reaches of the city limits. For higher income residents, this shift in economic factors was manageable: cars were affordable, roadways were expanded and enlarged, and better schools, jobs, and housing became available in the suburbs. However, for those in the lowest income bracket, the center-city remained, and still remains, home. Residents who rely on low-income housing, find the widest array of options within the city boundaries.⁴ Figure 1 shows that the greatest concentration of poverty in Rochester surrounds the boundaries of the Inner Loop and stretches north and west following the Genesee River. Poverty in these areas ranges from 45 to 78 percent of the population.⁵

The ReConnect Rochester Transportation and Poverty in Monroe County report indicates that for those who live in poverty, transportation plays a major role in access to jobs and the greater urban framework of Rochester. On average, car owners in Rochester earned at least $46,000 per year, leaving about 44% of the population unable to afford a car.⁶ In Rochester, 53% of non car owners rely on public transit to access the city and jobs within Monroe County.⁷ However, for those who rely on public transit only 63% of jobs in Monroe County are accessible, even when commuting for an hour or more. In comparison, automobile drivers are able to access 85% of Monroe County jobs within 20 minutes, and 100% of jobs within 40 minutes.⁸ This reality effectively maroons Rochester’s poorest to live in an area where educational quality, job prospects, and quality of life are at their lowest.⁹ Efficient and affordable transportation then becomes a critical element to implementing anti-poverty initiatives.

---

² Rochester Area Community Foundation, ACTrochester.org
⁷ Ibid. 15.
⁸ Ibid. 25.
⁹ “Transportation and Poverty in Monroe County,” 25.
Figure 2. Monroe County Population by Location.¹

Figure 3. Change in job losses and gains 2002 to 2015.²

² "Transportation and Poverty", 7.
Recent studies have begun to indicate exactly how important transportation is to anti-poverty initiatives.\textsuperscript{1, 2, 3} The \textit{Transportation and Poverty in Monroe County} report aptly states that

The fact that the majority of jobs that low-income residents have easy access to are high-income (and therefore potentially more difficult to get for low-income residents) highlights a potential spatial mismatch between low-income city residents and the types of jobs that are easily accessible...Drivers (who are whiter and wealthier than transit riders) face easy commutes and a wide access to jobs. Those who ride the bus face very long commutes and limited access to jobs. Given these differences, the transportation system writ large reinforces the disparities that already exist in the community rather than helping to reduce them.\textsuperscript{4}

Recognizing the weaknesses with Rochester's transportation system, the new comprehensive plan, \textit{Rochester 2034}, and the corresponding \textit{Long-Range Transportation Plan 2040} are committed to improving transportation choices for Rochester residents. Bicycle and pedestrian infrastructure is a major player in this freedom of transportation choice, with the City already beginning to require alternative roadway designs for redevelopment efforts.\textsuperscript{5}

By indicating the importance of pedestrian and bicycle infrastructure through code requirements and financial investment, the City has begun to make non-automobile transportation more accessible to all income levels. With the passing of Ordinance No. 2011-356, the Complete Streets Policy (Section 104-29) has been added to the Rochester municipal code. This amendment states, “the incorporation of bicycle, pedestrian, and transit facilities shall be mandated in all street construction, reconstruction, rehabilitation, and pavement maintenance projects undertaken by or on behalf of the city, except [in conditions deemed physically or financially unsuitable].”\textsuperscript{6} Improving non-automobile infrastructure is an important first step to encourage walking and bicycling as viable modes of transportation.

\textbf{1B. BICYCLING IN ROCHESTER}

If Rochester is to address its perpetually rising poverty rate, it must recognize the correlation between access to transportation and poverty. Providing affordable and safe transportation options that truly create equal access to jobs, educational opportunities, and amenities is critical to reducing poverty. Bicycling as a mode of transportation offers the benefits of independent transportation, without the prohibitive costs of car ownership.

Bicycling as a mode of transportation is faster than walking to a destination and cheaper than car ownership. Some organizations in Rochester even provide free or extremely low-cost bikes.\textsuperscript{7} Whereas the income level required for car ownership is $46,000 per year, the income level required for bicycle ownership is essentially $0 per year. Cycling as a mode of transportation allows commuters to travel on individual timetables and access the full network of Rochester’s roadways and trail systems. In this regard, cycling can be more convenient than bus transportation.

\textsuperscript{2} Martin Wachs, “Transportation Policy, Poverty, and Sustainability: History and Future,” Transportation Research Record, 2163, no. 1 (2010).
\textsuperscript{6} “Amending the Municipal Code,” ibid.
Figure 4. Existing bike lane conditions 2011.¹

The City of Rochester has been in favor of expanding the availability and quality of bike paths across the city since it announced the 2011 Rochester Bicycle Master Plan. This plan identified major deficiencies in and opportunities for bicycle infrastructure in the City, highlighting best practices in similarly sized domestic and international cities. The Report states, “While bicycling conditions naturally vary widely throughout the City, analysis shows that the arterial and collector network provides an average bicycle level of service of “D” on an A-F scale, which is typical for communities throughout the United States but lower than the Rochester community’s articulated expectations.”

As a relatively small city, Rochester’s compactness acts in its favor by reducing the breadth of new bike lanes that need to be added or reconstructed to realize the full master plan. Existing public works programs offer the opportunity to improve road conditions for bicyclists without separate projects or excessive additional funds.

The 2011 Rochester Bicycle Master Plan outlines several key initiatives and references for guiding successful bicycling programs, in both Rochester and other snow-heavy cities, by improving:

1. Bicycle infrastructure including bike lanes, paved shoulders, shared use paths, sharrows, and bike boulevards
2. Bicycle services including bike parking, bike sharing, end-of-trip facilities, and route/wayfinding signage
3. Municipal code language that supports bicycling, including zoning changes/recommendations
4. Education and outreach programs
5. Municipal staffing commitment
6. Private sector partnerships and/or incentives
7. Snow removal strategies
8. Strategies for dealing with on-street parking when attempting to retrofit roadways

This project will seek to address the first, second, and seventh points from the Bicycle Master Plan in order to better serve cyclists and encourage cycling as a mode of transportation.

**1C. Barriers to Cycling**

Piatkowski, et al. identifies three major factors governing the limited adoption of bicycling as a primary mode of transportation: safety as it relates to infrastructure, convenience as it relates to climate, and cost. In Rochester, these concerns are equally valid.

A primary challenge to Rochester’s budding cycling network, which seeks to be addressed in the Rochester Bicycle Master Plan, is the lack of designated bike lanes with clearance lines separating traffic from cyclists. Roads in Rochester are often excessively wide, meant only to accommodate automobiles, making left-hand turns extremely difficult. Many city streets lack shoulders on which to safely ride, instead providing “shared use” signage to alert drivers that cyclists may be riding in driving lanes. Figure 5 illustrates the lack of bicycle-only routes and roadway accommodations in Rochester. Additionally, many cyclists’ lack knowledge about how to ride safely in the road and on trails. Unaccommodating automobile drivers make Rochester’s cycling network particularly unaccommodating to cyclists. Figures 4 and 5 outline the poor condition and scarcity of cycling infrastructure in Rochester.

---

iii “Rochester Bicycle Master Plan.”
### Figure 5.
Map of existing bicycle infrastructure in Rochester.\textsuperscript{i}

### Table: Weather Indicators for Peer Bicycling Cities

<table>
<thead>
<tr>
<th>Weather Indicator</th>
<th>City</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Boulder</td>
</tr>
<tr>
<td>Yearly Rain (Inches)</td>
<td>21.4</td>
</tr>
<tr>
<td>Yearly Snow (Inches)</td>
<td>95.0</td>
</tr>
<tr>
<td>Average April-September Temperature (°F)</td>
<td>63.4</td>
</tr>
<tr>
<td>Average October-March Temperature (°F)</td>
<td>39.3</td>
</tr>
</tbody>
</table>


\textsuperscript{ii} US Climate Data, https://www.usclimatedata.com/

\textsuperscript{iii} ClimateData.org, https://en.climate-data.org/
Other challenges for cyclists in Rochester are the extended period of winter road conditions and unpredictable precipitation events. Specialized tires and braking systems often become necessary for winter cyclists as many cycling lanes and road shoulders remain unplowed. In precipitation events, cyclists are likely to avoid travel by bicycle, opting to utilize other modes of transportation.¹

However, other cities in variable climates have shown that it is possible to have successful bicycling networks, encouraging citizens to use this mode of transportation year-round. Copenhagen, Montreal, Denver, Boulder, Madison, and Seattle all have robust and well-used infrastructure from the height of summer to the depths of winter.² Each of these cities is united by several characteristics that support cycling enthusiasts and commuters: wide-spread systems of designated bike routes, allocated space on roadways, well-maintained infrastructure, and knowledgeable and accommodating automobile drivers.³ While these characteristics help to ensure the continuation of cycling in the city, a critical mass of cyclists is also necessary. Motivation for citizens to pursue bicycling as a form of transport or recreation include: benefits to health and well-being, minimization of fuel costs, avoidance of traffic congestion, and environmental concern.⁴ It can be reasonably assumed that the citizens of Rochester could be driven by similar motivating factors, and thus would cycle if convenient and accessible.

Of the cities studied for the Rochester Bicycle Master Plan, Madison, WI far outshone by dedicating 63 miles of bike sharrows and paved shoulders, three bike boulevards, and 134 miles of bike routes.⁵ In order to combat snow accumulation and removal on designated bike lanes, peer cities have implemented several strategies. Boulder, Colorado employs a dedicated snow-removal crew on its off-street bike trail system, and Montreal regularly plows its White Network, a 19 mile system of bike lanes. However, almost no cities have a dedicated snow-removal plan for urban bike paths. Instead, they simply allot “a reasonable time” for snow to be cleared from bike paths.⁶

Other psychological and physical barriers exist that limit ridership numbers in Rochester, including safety concerns, and lack of infrastructure. Piatkowski, et al. outline some of these barriers, and how they may be overcome:

> Bicycle route planning that avoids significant elevation change and prioritizes access to destinations over recreational routes can make bicycling more convenient relative to other modes. Convenience may also be closely associated with at work amenities. An enhanced focus on amenities like showers and bike storage can significantly impact bicycling to work (Geus et al. 2007; Pucher et al. 2011) and may offer an important solution for addressing barriers.⁷

For modern cities, filled with automobiles, bicycles, and pedestrians, incidents of casualties caused by collisions with automobiles can be high. In the European Union, pedestrian and cycling deaths combined account for 29.2% of all motor-vehicle fatalities, with bicycles accounting for 8.0%⁸ of that statistic.⁹ In contrast, the United States reports that pedestrian fatalities...
### Type of Collision

<table>
<thead>
<tr>
<th>City</th>
<th>Bicycle/Auto</th>
<th>Pedestrian/Auto</th>
<th>Auto/Auto</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>793/3,318 (24%)</td>
<td>416/3,318 (13%)</td>
<td>1,528/3,318 (46%)</td>
</tr>
<tr>
<td>Boulder, CO</td>
<td>183/3,275 (6%)</td>
<td>57/3,275 (2%)</td>
<td>3,035/3,275 (92%)</td>
</tr>
<tr>
<td>Montreal, QC</td>
<td>42/1,898 (2.2%)</td>
<td>334/1,898 (17.6%)</td>
<td>1,522/1,989 (80.2%)</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>30/1,000 Commuters</td>
<td>78/10,000 Residents</td>
<td>11,603 Total Collisions</td>
</tr>
<tr>
<td>Rochester, NY</td>
<td>157/4,319 (4%)</td>
<td>252/4,319 (6%)</td>
<td>3,247/4,319 (75%)</td>
</tr>
</tbody>
</table>

Figure 7. Types of roadway collisions by city and vehicle.

### Primary Mode of Transportation

<table>
<thead>
<tr>
<th>City</th>
<th>Automobile</th>
<th>Walking</th>
<th>Bicycling</th>
<th>Public Transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copenhagen, DK</td>
<td>34%</td>
<td>19%</td>
<td>29%</td>
<td>18%</td>
</tr>
<tr>
<td>Boulder, CO</td>
<td>58%</td>
<td>19%</td>
<td>18%</td>
<td>5%</td>
</tr>
<tr>
<td>Montreal, QC</td>
<td>74%</td>
<td>7% (Combined)</td>
<td>12%</td>
<td></td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>52%</td>
<td>12%</td>
<td>4%</td>
<td>23%</td>
</tr>
<tr>
<td>Rochester, NY</td>
<td>70%</td>
<td>6%</td>
<td>1%</td>
<td>8%</td>
</tr>
</tbody>
</table>

Figure 8. Primary mode of transportation per city.

### Kilometers Cycled to Fatalities

<table>
<thead>
<tr>
<th>Country</th>
<th>Bicycle travel per inhabitant (km)</th>
<th>Cyclists killed per billion km of bicycle travel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Netherlands</td>
<td>864</td>
<td>10.7</td>
</tr>
<tr>
<td>Denmark</td>
<td>513</td>
<td>14.6</td>
</tr>
<tr>
<td>Germany</td>
<td>368</td>
<td>15.2</td>
</tr>
<tr>
<td>Switzerland</td>
<td>261</td>
<td>18.4</td>
</tr>
<tr>
<td>Finland</td>
<td>267</td>
<td>20</td>
</tr>
<tr>
<td>France</td>
<td>88</td>
<td>27</td>
</tr>
<tr>
<td>UK</td>
<td>75</td>
<td>28.1</td>
</tr>
<tr>
<td>Korea</td>
<td>196</td>
<td>32.5</td>
</tr>
<tr>
<td>US</td>
<td>47</td>
<td>44</td>
</tr>
</tbody>
</table>

Figure 9. Cycling and safety per OECD country.

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16 Background
fatalities account for 14% of total roadway fatalities, with bicyclists only accounting for 2.3% of these deaths.¹

Several case study cities in Europe and North America show that between bicyclists, pedestrians, and automobiles, the majority of collisions are between automobiles (See Figure 7). From this small sample it can also be observed that pedestrian and automobile accidents are more likely than bicycle and automobile accidents. The notable exception is Denmark,² where bicycle and automobile collisions are about 20% more likely than in North American cities and are the second-most common collision type, at 24% of all collisions.³

At first glance it would seem that U.S. cities are safer places to travel via bicycle compared to European cities. However, ridership numbers must be taken into account. Fewer commuting cyclists on the road will result in statistics skewed toward fewer casualties. As the Figure 8 shows, Denmark has 28% greater ridership numbers than Rochester, NY, and significantly fewer automobiles on the road. Indeed, nearly 50% of Copenhageners walk or bike as their primary mode of transportation, compared to 7% of Rochesterians.

The Organization for Economic Cooperation and Development (OECD) has studied this correlation in depth and found that although casualties are more likely to occur in countries with higher rates of primary travel on bicycles, it is also true that greater number of miles traveled by bike leads to a lesser rate of collision instances over time (see Figure 9).⁴ The old adage of “safety in numbers” is still true where cycling is concerned. Increased cycling ridership equates a healthier community, yet increased ridership also equates higher rates of collision and greater overall risk. Few planning commissions include equitable provisions for massive improvements to bicycle and pedestrian infrastructure, which is necessary to help lower risk to drivers, cyclists, and pedestrians alike.

As a model city for bicycle infrastructure, Copenhagen, Denmark has shown that investment in bicycle infrastructure decreases casualty rates. The 2017 Copenhagen City of Cyclists report states that cyclists felt 60% safer after the city installed separated bicycle tracks. This improvement increased cyclist numbers by 15-20%, about the same percentage of decreased cyclist casualties in Copenhagen during the same time.⁵ When comparing Rochester’s prevalence of bicycle tracks and lanes to other case study cities, Rochester has significantly less mileage dedicated to bicyclists only (See Figure 10). This not only increases risk to cyclists who choose to ride in the City, it also discourages potential cyclists from attempting cycling as a primary mode of transportation.

In order to put more cyclists on the road, cities including Rochester need to focus on creating safe passage for riders. Infrastructure improvements are critical to improving cycling numbers in the City of Rochester.

---

² “Road accident fatalities.”
<table>
<thead>
<tr>
<th>City</th>
<th>Population</th>
<th>Bike Lane/Sharrow/Paved Shoulder (miles)</th>
<th>Shared Use Path (miles)</th>
<th>Bike Boulevard (miles)</th>
<th>Bike Route (miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boulder</td>
<td>107,125</td>
<td>37</td>
<td>9</td>
<td>Informal</td>
<td>43</td>
</tr>
<tr>
<td>Montreal</td>
<td>1,780,000</td>
<td>25</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Minneapolis</td>
<td>422,331</td>
<td>44</td>
<td>84</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Madison</td>
<td>255,214</td>
<td>63</td>
<td>42</td>
<td>3</td>
<td>134</td>
</tr>
<tr>
<td>Rochester</td>
<td>208,046</td>
<td>6</td>
<td>22</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 10. Existing bicycle infrastructure in peer cities.

Figure 11. Educational, civic, and community points of interest in the street network of Rochester.

i “Rochester Bicycle Master Plan,” 16.
2. Urban Framework in Rochester

2A. Existing Framework

The existing transportation fabric of Downtown Rochester can be characterized as discontinuous. Though employment, entertainment, economic, civic, and residential opportunities are becoming more widespread in the center city, the continuity of streets, pathways, city blocks, and places of interest does not reflect the same development. The 2014 Center City Master Plan identifies discontinuous or sparsely developed city blocks and overly large city blocks as current issues. Also mentioned is the over-reliance of automobile travel to, and overabundance of surface parking around destinations on the City. The city recognizes that “national trends are beginning to show a decline in per capita automobile use, especially among young people,” but asserts that “accommodating vehicles in a way that does not negatively impact the urban fabric of Downtown” is still necessary in the present term.

As shown in Figure 11, Rochester is host to major employment districts, academic institutions, cultural and entertainment venues, public spaces, and basic amenities. Primary, secondary, and higher education schools are shown as well as locations of publicly accessible venues for recreation, such as parks, plazas, and squares, and entertainment, such as major concert halls and sports arenas. Schools are dispersed throughout the city, while recreation and entertainment areas densely populate the center city. Large-scale points of interest, such as Blue Cross Arena, Frontier Field, and governmental buildings, are located within the Inner Loop and are indicated on the map. Neighborhood-scale points of interest, such as community centers, social services, art galleries, and grocery stores are located farther away from the center city and are not shown on the map. Special events and festivals hosted by the City of Rochester often take place in public spaces in the center city. Midtown EATS takes place in Midtown Plaza; Party in the Park music festival and the Rochester Holiday Village utilize Martin Luther King, Jr. Park; the International Jazz Festival, Fringe Festival and a multitude of parades utilize streets and parking lots in the East End.

As Figure 12 shows, a major portion of downtown Rochester is devoted to wide streets, with the Inner Loop highway cutting a wide swath through the urban framework. Surface parking occupies about 20% of land in downtown. In contrast, quality of pedestrian corridors are generally low when rated on a walkability scale. Additionally, bike routes throughout the city, though expanding due to the Bicycling Master Plan initiatives, are still few. Figures 5 and 13 show few continuous dedicated bike lanes throughout the center city. Even fewer exist outside of the area within the Inner Loop.

The diameter of downtown Rochester is approximately one mile, measured from I-490/Inner Loop split at the west and the Inner Loop/Main Street intersection at the east. It is generally accepted that pedestrians are willing to walk about half a mile to a destination and cyclists are willing to bike about 1 mile to a destination other than a commute. Although distances between points of interest in downtown Rochester are generally within these parameters, most visitors to downtown choose to drive due to the vast network of roadways, accessibility to parking, and poor quality and connectivity of pedestrian and cycling pathways.

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ii “Rochester Center City Master Plan 2014,”: 34-35.
iii ibid: 28.
iv ibid: 28.
v “Rochester Center City Master Plan 2014,”: 29.
vii “Strategic Cycling Analysis,”: 8
Figure 12. Surface parking, pavement, and pedestrian corridors in downtown Rochester. Walkability indicators based on a 10-point scale.

Figure 13. Bicycle infrastructure in downtown Rochester.

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ii “Center City Master Plan 2014,”: 27.
Rochester’s street network can be described as a radiating arrangement of boulevards converging within the Inner Loop highway. Within the Inner Loop, most vehicular corridors change to avenues with lower speed limits, design speeds, and total length of road. Figure 11 shows that a greater percentage of higher-speed boulevards exist in lower-income areas north of the central city, whereas wider residential blocs populate more affluent neighborhood to the south and east.\footnote{The AIA Street Classification System was used to categorize street types. By the AIA definition, boulevards are “A long-distance, medium speed vehicular corridor that traverses an urbanized area. It is usually lined by parallel parking, wide sidewalks, or side medians planted with trees. Buildings uniformly line the edges.” American Institute of Architects, Architectural Graphic Standards, Ninth Edition. J.R. Hoke, Jr., ed., 1996.}

Rochester’s bus network tends to follow the network of wider streets in the city, utilizing major boulevards and avenues in a “wheel and spoke” model: bus routes converge at the Transit Center then radiate outward toward the extents of the city. The bus service coverage map is extensive, however there are significant gaps in service to areas within the Greater Rochester area. When overlaid with data indicating areas of job growth (Figure 14), service coverage is more sparse. Large areas of job growth such as Pittsford, Henrietta, and Webster are at some points completely disconnected to bus coverage. Though bus routes are widespread in areas of high poverty, transportation to areas with greater employment and educational opportunities is difficult. Figure 15 indicates that it takes significantly longer to reach employment and educational centers by bus than by private automobile. For this example, the Edgerton Neighborhood was chosen as the origin point as it is identified as one of the poorest areas in the City.\footnote{“Neighborhood Data Base Maps,” City of Rochester, last updated 2014, https://www.cityofrochester.gov/neighborhooddatamap/} Residents here are less likely to own a car, and more likely to use the bus network. The four destination locations were chosen as example areas of high or growing employment opportunities, centers of education, and locations of recreation and entertainment. Of the four methods of transportation, bus travel took significantly more time than automobile and cycling.

\section*{2B. Areas of Opportunity}

The Center City Master Plan of 2014 lays out a broad range of action items to improve life in Rochester and fulfill the fundamental vision of “Lively Streets.”\footnote{“Center City Master Plan 2014.,” 36.} Several areas within this Master Plan are already designated as potential areas of connection where the city hopes to infill overly empty blocks, restore ground-use spaces, renovate public spaces, and remove some major infrastructure barriers.\footnote{“Center City Master Plan 2014.,” 34.}

Further analysis indicates opportunities to connect the urban fabric by creating better pedestrian and cycling infrastructure to complement City initiatives. Just as bus routes generally follow boulevards and avenues for speed and efficiency, improved cycling infrastructure should make use of these roadways to create the fastest non-automobile routes through the city. The network of cross streets that transverse boulevards and avenues is already primed to support pedestrian and cyclist infrastructure. However, creating cycling infrastructure on smaller streets, roads, alleys, and so on, would also encourage cycling as a safe option to travel between origin and destination, or to another method of transportation for longer journeys.

Consideration must also be given to connecting the city on a human scale. Areas of high poverty and decreasing employment opportunities should have easy, non-automobile focused commutes to areas with growing employment opportunities, educational services, and recreational areas. The center city of Rochester, where poverty is highest and car ownership is lowest should be considered for bicycle infrastructure investment as a means to quickly transverse the city to any destination.
Figure 14. Bus route network map and areas of 50% or more job growth, in blue, in Rochester.

<table>
<thead>
<tr>
<th>Origin</th>
<th>Destination</th>
<th>Time (Minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edgerton Neighborhood (Lorimer Street)</td>
<td>Strong Memorial Hospital (Major Employer)</td>
<td>15 34-45 75 26</td>
</tr>
<tr>
<td>Edgerton Neighborhood (Lorimer Street)</td>
<td>Calkins Corporate Park (Area of Job Growth)</td>
<td>18 80 170 56</td>
</tr>
<tr>
<td>Edgerton Neighborhood (Lorimer Street)</td>
<td>Rochester Institute of Technology (Educational)</td>
<td>16 100 135 41</td>
</tr>
<tr>
<td>Edgerton Neighborhood (Lorimer Street)</td>
<td>Martin Luther King Jr. Park (Urban Plaza)</td>
<td>9 30 45 14</td>
</tr>
</tbody>
</table>

Figure 15. Travel times by mode of transportation, estimated by Google Map services.

Given the statistics of extreme poverty in the city, Rochester should prioritize creating transportation routes that are safe and accessible to all citizens, no matter individual economic means. Less focus on automobile infrastructure and greater focus on pedestrian and cycling infrastructure would help to create a continuous urban fabric in the city. By creating logical, continuous pathways through the city without the need for vast amounts of pavement and surface parking, Rochester would start to achieve its goal of “lively streets.” Streets would become easier to navigate; employment districts, educational institutions, and public spaces would become faster to reach without an automobile; economic and health benefits could extend throughout the city.

¹ “Center City Master Plan 2014,” 36.
Figure 16. Map of London's cycling network.¹

3. TRANSPORTATION AND URBAN FRAMEWORKS IN PRECEDENT CITIES

3A. CYCLE SUPERHIGHWAYS, LONDON

London has been redesigning its relationship with cycling on city streets since the early 2000s. As outlined in the Strategic Cycling Analysis report, the Mayor of London has prioritized “plans for Healthy Streets...to help Londoners use cars less and walk, cycle and use public transport more.” Concerns about air pollution and the negative health consequences of a sedentary lifestyle prompted the City of London to investigate the possibility of making cycling, pedestrian, and mass transit routes more accessible, convenient, safer, and generally more attractive than private automobile usage throughout the city.

London’s transportation planning arm, Transport for London, extensively studied the interaction between cycling and pedestrian movement, and private and mass automobile traffic. That study, the Strategic Cycling Analysis, led to significant investment in cycling infrastructure throughout London. Three types of cycling-centric routes have been built since 2016: Cycle Superhighways, Quietways, and Mini-Hollands. The “Cycle Superhighways aim to provide protected space for cycling on some of London's busiest roads. They connect tube stations, town centres and key destinations, making them more accessible and easier for people to cycle to.”ii Quietways offer less-busy routes via which to travel while; Mini-Hollands create pleasant and safe experiences for pedestrians, cyclists, and mass-transit riders.

Though post-construction analysis is not published, each infrastructure solution implemented by Transport for London has provided safer routes for cyclists and pedestrians in several ways. All nine of the current and proposed Cycle Superhighways have physically separated cyclists from automobiles via curbing as well as re-timed traffic signals, and relocated bus stop locations. Pedestrian crosswalks and cycling lanes have also been prioritized on busy streets. Some Cycle Superhighways, like Superhighway 9, also aim to reduce automobile cross-traffic on residential streets.iii

In tandem with the Cycle Superhighways, the Mini-Holland program further links cycling to the urban environment. The Mini-Holland program invests in the infrastructure of town centers to create safe, convenient, and enjoyable destinations for cyclists and pedestrians.iv Each of the proposed locations has been identified as a key connection point between other alternative transportation routes, centers of employment, and residences.

Also of note are the location of two of the three Mini-Holland locations within identified nodes of poverty within the City of London. Figure 17 shows that Enfield and Waltham Forest both have poverty levels ranging from 10 to 40 percent of the population, with Waltham Forest exhibiting a more uniform poverty level of about 30 percent of the population.v While the Strategic Cycling Analysis report does not specifically identify poverty reduction as a goal of the Mini-Holland and Cycle Superhighway programs, it can reasonably be assumed that the selection of these areas for investment was partly driven by economic factors such as poverty.

The strategy of linking alternative transportation routes with the broader urban context is part of the goals outlined by the

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iii “Cycle Superhighway 9,” ibid.
iv “Mini-Hollands,” ibid.
Figure 17. Poverty rate estimates in London.\textsuperscript{i}

Strategic Cycling Analysis to “[improve] the connectivity of Londoners to jobs, services and public transport.” Without these connection points, it is possible that larger cycling routes like the Cycle Superhighways would lack integration into areas where people live, work, and play. Benefits such as increased economic activity, cleaner air, better health, and more aesthetic town centers are expected in Mini-Holland locations due to increased pedestrian and cyclist activity.

3Ai. Integration in Rochester

The connectivity of Rochester's urban environment is fragmented. Bus routes and cycling infrastructure often do not align in a way that is convenient for travelers to transfer between the two methods of transport. Likewise, bus and cycling routes often do not directly or conveniently serve the densest areas of population, employment, and commercial activity.

The programs pursued by Transport for London, Cycle Superhighways, Mini-Hollands, and Quietways, should serve as a best-practice example for Rochester to follow when considering expansion of alternative transportation routes. The research conducted prior to each infrastructure investment clearly outlined the connections of cycle and pedestrian routes to the broader urban context of London. Planning cycling routes to align with the densest areas of population, employment, and commercial activity created a transportation network that encourages alternative transportation. In the Walthamstow Village study for the Mini-Holland program, investment aimed to make transportation accessible to all: “With just over 40% of households with no access to a car and the number of people cycling on the increase [there is a] need to continue making...streets safer, while also improving access to public transport.” After construction completion, Waltham Forest saw an uptick in the cycling population: “In our 2016 resident insight survey, 17% (approx. 46,100 people) said they cycle, compared to 12% (approx. 32,500 people) the year before – and two-thirds (73%) said they cycle at least once a week, up from 62% in 2015.”

The increase in cycling based on route availability and connectivity to urban areas also led to an almost 50% decrease in automobile traffic in the area (8,493 average daily vehicles to 4,808 average daily vehicles post-construction).

Rochester should apply the same principles of infrastructure connectivity to replicate similar results to London’s transportation programming. Following London’s example could lead to a better connected urban framework, benefiting all residents, regardless of income. Connecting areas of extreme poverty to all areas of the city by creating aesthetic and well-designed infrastructure solutions is a concept that should be widely applied.

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i “Strategic Cycling Analysis,” 25.
iii “About Mini Holland.” ibid,
iv “Strategic Cycling Analysis,” 47.
Figure 18. Bicycling System Map, Berlin.

Figure 19. Rendering of a section of the proposed Radbahn cycle path.

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3B. Radbahn, Berlin

In Berlin, about 13% of daily commuters utilize cycling as a mode of transportation. Berlin's cycling infrastructure is extensive, connecting many areas of the city via protected bike-only paths, on-road cycling lanes, and off-road routes in and around the city. This well-established and functional system will be expanded when thirteen new bike “superhighways” are completed in the next few years. Figure 18 indicates that the bicycle infrastructure in Berlin tends to follow main roads and is equitably distributed throughout the city, providing equal access to bike transportation regardless of urban geography.

However, none of the current bicycle paths in Berlin are covered and protected from environmental conditions. A new concept plan developed by the non-profit group paper plans, e.V. changes that. The Radbahn project is a proposed nine kilometer cycling route that would connect Berlin via an east-west artery through the city. The proposed route is located directly under the existing U1 elevated subway line, in order to create a direct route through the city and provide protection for cyclist underneath the structure. As well as creating a protected area for Berlin's cyclists to ride, the project also centers around revitalizing the neglected area under the U1. Project planners proposed transforming the space from city parking “into a major urban thoroughfare and create a space for contemporary mobility, innovation, and leisure.”

The Radbahn project is a useful precedent in several ways. First, it is the first major municipally-funded cycling infrastructure project that intends to provide a covered route for travelers. To knowledge, all other cycling infrastructure projects are surface-only, providing ground level space but no covered protection. When constructed, the Radbahn project will provide a central route through the city whereby travelers may be protected from inclement weather for all or part of a trip. As outlined by the Piatkowski 2015, a major factor for potential cyclists not commuting by bike is the potential for inclement weather. By creating a covered bike path, the Radbahn may remove this barrier to cycling, increasing ridership in Berlin.

Second, the Radbahn design concept is an excellent example of how bicycle infrastructure can benefit the urban environment through seamless integration into larger transportation networks and compelling urban design. Stated major goals of the project are to improve social equality, environmental health, economic well-being, and the urban network of parks, public spaces, and transportation hubs through urban design. The Radbahn project not only creates a transportation route through the city, it also proposes investment in the urban design of Berlin. Under the scheme, currently derelict spaces would be beautified while creating useful connection points for transportation, social interaction, and economic exchange. By following the path of the U1, bicyclists would have ready access to Berlin’s subway system and other bus, car, and bike transportation networks that cater to it. The Radbahn also includes plans to connect to public spaces like the extensive network of public parks, canalways, street markets, open air art exhibitions and performance spaces (see Figures 20 and 21). Tying the Radbahn into the urban environment of Berlin is a necessary step for the project to meet its goals.

3Bi. Integration in Rochester

Although Rochester does not have an existing elevated roadway to utilize, it is still possible to apply some of the concepts of

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Figure 20. Proposed Radbahn route through Berlin.¹
Figure 21. Existing public spaces surrounding the proposed Radbahn route Lausitzer Platz.²

² “Radbahn.”
the Radbahn project to Rochester’s cycling infrastructure. First, the Radbahn’s carefully considered integration into the greater urban environment should be applied to cycling infrastructure projects in Rochester as well. Thought must be given to how bicycle lanes will connect to bus routes, residential areas, job and economic hubs, places of interest, and public spaces. If Rochester is able to create a logical and convenient network for bicycle transportation, emulating Berlin’s network, Rochester should see an increase in bike ridership and decrease in automobile usage.

Second, the Radbahn project makes a strong case for covered bike lanes in Rochester. As the project states, “Having a roof over your head is a basic human necessity...A roof provides shelter, a home and a sense of security.” The covered path of the Radbahn not only provides protection from precipitation but also creates a sense of security in a high-traffic area. Both issues have been cited as important factors when deciding to cycle. The Radbahn project shows a successful solution to both issues. The U1 subway line is a convenient roof for the project in Berlin, but Rochester will need to utilize alternative means to protect cycling lanes.

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i “Radbahn.”

Figure 22. Photo of Janet Echelman’s aerial sculpture “As if It Were Already Here” over the Rose Kennedy Greenway in Boston, 2015.¹

Figure 23. Photo of Janet Echelman’s aerial sculpture “As if It Were Already Here” at night.²

4. THE CASE FOR TENSILE FABRIC ARCHITECTURE

4A. TENSILE FABRIC STRUCTURES AS PLACE-MAKERS

As shown by the projects above, bicycling networks provide more than additional transportation options in urban areas. Cycling networks also engage travelers with the urban landscape, encouraging interaction on an economic, social, and environmental level. The Radbahn, Cycle Superhighway, and Mini-Holland projects outlined above exemplify the importance of continuity between transportation routes and platforms for engagement. Sense of place and sense of arrival are also two concepts that contribute to the overall functionality and harmony of cycling infrastructure and the urban environment. Place-making has the potential to bring communities together, united by a common sense of familiarity and comfort in an urban pace. It encourages comprehensive utilization of space to include transportation networks, building usage typologies, and engagement at street level.

Applying the concepts of place-making to Rochester would help to re-knit the urban fabric. Creating street-level connections via pedestrian and cycling routes throughout the city, extending routes to connect with residential areas, low-income areas, centers of urban activity, educational opportunities, and employment hubs would all help with the process of creating a city that is engaging. Combined with the city of Rochester’s initiatives to break up large blocks and oversized surface parking lots with ground-level uses, cycling and pedestrian infrastructure improvements could truly transform Rochester.

Several projects have utilized tensile fabrics to successfully transform under-appreciated, underutilized, or undefined areas into hubs of activity, interaction, and beauty. Each created a sense of place within a city as well as a destination point. Additionally, each project seamlessly integrated with surrounding transportation networks, facilitating ease of way-finding in large urban areas.

4Ai. Janet Echelman Aerial Sculpture in Boston

Sculpture artist Janet Echelman “reshapes urban airspace with monumental, fluidly moving sculptures that responds to environmental forces including wind, water, and sunlight.” Echelman’s suspended structures are created with a variety of textiles including polyethylene, polyester, twine, and embedded LEDs. The structures are meant to interact with their environment, creating a sense of place often described as “knitting together the urban fabric.”

A sculpture created for Boston’s Rose Kennedy Greenway is particularly relevant to the needs of Rochester. The textile installation, raised 600 feet in the air and spanning an area of 20,250 square feet, is meant to reinvigorate urban park space reclaimed after the deconstruction of an expressway through downtown Boston. The Rose Kennedy Greenway is a pedestrian and cyclist only urban park, linking sections of the city that were previously separated by high-speed traffic. The newly opened park not only provides opportunities for recreation and alternative transportation, but a chance for a community to be reunited. The woven and knotted structure serves to create a sense of place in the center of the park where the Boston

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iv “Janet Echelman Chronology,” ibid.
Figure 24. Tensile fabric structures installed for LuminoCITY Detroit, 2017.¹

¹ Stereobot, photograph, 2017, luminocitydet.com
community could linger, strike up conversation, and break down barriers.\textsuperscript{i,ii}

The choice of materials for the structure was critical to the success of the project. Textiles allowed Echelman to create a structure light enough to be lifted into the air, widely visible to the surrounding area. The structure could then act as a beacon or way-finding tool to funnel visitors to the park. Creating a sculpture with fluidity was key to the installation's interaction with its environment. The ultra-strong but lightweight textile fibers and LED nodes were able to flow in wind currents and change colors in differing lighting levels, creating a unique experience for every visitor.

In this case, the use of color both in the textile fibers and LED lighting nodes helped to make the sculpture a centerpiece of the Greenway. Bands of colored textiles were used to create deeper meaning in the sculpture, connecting symbolic colors to the history of the site; LED nodes illuminated the beacon, fluctuating according to environmental conditions.

Finally, the aerial sculpture also served as a roof, albeit permeable, over the park. One of the basic principles of human needs is shelter; by creating a roof under which a community could gather, Echelman also created a place of basic human comfort.

\textit{Application in Rochester}

The novel use of textiles in Echelman’s aerial sculpture in Boston to create a community-centered urban space is one that can be applied to cities like Rochester. As Echelman has shown, textiles are an excellent canvas for experimental, temporary, and unexpected forms. Like in Boston, textile forms can be applied to the urban landscape to shape not only the physical space but psychological interpretations of the urban environment as well.

Tensile forms may act as a visual guide, distant focal point, source of shelter, or definition of space in the urban fabric of Rochester. By mimicking Echelman’s use of lightweight textiles, a network of transportation pathways and urban destinations can be formed to unite Rochester’s community. The flexibility, ease of installation, and durability of textiles are appealing for the Rochester climate. And the adaptability of tensile architecture through material choice, coloration, lighting, pattern, and mounting height means that the concept can be applied in varied applications throughout the city. Larger installations of tensile fabric may serve as a focal point for travelers, identifying urban places of interest and larger areas of refuge. Smaller installations should be used for pedestrian and cycling route coverings lending all the benefits of textiles to an otherwise simple source of shelter.

\textit{LuminoCITY, Detroit}

In 2016, the City of Detroit used textile structures to “help create an environment that encourages people to walk and discover downtown.”\textsuperscript{iii} An installation of 16 textile sculptures, designed and installed by Stereobot, were placed at strategic locations in downtown Detroit forming a corridor of “public spaces, shops, restaurants, cultural institutions, galleries, and events.”\textsuperscript{iv}

\textsuperscript{ii} “As If It Were Already Here, Boston, MA, 2015,” ibid.
The installation was timed to coincide with the North American International Auto Show in the hopes of creating a more interactive downtown experience for Detroiter and visitors alike. Crucially, each installation was located within a several minute walk from the next, creating a network that could be accessed without the use of automobiles.

The Stereobot sculptures consisted of tensile fabric wrapped over space frame skeletons. Each sculpture was unique in shape, color, and lighting effects in response to the site and intention of each location. A large gateway, reaching over 100 feet tall, was placed at the start of the installation corridor, announcing the point of arrival. Other sculptures acted as invitations for interaction with the space: large plazas featured large, twisting sculptures mimicking movement and social interaction in these large urban areas. Finally, smaller sculptures placed at intervals along the installation corridor served as beacons, encouraging continued travel along the pathway and serving as way-finding tools.

According to Stereobot, the use of textiles as a building material is meant to create a sustainable combination of “economy of means, time and materials while simultaneously empowering the designer with a flexible and versatile set of tools for the resolution of complex interactions between structure, space and the environment.” In the case of the Detroit installation, the tensile fabric architecture installations created aesthetic appeal while adapting to wind and snow loads. Additionally, as a temporary installation, the tensile fabric structures were able to be assembled and disassembled quickly and materials reused for other projects. Stereobot indicates that sustainability of tensile fabric structures is a major factor in the firm’s method of design and construction: tensile fabric structures can be reused, recycled, cost less to ship, are easier to install, and can create stunning effects without damaging the environment.

Application in Rochester

The LuminoCITY project demonstrates the effectiveness of utilizing tensile fabric structures as a tool to invigorate the urban environment. Had a more solid form of sculpture been used, the effect would have been completely altered. In all likelihood, a non-tensile structure would have been necessarily smaller and shorter, limiting visibility from afar. Textiles also allowed light to be used in a spectacular fashion, engaging city-goers with colorful displays and gently guiding visitors through designated corridors.

The versatile nature of tensile architecture would be a benefit to Rochester, particularly to create urban spaces that are engaging and useful. Utilizing textiles as both canvas and structure for urban destination and way-finding tools would directly apply to the concept of a bicycle network canopy in Rochester. Bicycle network canopies could utilize similar textiles: the products used to create LuminoCITY were able to withstand typical Northeast weather conditions and maintain structural and aesthetic integrity. Points of interest throughout the city of Rochester could be identified by alternative shapes of tensile structures, different lighting schemes, or increased scale factors. Additionally, LuminoCITY shows that a similar concept in Rochester could be easily installed, dismantled, relocated, and reused.

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ii “Stereobot,” ibid.
4B. TENSILE FABRIC STRUCTURES AS PEDESTRIAN SHELTER

Whereas large-scale textile projects may be utilized to define and order large urban spaces, smaller-scale tensile fabric projects are often used to provide shelter over more compact areas. The projects below utilize tensile fabric architecture in lieu of traditional architectural products and designs for textiles’ superior performance when compared to weight, durability, ability to be transported, and aesthetic quality.

4Bi. Denver Union Station Train Hall, Denver

Skidmore, Owings & Merrill (SOM) was tasked with designing a structure that would both protect train passengers from the elements and span the 180 feet across multiple train platforms. The project was not intended to support interior uses, thus SOM was able to be designed as an “efficient and formally expressive...response to a series of programmatic requirements.”

The tensile fabric canopy sweeps over the passenger platforms in a series of shell-like arches, supported by steel trusses. A large, open-air oculus over the train tracks allows sunshine to permeate the platforms.

The result is an aesthetic structure that provides shelter for train passengers while simultaneously creating “a new grand civic space for the city of Denver.” By utilizing tensile fabric, Denver Union Station was able to achieve several unique characteristics. The overall design effect of the tensile fabric structure is that of lightness and mobility: curvature of the structure visually underlines the movement associated with train travel. Additionally, the tensile fabric, by being a thin, light transmissive, and reflective material, helps to create a bright, friendly, protective structure in both daylight and nighttime conditions. During daytime hours, the tensile fabric diffuses direct sunlight creating comfortable shaded areas below; during nighttime hours, the fabric reflects and absorbs site lighting to create a uniformly well-lit, safe environment. As interior light is reflected off the white tensile fabric roof, views from the exterior are welcoming without feeling overly obtrusive into surrounding areas. Had a solid material been chosen for the structure, the warm, diffuse glow of the Station may have been lost.

Finally, because SOM used tensile fabric architecture, the design of Denver Union Station is both entirely unique and perfectly suited to the project. The overhead canopy provides shelter for the entire station, via a single structure that is both massive in span yet not overwhelming in scale. The structure's height is taller where it acts as an urban beacon and sweeps downward at passenger platforms where a more human-scale is needed. Tensile fabric provides a graceful solution for this programmatic requirement.

4Bii. Porirua Shopping Centre, Wellington, NZ

The central shopping district of the New Zealand town of Porirua chose to utilize tensile fabric architecture to create a protected area for shoppers. An 87,000 square foot tensile fabric canopy stretches between local shops and cultural centers along the main street of Porirua to create a weather-free but open-air shopping experience. Though only 328 yards wide, sections of tensile cones repeat down the entire street. “The resulting continuum of canopies creates a light-filled, open-air feeling during the day; at night the shapes are softly illuminated, which gives the town center a welcome touch of glamor.”

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ii Ibid.
By utilizing tensile fabric for this project, the entire street was able to be transformed into a welcoming, safe passage for shoppers, visitors, pedestrians, and cyclists. The open-air aspect of the canopy also creates an atmosphere that rejects the enclosed feeling of shopping malls, the major competitor of Porirua's shopping district. Oculi in the tensile fabric allow direct light and sea breezes to enter the space below, but shield almost all areas from inclement weather.

The bright white canopy acts like a beacon in the center of the community, a meeting place in which to gather, and a pathway down which to travel. By floating lightly above the street, the tensile canopy ties the district together without restricting growth and dynamic change in the urban fabric. Tensile fabric architecture was the appropriate solution to stimulate economic growth, and community activity to the urban center of Porirua.

4Biii. United Nations Porte Cochere
In response to the need for a temporary, sustainable, yet functional canopy system, the United Nations chose to employ a tensile fabric structure. Devised to protect visitors to the temporary UN Assembly building in New York from foul weather, a transportable porte cochere was developed by FTL Design Engineering Studio. “Drawing its inspiration from the surrounding landscape, the canopy...[utilizes] the contours of the site as a visual buffer. Helical arches undulate and twist along the length of the roadway gently peeling away from the main building.”

Sustainability in design and speed of installation were two major factors of the project. Tensile fabric architecture allowed FTL to design a modular system with minimal anchorage points, that could be installed, dismantled, and reinstalled at a different location with much less effort than traditional building materials.

As a first impression of the temporary UN Assembly building, the textile Porte Cochere presents a bright, graceful entrance. The reflective white canopy, glows warmly at night, acting as a beacon to pedestrian and automobile visitors. During daylight hours, the canopy absorbs and refracts sunlight to both shade and brightly illuminate the loading and unloading zone below. From a functional standpoint, the open-air aspect of the tensile frame provided passive ventilation for automobile exhaust.

In this project, tensile fabric architecture was better able to meet the project needs of sustainability in materials, aesthetics in form, and functionality in design.

4Biv. Soundforms
Another tensile fabric architecture project that highlights the unique characteristics of this building technique is the innovative “Soundforms” product devised and deployed by Flanagan Lawrence. A truly innovative product, Soundforms are inflatable, transportable, and acoustically advanced performance stages. Intended for outdoor use and able to withstand a variety of weather conditions, these concert stages feature a lightweight, collapsible structural skeleton over which tensile fabric is inflated to create a sound “shell.” The textile skin simultaneously projects sound into the audience and reflects it back for performers to hear.


The benefits of the Soundform shells extend beyond superior acoustic qualities. The lightweight of the entire system lends itself to transport and widespread installation. The functionality of the textile skin to both protect and enhance the performance of musical performers within the space makes it a marketable product. And the aesthetic qualities of the system as a whole helps to engage listeners and passersby.

Additionally, the sustainability of the product is a strong benefit. The prototype Soundform shell was used extensively throughout the 2012 London Olympic Games, creating a point of interest that was able to be removed and entirely reused after the Games were concluded. The easy portability and physical lightness of the Soundform shells minimizes negative impacts to sites.

These projects highlight the benefits of tensile fabric architecture. It is unique in its ability to create fully functional yet light-filled, light-weight, and visually appealing designs with minimal permanent impact to surrounding areas. Many textile systems can be reused in their entirety, benefiting the overall sustainability of a project. Additionally, tensile structures possess a unique ability to define urban spaces in expressive ways. When considering products to define a sheltering system for Rochester bicycle and pedestrian networks, and to unite that system seamlessly with the urban framework, tensile fabric architecture is an appealing choice.
5. CONCEPTS OF TEXTILES AND TENSILE FABRIC ARCHITECTURE

5A. HISTORY OF TEXTILE BUILDING MEMBRANES

Textiles as building materials have an ancient history. Early hunter gatherers stretched animal hides and wool over simple frames for shelter. Midwestern Native Americans and nomadic Mongolians and Turks utilized animal hides for transportable tepees, yurts, and tents. Ancient armies made extensive use of tensile structures to house troops—the light weight of the materials made tents easy to carry long distances, much as the modern camping tent is utilized today.

Ancient Navies developed textiles that could reliably span larger surface areas: sails essentially tested flexural strength of fabrics making products like the velarium of the Colosseum in ancient Rome possible. Over time, structural supports became strong enough to support extremely large tents and pavilions, which became increasingly popular during the 18th and 19th centuries.

The “modern” era of tensile structures was ushered in during the mid-twentieth century, when “engineering practice, research into innovative structures, and sensitivity to both beauty and potential sustainability attributes of lightweight building systems” could be combined. With present-day improvements in thermal and structural capabilities, textile structures are now applied in more climates in increasingly innovative ways.

5B. TEXTILES AS BUILDING MATERIALS

An array of textiles that can be utilized for tensile fabric structures are characterized by several factors. These factors create different physical characteristics for each textile family, and textile sub-category. This versatility in manufacturing means that tensile membranes can be modified to different specifications based on project requirements.

The most critical characteristics for textile integrity are: i) fiber ii) material structure and iii) finish. Due to their physical characteristics, the most common fibers utilized for tensile fabric structures are historically PTFE, ETFE, PVC coated polyester, and vinyl. However, a variety of newly developed textiles are entering the commercial market, offering improved fire retardancy, strength, energy generation, and life expectancy.

Textile membranes are renown for their light transmissibility characteristics allowing for interiors to be lit during daylight hours without the need to artificial lights. By allowing daylight to penetrate the interior of the proposed protective structure, there is reduced need for artificial lighting.

5Bi. Materials

The simultaneous advantage and disadvantage of textiles in architecture is their unlimited design potential. The obvious benefit of textiles is the ability to experiment with a multitude of designs and fibers. The disadvantage is the difficulty in ensuring structural integrity of built forms. The modern building textile inventory includes a few materials that have shown, through

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iv Though de Llorens attributes this culmination with the legendary architecture Frei Otto, the author is of the position that the mid-century provided an atmosphere ripe for this type of scientific collaboration, making the technology impossible to attribute to any one man.


historical usage, study and experimentation, to be successful at creating and maintaining structural integrity, weather resistance, and aesthetic characteristics over time: PTFE (Polytetrafluoroethylene), PVC coated polyester, and nylon. Each textile has its own performance characteristics based upon the application of finishes, thicknesses, and the weaving pattern of the fabric.

1. PTFE (Polytetrafluoroethylene)
   a. History

   Polytetrafluoroethylene was created by Roy Plunkett in the DuPont labs in 1938. While searching to develop safer refrigerants, Plunkett developed a chemically-resistant polymer, which “cannot be dissolved in any solvent, acid, or base, and when melted it forms a stiff clear gel with no flow.” Through continued research and development of the powder, alternative forms of PTFE were created, that could be utilized as coatings and in extruded forms.

   Advancements by W.L. Gore led to that PTFE being used for much more than coating technologies. Gore discovered how to stretch the polymer, which gave it a new set of properties and thus a new name: Expanded polytetrafluoroethylene. “The expanded form possesses the basic properties of PTFE—including chemical inertness, low friction constant, wide-use temperature range, hydrophobicity, outdoor durability, and biocompatibility—in addition to porosity, air permeability, and extreme strength.” PTFE textiles are made of this expanded version of the polymer.

   Fibers made from ePTFE are generally produced using a “paste extrusion” process, whereby “PTFE resin is processed into membrane, tape, and fibers and expanded. To produce fiber from tape, membranes are slit into fiber after expansion.” This type of manufacturing creates a product that has a tensile strength of <4g/denier, and a shrinkage of 3-5%. Heat treatment can further strengthen the fibers.

   b. Benefits and Disadvantages

   PTFE and ePTFE are widely used in the building industry due to their superior structural characteristics. High high tensile strength, abrasion resistance, resistance to UV degradation and flame, and minimal stretch under loading conditions make ePTFE fibers optimal for outdoor uses. Additionally, the ability of the fabric to breathe while remaining impermeable to water can make indoor environments more comfortable.

   However, PTFE does have some disadvantages. The material’s extreme bonding strength prevents it from breaking down organically over time, causing environmental concern. Additionally, PTFE is a costly material. Compared to other outdoor use fabrics, PTFE fibers may not be suitable for a project simply due to the cost-to-life-expectancy ratio.

   b. Use and Precedents

   An extensive array of projects have utilized PTFE and ePTFE as tensile membranes. As a modern, durable, and aesthetically pleasing product, PTFE has been utilized in projects ranging from the immense, such as the O2 Millenium Dome in Greenwich, BC Place Stadium in Vancouver, and the new Khalifa International Stadium in Doha, Qatar to the small, such

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i Huntington, Tenile Fabric Structures.
ii Koch, Membrane structures: 58-59.
v ibid.
<table>
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<tr>
<th>Top Coating</th>
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Figure 25. Comparison of fabric performance

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as the Strong National Museum of Play Butterfly Garden in Rochester, NY, and many shade, parking, and entrance canopy structures.

The Saint-Gobain Headquarters in Philadelphia, PA features a 1,400 square foot PTFE membrane canopy, designed and built by Bernardon Harbor Holloway architects and Birdair.¹ The structure consists of a partial ellipse membrane mounted on structural steel. Meant to provide a sense of place, shading, and weather protection for employees and visitors, the membrane is daylight permeable, reflects night lighting in an aesthetic way, and is impermeable to water. However, the lightness of the canopy is somewhat lost due to the size and number of structural steel supports. With no structure to which to tie the cantilever back, the canopy must rely on large foundation caissons for structural integrity.

The Tulsa International Airport canopy, designed by Demattei Wong Architecture and Pfeifer FabriTec, features a similar design on a slightly larger scale.² Curved structural steel supports the 1,642 square foot PTFE canopies that cantilever over the airport’s arrivals and departures zones. Although structural steel is in abundance in this canopy, the overall effect is light: the curved beams create an illusion of movement in the fabric, recalling aeronautical flight. Stretching over the passenger loading and unloading zones, the canopy provides weather protection for passengers below while allowing natural light to penetrate into adjacent interior spaces. The reflectivity of the PTFE canopy also helps to light the area during evening hours.

2. Polyvinyl Chloride (PVC) coated Polyester

a. History

Polyvinyl Chloride (PVC) coated polyester is another commonly used architectural textile. The polyester substrate is usually a synthetic polymer commonly known as PET (Polyethylene terephthalate). Like PTFE, PET is chemically stable and heat tolerant up to 265°C.

Polyester textiles are almost always coated if they are to be used for architectural purposes. As a stand-alone material, polyester has a shorter lifespan due to lack of UV resistance, fire-retardancy, and water permeability. Thus, architectural polyester fabrics are almost always coated with additive-rich PVC to improve these deficiencies. However, PVC alone is not adequate to provide the type of long-term protection architectural fabrics require for continued use. In addition to PVC, PET textiles are also frequently top-coated with polyvinylidene fluoride (PVDF), a plasticized polymer used to provide additional fungal and UV resistance.³

b. Benefits and Disadvantages

Though PVC coated polyester has been used for decades in architectural applications, it does have some disadvantages. Polyester is prone to damage from UV rays. “Although a PVC/Polyester fabric will have a structural lifespan in excess of 20 years its quoted lifespan is based on visual appearance. Plasticisers in the PVC will migrate towards the surface over a period of time making the surface harder to clean.”⁴ Though a plasticized polymer, PVDF coatings decrease flexibility to the PVC coated polyester, which can create top-coating cracks, opening the piece up to fungal, UV, and water-borne damage. Additionally, the

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³ Michael Seidel, Tensile Surface Structures.
PVDF topcoat is not weldable, thus seams are vulnerable areas at which the underlying textile may be exposed to the elements and begin to degrade.

Like PTFE, PVC-coated polyester contains plasticized polymers and a number of chemical additives. Additives like phthalates, commonly used to increase flexibility and water-impermeability, have been shown to be potentially dangerous to human health. According to Prof. Milan Maric of the Department of Chemical Engineering at McGill University, “despite the improvement in properties in such blends, one the most common group of plasticizers, the phthalates have become increasingly under scrutiny due to concerns regarding toxic metabolites, which can encounter humans via migration from articles, such as blood bags and children’s toys.” Maric cites the higher incidence of endocrine issues in humans in contact with these chemicals, and potential for damage to the environment when the polymers degrade. In urban projects, degradation of polymers into the environment poses a risk to the health of waterways, landscapes, and human beings through direct and indirect contact.

However, the relatively inexpensive cost of PVC coated polyester, particularly compared to PTFE and other coated fabrics, makes it a natural choice for smaller projects with shorter life expectancies.

c. Use and Precedents
Because of its wide availability and inexpensive nature, PVC-coated polyester has been used extensively in tensile fabric architecture.

Birdair utilized PVC-coated polyester for several large projects including the Cape Town Stadium in Cape Town, South Africa. A 340,000 square foot PVC coated polyester ring surrounds the top of the stadium to provide shade and protection for the 68,000 spectators below. The size and shape of the textile shade is reminiscent of the ancient Roman velarium which protected spectators in the Roman Colosseum. One may surmise that PVC coated polyester was an appropriate material choice for this project due to the environmental factors in Cape Town.

FabriTec utilized PVC-coated polyester in smaller projects. The Austin-Bergstrom International Airport South Terminal project in Austin, Texas is a collection of 23 inverted umbrella-like free-standing awnings. Intended to protect deplaning passengers from the elements, Fentress Architects utilized conical shapes to emphasize the curvilinear nature of flight, keeping supporting wires out of sight above the fabric. Sturdy concrete foundation pillars anchor the tensile fabric structure to the ground, while curved metal supports hold the fabric in tension from above.

3. Nylon
a. History
Wallace Carothers and his team at DuPont Corporation developed nylon fibers in 1934. Carothers and his team utilized a

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polymerization reaction between “the chemicals amine, hexamethylene diamine, and adipic acid.” The resulting fibers were “long, strong, and very elastic. DuPont named this product nylon. The chemists called it Nylon 6,6 because the adipic acid and hexamethylene diamine each contain 6 carbon atoms per molecule.”

b. Benefits and Disadvantages
As a standalone textile, nylon offers several advantages over non-synthetic materials. It is wrinkle resistant at normal temperatures as well as resistant to water, mildew, fungus, and chemicals.

Nylon is hygroscopic, meaning that it “will absorb or desorb moisture as a function of the ambient humidity. Variations in moisture content have several effects on the polymer. Firstly, the dimensions will change, but more importantly moisture acts as a plasticizer, lowering the glass transition temperature (Tg), and consequently the elastic modulus at temperatures below the Tg.” This means nylon will warp out of its intended shape in the presence of water, losing strength, stability, and form when wet.

Like previously discussed fibers, nylon is a polymer, or plastic, making it non-biodegradable and only recyclable through specialized industrial processes. However, nylon recycling has become more available. Companies like Econyl and FLOR developed specialized processes and facilities to accommodate various nylon products, leading the way to prove that nylon can be recycled into new product. Though the apparel and flooring industries are becoming more successful at utilizing recycled content, recycled nylon textiles for tensile structures remains unexplored.

c. Use and Precedents
Due to its hygroscopic nature, most utilization of nylon is for interior purposes. However, temporary structures such as pop-up canopies and outdoor tents have been made from nylon fabrics.

4. Solar Textiles
   a. History
As Fan, et al. aptly states, “…mechanical energy may be the most widely distributed [energy] that is ubiquitously available and is specialized for human motion-related applications. It exists abundantly as different forms and is frequently located in our local environment, but the vast majority is ignored and wasted, such as human motion, walking, mechanical triggering, vibration, wind, flowing water and so forth.”

The viability of fabrics with energy capturing capability, or solar fabrics, is now being investigated, with several prototype

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materials already reported. Presently, solar fabrics can be manufactured in two ways: by weaving conductive fibers into the fabric itself, or applying solar films or coatings to already woven “off-the-shelf” fabrics. By combining the unique performance of technical fibers such as PTFE, polyester and nylon with energy generation technology, tensile fabric structures may become sources of energy in the future.

Two classes of solar textiles are currently being studied. The first method involves applying flexible solar films to existing textiles. Solar films are thin, flexible photovoltaic sheets. As far back as the 1990s, companies like FTL, now pvilion, have directly sewn flexible solar films onto canvas tents utilized by the U.S. Army. However, these films utilize silicon as the major conductive agent in the solar cell. As a brittle material, it was realized that silicon solar films could not be adapted to large-scale, flexible, demountable applications.

The second method of creating solar fabrics is still in research and development. Various materials and methods are currently being investigated, but the general principle is the same: photovoltaic yarns, such as zinc oxide or perovskite, are woven alongside conductive yarns, such as copper, to create fabric able to generate power. Flexible battery solutions are also in development: “polyester yarn coated with nickel and carbon combined with polyurethane can produce a flexible battery that continues to work even when repeatedly bent and folded.”

Triboelectric energy, energy generated utilizing friction potential, and piezoelectric energy, energy generated utilizing mechanical stress potential, are other areas of solar textile research. By harnessing energy created simply by the movement of or stress placed on materials, textiles may soon be able to power those entities they protect. Should researchers continue to refine the technology to achieve greater power conversion, tensile fabric structures utilizing solar fabric may be able to partially meet the energy needs of buildings or structures.

b. Benefits and Disadvantages

Solar textiles have the advantage of potentially providing energy to whole or partial system. Power generation of fabrics is variable and dependent on the method of solar integration. However, preliminary schematic analysis indicates that some solar textiles have the potential to generate up to 120 watts per square meter. This estimate suggests that a small solar canopy may be able to provide enough energy to power a small array of sensors and motors.

The ability to customize power generating textiles to suit programmatic needs is also a strong advantage. With the option of

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iv “History,” p vilion, ibid.

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weaving photo-voltaic yarns into performance fabrics, architectural tensile fabrics could generate electricity.

As promising as the future prospects for solar fabrics are, current estimates put power conversion from solar threads at 1-7%\textsuperscript{i}, well below conventional PV arrays, which can reach conversion efficiencies of up to 46%\textsuperscript{ii} This limited output is not yet viable for large-scale adoption in the building industry. Additionally, there is inherent risk associated with exposing electronic fibers to environmental factors such as water. Some materials used in electronics are also toxic, posing a risk of leaching into the environment.

**c. Use and Precedents**

One of the most recognizable projects using solar textiles is the Pvilion sponsored “Techstyle Haus” for the 2014 Solar Decathlon\textsuperscript{iii}. The innovative structure makes use of tensile fabric as an “attractively undulant tensile membrane...that includes three layers of four-inch fiberglass insulation sandwiched between the exterior and interior membranes” of fiberglass fabric\textsuperscript{iv}. The top layer consists of “flexible monocrystalline PV cells laminated to vinyl fabric.”\textsuperscript{v} Though an early representation of the technology, the Techstyle Haus effectively demonstrates the potential for thin solar films applied to tensile fabrics.

Solar film developer PowerFilm has also developed textiles with rollable and foldable solar films sewn directly into textile backings. The textile products, by utilizing flexible solar films is able to be applied in versatile and customizable ways. This portable concept has been integrated into structures as diverse as off-grid military operations to powered bike locks\textsuperscript{vi}.

**5C. Structural Supports**

As Huntington notes, the structural design of beams, columns, masts, and rings “does not usually influence the membrane design.”\textsuperscript{vii} Though dynamic structural loading effects membrane design, it does not have categorical influence on the supporting structures. Design loads can be calculated using established codes and guidelines for chosen materials. However, material for structural supports must be “designed to resist the maximum probable load the membrane could deliver and to remain stable in the event of sudden failure of a portion of the membrane surface.”\textsuperscript{viii} Due to its loading predictability, steel structural supports are most commonly utilized for tensile fabric structures.

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\textsuperscript{i} LH Zhang, EZ Shi, CY Ji, Z. Li, PX Li, YY Shang, YB Li, et al., “Fiber and fabric solar cells by directly weaving carbon nano tube yarns with CdSe nanowire-based electrodes,” Nanoscale 4, no. 16 (2012): 4954-9

\textsuperscript{ii} Lacy Cooke, “Durable canvas cloth with embedded solar cells.”


\textsuperscript{iv} Ibid.

\textsuperscript{v} Ibid.

\textsuperscript{vi} PowerFilm Solar. https://www.powerfilmsolar.com/.

\textsuperscript{vii} Craig G. Huntington, ed., Tensile Fabric Structures.

\textsuperscript{viii} Ibid.
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IV. Methods

It has been shown that Rochester suffers from several interrelated issues affecting the urban fabric: a high rate of poverty, a biased transportation network catering toward automobiles, and a rich yet discontinuous urban framework. Other cities including London and Berlin have seen success at creating an inclusive transportation network and urban fabric by prioritizing bicycling infrastructure. Tensile fabric structures have been successful at uniting the urban framework in cities like Boston, Detroit, Denver, and Wellington. The City of Rochester is in a position to take similar action to create and expand bicycle infrastructure through the priorities set forth in the Bicycle Master Plan and city-wide ordinances.

A canopy structure is a scalable, straightforward approach to providing bicycle and pedestrian protection. Utilizing the methods of tensile fabric architecture, canopies may be designed to apply concepts from innovative urban design within the existing transportation network. As a concept, the proposed design is a connected series of individual tensile fabric structures that interact to create an urban network of bike lane coverings. Termed the Bicycle Lane Intelligent Network Canopy (BLINC), the design is embedded with smart technologies such as automated movement and lighting.

Proposed installations within the urban network include select roadways and public spaces in Rochester. The BLINC is intended to be installed on the existing street network in Rochester, along routes that promote equal access to the urban fabric of employment, education, amenity, and recreational opportunities in the city. Selected installation routes also encourage bicycling as a mode of transportation by protecting cyclists and pedestrians from weather events and automobile traffic.

The following sections intend to investigate the effectiveness of designing tensile fabric structures as bicycle path coverings in order to promote cycling as a mode of transportation, expand equal access to effective and efficient transportation, and connect the urban fabric of Rochester. A successful design for a network of bicycle path coverings will maintain structural and performance integrity while presenting an aesthetic and functional solution for unifying the urban framework through promotion of cycling. Two distinct areas of investigation are required: design characteristics of proposed tensile fabric structures, and design characteristics of proposed cycling infrastructure routes.

1. Cycling Infrastructure Within the Urban Framework

In order to identify the most effective installation routes for the BLINC system, three factors were considered: 1) continuity of the roadway through the center city, 2) adjacency of the roadway to low-income areas, areas of employment, and civic amenities, and 3) ability of the current roadway to support BLINC installation.

Roadways that transversed downtown were listed in a tabular format then rated on a five point scale based on the successive design factors. Wider roadways capable of supporting two car lanes and a six-foot buffered bike lane were given five points; roadways incapable of meeting these criteria were rated at zero.

Potential routes that continued, uninterrupted for at least one mile in each direction from the center city were given five
points; routes that did not continue out of the city were given zero points. Additionally, routes were scored based on adjacency to low-income areas, areas of employment, and civic amenities. Routes that pass by a greater quantity of these areas were rated higher, routes that pass by fewer areas were rated lower.

2. TENSILE FABRIC BICYCLE PATH COVERING

In order to ensure the viability of the BLINC structures design configurations, materials, and installation locations were rated and tested.

Proposed design solutions for the BLINC were subjectively evaluated based on five factors: 1) cyclist accessibility, 2) buildability, 3) adaptability, 4) potential for integration into current infrastructure, and 5) design appeal. A rating scale of zero to five was used: a score of zero indicated failure to meet the design requirement, a score of five indicated an exceptional solution to the design requirement.

A sixth design factor, structural stability, was evaluated objectively based on structural loading guidelines specified by ASCE 7\(^i\) and the International Building Code of New York State (IBCNYS 2015). In order to obtain accurate results, a virtual structural analysis program, RFEM, was used to model and analyze each proposed design under ASCE 7 and IBCNYS specified loading conditions. Material data such as tensile strength, elasticity, and thickness were also programmed into the RFEM models to represent real-world parameters for the membrane structures. RFEM analyses provided graphic and diagrammatic results, used to rank each design for structural stability on a scale of zero to five. Designs that deformed less under loading conditions were rated higher; designed that deformed more were ranked lower.

Textile materials were scored based on several factors. General, performance, and environmental characteristics of each material were collected from manufacturer datasheets and objectively reported in a tabular format. Project preferences for textile performance characteristics were outlined so as to guide selection of appropriate textiles. In general, materials that met or exceeded the given specifications were identified as preferred materials.

Integrated accessories such as solar panels, weather sensors, motors, controllers, and LED lights were directly reported from manufacturer datasheets for informational purposes only. Structural steel materials were not assessed as it was assumed that design guidelines set forth by existing building codes would be sufficient to specify structural products.

After determination of the ideal tensile fabric and canopy design, a final BLINC was specified.

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50 Methods
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Figure 26. Continuity of roadways within the center city of Rochester.
1. CYCLING INFRASTRUCTURE WITHIN THE URBAN FRAMEWORK

Potential installation routes for the BLINC system not only create paths of safe passage for cyclists, but also create direct paths between schools, employment areas, residential areas, and places of urban interest. By identifying existing roadways that connect these points of interest in the center city of Rochester, a compact network map for BLINC installation is formed.

1A. PROPOSED ROUTE NETWORK

The proposed route network for the BLINC system was shaped through analysis of several factors: continuity of the roadway through the center city, adjacency of the roadway to low-income areas, areas of employment, and civic amenities, and ability of the current roadway to support BLINC installation.

1Ai. Continuity through Center City

Of the 85 streets that are in the boundaries of the Center City of Rochester, ten travel continuously through the urban core and outward toward the greater Rochester area. Plymouth Avenue, State/Exchange Street, St. Paul Street, Clinton Avenue, Chestnut Street, Scio Street, and S. Union Street transverse the city on a north-south axis. Main Street and University Avenue transverse the city on an east-west axis.

As Figure 26 shows, several streets extend for significant distances away from the center city, including State/Exchange Street, St. Paul Street, Clinton Street, Chestnut Street, and Main Street. State Street extends for nearly nine miles, beginning just south of the Inner Loop and continuing north to terminate at Lake Ontario. St. Paul Street begins as South Avenue in the suburb of Brighton, three miles south of the center city; it extends to the shores of Lake Ontario for a ten-mile journey. Clinton Avenue travels for seven miles, stretching three miles in each direction of the center city. Main Street is continuous for nearly 35 miles, stretching from the east side of the City of Rochester to Batavia, NY, located 32 miles west of Rochester. Chestnut Street becomes New York State Route 31 outside of the Center City, which stretches from the northern suburb of Irondequoit to Baldwinsville, a suburb of Syracuse, NY. The entire journey along this route is approximately 90 miles.

Plymouth Avenue and Scio Street travel north from the center city for about two miles; South Union Street extends north and south for about three miles.

1Aii. Adjacency to Areas of Interest

In order to promote equality in urban connection and transportation through the City of Rochester, the BLINC route network is adjacent to low-income residential areas, areas of employment, educational institutions, and civic amenities. Each street identified as being continuous through the city was also assessed based on its adjacency to these areas, as shown in Figure 27.

Adjacency to areas with high poverty is a main objective of the BLINC network. Plymouth Avenue, State/Exchange, S. Paul, Clinton Avenue, and Main Street transverse the poorest areas of the city, with poverty rates at 60% or greater. However, as Figure 1 shows, as each roadway extends farther from the city center, poverty rates decrease. The gradient of low and high

V. RESULTS
<table>
<thead>
<tr>
<th>Existing Roadway</th>
<th>Number of Schools (5 mile radius)</th>
<th>Poverty Rate Along Route</th>
<th>Number of Civic Amenities (5 mile radius)</th>
<th>Width of Roadway</th>
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</thead>
<tbody>
<tr>
<td>W. &amp; E. Main Sts.</td>
<td>4</td>
<td>16-77.6%</td>
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<td>47 ft</td>
</tr>
<tr>
<td>Plymouth Ave.</td>
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<td>0-77.6%</td>
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</tr>
<tr>
<td>State/Exchange Sts.</td>
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<td>16-77.6%</td>
<td>9</td>
<td>60 ft</td>
</tr>
<tr>
<td>St. Paul St.</td>
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<td>46 ft</td>
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<tr>
<td>N. &amp; S. Clinton Aves.</td>
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<tr>
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<td>3</td>
<td>56 ft</td>
</tr>
<tr>
<td>Scio St.</td>
<td>1</td>
<td>0-16%</td>
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<td>30 ft</td>
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<tr>
<td>University Ave.</td>
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<td>Genesee Street</td>
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<td>Jay/Lyell/Upper Falls</td>
<td>8</td>
<td>0-77.6%</td>
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<td>40 ft</td>
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</tbody>
</table>

Figure 27. Roadway adjacency to educational, economic, civic, and employment factors of potential BLINC routes.

Figure 28. Potential BLINC network map indicating BLINC routes, existing roadways and urban points of interest. Diagram by author.
poverty areas along these routes is a valuable factor for the BLINC network.

The more westerly streets, Chestnut, Scio, University and Union, are adjacent to areas with a lower percentage of poverty, an average of 15% of the population.

Figure 28 indicates, the adjacency of potential BLINC routes to schools, employment districts, and major civic amenities in downtown Rochester is useful in linking these areas cohesively. Areas that are free or low cost, open to the public, and promote a sense of community were considered as amenities important to the fabric of downtown Rochester. Recreational parks, sports fields, public libraries, places of worship, and open air markets were included.¹

Union Street passes by the Rochester Public Market, an open-air farmers market and community gathering place, as well as Martin Luther King Jr. Park, and several places of worship. Plymouth Avenue is adjacent to Frontier Field baseball stadium. State and Exchange streets pass by Blue Cross Arena, many churches, and the Lower Falls recreational park.

As Figure 27 and 28 show, at least four schools are located along the St. Paul Street corridor, as well as churches, High Falls Terrace park, and the Rochester Public Library. Clinton Avenue provides access to at least three schools, numerous places of worship, and Persimmon recreational park. The Eastman School of Music, several middle and high schools, Parcel 5, the Rochester Public Library, and the Liberty Pole are all along Main Street. University Avenue is home to two middle and high schools. Scio and Chestnut Streets both have one high school and one place of worship.

In terms of access to employment, the center city of Rochester is home to several large employers including the Xerox Corporation, and governmental offices. The University of Rochester, including Strong Memorial Hospital and Highland Hospital, is the largest employer in the city. These locations are easily accessible via the Saint Paul corridor and the Genesee Riverway trail system. Larger areas of job growth in city suburbs are connected to areas of high poverty via the proposed BLINC network, as shown in Figure 31.

I Aiii. Infrastructure Capacity

Infrastructure capacity of each potential roadway dictated the ability to install the BLINC system. As illustrated in Figure 34, the BLINC system requires six feet of clearance. According to the National Association of City Transportation Officials, automobile lanes should be ten feet wide with three feet of clearance between cycling lanes and traffic lanes.ii Therefore, potential BLINC roadways are required to be at least 29 feet wide.

The widest roadways identified as potential candidates for BLINC incorporation, and listed in Figure 50, were Chestnut Street, Plymouth Avenue, and State/Exchange Street. These streets each have at least three lanes of traffic and one lane for parking. Main Street, Clinton Street, Saint Paul Street, and South Union Street were slightly narrower roadways, but featured the same pattern of three lanes of traffic. Scio Street and University Avenue were much narrower, containing two lanes of traffic and at least one lane for parking. All potential roadways were determined to be wide enough to incorporate the BLINC system.

¹ Traditional services such as grocery stores, medical offices, and social services were excluded from this listing, due to scope considerations. Further research should address cyclist access to these services.

Figure 29. Proposed BLINC route network, highlighting Main Street, St. Paul Street, and Clinton Street as well as adjacent civic amenities and schools. Illustration by author.

Figure 30. Areas of job growth, unemployment rates, and proposed BLINC network roads. Diagram by author.
As Figure 28 illustrates, Saint Paul, Clinton Avenue, and Main Street were identified as prime roadways to incorporate the BLINC transportation route system due to the continuity, adjacency, and current infrastructure of each. Secondary routes, running east to west north of the center city along Genesee Street, Jay Street, Lyell Avenue, Upper Falls Boulevard, and Central Park are also incorporated into the BLINC network in order to provide additional connection points through the city.

1B. PROPOSED ROUTE NETWORK CHARACTERISTICS

The BLINC system network is designed as a procession of individual BLINC system modules, mounted along the perimeters of identified roadways. On each roadway block, individual BLINC modules are mounted at specified intervals to form a continuous protective pathway for cyclists. As a safety precaution for visibility, the BLINC structures terminate at least 20 feet prior to roadway intersections. Figure 53 illustrates the design intent.

The proposed BLINC network is meant to work in tandem with the existing bicycling infrastructure network in Rochester, identified in Figure 5. Each proposed BLINC route acts to create safe cycling roadways where no cycling infrastructure currently exists or to improve cycling conditions where bike lanes do exist. For example, bike lanes do exist on Main Street where the BLINC system is meant to enhance cyclists’ experience. However, on Saint Paul and Clinton Street little to no cycling infrastructure exists, the BLINC system is intended to create this infrastructure.

Additionally, the proposed routes intentionally cross existing alternative transportation routes including trailways along the Erie Canal, Genesee River, and Union Street Cycle Track. These existing routes connect educational institutions and employment areas around the University of Rochester, Rochester Institute of Technology, and the suburbs of Henrietta and Pittsford.

In order to further connect the urban fabric of Rochester, the BLINC route network passes public urban spaces like Parcel 5 and Martin Luther King Jr. Park. At these junctions, the tensile fabric BLINC structures are intended to be adapted and incorporated into coverings for the public spaces. Additional, large-scale tensile fabric structures would form a primary covering for the urban space, while the connection into these areas would be defined by the BLINC system. By forming seamless intersections and branching into lively urban spaces, the BLINC route network helps to connect the city through alternative transportation.
Figure 31. Exploded diagram of the quarter round design. Diagram by author.

Figure 32. Fabric to cable connection diagram. Diagram by author.

Figure 33. Detail of top rail. Diagram by author.
2. TENSILE FABRIC BICYCLE PATH COVERING

2A. PROPOSED DESIGNS

The most recognizable and commonly used tensile architectural forms are the conic form, rounded form and the hyperbolic paraboloid, or hypar form. Conic forms are utilized in structures like the classic circus tent; hypar forms are typically used for shade sails. Rounded forms are used in traditional entrance canopies. In order to support the tensile fabric in equilibrium, specific structural requirements are necessary. While quarter rounded shapes are generally “self-supported” through identically shaped structural bearing supports, conic shapes generally require larger masts, deep foundation supports, and overhead corner-supporting arms. Hypar structures require angled structural legs and guy wires to maintain high tensile loads needed for stability.

When considering the ideal form for bike path canopies, several factors come into play. Based on background review and structural design assumptions, the following criteria represent desired aspects of design:

1. Cyclist accessibility. Access to the area under the tensile canopy needs to be free of obstructions from structural supports. Designs that incorporate minimal structural supports are ideal.
2. Buildability. In order to encourage widespread adoption, simplicity in structural design and installation procedure is ideal. Designs should be simple enough to be installed quickly by non-professionals without specialized knowledge of tensile fabric design. Additionally, potential BLINC designs need to conform to a shape that is easily manipulated while maintaining pre-defined form and stability while moving.
3. Adaptability. Adaptability to alternative spans, widths, heights, and other potential specifications is beneficial when meeting specific requirements for a variety of potential installation locations.
4. Potential for integration into current infrastructure. Each potential BLINC design is expected to be integrated into the current infrastructure in Rochester with ease, without overstepping the boundaries of current bike lanes or sidewalks.
5. Design appeal. Each potential form must be visually appealing in an architectural sense, able to draw interest from cyclists, pedestrians, and motorists, encouraging cycling and other bipedal modes of transportation through a sense of novelty and utility.

In order to meet these demands, several forms were designed to determine which one form is best suited to the context of Rochester streets and supports the intended function of the BLINC. Several forms, the quarter round, triangular tee, and umbrella, were proposed in order to explore the potential advantages and disadvantages of alternative shapes and movement capabilities. Each design was evaluated on a subjective level, based on the criteria listed above, utilizing a scale ranging from zero to five, whereas zero is the least effective or desirable and five is the most effective or desirable.

Though each design is unique, all have the capability of deploying and retracting the tensile canopy in order protect the structural integrity of the structure during times of high winds or extreme weather, or provide aesthetic variation in form when installed over long distances.

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Figure 34. Plan view of the quarter round design in various stages of deploy. Far left shows the canopy fully deployed; far right shows the canopy fully rolled within the top rail. Diagram by author.

Figure 35. Rendering of the quarter round design mounted on Broad Street, Rochester, NY. Rendering by author.
Quarter Round

Design

A classic round tensile form offers several advantages: simplicity in design and installation, ease of movement along the structure during deployment and recoiling, and variability in mounting configurations. Additionally, the bottom curvature of the tensile fabric can be adjusted to allow for entry of cyclists at various points along the path, or designed to stay low to the ground to protect against road debris.

Figure 32 illustrates the simplicity of the quarter round design. Two side supports and one top rail, both made of light-weight, high-tensile steel, provide connection points between the tensile fabric and structural frame. Steel side supports house a steel cable around which the tensile fabric is welded (see figure 33), and feature a channel which guides the canopy when deployed and retracted. The cables are stayed at ground level by a steel base plate and a jaw and eye turnbuckle, allowing for tension adjustment. This tensioning system is nested inside the side supports to avoid tampering and protect against weather erosion. The side supports are connected to the tubular top rail via a tee joint, allowing the cable to be out over the structural supports.

The top rail houses critical elements of the quarter round canopy design (see Figure 34). It serves as a protected location into which the textile rolls when not in use, a mounting surface for solar energy harvesting tape, rain sensors, and anemometers, the location for a small battery, and the location for a tubular motor which powers the entire mechanism.

Cyclist Accessibility

As a method to promote cycling as a mode of transportation, cyclists should be valued as customers of the BLINC design. If cyclists cannot easily access the protected space under the canopy, then the design is ineffective. The quarter round form is the least accessible of the three designs, despite the variability of bottom hem heights. Though the shape of the tensile fabric may be altered to align with bicyclists access points, as shown in Figure 36, the area of clear space for cyclists to enter the canopy is limited in practice to the pedestrian side of the canopy. This “full coverage” design provides more protection from road debris than the other designs, but is a limiting factor for cyclists wishing to enter and exit the space at will. Turning points and intersections may be particularly difficult as well, contributing to this form receiving a moderate score of 3 for cyclists accessibility.

Buildability

As shown in the preceding diagrams, the quarter round design is advantageous due to simplicity: each component is readily available in a multitude of lengths, diameters, and strengths. The side supports and top member are easily designed for structural capacity. Structural connections can be made with readily available components. And, as the movable components have a basis in marine designs, these are also easily engineered.

However, the quarter round shape does present challenges to construction. Compared to the other designs, the quarter round requires more materials to construct: Two side supports instead of one, two cable tracks, and two guide rings. Materials costs and installation efforts will subsequently be increased to accommodate the additional surfaces to connect. Though not a difficult construction, the aforementioned factors contribute to a median score of 3 for constructibility.
Figure 36. Diagram indicating the required spacing for comfortable ridership under the BLINC structure. Spacing recommendations were provided by the National Association of City Transportation Officials.\textsuperscript{i}

Adaptability

The adaptability of the quarter round design is a distinct advantage. Distance between supports may be extended or shortened, height of the top rail, and shape of the side supports are adjustable to suit particular design requirements, structural needs, or municipal regulations without affecting the function of the canopy. For example, the width of each module may be increased, only requiring a modification to size of the top rail and tensile fabric. The bottom hem of the tensile fabric may also be sewn in nearly any iteration of a curved shape to create different effects at the bottom of the canopy: a straight hem, parallel to ground, creates a wall of fabric, while an exaggerated parabola will create an opening for cyclists to enter an exit.

Compared to the other designs, the quarter round is more adaptable to each environment or specific sets of requirements, earning it a score of 5 for adaptability.

Integration into Current Infrastructure

When considering the potential to integrate the quarter round BLINC shape into the current street infrastructure, particularly in the Rochester street-scape, the complexity, space utilization, and proximity of structural supports to driving lanes are all of concern. Because the BLINC module is intended to be mounted on the traffic side of bike lanes, instead of the pedestrian side, free clearance limitations and visibility for automobiles is decreased. For safety, visibility between automobile lanes and bicycle lanes should be uninterrupted; the quarter round design does not account for this requirement. Additionally, inadequate space between bike lanes and driving lanes, recommended to be at least three feet, creates dangerous conditions for cyclists.

The inability to mount the quarter round design in existing infrastructure in Rochester earns the design a zero for this evaluation category.

Design Appeal

From a subjective evaluation, the aesthetic appeal of the quarter round BLINC design is functional yet anemic. The rectilinear tensile fabric of the quarter round design is effective at protecting cyclists from inclement weather but it is visually heavy in the streetscape, presenting a large expanse of textile fabric with little perforation. Business storefronts lining streets may be visually blocked by the tensile fabric, decreasing the overall design appeal of the city and counteracting the desired effects of the BLINC. Additionally, the relatively large amount of structural support required for this design creates an overtone of utility over aesthetics.

However, the tensile fabric is customizable and variable in shape and height. It is possible to configure the ground plane hem to any structurally sound height and curvature. Alternating heights may be specified for each module to form an undulating pattern along the streetscape. For cyclists and drivers, this pattern provides visual interest in a non-distracting way.

Combined, these factors contribute to the quarter round’s score of 3 for visual appeal.
Figure 37. Exploded diagram of the umbrella design. Diagram by author.

Figure 38. Fabric to side arm connection. Diagram by author.
Umbrella

Design

The second potential BLINC design is a movable umbrella form, featuring secondary arms which move in a scissor action to deploy the shade canopy. The basic design concept, illustrated in Figure 38, encompasses a continuous central structural support from ground level to the desired termination height over the bike path. This structural member supports two bi-lateral secondary arms, mounted to the central support via bi-directional hinges. The canopy is permanently attached to each secondary arm and the central support via a clamp system, illustrated in Figure 39.

The umbrella design does not include a provision for the canopy to be rolled or otherwise deployed along the structural frame. All connection points between the structural frame and tensile fabric are permanent. When the canopy is not deployed, the two secondary structural arms are parallel to the central support and the tensile fabric hangs in a draped fashion underneath it. When the canopy is deployed, the arms splay bi-laterally away from the support, stretching the fabric to its fully-tensioned state.

The umbrella form is structurally supported at the bilateral arms and the central horizontal steel. Each of tensile canopy connections is rigid: the tensioned fabric is connected to the steel frame via a clamp plate, unable to hinge up or down. Because the tensile fabric is limited to motion to one plane, hinged movement is not required.

Cyclist Accessibility

The umbrella is the only design that offers cyclists nearly full accessibility under the canopy. Structural supports are placed at predefined and infinitely variable intervals, producing the only hindrance to entering the protected area. Much the same size and shape as other structures along the roadway, the vertical supports are hardly a barrier to cyclists, but do act as a barrier to motorists. Because of the free and open nature of the umbrella system, a high score of five was awarded for accessibility.

Buildability

Tensile fabrics, structural supports, connection mechanisms, and moving elements utilized in the design of the umbrella canopy are all widely available and easily integrated. Like the triangular tee and quarter round designs, the umbrella is able to be built off-site and installed only when fully functional.

However, the umbrella design is complex in its integration of motors and tracks for the side arms. Rack and pinion and worm motor systems are potential solutions to the movement of the side arms, but do require motor and programming synchronization between both arms. Although not a difficult build, this system does require more mechanical engineering knowledge to succeed, earning it an overall score of four for buildability.

Adaptability

The umbrella design is as adaptable as the quarter round and triangular tee structures, with the ability to increase or decrease height, depth, and wing span as desired. Distance between modules is also adaptable: modules may be installed at any interval desired as no coordination between units exists. The customization potential of the umbrella design contributes to its score of
Figure 39. Plan view of the umbrella design in various stages of deploy. Far left shows the canopy fully deployed; far right shows the canopy fully rolled within the top rail. Diagram by author.

Figure 40. Rendering of the umbrella design mounted on Broad Street, Rochester. Rendering by author.
five for adaptability.

*Integration into Current Infrastructure*

The umbrella canopy design is easily integrated into existing infrastructure, should appropriate spacing between bike lanes and automobile lanes exist. Like the previous design, a several-foot distance separation must exist in order for the umbrella module to be safely installed for drivers and cyclists. However, as the structural posts supporting each module are installed in a way similar to roadway stanchions, street lights, and other street furniture, crews can easily install the BLINC modules.

Additionally, the umbrella design is the only BLINC design that offers clear sight-lines. Without tensile fabric mounted vertically on the structure, cyclists and motorists are able to see in all directions, promoting safety. A score of five was awarded for infrastructure integration of the umbrella design.

*Design Appeal*

Evaluated subjectively, the umbrella design is not as aesthetically appealing as the other BLINC designs. The umbrella design's movable arms are innovative and would create a visually interesting display when in motion. This is a static design, devoid of the appealing curvilinear shapes that tensile fabrics have come to represent. The sense of motion, lightness, and flight that the triangular tee design presents stands at stark contrast to the more utilitarian feeling of the umbrella design.

Large, exposed structural supports are also unappealing in a design that is meant to suggest movement, speed, and innovation. However, the umbrella design does preserve the visual appeal of urban storefronts and streetscapes. By not including tensile fabric in sight planes, building facades are still visible even when the BLINC structure is present.

As an individual element, the umbrella design is lacking design appeal, but as part of the urban landscape, the umbrella design is more effective at maintaining storefront appeal. The umbrella design earned a score of three for design appeal.
Figure 41. Exploded diagram of the triangular tee design. Diagram by author.

Figure 42. Cable to cable connection. Diagram by author.
Triangular Tee

Design

The triangular tee design is characterized by a triangular sheet of tensile fabric stretched over a structural T-frame. The basic design, illustrated in Figure 42 is closely related to the quarter round design, with the exception of connection points. The triangular tee has only one support, which supports the center of the shade sail. This center support serves two purposes: to keep the tensile fabric in the desired form and to house the central cable support and movement mechanisms.

The bottom of the tensile fabric is joined to a cable-to-cable connection plate, illustrated in Figure 43, making only one point of contact at the bottom of the structure necessary. This central plate moves along the central support, guided by a pulley anchor at ground level and a reel housed in the top support. This inner tube creates an impediment-free space where the tensile fabric and cables can be wound freely. A channel in the top rail allows the tensile fabric and cable to be fed from the exterior of the system to the interior. Like the quarter round system, a tubular motor rotates the inner tube while keeping the outer top support stationary. Cables embedded in the sides of the tensile fabric, shown in Figure 33, help to ensure that the shape of the structure is maintained.

Solar tape adhered on the top rail harvests energy to power the tubular motor, sensors, and lights for the structure, routing excess energy to a small battery.

The triangular tee design is supported by two hinged supports: a horizontal connection at the top rail and a curved connection at the central support, which bisects the tensile fabric canopy. These hinged supports are continuous for the length of the canopy, connecting it to the steel frame. However, range of motion is maintained to allow the fabric to move outward and inward under wind, snow, and other loading conditions. Cables welded into the sides of the triangular fabric are anchored at the distal ends but do not act as rigid connection points, instead allowing free range of motion around the point of connection.

Cyclist Accessibility

The triangular tee performs better than the quarter round, but worse than the umbrella designs in terms of cyclist accessibility. By only requiring one vertical support, a route network of triangular tee designs creates adequate space for cyclists to enter or exit the protected canopy area from street or pedestrian sides. However, tensile fabric mounted on the vertical plane does create a physical barrier that the umbrella design does not posses.

The perforated nature of the triangular tee design creates a compromise between the umbrella design’s open accessibility but lowered protection, and the quarter round design’s lack of accessibility but heightened environmental protection. These factors contributed to the score of five for cyclist accessibility for the triangular tee design.

Buildability

Drawing on the simplicity of the quarter round design, the triangular tee utilizes the same concepts of construction and functionality. By utilizing proven technologies that are easily configured, assembled, and adjusted, the design is considered highly buildable. Off-the-shelf connections, motors, and accessories substantially decrease the effort necessary to build the structure in the field. In fact, it is even possible to prefabricate each module in full off-site, under controlled conditions, and
Figure 43. Plan view of the triangular tee design in various stages of deploy. Far left shows the canopy fully deployed; far right shows the canopy fully rolled within the top rail. Diagram by author.

Figure 44. Rendering of the triangular tee design mounted on Broad Street, Rochester. Rendering by author.
install the structure when fully assembled, tested, and functioning properly. The design earned a score of five for buildability.

Adaptability
The triangular tee structure offers several means of adapting the design to suit particular requirements. First, it provides freedom to space modules along bike lanes and roadways at differing intervals. The fact that the supporting structure is unconnected to other modules in the system, unlike the quarter round design, this design could be spaced as close to or as distanced from other triangular tee modules as desired. Modules spaced at greater intervals would create gaps in protection for cyclists, but would create a new aesthetic.

Secondly, the span of the tensile fabric stretched over the supporting steel can be modified to create thinner or wider modules. Though the triangular point of the fabric will remain connected at the bottom of central support, at street level, the section at the top rail could be stretched as far as structurally possible. This customization to suit specific projects is valuable to the project’s success.

The triangular tee design earned a score of five for adaptability.

Integration into Current Infrastructure
The structural requirements for the triangular tee design necessitate one central support to be mounted along the street-side of the bike lane in order to adequately protect cyclists from automobiles. In the same way that the design intent of the quarter round design is prohibitive toward installation in roadways with restricted space for bike lanes, the triangular tee is not recommended for mounting in roadways lacking buffered bike lanes or extra space between automobile lanes and bike lanes. Though the triangular shape of this design is visually less intrusive into roadways, the mounting hardware still requires a physical offset from driving lanes to minimize risk of interference.

However, as the span of the entire module may be increased or decreased to suit unique projects, the overall space requirements may be adjusted as well. This could create less disruption in existing infrastructure. A score of four was awarded for current infrastructure integration.

Design Appeal
From an subjective aesthetic perspective, the triangular tee design is more attractive than the quarter round and the umbrella designs. The tensile fabric of the triangular tee design is stretched in a way that is more similar to modern, popular shade sails, and represents a more modern-looking form. Whereas the quarter round features extensive areas of fabric, the triangular tee has a smaller surface area of fabric, making the overall effect visually lighter. Additionally, the shape of the tensile fabric more closely represents a sail, giving the entire form the perception of flight and movement, especially when the tensile fabric unrolls from the top support down the central support to its fully deployed state.

Finally, by creating space between the tensile fabric areas, a pattern of visual perforation is produced. This helps to maintain sight-lines to storefronts and the urban appeal of downtown neighborhoods. The triangular tee earned a score of five for design appeal.
<table>
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<th>Triangular Tee</th>
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Figure 45. Subjective and objective evaluation of the quarter round, umbrella, and triangular tee designs. Scores are based on a zero to five scale.
2B. Materials

The main element of the BLINC design is the tensile canopy. This covering serves several purposes including environmental protection, visual signal, aesthetic appeal, and energy generation. In order for the final product to strike a balance between each of these elements, physical characteristics of each textile must be weighed. The following criteria will guide the procedure.

2Bi. General Characteristics

Coating

Each potential textile type may be coated with a unique top-coat to improve a variety of factors: light transmittance, UV resistance, fire-proofing, and water impermeability. Coatings also affect the sustainability and recyclability of architectural fabrics, making their presence or absence significant. Materials that achieve desirable characteristics either without a coating, or with a sustainable and easily removable coating are preferred.

Structure

Architectural textiles may be woven structures or polymer sheets. Textile structure is critically important for obtaining desirable characteristics. The BLINC project only assessed textiles that have been categorized by manufacturers as suitable for tensile applications, which include polymer sheet and tightly woven textiles. Preference for textile structure is not assigned as preliminary product choice has already accounted for these factors.

Predominant usage

Textiles may be specified for indoor or outdoor usage, indicating expected weathering capabilities. Preference is given to textile intended for use outdoors.

Weight

Textile weight can be a significant factor in design, particularly for structural supports. However, stressed loads are the predominant structural design factor, making textile weight of minimal importance for product preference. Textiles that combine high strength characteristics with lower weight are preferred.

Color Availability

Though an optional characteristic, color enhances the overall design by providing customization, branding opportunities, visual saliency, and overall attractiveness of a structure. The BLINC, as a system meant to engage the public and encourage use, may incorporate color via textiles or via lighting. Therefore, preference will not be assigned based on textile color availability.

Visual Appeal

It is necessary to balance utility of the proposed structure with design appeal so as to create and maintain the look and feel of the community, and appeal to all community members. The BLINC aims to balance these priorities by creating a shape that is appealing, yet not overtly pragmatic. A design that creates a balance between efficacy and visual appeal is favored.

Recyclability

Choosing sustainable materials is a responsibility of every designer in the modern world. Sourcing, utilizing, and disposing of
materials in ways that encourage preservation and improvement of the natural environment should be prerequisites for any project. Therefore, textile materials that are composed of pre- and post- consumer recycled content, have a long life expectancy, and are recyclable are preferred.

2Bii. Strength Characteristics

Tensile Strength
A wide array of forces act on the canopy and its cable supports. Therefore the most critical determining factor for each textile is its overall strength. Textiles exhibit some of the same physical characteristics as structural architectural materials such as tensile strength, modulus of elasticity, compressive, flexural, and shear strength. However, some textiles have the unique ability to react in a multitude of directions and unexpected ways based on a variety of factors which could include: material structure, thread count in warp and weft directions, yarn quality, and manufacturing specifications. Industrially-produced fabrics are rigorously tested and reported, so each strength characteristic is able to be calculated in to the final product design.

The greatest forces that the BLINC needs to resist are related to wind loading, particularly uplift, impacts from road debris, and structural design forces. A large factor of safety is factored in to minimize risk of failure due to the complex structural analysis that must take place for tensile structures. Stronger materials are favored for the design of the BLINC.

Tear Resistance
Whereas tensile strength tests analyze whole pieces of fabric in a bi-directional, uni-axial fashion, tear resistance tests determine the bi-directional force necessary to continue a tongue-type tear. This characteristic is particularly important when considering mounting configurations, and potential in-field damage. Preference is given to materials that demonstrate higher tear resistance values.

Adhesion
Textile adhesion tests determine the bond strength between textiles and applied coatings. Higher adhesion values are preferred for textiles in the use phase. However recyclability is affected by extreme adhesion value, which may cause materials to be unusable for future recycled products. Adhesion values differ for every coated textile, therefore no preference is given based upon this parameter.

Elongation
Elongation measures the extension in a textile. Most tensile fabric structures allow a slight amount of material movement in order to release excess tension, much the same reasoning for providing control and expansion joints in solid building construction. Movement joints are required for textiles without elongation values. Preference is given to textiles that exhibit elongation of 1% or less.

Residual Elongation

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i Zito, John P.E., Personal Interview at CPL, Rochester, NY, 18 September 2018.
After a textile material is stretched, it may or may not return to its original size, shape, and length.\(^1\) The amount of stretch percentage that is not recovered to the original form, post-stress, is deemed residual elongation. In tensile fabric architecture, greater residual elongation values are detrimental to structural stability. Preference is given to textiles with negligible residual elongation values.

2Biii. Environmental Characteristics

Visible Light Transmittance
The amount of visible spectrum light that is able to pass through a material or textile membrane is visible light transmittance (VLT). The greater the value of VLT, the more light is available on the opposite side of the membrane. Though most tensile structures are intended as shading devices and thus would require smaller values of VLT, the BLINC design is intended to block enough light to protect cyclists and pedestrians from excessively harsh sunlight in summertime, without causing visual impairment during daylight hours. As the BLINC is schematically designed to be fully extended during daylight hours, it is critical that riders and pedestrians below have the full visual benefit of sunlight. Therefore, visible light transmittance should be at a suitably high level to allow most light to penetrate the textile material, maximizing daylight visibility and transmittance of streetlamp light during evening hours.

Visible Light Reflection
Reflection of light can be just as important as absorption or transmission of light, particularly for structures intended for areas in or around roadways. Too great a reflection level may cause drivers, pedestrians, or cyclists to be distracted or temporarily blinded by structures with over-mirrored and reflective finishes. Too low a reflection level and dawn, dusk, and nighttime drivers and cyclists may have a difficult time seeing the structure. Though not a critical determining factor, the BLINC should have a moderate amount of light reflectance.

Visual Saliency
The BLINC serves as a visual aid to help drivers identify the locations of bicycle lanes, bicyclists, and pedestrians, therefore the design of the structure should be designed to increase visual saliency. Colorful materials and application of lighting elements of the structure help to draw drivers' attention without distraction. Of particular importance is the safety of cyclists and drivers during evening hours when human eyes are not able to function at full capacity.\(^2\) Materials that are able to provide visual saliency through color or light reflectance are preferred.

UV Transmittance
The passage of ultraviolet rays through a material is referred to as UV transmittance. As with traditional shading structures, the BLINC should protect those under it from excessive UV exposure. Textiles with lower UV transmittance values are given preference.

UV Resistance
Some textiles break down faster than others under UV exposure. As the BLINC is meant to provide protection year-round and

---

\(^1\) Seidel, “Tensile Surface Structures.”

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Polyester 1100/1670 Dtex</th>
<th>Nylon*</th>
<th>PTFE</th>
<th>Solar Fabric**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proprietary Name</td>
<td>Serge Ferrari* Flexlight Perform* 91 S2</td>
<td>Stern and Stern* Nylon 6,6 A5970</td>
<td>Sefar* Tenara* 4T20HF</td>
<td>CdSe nanowire-grafted Ti wire and carbon nanotube (CNT)</td>
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<td>Coating</td>
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<td>Can be specified</td>
<td>100% Fluoropolymer (Removable)†</td>
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<td>Plain 1/1</td>
<td>Modified satin</td>
</tr>
<tr>
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<td>Internal/External†</td>
<td>External†</td>
<td>External†</td>
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<td>12400 psi</td>
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<td>Not specified</td>
<td>Unknown</td>
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<tr>
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<td>Unknown</td>
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<td>Not specified</td>
<td>Unknown</td>
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<td>Visible Light Transmittance (Tv)</td>
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<td>Varies</td>
<td>19%†</td>
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<tr>
<td>Visible Light Reflection (Rv)</td>
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<td>Varies</td>
<td>79%†</td>
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<tr>
<td>UV Transmittance</td>
<td>0%†</td>
<td>Varies</td>
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<td>Unknown</td>
</tr>
<tr>
<td>UV Resistance</td>
<td>Good</td>
<td>Significant degradation over time</td>
<td>Permanent†</td>
<td>Unknown</td>
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<tr>
<td>Longevity (yrs)</td>
<td>10 yr warranty</td>
<td>Not specified</td>
<td>15 yr warranty†</td>
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<tr>
<td>Color Availability</td>
<td>White only†</td>
<td>Wide Range†</td>
<td>White only†</td>
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<tr>
<td>Self-Cleaning Ability</td>
<td>Yes†</td>
<td>No</td>
<td>Yes†</td>
<td>Unknown</td>
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<tr>
<td>Resistance to Chemicals</td>
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<td>Alkaline resistance</td>
<td>Yes†</td>
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<tr>
<td>Suitability for Rolling Membranes</td>
<td>Yes†</td>
<td>Yes†</td>
<td>Yes†</td>
<td>No</td>
</tr>
<tr>
<td>Recyclability</td>
<td>Yes† Texyloop*</td>
<td>Manufacturer-to-manufacturer basis</td>
<td>Yes†</td>
<td>No</td>
</tr>
<tr>
<td>Overall Preference</td>
<td>Acceptable (8/16 preferred characteristics)</td>
<td>Not Preferred (5/16 preferred characteristics)</td>
<td>Preferred (12/16 preferred characteristics)</td>
<td>Not Preferred (Not enough information to rate)</td>
</tr>
</tbody>
</table>

* Due to the availability of many varieties of nylon 6,6 textiles, this case study Nylon 6,6 was chosen based upon suitability for outdoor architectural applications.
** Due to the experimental nature of solar woven fabrics, the results below are as reported by Zhang, et al. 2012.

Figure 46. Material characteristics of proposed textiles for the BLINC structure. Preferred characteristics are indicated with a †.

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i “Flexlight Perform 912 S2 Product Data Sheet,” Serge Ferrari.
have a maximized life-span, the structure needs to minimize degradation from UV sunlight. Textiles with greater UV resistance is given preference.

**Longevity**

Longevity is affected by many characteristics such as UV resistance, residual elongation, water tightness, tensile strength, tear resistance, mechanical wear resistance, and chemical resistance. As such a complex characteristic, it is necessary to consider these factors in sum to rate overall longevity. Because the BLINC is meant to be an economical alternative to unprotected bike lanes, it is necessary to identify fabrics with greater longevity.

**Self-Cleaning Ability**

The ability of tensile fabric materials to resist the build up of dirt, dust, and other environmental contaminants has improved over time. As the climate changes, more environmental contaminants affect the chemical composition of precipitation, leading to the potential for chemical erosion of materials. Materials at street-level are affected by non-environmentally-based chemicals, such as road salt and silt, and vandalism-related application of chemical products, such as paint. As a street-mounted structure, it is important that the BLINC is able to resist premature aging and break-down from these contaminants. “Self-cleaning” fabrics are those that are cleaned by precipitation. As factors related to longevity, greater self-cleaning ability and chemical resistance are desired for the BLINC.

**Suitability for Rolling Membranes**

The BLINC is designed to be deployable, meaning rolled up and expanded at the cue of environmental factors. This requires the textile material to be rolled and unfurled on a daily basis. The ideal textile material must be able to resist adverse effects from this constant mechanical motion, ensuring longevity the structure.

**Water Impermeability**

The canopy material must be able to repel water at a rate great enough to prevent precipitation from entering the bike lane network. The form of the BLINC is also important for the ability of the structure to shed water away from pedestrians and cyclists below.

**2Biv. Preferred Material**

Based on the performance of each textile in Figure 47, PTFE is the preferred material for use in the BLINC system. Coated PTFE outperforms polyester and nylon in tear resistance, visible light transmittance, visible light reflection, UV resistance, durability and resistance to chemicals. Polyester, nylon, and PTFE perform similarly in terms of tensile strength, elongation, self-cleaning ability, rollability, and recyclability. Though nylon is much lighter than the other fabrics, its poor performance in tear resistance, and lack of durability over time make it an undesirable material for the BLINC. Though PTFE is heavier than polyester and nylon textiles, it has proven to be reliable in tensile fabric architecture precedents.

Solar fabric, as an experimental material, is not a viable alternative to PTFE and other tested architectural textiles. At present, solar tape and other solar power generating devices can easily be integrated into BLINC designs to compensate for the loss of power that could be generated by solar fabric. In the future, if integrated solar textiles are proven as an alternative to architectural textiles, they could replace PTFE as a BLINC covering.
<table>
<thead>
<tr>
<th>Type</th>
<th>InfinityPV Solar Tape</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Grade C PCE &gt; 4% Bidirectional</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>60</td>
</tr>
<tr>
<td>Thickness (µ)</td>
<td>125-150</td>
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<td>Voltage (per meter)</td>
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<tr>
<td>Current (mA)</td>
<td>60-70</td>
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<tr>
<td>Power (mW/meter)</td>
<td>800</td>
</tr>
</tbody>
</table>

Figure 47. Power potential for Infinity PV Solar Tape.¹

Figure 48. Input flow diagram for BLINC deploy control. Diagram by author.

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2C. SENSORS AND MOTORS

The BLINC system is embedded with several technological elements to trigger motion, provide safety elements for cyclists and pedestrians, and increase the overall aesthetic appeal of the canopy. Motors power pulley systems to roll the canopy into its housing or extend it along the structural frame. Rain sensors and anemometers monitor environmental conditions to trigger the motor system. LED lights provide illumination for safety and aesthetic design. And, photovoltaic tape collects solar energy to power motor systems.

As non-structural, non-architectural elements of the BLINC, these elements are specified based upon technological capabilities, wide availability, and ease of use. The accessories listed below indicate minimum requirements for the BLINC, and provide a basic platform from which to develop more sophisticated systems.

2Ci. Solar Power

In order for the BLINC to function as intended, electric energy must be available to power the sensors, motors, and lights on the each structure. While it is theoretically possible to tie the BLINC system into the municipal electric grid, this solution is neither sustainable or practical over long distances. A renewable energy system is more practical to support the BLINC systems.

One widely available and portable solution is solar power. While traditional photovoltaic (PV) panels are impractical for the BLINC due to weight and size, flexible solar films are extremely light-weight, small, and able to be mounted to almost any surface.

InfinityPV produces a “flexible organic solar cell foil with optional semi-transparent lined adhesive on the front or backside and functions as a solar sticker.” The tape is waterproof and suitable for outdoor applications, making it well-adapted to be adhere to the top rail of the BLINC structure. Additionally, the tape is easily integrated with power converter boards, making battery power storage possible and straightforward.

As shown in Figure 48, the maximum power potential from one length of InfinityPV tape adhered to one BLINC module is 2.4 watts, assuming a ten foot span of uninterrupted solar tape. While this power potential is small, the alternative energy it provides is valuable for sustainable initiatives. As an alternative solution for generating more power, traditional solar panels may also be mounted to the BLINC. This solution would be more viable for applications where complete dependence on solar power is necessary to power the BLINC.

2Cii. Hydro Sensor

Rain sensors allow mechanical systems to respond to environmental factors. In the BLINC system, the presence of rain is a trigger for the tensile fabric to deploy from its housing, in order to protect cyclists, day or night, from rain, snow, or sleet. As poor weather is recognized as one of the biggest barriers to cycling as a mode of transportation, this functionality of the canopy is critical for the project’s success.

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ii Ibid.

iii Ibid.
The BLINC utilizes a physical rain sensor, which functions by detecting weight changes on the sensor to indicate the presence or absence of water. This small sensor is easily mountable on the BLINC and easily integrated with the system micro-controller and shield. When the sensor detects moisture, the canopy is programmed to deploy. During non-rainy conditions, the sensor signals the canopy to retract or remain open, depending on time of day. Figure 49 illustrates other variables which determine deploy, retraction, or idle states of the BLINC.

2Ciii. Anemometer
An anemometer an important protective feature of the BLINC system as tensile canopies may be damaged by high winds. In order to protect the tensile fabric from potentially damaging conditions and to prevent detrimental uplift scenarios, the BLINC is equipped with an anemometer. This sensor triggers the canopy to retract if wind speeds are too high for safe operation. According to the Beaufort Scale, used to categorize wind speeds and their potential for damage, unstable uplift forces are likely to occur at 25-31 mph (11-13.5 m/s). In order to minimize the danger from strong winds, the micro-controller will trigger the motor to retract the canopy at wind speeds of 15 mph.

2Civ. Micro-controller
The sensors listed above provide inputs to guide the programmed functions of the BLINC system. However, in order to translate sensory inputs into mechanical actions, a micro-controller is necessary. Easy to install and program, open-source boards like Arduino and Adafruit, are effective for producing functioning prototype BLINC modules.

Figure 49 outlines the inputs required to produce particular functions via the micro-controller.

2Cv. Tubular Motor
As a dynamic canopy system, the BLINC requires a source of torque power in order to deploy and retract the tensile fabric. A tubular motor, normally used in interior roller blinds and exterior shade canopies, provides a simple solution to move the BLINC canopy.

The ASCE Guidelines for Minimum Design Loads for Buildings and Other Structures (ASCE 7) is the standard from which the torque and tensile loading capacities of the BLINC are calculated. ASCE 7 outlines design requirements for structures according to occupancy category, exposure category, enclosure classification, and surface roughness. For a simplified calculation to determine minimum loading requirements, it is assumed that the BLINC is in occupancy category I (low hazard to human life in failure).

The tubular motor will need to provide 16.08 lb/ft² of torque in order to successfully pull the fabric taught and secure across its support:

---


\[ q = 0.00256 \, K_z \, K_{zt} \, K_d \, V^2 \text{ (lb/ft}^2) \]
\[ q = 16.08 \text{ lb/ft}^2 \text{ (0.77 kN/m}^2) \]

Whereas:

\( q \) = velocity pressure

\( K_z \) = exposure velocity pressure coefficient

\[ K_z = 2.01 \left( \frac{z}{z_g} \right)^{2/\alpha} \]

Whereas, \( z \) is equal to the height of the structure (9'-0” for the BLINC), \( z_g \) is equal to 1,200' for Category B exposure (urban to suburban areas), and \( \alpha \) is equal to 7.0 (a constant for Category B exposure).

\( K_{zt} \) = topographic factor

This factor is assumed to be negligible due to the variability of where the BLINC may be installed. Should the project proceed to construction development, a qualified structural engineer should be employed to ensure load factors are appropriate and structural design is sufficient.

\( K_d \) = directionality factor

Whereas, \( K_d \) is a constant, 0.95, defined by ASCE 7 Table 26.6.1. A trussed framework is assumed for the BLINC.

\( V \) = basic wind speed

Whereas, according to ASCE Figure 26.5-1A, \( V = 115 \text{ mph (51m/s)} \) in Rochester.

Tubular motors are widely available, in a multitude of diameters, power thresholds, torque capabilities, and other specifications. Elero tubular drives are specified for the BLINC project due to the reliability of the drives in exterior applications, for commercial tensile fabric applications, and integration with solar power systems. The SunTop L-868 DC motor is capable of producing 40 Nm of torque at 120 Watts of power consumption, is radio-controlled, and is specifically designed to be integrated with solar-generated power. Additionally, this motor has an operating range of -20-60°C, well in the temperature range of the Rochester, NY. As the shaft diameter is 63 mm (2.5”), the structural arms of the BLINC can be minimized.\(^i\)

2Cvii. LED Lighting

Lighting on the BLINC is an important safety feature as well as an aesthetic element for the canopy. In order to prevent automobile collisions and call attention to the structures, small LED lights are integrated into the vertical structural supports. Additionally, LED lights mounted to the interior of the canopy light the bike route below, illuminating the entire structure.

Low-energy LED are now ubiquitous, making integration into the BLINC systems simple. Additionally, many LED systems are programmable to different color and timing inputs to create a fully customizable canopy system. For example, solid red lights may be suitable for nighttime application, while flashing white lights would be suitable for day-time application.

Small LED button lights can be easily installed in steel support members, at specified distances, and integrated into the solar power systems of the BLINC.

Figure 49. Deformation results from RFEM Form Finding for the quarter round design.

Figure 50. Elevation view of deformation results from RFEM Form Finding for the quarter round design.
2D. Structural Evaluation

2Ci. Quarter Round

In order to support the quarter round design, the quadrangle canopy is structurally supported on three sides with continuous hinged connections, shown in Figure 50 as green arrows. The top side, connected to the textile canopy tube encircling the tubular motor is a rigid connection, only able to move while rolling. Hinged connections occur at each side of the canopy, where the fabric is able to rotate along the plane of the steel cable supports. The bottom hem of the tensile canopy remains unconnected to any rigid or hinged support, however a tensioning cable sewn into the hem keeps the bottom side of the fabric from excessive deformation.

Analysis by RFEM, as shown in Figures 50 and 51, indicates the quarter round tensile fabric will have a maximum deformation of 136 in at the unsupported bottom hem. Areas of larger deformation are indicated in red. This deformation from the intended uniform plane of the canopy occurs under maximum loading conditions, as defined by ASCE 7. Three-dimensional visual outputs show that the tensile fabric will bow inward toward cyclists when fully tensioned. Figure 49 shows the central area of the canopy as deformed while the supported edges remain stable. Figure 50 is a planar view of the deformation, indicating the depth of the deformation in the X-axis.

Due to the large degree of deformation in the canopy, which would be detrimental to the overall effectiveness of the design and compromise the mobility of the fabric, a tensile cable was integrated into the bottom hem. This tensioning but flexible cable will tie the tensile fabric into the structural supports, providing enough force to counteract the deformation, bringing the fabric closer to the same plane as the remainder of the fabric.

2Cii. Umbrella

Analysis by RFEM, shown in Figure 51, indicates that the umbrella structure will deform to a degree of 26 inches when under loading conditions. Although the supports at all edges of the tensile fabric are in the same plane, the front, unsecured hem will still be pulled back toward the vertex of the fabric, indicated in Figure 51 as red areas. As the other edges of the fabric are rigidly secured to the structural frame, RFEM analysis shows a more erratic deformation diagram than the triangular tee and quarter round designs.

Though the 26 inch maximum deformation out of the intended plane is not as severe as the quarter round deformation, it would nevertheless be detrimental to the effectiveness of the design. As with the quarter round design, a tensioned cable along the front edge of the tensile fabric, indicated in Figure 52 as green arrows, was integrated into the fabric and tied into the secondary arms to minimize this deformation. When fully deployed, the tensile fabric should only show a deformation of a few inches with this modification. The deformation analysis output shown in Figure 52 indicates equal, minimal deformation shown in blue.

2Ciii. Triangular Tee

Deformation analysis by RFEM of the triangular tee design indicates that the maximum deformation of the fabric under

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i. Note that RFEM Form Finding analysis for the umbrella was isolated to one half of the entire module. i.e. the total area of the tensile fabric was split at the median line occurring at the central support. Therefore, the deformation results would occur at each side of the entire tensile fabric.
Figure 51. Deformation results from RFEM Form Finding for the umbrella design.

Figure 52. Deformation results from RFEM Form Finding for the umbrella design with added tensioning cable.
maximum loading conditions is 2.5 inches (see Figure 53). Though the sides of the triangular tee canopy are supported via
tensioned cables and the top of the canopy is secured with a rigid connection to the top rail, minimal deformation still occurs
in the tensile fabric. Interestingly, maximum deformation areas occur in two places in the fabric, either side of the equatorial
line, with the fabric deforming in opposite directions. The deformation scale factor was increased to show this deformation
more clearly in Figure 54. The bottom half of the canopy will deform outward during loading conditions while the top of the
canopy with deform inward, shown as red gradients in Figures 53 and 54.

This result is significantly better than the quarter round and umbrella deformation analysis, prior to additional modifications,
due to the integration of hinge supports along each fabric edge. Because the top hem is secured to the top rail, side edges
are tensioned via cables tied into the structural frame, and the bottom point is secured to the connection plate, minimal
deformation will occur in the fabric under loading conditions. Stronger rigid connections at the top rail and appropriately
tensioned cables at the side hems are necessary to minimize the 2.5 inch deformation and prevent damage from excessive
movement and flapping.

---

i. Note that RFEM Form Finding analysis for the triangular tee was isolated to one half of the entire module, i.e. the total area of the tensile fabric was split at the median line occurring at the central support. Therefore, the deformation results would occur at each side of the entire tensile fabric.
Figure 53. Deformation results from RFEM Form Finding for the triangular tee design.

Figure 54. Elevation view of deformation results from RFEM Form Finding for the triangular tee design. Note: deformation factor has been increased to emphasize directionality.
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### Subjective and Objective Evaluation of BLINC Design

<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Quarter Round</th>
<th>Umbrella</th>
<th>Triangular Tee</th>
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<tbody>
<tr>
<td>Cyclist Accessibility</td>
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<td>5</td>
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<tr>
<td>Buildability</td>
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<td>Adaptability</td>
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<td>Design Appeal</td>
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<tr>
<td>Structural Integrity</td>
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<td><strong>28</strong></td>
<td><strong>28</strong></td>
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</tbody>
</table>

Figure 55. Subjective and objective evaluation of the quarter round, umbrella, and triangular tee designs. Scores are based on a zero to five scale.

Figure 56. Illustration of the BLINC canopy on St. Paul Street, showing canopy illumination, red LED safety lights, and interaction with storefronts. Rendering by author.
VI. Analysis

As a means of utilizing tensile fabric structures to protect cyclists and pedestrians on Rochester’s transportation network in order to promote cycling as a mode of transportation, to expand equal access to efficient transportation, and to better connect the urban framework of the city, the BLINC system is successful in theory.

Analysis of the chosen form of the BLINC structure is conducted in order to give context to the broader discussion of how the BLINC system addresses the problem statement outlined above.

1. Form Analysis

Through subjective and objective analysis based upon cyclist accessibility, buildability, adaptability, integration into current infrastructure, design appeal, and structural performance, it was determined that the ideal form for the Bicycle Lane Network Canopy is the triangular tee design utilizing PTFE architectural fabric.

As outlined in Figure 55, evaluation of the umbrella and triangular tee designs yielded identical overall scores, indicating that both designs are viable options for the BLINC network. However, the triangular tee design best epitomizes the goals of the project: a canopy that encourages cycling as a mode of transportation by creating safe passage for cyclists, protection from environmental elements and automobiles, and representative of a design style that recalls lightness, motion, and modernity.

Ultimately, the aesthetic appeal of the triangular tee BLINC design was favored over the umbrella design as it has a greater potential to affect the urban environment in Rochester. Though the umbrella design is functional, the triangular tee is more dynamic in a design sense. This dynamism is important when considering the BLINC system's role in shaping the urban fabric. A compelling design is able to kindle conversations, interactions, and unity in urban spaces, as has been shown by Janet Echelman's aerial sculptures in Boston, the Porirua Shopping Centre in Wellington, LuminoCITY in Detroit, and Union Station in Denver.

Space between the triangular canopy modules provides accessibility to the protected bike path from pedestrian or traffic sides of the roadway. The structure is relatively straightforward to prefabricate as many movable connections are based on maritime technology, and components are widely available. As shown in Figure 56, modules are able to be customized with alternative spans, heights, and curvatures. Provided appropriate buffering space between traffic and bike lanes, the triangular tee design is easily integrated in the existing roadway infrastructure and is structurally stable. Further design development of the triangular tee canopy is possible in order to integrate creative lighting concepts, textile styles, and alternative spacing layouts. These positive attributes ensure that the triangular tee tensile fabric structure is an effective bike path covering.

The triangular tee design is an aesthetic solution for creating bike path coverings that contribute to the fabric of the urban environment in Rochester. These canopies represent transportation infrastructure intended specifically for cyclists and pedestrians to traverse the city in a safe way. Additionally, individual triangular tee BLINC modules array in a functional and graceful way to create wider transportation route networks throughout the city.
Figure 57. Map of Monroe County indicating areas of high employment rates, poverty rates, and the proposed BLINC route network. Diagram by author.
2. IMPROVING THE BUILT ENVIRONMENT THROUGH CYCLING

2A. PROMOTE CYCLING AS A MODE OF TRANSPORTATION

The BLINC system successfully promotes cycling as a mode of transportation, by overcoming the major barriers of cycling adoption, as outlined by Piatkowski.¹

2Ai. Improved Safety

The BLINC system improves safety of cyclists in several ways. First, it provides a dedicated lane for cyclists on existing streets, removing cyclists from automobile driving lanes. Dedicated bike lanes are known to be safer for cyclists, with physically separated lanes being the safest.² The BLINC system creates a physical, albeit penetrable, barrier between drivers and cyclists to keep cyclists safe.

Additionally, lights mounted on the BLINC structures keep cyclists safe during evening hours by illuminating paths of travel to keep cyclists visible. The design intent of the BLINC network is shown in Figure 56, where night lighting and physical separation between cyclists and drivers can be seen.

2Aii. Improved Convenience

The BLINC system improves the likelihood of utilizing cycling as a mode of transportation by improving the convenience factor of cycling. As shown in Figures 57 and 58, because the streets included in the BLINC network are continuous through the city of Rochester, adjacent to areas of growing employment, educational institutions, urban points of interest, and bus stops, the convenience of cycling through the city is greatly improved. Commuters through the city may find that cycling on the BLINC network provides a faster, more direct route to destinations.

Additionally, the adjacency of the BLINC route network to existing bus stops, as shown in Figure 58, improves the access of commuters to more distant areas of travel. Commuters may utilize several modes of transportation easily, biking to a bus stop, riding for a distance, then continuing to a final destination via bike, or vice versa. Combined with the existing bus network, the BLINC route network creates a convenient and faster method to travel through the city.

2Aiii. Improved Environmental Protection

By providing a covered route, the BLINC system improves cyclist protection from environmental elements. The triangular tee design is effective at creating a bike path covering system to protect cyclists from inclement weather, and promote cycling as a mode of transportation in Rochester. As Piatkowski, et al. identifies inclement weather and perception of risk are two main factors in deterring potential cyclists. The triangular tee design creates weather protection via spans of tensile fabric that face the automobile traffic and overhead sides of the bike lane. The curvilinear shape is able to shed snow and rain, allowing commuters to travel by bike in more comfort during inclement weather. Additionally, while the fabric canopy is not capable of preventing snow accumulation from drifts or snow plows, sidewalk plows can easily fit under the 10'-0” clear height of the BLINC structural frame to clear residual snow.

Figure 58. BLINC route network map with roadways, places of interest, and bus stops identified. Diagram by author.

Figure 59. Diagram illustrating the area of travel of pedestrians and cyclists beyond a defined BLINC routes.
**2B. Expand Equal Access to Efficient Transportation**

Most importantly, the BLINC route network addresses inequality in transportation by creating free and convenient alternative transportation routes through the city. As shown by the ReConnect Rochester *Transportation and Poverty in Monroe County* report, non-automobile transportation is a critical element in addressing mobility in Rochester. As shown in Figure 57, streets included in the BLINC network are adjacent to areas of high poverty as well as areas of growing employment opportunities. By creating a system that contributes to efficient access to major employment districts and multiple schools and universities, the BLINC route network is a factor in anti-poverty initiatives in Rochester. By developing infrastructure to support cycling as an alternative means of transportation, Rochester commuters may physically access jobs and educational institutions faster than bus transportation and cheaper than automobile transportation.

As shown in Figure 15, it is estimated that cycling travel times are reduced for cross-city destinations when compared to bus travel times. Additionally, as the BLINC route network is purposefully adjacent to other alternative transportation routes, a larger network of alternative transportation options may be combined to suit travelers’ needs. For example, a commuter from the Edgerton neighborhood may ride the RTS bus route 150 to the Transit Center, then cycle along the BLINC network on the Saint Paul Street corridor to a final destination at Strong Memorial Hospital. Without access to a car, this route would take 47 minutes by bus, or 83 minutes by walking. With the BLINC route network in place, the commute would take 33 minutes.

Additionally, with the BLINC network in place, the accessibility of Monroe County to those without automobiles improves. The *Transportation and Poverty in Monroe County* report states that 63% of Monroe County is accessible to those who rely on public transportation. Cyclists are able to access half a mile more by bicycle than by foot, increasing the area of access surrounding bus and BLINC routes by one mile total (see Figure 59). As the area of Monroe County is 1,367 square miles, and the BLINC network adds an additional 56.5 square miles of access surrounding alternative transportation routes, 4% more of Monroe County is accessible. In other words, if it is assumed that cyclists are willing to commute for one mile, and cyclists would take at least part of any journey by bus, the BLINC network would improve Monroe County access for those without automobiles to 67%.

<table>
<thead>
<tr>
<th>BLINC Route</th>
<th>Route Length</th>
<th>Area of Pedestrian Access (1 mi buffer)</th>
<th>Area of Cyclist Access (2 mi buffer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saint Paul Street</td>
<td>10 mi</td>
<td>10 mi x 1 mi = 10 sq.mi</td>
<td>10 mi x 2 mi = 20 sq.mi</td>
</tr>
<tr>
<td>Main Street</td>
<td>35 mi</td>
<td>35 mi x 1 mi = 35 sq.mi</td>
<td>35 mi x 2 mi = 70 sq.mi</td>
</tr>
<tr>
<td>Clinton Avenue</td>
<td>7 mi</td>
<td>7 mi x 1 mi = 7 sq.mi</td>
<td>7 mi x 2 mi = 14 sq.mi</td>
</tr>
<tr>
<td>Jay Street</td>
<td>4.5 mi</td>
<td>4.5 mi x 1 mi = 4.5 sq.mi</td>
<td>4.5 mi x 2 mi = 9 sq.mi</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>56.5 mi.</strong></td>
<td><strong>56.5 sq.mi</strong></td>
<td><strong>113 sq.mi</strong></td>
</tr>
</tbody>
</table>

Though a four percent increase in access is a small statistic, it can be assumed that cyclists may gain even greater access to the county due to proximity to other areas. As outlined in the map on Figure 58, the BLINC route network forms connections with other safe bicycling routes like the Genesee Riverway trail, as well as low-cost bus transportation routes. The lengthy

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ii “Transportation and Poverty in Monroe County”: 25
Figure 60. The BLINC system deployed along Clinton and St. Paul Streets. Rendering by author.
streets included in the BLINC transportation network are intended to create uninterrupted non-automobile travel over
distances commonly traveled by car. If additional BLINC routes are included in the network in the future, it can be assumed
that access will be increased proportionally.

2C. IMPROVE URBAN FRAMEWORK OF ROCHESTER

Several roadways were determined to be suitable for BLINC installation due to the capacity of each to connect the population
of Rochester in a meaningful way. Each roadway within the BLINC route network is continuous throughout the city, and
forms connections between areas of various levels of poverty and employment opportunity, as shown in Figure 57. Additionally,
each route roadway is adjacent to schools, civic amenities, and is wide enough to install the BLINC system. The proposed route
meets all required design criteria as well as successfully addresses the problem statement.

As a means of connecting the urban fabric, the BLINC route network, consisting of St. Paul Street, Clinton Street, and Main
Street, creates a cross-section of downtown Rochester. The north-south running St. Paul and Clinton Streets and east-west
running Main Street provide cyclist access to the core and extents of Rochester efficiently, while enhancing the sense of place
that the urban framework provides. As Figures 57 and 58 show, the BLINC network creates access through diverse areas within
the city without the need for an automobile.

The BLINC route network also helps to connect the urban fabric, particularly in areas identified by the Center City Master
plan. As shown by Figures 60 and 61, the BLINC network creates a visual connection throughout the city to link overly-
sized blocks or parking lots without major infrastructure development. As the Berlin Radbahn project, Janet Echelman aerial
sculptures and Detroit LuminoCITY structures showed, tensile structures can be successful at creating a sense of place within
the urban framework. Like the proposed BLINC route network, each of these structures was installed in an area of little urban
interest or connection; the presence of the structures created a sense of continuity and integration into the urban fabric. Where
the BLINC route network passes large areas of urban space, like Parcel 5 and Martin Luther King Jr. Park, the tensile canopy
system works in tandem with various event programming to bring event attendees to the space and create a more lively urban
environment.

As the Strategic Cycling Analysis report indicates, “cycling connections...support multimodal trips by improving cycle access to
important [public transportation] stations. In these areas, cycling routes...better connect stations to their surrounding areas and
contribute to reducing the dominance of motorised traffic.”

As the Cycle Superhighways demonstrated in London, bicycle infrastructure provisions help to boost ridership numbers by
creating convenient access points to multiple neighborhoods, and working seamlessly with other modes of transportation. In
Rochester, the BLINC network has the potential to create similar unification in the urban environment through continuous,
linear installations through the city of Rochester, linking city streets to residential, employment, and recreational areas.

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Figure 61. Rendering of the triangular tee BLINC route along Main Street in Rochester. Rendering by author.
VII. DISCUSSION

In addition to the three major goals addressed in Section VI Analysis, installation of the BLINC route network is expected to have additional beneficial effects on areas of the city and community of Rochester, reaching beyond cyclist safety and transportation equality.

1. COMMUNITY EFFECTS

1A. IMPROVE COMMUNITY HEALTH

Installation of the BLINC will affect community health in a positive way. Increases in bike ridership correspond to improved overall health indicators. Cycling as a mode of transportation, instead of sedentary driving, has been shown to improve physical and mental health. The BLINC will increase bike ridership by redesigning Rochester’s streets for people instead of cars. Though cycling is not a be-all-end-all concept, any step toward encouraging a more active community should be pursued.

1B. LOWER GREENHOUSE GAS EMISSIONS

Fewer automobiles and more cyclists on Rochester’s roadways corresponds lower greenhouse gas emissions. Because the BLINC encourages cycling as a mode of transportation, Rochester’s air quality will improve as more commuters choose to cycle. As a city dedicated to maintaining the sustainable goals of the Paris Accords, lowering car emissions by redefining roadways for pedestrians and cyclists should be a top priority. By installing the BLINC system along bike lanes throughout the city, Rochester is visually indicating its commitment to sustainability.

1C. PROMOTE LOCAL BUSINESS

Increase in ridership numbers due to improved infrastructure may also lead to economic benefits. Compared with automobile drivers, cyclists tend to shop more locally and are more likely to stop along their travel route. By installing the BLINC in a radial formation, from the center city out through city neighborhoods, multiple areas of the city could benefit. As a bicycling route, instead of an automobile route, it is more likely that cyclists will stop and enjoy adjacent amenities, boosting the local economy.

2. CITY OF INNOVATION

2A. INNOVATIVE IDEAS FOR URBAN REVIVAL

Many cities and states have elected to pursue diverse sustainability goals separate from any national mandate. Rochester has a history of promoting sustainable initiatives. In 1999 the City agreed to include provisions for reducing environmental contamination and pollution; in 2018 Mayor Lovely Warren became a Climate Mayor, committed to upholding the principles and standards of the Paris Climate Accords.

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 v Ibid.
viii Ibid.
At this time, the City of Rochester is actively pursuing new, innovative, and sometimes experimental urban renewal projects.\textsuperscript{i,ii,iii} With cities across the U.S. moving to increase the vitality of their urban cores, promote healthy living, and become more sustainable and vibrant communities, the expansion of bike lane systems is a low-effort, high-return opportunity. Installation of the BLINC route network will integrate with the City’s current implementation of the Bicycle Master Plan. The BLINC route network also creates a high-visibility, marketing-friendly project to promote bicycling as a viable transportation solution and Rochester as a hub of innovation and sustainability.

Though conceptualized as a solution for bicycle networks, the concepts of the BLINC can also be expanded to other typologies and uses. In situations where temporary, small scale, or light-weight structures are utilized or desired in the urban environment, the concepts of the BLINC may be applied. Alternative applications could include bus stop shelters, shading devices for public spaces, and even temporary roofing structures.

With Rochester’s inner city highway system and other arterial streets under scrutiny for being oversized based on traffic density,\textsuperscript{iv} now is the perfect time to integrate the BLINC route system into roadway master planning strategies. Just as the infill of the Inner Loop East brought a new vibrancy to the Union Street/East End neighborhood,\textsuperscript{v} the BLINC network will humanize the sections of city currently defined by underused, excessively-sized areas of pavement.

Mayor Lovely Warren’s commitment to continue pursuing the goals of the Paris Climate Accords indicates that Rochester will continue to pursue a model of sustainable urban development. Innovative, experimental ideas like the BLINC route network are a way forward in this unique climate of political unrest: the old, trusted, ways of doing things must be updated if the system is to remain relevant. Only through trusting new ideas can we move forward into a better future.

3. Further Research

3A. Evaluation Survey

Due to the subjective nature of the BLINC form analysis, it would be prudent for future researchers to conduct a more objective analysis of potential BLINC forms. A survey of potential users and stakeholders would form a more complete and less-biased result of the most appropriate BLINC form.

3B. Alternative Forms

Though the triangular tee form was determined to be best suited for Rochester’s urban context, alternative BLINC designs may be suitable for other urban contexts. The utility of the barrel and umbrella designs in other environmental contexts should be explored. Though unsuitable for an urban site, the barrel design may be useful in rural, recreational contexts where automobile sight-lines are less critical to project success. The umbrella design may be equally useful in areas where only overhead protection is necessary or possible. Additionally, a myriad of other designs could prove equally successful at protecting cyclists along

\textsuperscript{i} “Inner Loop Improvement Project: Project Scoping Report,” City of Rochester Department of Environmental Services, March 2010.
\textsuperscript{iii} “Rochester Center City Master Plan 2014,” City of Rochester, (2014).
\textsuperscript{iv} “Inner Loop Improvement Project: Project Scoping Report,” City of Rochester Department of Environmental Services, March 2010.
transportation routes, and should be explored in further research.

3C. Alternative Textiles
A variety of other textiles may be utilized for the tensile canopy, including acrylics and natural fibers such as bamboo, jute, and cotton. While acrylic textiles may be particularly useful in the current BLINC structure, alternative textile performance characteristics may be useful for future project requirements. Alternative textiles may also possess unique characteristics related to light penetration, reflection, or color, which could better suit projects based in different environments or contexts. Future research should explore the possibility of utilizing a variety of other textile options to maximize the effectiveness and appeal of the BLINC structure.

3D. Full Scale Mock-Up
A full-scale mock up of the BLINC structure should be pursued during future research in order to determine construction feasibility. Constructing a mock-up would allow for further study of material choices, structural integrity, and intended performance. As the BLINC structure contains an array of moving parts, testing functionality in a controlled environment, and making needed adjustments would be beneficial. The full-scale model would also allow for testing of alternative materials, particularly textiles.

3E. Intersection Interaction
The behavior of the BLINC structures at roadway intersections should be explored in detail during future research. Intersections are some of the most dangerous places for cyclists. Creating safer intersections for cyclists, pedestrians, and automobile drivers should be a priority.

The current BLINC system terminates prior to intersections and restarts after intersections. This placement method prioritizes high visibility for all roadway users, but does not fully protect bicyclists at high-risk areas. Future research should focus on exploring BLINC configurations that create uninterrupted protective pathways through and beyond intersections.

3F. Expansion of Route Network
The current BLINC route network is shown to improve access in Monroe County between residential areas, employment areas, educational institutions, and areas of urban interest. The interaction of the BLINC route network with existing bus routes, bike lanes, and recreational trails creates a seamless multi-modal transportation network through the City of Rochester and beyond. However, expansion of the proposed BLINC route network should be considered. As the current proposed network is able to expand access in Monroe County by 4%, it follows that adding additional roadways into the network would create even greater access.

In order to create a transportation system that truly serves the residents of the City of Rochester and alleviates the transportation inequality perpetuating high poverty rates in Rochester, bicycle transportation should be prioritized. Further research should determine the feasibility of adding additional roadways to the BLINC route network until all residents have access to protected bike lanes.

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