Breaking the Cycle of Congestion

AN EXAMINATION OF TRAFFIC CONGESTION IN COPENHAGEN

REPORT

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Submitted to the Faculty of

Worcester Polytechnic Institute

in partial fulfillment of the requirements for the degree of
Bachelor of Science

Date:

May 02, 2017

Acknowledgements

We would like to begin by thanking our sponsor, Claus Knudsen, and the entire team at Miljøpunkt Amager for arranging and helping guide our project. His assistance, especially in introducing us to other organizations in Denmark, was vital to the success of our work, in addition to the hospitality that we received from Miljøpunkt Amager. We would also like to thank Joe Collins and the members of the Bicycle Innovation Lab for assisting us with our project by allowing us to borrow bicycles and giving us feedback and suggestions on the scope of our project.

Additionally, we would like to thank the individuals who took the time out of their days to work with us and provide us with feedback on the viability of our potential strategies. The knowledge they shared was invaluable in understanding our strategies from the point of view of a Copenhagen cyclist.

Our thanks also go out to many professors at Worcester Polytechnic Institute. Professor Suzanne LePage offered us insight and advice on the usage of traffic modeling software, which was instrumental in the success of our project. Professor Nicola Bulled, our Social Science Research instructor, guided us in the preliminary phases of our project. Professor Steven Taylor, the Copenhagen Project Center director, provided us with the opportunity to complete this project. Professor V. J. Manzo and Professor Lauren Mathews offered us comments and guidance regarding improving our project. It would not have been what it is without them.

Finally, this project would not have been possible without the contributions of Kevin Lee, a student at Worcester Polytechnic Institute and former group member. Unfortunately, Kevin was unable to complete the project with our group, but he was present through the initial proposal and first three weeks at our project center location. We could not credit Kevin in this report because he is completing his own project, which will build on our results. We would like to thank Kevin for the content and time he contributed to our project.

Abstract

Due to the large number of cyclists in Copenhagen, bicycle traffic congestion has recently become a significant problem. By modeling currently congested intersections in Copenhagen and interviewing experts, we evaluated strategies to reduce congestion along with the social implications of implementing those strategies. Each strategy we tested had different effects on the resulting traffic behavior, each with respective pros and cons. Based on our data, we found that altering the traffic light cycles and increasing the bicycle lane widths were the most effective strategies, although we concluded that changing traffic light timings was the most viable. Implementing these strategies will reduce traffic congestion at intersections throughout Copenhagen and allow traffic to flow more smoothly.

Table of Contents

Introduction

To develop strategies to reduce congestion within Copenhagen, we first needed to research the history of bicycle traffic and culture in the city. By understanding the social and technical factors that contributed to bicycle congestion, we could create strategies that would benefit not just the city of Copenhagen, but its citizens as well. In this section, we review the background information that is critical to understanding our project; for a detailed analysis of background information, see the supplemental materials.

Cycling in Copenhagen: Past, Present, and Future

Since the implementation of the first bicycle infrastructure in 1910, cycling has become the most popular method of transport in Copenhagen, Denmark. As seen in Figure 1, over 675,000 bicycles exist in Copenhagen and that number is on the rise, according to Claus Knudsen, director of the Bicycle Innovation Lab (personal communication, 2017). Knudsen also reported that the Copenhagen city council has introduced varied bicycle infrastructures in an effort to promote cycling, including spending over $150 million in the past 10 years to expand bicycle lanes that currently measure 370 kilometers in length.

Estimates indicate that this strategy has been effective with at least 41% of Copenhagen residents commuting to work and educational institutions by bicycle in 2016 (City of Copenhagen Technical and Environmental Administration, 2016), in comparison to 35% in 2010 (The City of Copenhagen Technical and Environmental Administration Traffic Department, 2016). The efforts of organizations, such as the Danish Cycling Federation (DCF) and the Cycling Embassy of Denmark, and investments by city government have resulted in 80% of the city's population owning or having access to a bicycle (Nielsen et al., 2013).

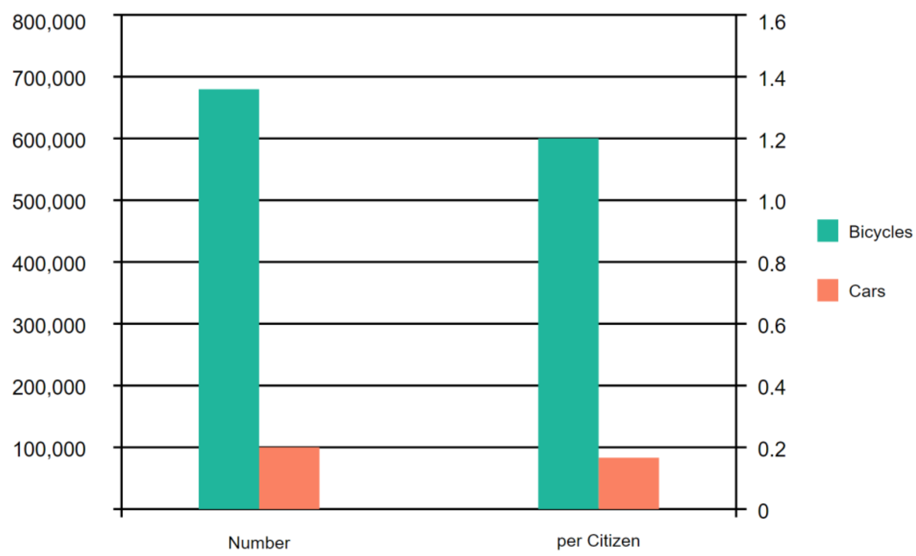

Figure 1: The number of bicycles vs. cars in Copenhagen (left) and the number of bicycles vs. cars owned by Copenhagen residents (right) (The City of Copenhagen and Environmental Committee, 2016).

The City of Copenhagen's Technical and Environmental Committee published a bicycle report in 2016 on an overview of Copenhagen's allocation of resources and the resulting projects implemented to increase cycling in Copenhagen with a concentration on accessibility for all, safety and security, and bicycle parking. The committee's objectives were outlined in the *Copenhagen Bicycle Strategy 2011-2025* and included plans to increase bicycle usage to 50% by 2025, while also increasing bicycle specific infrastructure by 35% for the year 2025 (City of Copenhagen Technical and Environmental Administration, 2016).

A Popular Solution Turns into a Problem: Copenhagen's Bicycle Congestion

While the increase of cyclists is beneficial for personal health and environmental initiatives, the overwhelming number of bicycles has resulted in growing bicycle traffic congestion. The 2016 Bicycle Report listed bicycle congestion as a major issue in Copenhagen for the first time (Knudsen, personal communication, 2017). The busiest areas of Copenhagen are Nørrebrogade and Knippelsbro, which see an average of 42,600 and 41,500 cyclists every weekday, respectively (The City of Copenhagen, 2014). The most congested intersections on these roads are immediately before or after bridges, like the Dronning Louises Bro seen in Figure 2. In fact, congested intersections occur most frequently on roads that cross Copenhagen's waterways, or lead to or away from these crossings. These bridges seem to be "choke points" of bicycle traffic, with crowded intersections most likely both before and after a bridge.

Figure 2: The Nørrebrogade/Søtorvet intersection during rush hour, where it meets Dronning Louises Bro (Graham, 2014).

With the bicycle lanes of these intersections overcrowded, cyclists have begun to ride outside of the designated lanes, causing frustration among motorists and pedestrians. Bicycle accidents have been at an all-time low, but Knudsen stated that cycling activists fear that if cyclists continue to act recklessly because of congestion, accidents might begin to rise again. This reckless behavior has caused public opinion of cyclists in general to decline, and cyclists are being increasingly viewed as "egoistic, unaware, threatening and even dangerous" (Knudsen, personal communication, 2017). Frits Bredal of the DCF expands on this aggressive behavior further, explaining, "I increasingly see people bring themselves and others into dangerous situations. They break the laws and use their bikes in completely reckless ways" (Hill, 2011). If this negative perception of cyclists were to continue, the goal to make 50% of all trips in Copenhagen in 2025 by bicycle will be difficult to attain (The City of Copenhagen, 2014). Therefore, it is imperative that the City of Copenhagen addresses the growing problem of bicycle congestion.

However, most of Copenhagen does not currently have crippling cycling congestion. While there are many cyclists in bicycle tracks or lanes during rush hour, they are able to travel through most intersections in one light cycle. Nonetheless, due to the projected population increase in Copenhagen, bicycle congestion is likely to become a more significant and widespread issue. In 2015, the city (not counting the outskirts and suburbs) contained about 580,000 citizens, but by 2025 the 2015 Municipality Plan projected that number to grow to 684,000 (The City of Copenhagen, 2016). This 18% increase in population could result in a growth of bicycle rush hour traffic by as much as 35%, as shown in Figure 3 (The City of Copenhagen Technical and Environmental Committee, 2016). This increase in bicycle congestion necessitates an optimization of intersections to handle a greater volume of cyclists before the problem worsens.

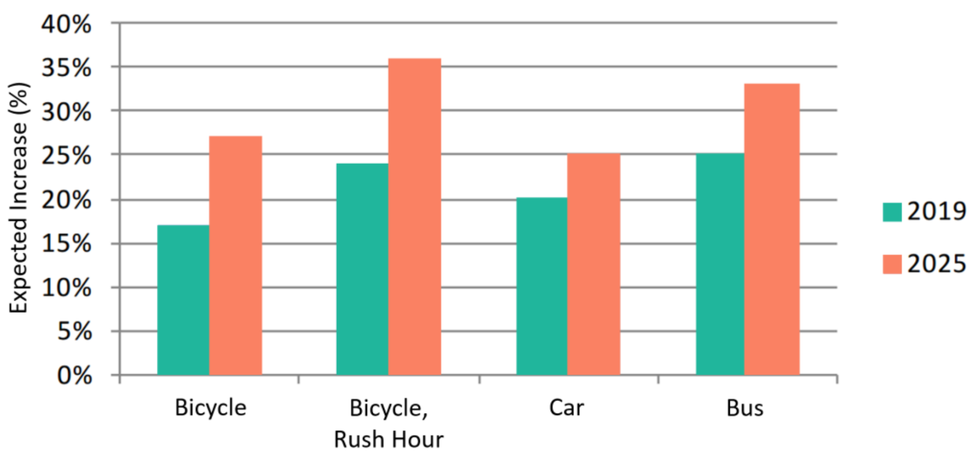

Figure 3: The projected increase of traffic by percentage in Copenhagen by 2019 and 2025 (The City of Copenhagen Technical and Environmental Committee, 2016).

Current Strategies to Alleviate Congestion

Because the growing congestion threatens the goal to increase the proportion of commuters that cycle to 50%, Copenhagen officials have begun work on ways to combat the congestion. These include creating bicycle specific infrastructure, such as separate roads, highways, and bridges, solely for cyclists. This would curtail the bicycle congestion in the city, as outlined in the City of Copenhagen's Bicycle Strategy 2011-2015 (The City of Copenhagen Technical and Environmental Administration Traffic Department, 2011). However, while there are many projects for bicycle specific infrastructure, there are fewer ways to improve bicycle traffic flow in intersections shared with cars. No matter where cyclists travel in the city, they have to use the main roads, and if those intersections are congested, then that affects the bicycle specific infrastructure.

An example of bicycle specific infrastructure are the bicycle superhighways, which are considered one of the most viable and effective solutions to bicycle congestion. Bicycle superhighways are wide bicycle lanes that travel from Copenhagen to its neighboring suburbs. The wide lanes allow cyclists to ride side-by-side or pass one another and consist of 20 routes stretching over 300 kilometers that run through major places of business, education, and residence. Along with promoting minimized stops and flexibility, bicycle superhighways have significantly reduced bicycle congestion (Nielsen et al., 2013). The City of Copenhagen created the bicycle superhighways shown in Figure 4 in April 2012, and plans to add more superhighways to increase the percentage of people commuting from the suburbs to the city on bicycles rather than automobiles.

Figure 4: Bicycle superhighway lanes (left); Map of Copenhagen bicycles superhighways (right) (Nielsen, Skov-Petersen, and Carstensen, 2013).

Another form of bicycle specific infrastructure is the “Bicycle Snake,” or Cykelslangen. The Bicycle Snake is a long bridge that connects the Havneholmen district and Fisketorvet shopping center, as shown in Figure 5. The Municipality of Copenhagen completed this bridge in 2014 to redirect foot and bicycle traffic across the Inner Harbor from the Bryggebroen Bridge. Nearly 12,500 cyclists use this bridge daily to pass through the area, diverting traffic from other roadways and reducing congestion in the area (Dissing+Weitling, 2017).

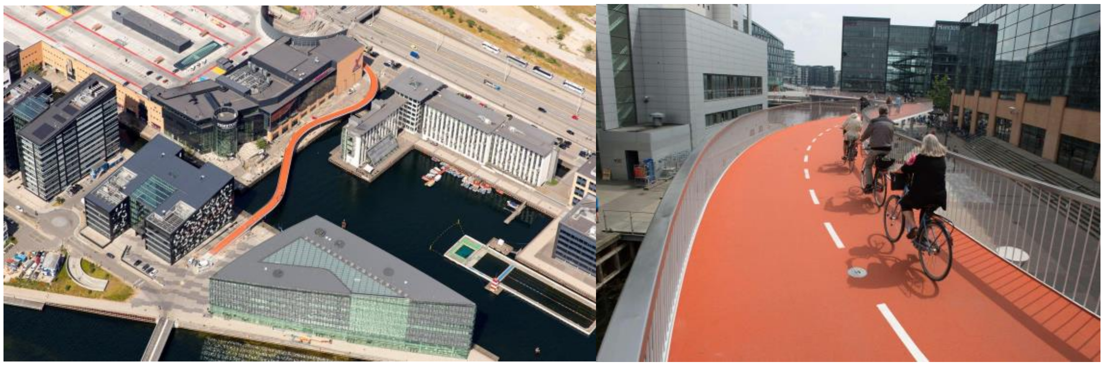

Figure 5: The Bicycle Snake (Dissing+Weitling, 2017).

The *Green Wave* project focuses on the long-term goal of decreasing the time it takes cyclists to commute by adding technology to existing bicycle infrastructure. The inconvenience of decelerating, stopping, and re-accelerating caused many cyclists to take routes with fewer traffic signals (State of Green, 2017). The *Green Wave* involves series of traffic lights embedded in the pavement that turn on and off allowing cyclists to visualize when the traffic lights are about to turn red or green, as shown in Figure 6. Given traffic light timing cycles, cyclists are motivated to travel at an average speed of 20 kilometers per hour in order to hit all the traffic lights on green (State of Green, 2017). If the lights on the pavement are green, cyclists know that they can pass through all green lights if they continue at 20 kilometers per hour, which reduces the number of cyclists forced to stop at red lights, and with it, congestion.

Figure 6: The *Green Wave* for cyclists in Copenhagen (State of Green, 2017).

Methodology

This project intends to assist the Bicycle Innovation Lab in modeling and evaluating viable strategies to reduce bicycle congestion in Copenhagen. In order to accomplish this, we established the following objectives:

1. Analyze intersections with bicycle congestion in Copenhagen and record intersection infrastructure and traffic patterns in each intersection.
2. Assess strategies to reduce bicycle congestion with non-government organizations and government organizations.
3. Model potential strategies that could reduce the volume of bicycle congestion.

To complete these objectives, we used several methods of gathering and analyzing data. These methods included case studies on particular intersections in Copenhagen, the use of traffic simulation software to model potential strategies to reduce bicycle congestion, and interviews with traffic experts and city officials. This section analyzes these methods and explains why we chose each one. Additional information can be located in the supplemental materials.

Objective #1: Case Studies of Intersections

In order to understand and accurately model bicycle congestion in Copenhagen, our team conducted case studies on two specific traffic intersections throughout the city. We analyzed these intersections to obtain different traffic patterns and infrastructure characteristics so that we could develop strategies that would reduce traffic congestion in similar intersections throughout Copenhagen.

We selected these intersections using the following criteria:

1. The number of total vehicles utilizing the intersection during a given day
2. The location of the intersection
3. The complexity of the intersection

From these criteria, the intersections we chose were the Gothersgade-Øster Voldgade and Dronning Louises Bro-Søtorvet intersections, as shown in Figure 7.

Figure 7: The locations of the two intersections studied.

We focused our analyses on the morning and evening rush hours - between the hours of 8:00-9:00 and 16:00-17:00 - as these time periods contained the highest levels of traffic. We collected data from each of the corners of the intersection to obtain an unobstructed view of the intersection, as shown in Figure 8. We examined each intersection in depth for two days and conducted two observations, which meant that each intersection received four observations in total, all of which used the following investigations:

- Numbers of cyclists and motorists

To accurately model the selected intersections, we measured the number of cyclists and motorists who passed through each intersection. To do this, we videotaped the intersections and manually looked back through the video to count the cyclists and motorists. We did this by having one team member stand at each corner of the intersection and film, as shown in Figure 8. To get an average number of vehicles, we filmed three five-minute intervals during each observation hour.

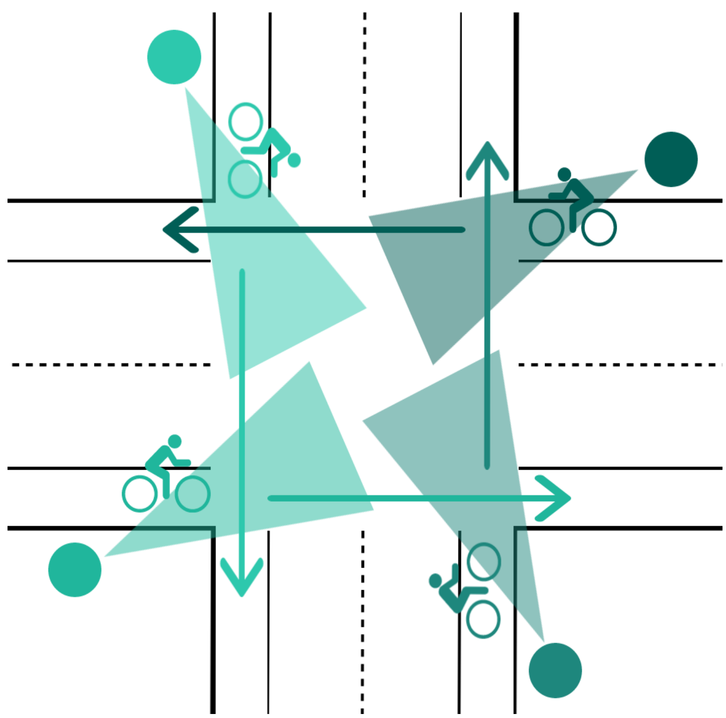

Figure 8: A diagram showing how we filmed the cyclists of an intersection. Filled dots represent each team member video recording the intersection, and wedges of like colors show who filmed each lane.

Following the recording of these videos, we watched each video multiple times to count the following statistics:

1. The total numbers of cyclists and motorists per hour (counted separately)
2. These total numbers were subdivided into morning and afternoon traffic rates
3. Additionally, these were further divided into numbers of motorists and cyclists who turned left, right, and straight
    a. For cyclists, additional categories were listed for those who performed illegal right turns and take alternate turns onto other paths

We later used these hourly rates to model the intersections with traffic modeling software to develop strategies for reducing traffic congestion.

- Traffic light patterns

In order to model each intersection accurately, we also noted the traffic light patterns and timed the duration of the traffic lights. We measured the duration of green, yellow, and red lights. If there were bicycle traffic lights, we measured them separately from the traffic lights of the main road. This was because bicycle traffic lights often turn green first to give cyclists a head start. We also measured the red light delay of the intersection, when all traffic lights for vehicles had turned red.

We also used resources provided from Emil Tin from the Copenhagen Municipality to confirm that none of the intersections examined had adaptive signals, which would change the current traffic light cycle based on traffic flow, thus changing the simulations conditions. All three intersections use standard controllers, which do not contain adaptive signals.

- Intersection infrastructure and developing strategies

For each intersection, we also made note of the structure and layout of the intersection itself, such as the number of lanes. Additionally, we examined the existing bicycle infrastructure and noted whether the roads separated cyclists from motorists.

We also made notes of where the intersection was most congested. We did not use this in later modeling, but was useful in understanding the intersection and developing strategies to improve it. The specific strategies we came up with were widening the bicycle lanes leading up to the intersection, creating a dedicated right turn lane separate from the intersection, allowing right turns on red lights, and adjusting the green light times to favor the direction with the largest number of cyclists.

Objective #2: Stakeholder Interviews

In order to assess the viability of potential strategies to reduce bicycle congestion, we conducted semi-structured interviews with stakeholders, particularly government and non-government organizations involved in cycling culture and traffic infrastructure in Copenhagen. We presented potential strategies to stakeholders, which we then modeled using the PTV Vissim software based on feedback and recommendations gained from the interviews. The primary objective of these interviews was to evaluate stakeholder opinions on potential strategies before modeling, as the organizations interviewed possessed expertise regarding logistical and cultural considerations through qualitative data on the effectiveness and practicality of the proposed strategies.

During each interview, we presented preliminary strategies to reduce bicycle congestion, as well as data obtained from our case studies of intersections. We discussed details regarding the implementation of these strategies to obtain the interviewee's opinions, feedback, and recommendations. We discussed the pros and cons of each presented strategy, as well as their opinions on general bicycle congestion in the city and what they - as cyclists - saw as the most pressing issues for cyclists in the city. We used this information to understand the social effects our strategies would have if implemented in the city so we could adjust our strategies if need be. The supplemental materials contain more information on conducted interviews.

From the information gained from the interviews, we adjusted our strategies to address the issues raised by the interviewees. For example, if the interviewees voice concerns that adjusting the traffic light timings would increase motorist congestion, instead of switching the traffic light timings as we originally planned, we would try different variations of changing traffic light timings so we would have more options from which to choose. Also, two of the interviewees suggested a way to improve our strategy of allowing cyclists to turn right on a red light by dividing the bike lane into a section for people going straight and a section for people turning right.

Objective #3: Modeling of Potential Strategies

To model the data we collected from the case studies of intersections, we used PTV Vissim software, a traffic modeling software package designed to simulate many types of traffic, such as cyclists, motorists, and even pedestrians (PTV Group, 2017). We modeled an intersection through the following steps:

1. Roadways, or “links,” (blue lines in Figure 9) were constructed manually using satellite imagery as reference to ensure their accuracy.
2. These links were joined together using connectors (violet lines in Figure 9), which define possible options for traffic in each lane, such as going straight, turning left, and turning right.
3. Following the implementation of links and connectors - which form the basic framework of an intersection - we added controls. These consisted of any type of road sign or signal that someone may encounter, such as a stop sign or traffic light.
4. “Conflict zones,” shown by the red/green strips in Figure 9, allow for the modification of the rules of the road. PTV Vissim defines conflict zones as locations where vehicles traveling through the intersection may collide, such as a motorist turning left across another lane of traffic that is continuing straight. The green strips in Figure 9 indicate the type of traffic that has the right of way.
5. Additionally “signal heads” can also be used to control traffic, as they are placed anywhere along a link or connector where a stop is desired. “Signal groups” can group signal heads together, which a “signal controller,” a program that synchronizes signal heads together, then controls. PTV Vissim most notably uses these signal heads to model traffic lights.

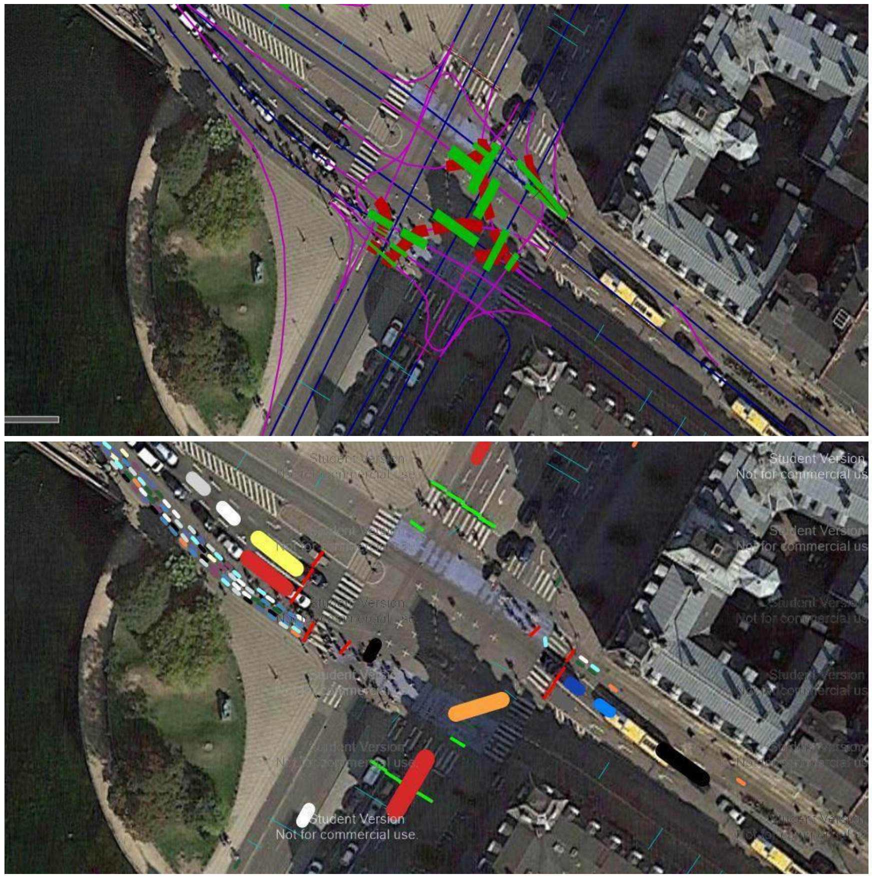

Figure 9: Screenshots of the PTV Vissim software. The upper image shows links, connectors, and conflict areas installed over the background image of the Nørrebrogade intersection. The lower image shows vehicles navigating the intersection.

Once the intersections were constructed using the data gathered from the case studies, such as traffic flow data and traffic light cycle information, we were able to test different strategies intended to decrease congestion in each intersection.

One of these strategies was to increase the width of the bicycle lane. This would allow more cyclists to occupy the space leading up to the intersection. We experimented with widening all bicycle lanes for each individual street, as often one road would experience greater bicycle traffic than others. We tested this without modifying the overall width of the road or reducing the total number of lanes on the road, as doing so would significantly the efficiency of the intersection.

Additionally, we tested modifying the rules of the road to allow cyclists to turn right on a red light, as well as constructing a designated cycling track - shown in Figure 10 - for cyclists making a right hand turn.

Figure 10: Implementation of tracks for right turns – highlighted in red - for the Gothersgade-Øster Voldgade intersection (left) and the Dronning Louises Bro-Søtorvet intersection (right).

We also examined how these strategies would function in future years due to the projected population growth by increasing the traffic flow per hour proportionally to the outlined increase predicted by the City of Copenhagen (2015). In doing so, we assumed that the numbers of motorists and cyclists would both increase in direct proportion to the population increase, even though much of the influx of residents would likely settle in regions outside the center of Copenhagen. However, because we did not have quantitative data on how the projected population increases by region, we were unable to make specific estimates of how our targeted intersections would change accordingly.

The net changes in traffic flow for motorists and cyclists determined the effectiveness of a given strategy, in that an increase in traffic flow meant that congestion had decreased and the strategy was therefore effective. We calculated the traffic flow of motorists and cyclists separately to yield values for the average change for each by comparing the total numbers of cyclists from the unchanged simulations to the total numbers of cyclists from each result, averaged for both the morning and afternoon rush hours. We used the same process for motorists, and again when we simulated a total population increase to evaluate how each strategy would behave in the future.

We concentrated our efforts on an improvement of traffic flow for cyclists, and understood that doing so would likely increase motorist congestion. According to Suzanne LePage, Professor of Civil and Environmental Engineering at Worcester Polytechnic Institute, favoring bicycles over motor vehicles too much could cause issues regarding air pollution as forcing motorists to wait in favor of cyclists causes them to needlessly spend fuel while idling, increasing total emissions (LePage, personal communication, 2017). Because of this, we worked to develop strategies that increased both cyclist and motorist traffic flow through an intersection.

Based on feedback from the interviewees, we revised our strategies to consider social and economic concerns. For widening the bicycle lanes, we tested an increase in lane width of 0.5 and 1.0 meters only on Dronning Louises Bro and Gothersgade. We did this because of concerns from the interviewees that widening the lanes might increase motorist congestion, so multiple variations gave us more flexibility in our options. Likewise, we conducted two variations of adjusting the traffic lights to see if we could minimize the increase in motorist congestion while also decreasing bicycle congestion. For the designated right turn on red strategy, we only tested it in areas where there was enough space to do so, on the corners of North Søtorvet / East Dronning Louises Bro, South Søtorvet / East Dronning Louises Bro, North Øster Voldgade / East Gothersgade and South Øster Voldgade / East Gothersgade. Lastly, for right turns on red, we allowed right turns at all streets and divided the bicycle lanes into sections for going straight and turning right, a suggestion we received during our interviews. We also only allowed cyclists to make a right turn on red, as three of our interviewees believed it would be too dangerous to allow motorists to turn right on red as well.

Results

Objective #1: Case Studies of Intersections

In this section, we examined intersections to gather observations and collect data that we later used to model the intersections and test strategies. As detailed in the Methodology section, we counted the numbers of vehicles travelling through the intersection during the morning and afternoon rush hours and recorded the timing of the traffic light cycles. This section details the results of the case studies.

Gothersgade-Øster Voldgade

The first intersection we investigated was the Gothersgade-Øster Voldgade intersection in Nørreport, as shown in Figure 11. All the roads have bicycle tracks that were separate from the road, except the eastbound portion of Gothersgade on the left side of the intersection, which had a right hand turn lane for motorists that merges with the bicycle lane. Only Øster Voldgade had separate bicycle traffic lights for cyclists, while Gothersgade cyclists followed the main traffic light.

Figure 11: The Gothersgade-Øster Voldgade intersection. Gothersgade runs approximately from west to east (left to right), and Øster Voldgade runs approximately from north to south (top to bottom).

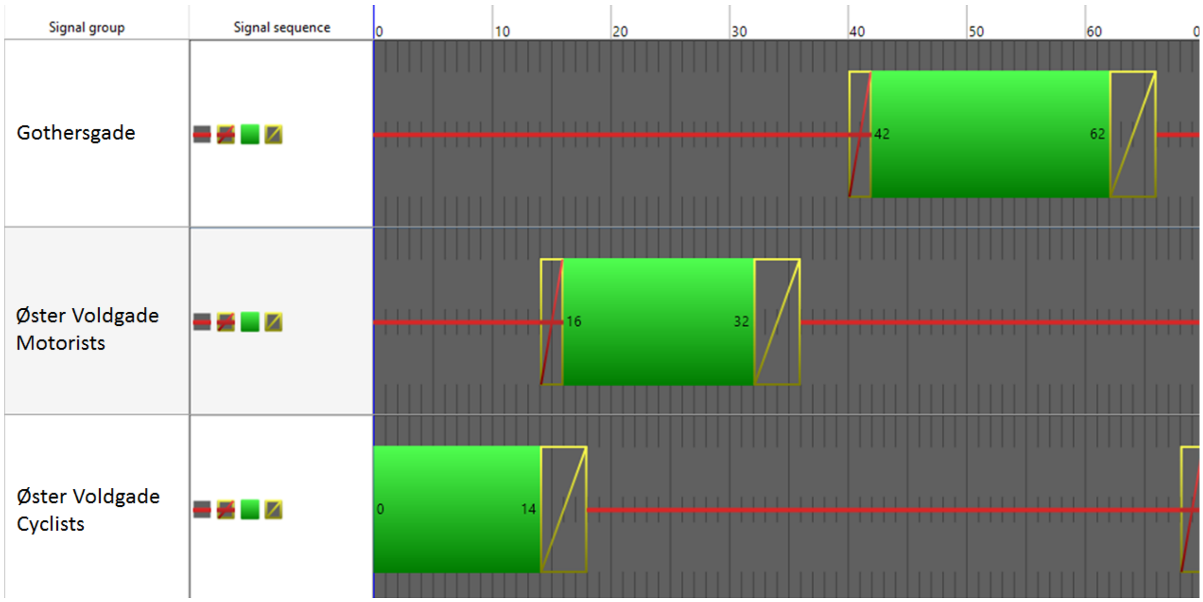

Figure 12: Light timings for the Gothersgade-Øster Voldgade intersection (in seconds).

In many ways, this was a simple four-way intersection, although a very large amount of vehicle traffic, specifically buses, congested it. This was because Nørreport Station, which serves both the S-train and Metro, is located just below the intersection on Øster Voldgade, and there are bus stops on either side of the road, servicing the station and further congesting the intersection.

A problem we saw during our observation was that 2000 cyclists per hour entered the intersection using Gothersgade, which had 20 seconds less green time, as shown in Figure 12. Because of this, we felt like adjusting the traffic light timing might be a good way to reduce cyclist congestion at the intersection. It is also important to note that there were periods during the light cycle where all traffic lights in the intersection were red for about 5 seconds. This allowed motorists to clear the intersection and to make right turns they were unable to make because of cyclists riding in the bicycle lanes, but it also increased wait times for both motorists and cyclists.

Figure 13 shows the overall traffic traveling in and out of the Gothersgade-Øster Voldgade intersection.

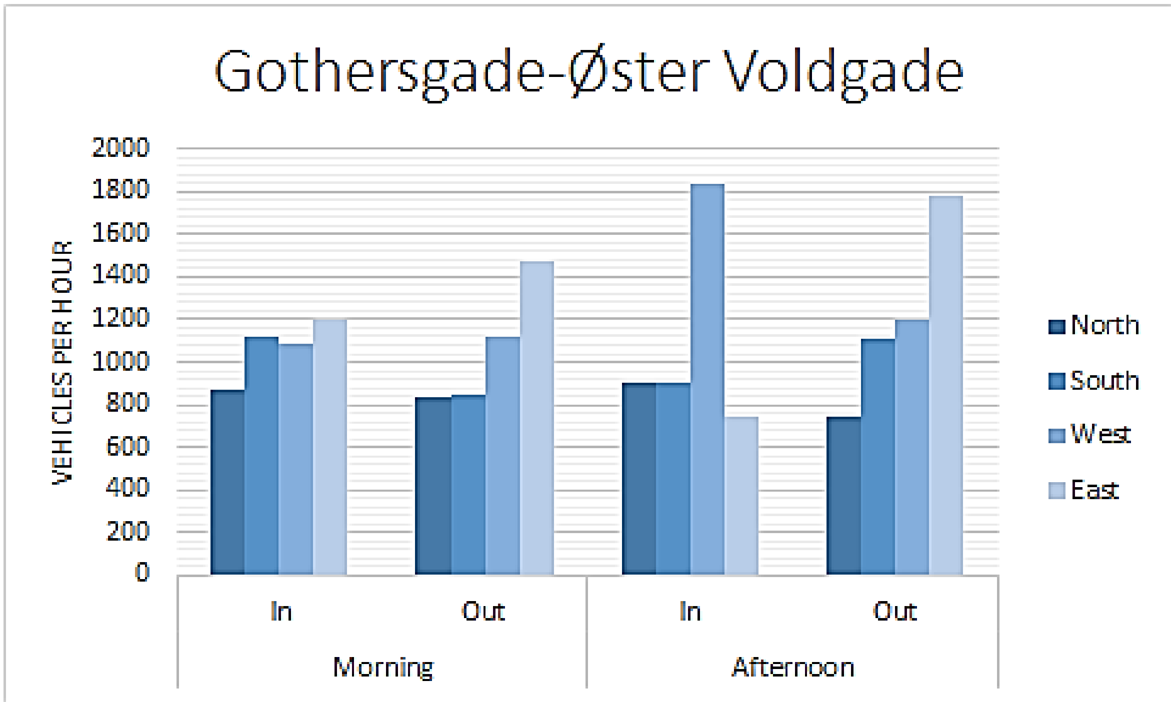

Figure 13: Net traffic in and out of each side of the Gothersgade-Øster Voldgade intersection. The data used for this graph is located in the supplemental materials.

Dronning Louises Bro-Søtorvet

The Dronning Louises Bro is part of Nørrebrogade, which is one of the most cyclist-heavy roadways in Copenhagen. It crosses Peblinge Lake, and is one of the few direct ways for cyclists to travel directly to the center of Copenhagen. As seen in Figure 14, Dronning Louises Bro travels from northwest to southeast, and Søtorvet travels from northeast to southwest. There were separated bicycle tracks for all directions of travel except for the westbound Dronning Louises Bro, which was to the right of the intersection. This bicycle lane merged with the right turn lane for motorists.

Figure 14: The Dronning Louises Bro-Søtorvet intersection. Dronning Louises Bro crosses Peblinge Lake (the water in the image) and goes approximately from west to east (left to right), while Søtorvet travels approximately from north to south (top to bottom).

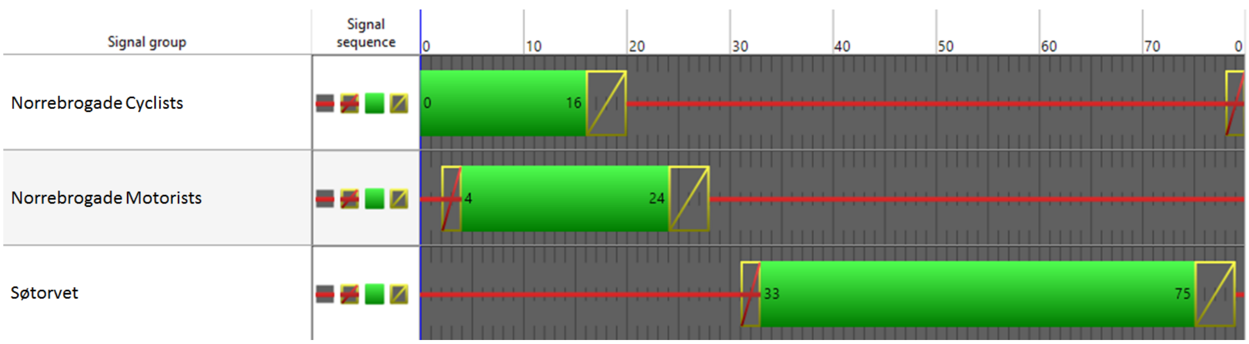

Figure 15: Light timings for the Dronning Louises Bro-Søtorvet intersection (in seconds).

The green light disparity shown in Figure 15 caused bicycle traffic to back up, especially during the morning of Dronning Louises Bro. Because of this, we saw many people execute illegal right turns by riding along the pedestrian pavement to turn onto Søtorvet, as seen in Figure 16. We also observed this in the afternoon, where cyclists turned from southbound Søtorvet onto westbound Dronning Louises Bro.

Figure 16: A pedestrian takes an illegal right turn onto the pedestrian pavement to turn onto Dronning Louises Bro.

Figure 17 shows the overall traffic traveling in and out of the Dronning Louises Bro-Søtorvet intersection.

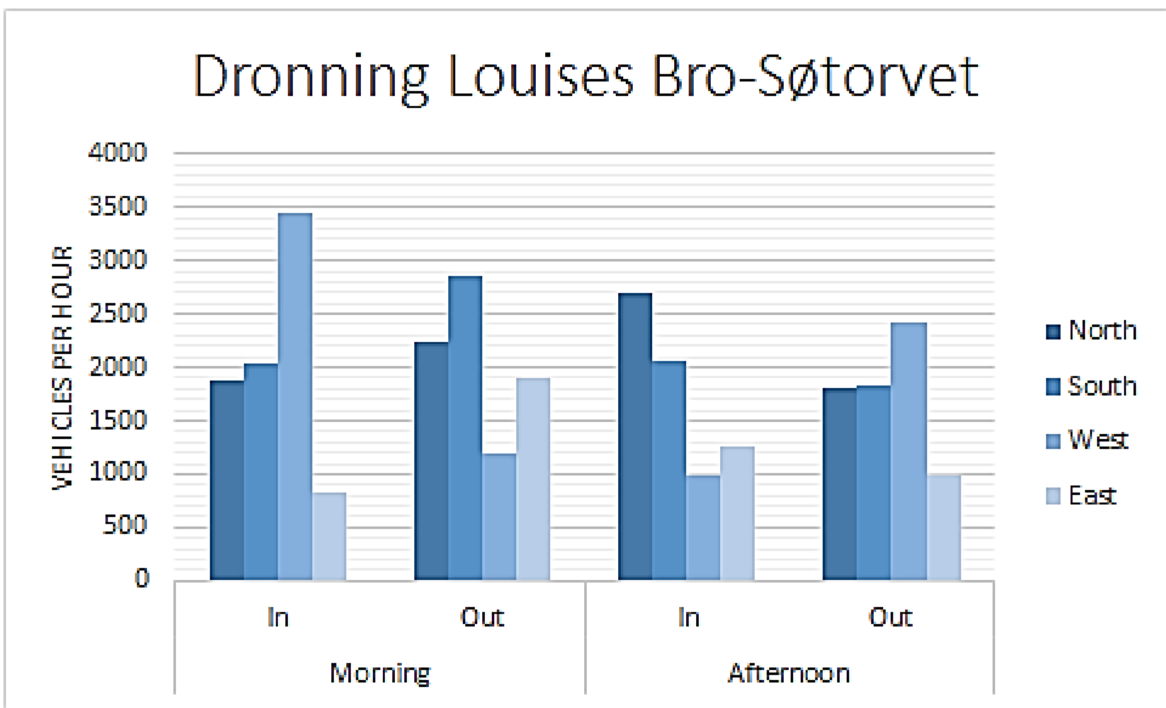

Figure 17: Net traffic in and out of each side of the Dronning Louises Bro-Søtorvet intersection. The data used for this graph is located in the supplemental materials.

Objective #2: Stakeholder Interviews

We contacted fifteen individuals for interviews. We received a response from the five individuals listed below.

- Klaus Bondam, Director and CEO of the Danish Cyclists' Federation, former Mayor of the City of Copenhagen Technical and Environmental Administration
- Flemming Møller, Danish Cyclists' Federation
- Morten Skou, Owner Copenhagen Bicycles
- Jos van Vlerken, Project Manager for the City of Copenhagen Technical and Environmental Administration
- Helen Lundgaard, Senior Consultant at Capital Region of Denmark

The interviewees are employed by various non-profit, private companies, non-government and government organizations, which provided different perspectives on our potential strategies and how they would affect Copenhagen residents socially and economically. They also provided information on the conditions of cycling in Copenhagen and the main difficulties that cyclists face. The full transcripts of these interviews are located in the appendix to the supplemental material.

One of the underlying ideas that most of the interviewees spoke about was making sure that additional infrastructure accommodated the needs of current cyclists, including accessibility to new cyclists. Van Vlerken elaborated that this is the biggest challenge that the city faces when it comes to cycling, as the cramped and crowded nature of bicycle traffic discourages new cyclists. To reach the goals stated in the 2016 Bicycle Report, "we need to make it so less experienced riders and newcomers are welcomed and are comfortable" (Van Vlerken, personal communication, 2017). Making bicycle lanes more accessible to new cyclists achieves this goal. Decreasing bicycle traffic congestion assists in this goal, making it a priority if the City of Copenhagen wishes to foster the cycling culture in the future.

Lundgaard agreed with the importance of getting new cyclists, but looked at it from a different point of view. She explained choosing transportation as a convenience hierarchy, as people choose the mode of transportation that is the most convenient for them. So to get more people to start cycling, the convenience of cycling in the city of Copenhagen must be equal to, or greater than, the convenience driving or taking public transportation (personal communication, 2017).

We concluded from this line of questioning that we should look for a strategy that makes it more convenient to cycle, and allows newcomers to be comfortable cycling around the city. To understand the concerns that cyclists have better, we asked each of our interviewees (who are all regular cyclists in Copenhagen) what they felt was the most inconvenient or annoying thing about intersections for themselves and others in Copenhagen.

Bondam and Møller both pointed out how traffic light timings do not favor cyclists, with Møller in particular saying that green lights were not long enough for cyclists. Skou, on the other hand, said that not being able to turn right on red legally was his biggest grievance with intersections (personal communication, 2017). However, both Van Vlerken and Lundgaard mentioned something that underlay all of the prior grievances, which is that the most inconvenient thing for cyclists was to have to stop at the intersection (personal communication, 2017). This is bad since stopping as a cyclist is much different from in a car, and it is much more difficult to get moving again as a cyclist, especially in a crowded lane during rush hour traffic. Naturally, it is impossible to prevent all stops at an intersection, but judging from the responses of the interviewees a strategy should be able to limit the number of light cycles through which cyclists have to wait.

We then presented the strategies that we planned to use in our modeling. They were creating a designated right turn lane, adjusting traffic lights to benefit cyclists, widening the bicycle lanes, and allowing cyclists to turn right on a red light.

The interviewees were skeptical that the positives of a designated right turn lane for cyclists at an intersection would outweigh the negatives. Bondam and Van Vlerken pointed out that it would just cause conflict between cyclists and pedestrians, because the lane would create another area where cyclists and pedestrians have to be careful not to run into each other. Skou added that Danes are very “right of way oriented,” and will not yield if they believe they have the right of way, which he believed would cause problems at a right turn lane for cyclists. This is because pedestrians would cross, believing they were in the right, only to be met by cyclists on the lane who thought they were in the right (personal communication, 2017). Van Vlerken also stated that the municipality of Copenhagen has a goal of getting more people to "hang out" in public places, and that the Dronning Louises Bro in particular is very popular as a spot for citizens to gather for lunch and to talk during the afternoon, as seen in Figure 18. He believed that having a bike lane run through the middle of the pedestrian walkway would discourage people from walking along the bridge (personal communication, 2017).

Figure 18: Pedestrians gathering at the Dronning Louises Bro.

The interviewees thought that the adjustment of the traffic lights could work, but also that there could be some serious drawbacks, in that they would negatively affect car traffic on the roads opposite of the heavy bicycle traffic. Skou and Van Vlerken pointed out that the car traffic on Søtorvet and Øster Voldgade is particularly heavy (personal communication, 2017). The reason for this, Van Vlerken explained, is that they are both major arteries from motorists going through the city (personal communication, 2017). Bondam agreed, stating that while changing the traffic lights would increase bicycle traffic flow, it would congest the car traffic too much, and give unequal priority to cyclists at the expense of motorists (personal communication, 2017). Lastly, Skou suggested that a bicycle bridge would solve the problem without congesting the vehicles, but conceded that building a bicycle bridge would be impossible in the intersections we looked at, because there was simply not enough room (personal communication, 2017).

We noted a similar theme in our interviewee's response to widening the bike lanes, as they were concerned that it would hurt the car traffic too much. Bondam stated that the bicycle lane on Dronning Louises Bro is already so wide that widening it even more would probably force the car traffic on that side of the bridge into one lane (personal communication, 2017). Lundgaard also pointed out that it would not be very effective at reducing congestion either, saying that it would fix the issue for a little while, but it would encourage more traffic to take that route, which would nullify the benefit of the widened lane (personal communication, 2017). Van Vlerken mentioned that work is already underway at the Dronning Louises Bro Intersection, with the westbound bicycle lane converting to a bicycle track, so cyclists will no longer have the share a lane with vehicles turning right, which is a dangerous situation in Copenhagen intersections (personal communication, 2017).

Of all of the strategies presented to them, the interviewees thought that allowing cyclists to turn right on red would cause the least amount of conflict with other modes of transportation at an intersection. Skou, Møller, Bondam, and Van Vlerken all mentioned that the city is already experimenting with allowing right turns on red at certain intersections (personal communication, 2017). Møller also worried that because right on red is legal in a few parts of the city, cyclists will believe that it is legal everywhere, and will turn right on red regardless.

All five interviewees believed that allowing right on red was a viable option; however, Møller voiced concerns about making sure that cyclists were educated on when it was safe to make a right turn on red, such as looking to see that the bicycle lane they are turning into is sufficiently clear for them to make a safe right turn. Despite this, he believed that Copenhagen allowing right turns on a red light would force cyclists to be more observant than they are currently (personal communication, 2017). Skou and Van Vlerken also specified that this new change to the traffic laws should exclusively permit cyclists to turn right on red, as permitting cars would be too dangerous. Skou explained this as cyclists must be more alert and careful when making a right turn: "If a cyclist hits a pedestrian, then both the cyclists and pedestrian are going to get hurt badly. But if a car hits a pedestrian, only the pedestrian is hurt," so the driver of the car will not be as careful in looking for pedestrians as the cyclists (personal communication, 2017). Lundgaard showed cautious optimism for the strategy, saying that while it was a very viable solution, by itself it would not increase traffic flow substantially, and would probably need to work in conjunction with another strategy (personal communication, 2017). She also suggested dividing the bike track into two lanes near the intersection, one for turning right and the other for going straight.

Objective #3: Modeling of Potential Strategies

We compared each strategy we tested to an unaltered model of each intersection to obtain a net change in traffic flow, which helped us evaluate the effectiveness of each strategy. We did this using current traffic rates, and then repeated using an inflated population to simulate future growth. This section details the results of these tests. The supplemental materials report additional data used in this section.

The first strategy we tested was increasing the width of the bicycle tracks to redesign the streets to handle the large number of bicycles better. The bicycle track widths were changed twice, widened first by 0.5 meters, and then by 1.0 meters. We compared both tests to a control intersection, which was unchanged throughout the test, as shown below in Tables 1 and 2.

Table 1: Percent change in numbers of cyclists and motorists traveling through the simulated intersection per hour by increasing width of bicycle tracks by 0.5m.

+0.5m	Current Population		Future Population	
	Motorists	Cyclists	Motorists	Cyclists
Gothersgade-Øster Voldgade	-0.71%	1.05%	3.23%	3.52%
Dronning Louises Bro-Søtorvet	-1.40%	2.59%	-3.40%	2.72%

Table 2: Percent change in numbers of cyclists and motorists traveling through the simulated intersection per hour by increasing width of bicycle tracks by 1.0m.

+1.0m	Current Population		Future Population	
	Motorists	Cyclists	Motorists	Cyclists
Gothersgade-Øster Voldgade	1.46%	1.91%	1.12%	6.95%
Dronning Louises Bro-Søtorvet	-4.32%	9.22%	-2.44%	6.35%

The traffic laws in Copenhagen forbid bicycles (and other vehicles) from performing right turns during a red light. However, this law increases congestion, as these bicycles must wait until a green light to turn right. Our second strategy was to allow bicycles on all roads to turn right, and divide the lanes into one section for cyclists turning right and the other for cyclists going straight. Table 3 details the results of these tests.

Table 3: Percent change in numbers of cyclists and motorists traveling through the simulated intersection per hour by allowing cyclists to turn right during a red light.

Right on Red	Current Population		Future Population	
	Motorists	Cyclists	Motorists	Cyclists
Gothersgade-Øster Voldgade	0.63%	-8.66%	1.27%	-5.21%
Dronning Louises Bro-Søtorvet	-3.38%	-14.65%	-3.75%	-15.81%

One additional strategy that accomplished a similar goal to allowing vehicles to turn right during a red light was creating a dedicated right turn track. We implemented separate lanes, away from the bicycle lanes and the intersection in general, to allow cyclists to turn right without backing up the bicycle lane during a red light. Table 4 displays the resulting traffic flow rates.

Table 4: Percent change in numbers of cyclists and motorists traveling through the simulated intersection per hour by implementing a dedicated right turn track for cyclists.

Right Turn Track	Current Population		Future Population	
	Motorists	Cyclists	Motorists	Cyclists
Gothersgade-Øster Voldgade	5.29%	2.87%	1.48%	-0.74%
Dronning Louises Bro-Søtorvet	-3.36%	3.93%	-1.20%	-0.09%

Our final strategy was altering the timing of the traffic lights. We did this because the current traffic lights prioritize motorist-heavy roads over bicycle-heavy roads despite the increasing popularity of bicycles. We tested two variations of this strategy: inverting the light timings and prioritizing streets by adding 5 seconds to specific lanes to provide them more time to cross the intersection. We inverted the light timings between each side of the intersection - so that a street travelling in one direction would have its timing switched with the street it intersects. We did all this without changing the time where all traffic lights are red, as this allows cars to clear the intersection before the next road gets a green light.

For the Gothersgade-Øster Voldgade intersection, we inverted the light timings and tested the strategy of adding seconds twice, once for Gothersgade and again for Øster Voldgade. For the Dronning Louises Bro-Søtorvet intersection, we inverted the light timings and prioritized Dronning Louises Bro. We chose not to test prioritizing Søtorvet because we knew that the majority of bicycle traffic crossed Dronning Louises Bro, and reducing its green light duration would greatly reduce the overall traffic flow. Tables 5 and 6 display the results of these tests.

Table 5: Percent change in numbers of cyclists and motorists traveling through the simulated intersection per hour by inverting traffic light timings.

Inverting Traffic Lights	Current Population		Future Population	
	Motorists	Cyclists	Motorists	Cyclists
Gothersgade-Øster Voldgade	3.06%	0.38%	4.32%	-5.25%
Dronning Louises Bro-Søtorvet	-12.20%	10.00%	-18.42%	11.71%

Table 6: Percent change in numbers of cyclists and motorists traveling through the simulated intersection per hour by adding additional time for lanes.

Additional Time (+5s)	Current Population		Future Population	
	Motorists	Cyclists	Motorists	Cyclists
Gothersgade-Øster Voldgade (Gothersgade prioritized)	1.02%	3.91%	-1.85%	2.81%
Gothersgade-Øster Voldgade (Øster Voldgade prioritized)	2.83%	-1.92%	4.02%	-3.67%
Dronning Louises Bro-Søtorvet	-5.77%	6.33%	-0.20%	5.64%

In addition to these strategies, we tested one combination of two strategies. In this, we simultaneously modeled increasing the bicycle track widths by 0.5 meters and adding 5 seconds for specific roads in the intersection. Our results indicated these were the two most effective strategies and were compatible enough to they could be tested in conjunction. Table 7 details the results of this strategy.

Table 7: Percent change in numbers of cyclists and motorists traveling through the simulated intersection per hour by increasing bicycle track widths and adding additional time.

+0.5m & Additional Time	Current Population		Future Population	
	Motorists	Cyclists	Motorists	Cyclists
Gothersgade-Øster Voldgade (Gothersgade prioritized)	-4.79%	-1.58%	-2.91%	5.34%
Gothersgade-Øster Voldgade (Øster Voldgade prioritized)	3.45%	-3.82%	7.07%	-0.14%
Dronning Louises Bro-Søtorvet	-5.43%	8.34%	-4.52%	9.76%

Conclusions and Recommendations

Conclusions

Based on our own case study observations, feedback from stakeholders, and the modeling, we made the following conclusions on the effectiveness and practicality of implementing the four strategies to determine which was the most viable.

Widths of Bicycle Lanes

While increasing the lane widths by 0.5 meters was not particularly effective, increasing the lanes by 1.0 meters was one of our most effective strategies. Bicycle traffic flow on Dronning Louises Bro-Søtorvet increased by more than 9% when we widened the bicycle lanes by 1.0 meters, and increased by more than 6% in the projected intersection in 2025. Widening the bicycle lane or track allows for greater cyclists traffic through an intersection because more cyclists can ride side-by-side. Additionally, widening the bicycle lanes can accommodate cyclists overtaking wider bicycles, such as cargo bikes or tricycles. Newer, younger, or elderly cyclists are more comfortable using wider types of bicycles than using smaller traditional bicycles because experienced cyclists can leave more space for the less experienced cyclists to react to traffic. As a result, widening the bicycle lanes accommodates people who the traffic congestion created by smaller bicycle lanes otherwise deters. Widening the bicycle lanes would decrease motor vehicle traffic flow, however for Dronning Louises Bro the traffic flow only decreases by 4.32% and 2.44% for current and projected population, respectively. In fact, for Gothersgade motorist traffic flow actually increased during the current and projected population by 1.46% and 1.12%. However, since all evidence from our research and interviews pointed to motorist traffic decreasing, we assumed that these numbers were within the predicted margin of error produced by the simulation, although they still pointed to the actual decrease in motorist traffic flow being much smaller than expected. In addition, widening bicycle lanes requires re-construction of the bicycle lanes or tracks. Detours because of bicycle lane or track re-construction would negatively affect the flow of bicycle traffic through the intersection.

Allowing Vehicles to Turn Right on Red

The feedback from our interviews suggested that legalizing right turns on red by bicycles was our most practical strategy. Based on our modeling, however, the right turn on red was not effective. Bicycle traffic flow on Dronning Louises Bro-Søtorvet decreased by more than 14%. We modeled the right turn on red in combination by implementing a designated right turn lane within the bicycle track. As a result, the right turn lane reduced the area for cyclists turning left or straight. The strategy decreased bicycle congestion by almost 10% on North Søtorvet where half of the cyclists turned right. Therefore, the strategy is effective only if there is a large percentage of cyclists are turning right. However, implementing the right turn on red does not require a designated right turn lane. In general, the interviewees stated legalizing right turns on red for cyclists would be useful because the cyclists commonly disregard the current traffic law. Legalizing right turns on red would decrease the stop-and-go time for cyclists at a red light, which was a concern with the interviewees. The City of Copenhagen has tested implementing the right turn on red in select areas throughout the City and there is no cost or time to implementing the legal right turn on red citywide.

Dedicated Right Turn Tracks

Constructing right turn tracks was our least practical strategy, according to our interviewees. Similar to the legal right turn on red, the right turn only track is only effective if nearly half of the cyclists turn right. The right turn track increased bicycle traffic by about 3% on Gothersgade-Øster Voldgade and 4% on Dronning Louises Bro-Søtorvet, although bicycle traffic flow would decrease based on the estimated increase in population growth to about -1% for Gothersgade-Øster Voldgade and 0% for Dronning Louises Bro-Søtorvet. Compared to the right turn only lane, the right turn track does not reduce the area for cyclists turning left or straight and reduces bicycle accumulation at the traffic light. Van Vlerken stated that the right turn track would not be viable because of the cost of construction would be so high (personal communication, 2017). Additionally, the bicycle track would reduce the sidewalk area available to pedestrians and the City of Copenhagen cannot implement this citywide because it is limited to the available sidewalk area.

Altering Traffic Light Timings: Inverting Traffic Lights & Additional Time

Adjusting the light timings was our most viable strategy because it is both effective and practical. Overall, the strategy reduced motorist traffic and increased bicycle traffic, particularly on Dronning Louises Bro-Søtorvet, in which there is a high percentage of cyclists riding in the same direction. Based on our modeling, we found that inverting the traffic light timings on Dronning Louises Bro-Søtorvet increased bicycle traffic by 10%, and increasing the light timings by five seconds for Dronning Louises Bro-Søtorvet increased bicycle traffic by more than 6%. The cost of implementing the strategy would be dependent on man-hours to reprogram the traffic controllers, but there is no construction required to implement the strategy. Adjusting light timings could affect bus routes and synchronized lights in nearby intersections, such as the Green Wave.

Combined Strategies: Bicycle Lane Width & Additional Time

Based on the effectiveness of widening the bicycle lanes and adding additional time to the traffic lights, we modeled the combined strategies. Increasing the bicycle lane width by 0.5 meters and adding 5 seconds to the traffic light timing increased traffic flow by almost 5% on Dronning Louises Bro-Søtorvet. Although modeling the combined strategies was effective for both the current population and the projected population growth, there was not a significant increase in effectiveness compared to increasing only the traffic light timing.

Recommendations

Because of our interviews with stakeholders and modeling of implementing our strategies on specific intersections, we found that altering the traffic light cycle timings and increasing the bicycle lane widths were the most effective strategies. While widening the bicycle lanes increased traffic flow, our interviewees felt that doing so would be impractical, as it would require a significant amount of infrastructural construction. Because of this, modifying the traffic light timings was the most effective strategy, as it had a large positive effect on the overall traffic flow while remaining cost-efficient, and the City of Copenhagen can easily apply this strategy to other intersections that are having difficulty with bicycle congestion. Overall, we feel that adjusting the traffic light timings to favor bicycle-heavy roads would be the best strategy to reduce bicycle traffic congestion throughout Copenhagen based on current infrastructure and projected population trends.

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