DESIGNING DEMAND RESPONSIVE TRANSPORTATION SOLUTIONS ON WATER TO CONNECT URBAN EXPANSION PROJECTS LIKE ARTIFICIAL ISLAND TO "MAINLAND" CITIES.

A conceptual autonomous demand responsive transportation solution to be deployed on the waters between Copenhagen's city centre and the urban expansion project and artificial island Lynetteholm, to be constructed in the Northern harbour of Copenhagen by 2070.

Master Thesis

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Executive summary

Navigating Urban Expansion and Mobility Innovation in Copenhagen's Lynetteholm

In the face of accelerating urbanization and the consequent surge in housing demands, particularly in European capitals, Copenhagen is at the forefront of adopting innovative urban development strategies. One such strategy is the conceptualization and eventual realization of Lynetteholm, an artificial island designed to mitigate housing shortages while fostering sustainable urban growth. This initiative reflects a broader trend towards exploring new urban spaces that cater to the burgeoning population, leveraging the potential of reclaimed land and waterfront development.

This thesis situates the Lynetteholm project within the broader context of Copenhagen's historical commitment to sustainable urban development and efficient public transportation systems. It explores the unique challenges and opportunities presented by this ambitious project, particularly in the realm of mobility and transportation. By drawing on comparative analyses with cities like Amsterdam and Venice, which share Copenhagen's characteristic of being intertwined with waterways, the research aims to distill valuable insights into managing urban mobility in water-centric urban environments.

Central to the thesis is the exploration of smart mobility solutions, specifically Autonomous Navigation Systems (ANS) and Demand-Responsive Transportation (DRT), framed within the increasingly popular concept of Mobility as a Service (MaaS). The investigation delves into the potential synergy between these technologies and the existing urban transport framework in Copenhagen, with a particular focus on enhancing the "Harbor Bus" service. The envisioned autonomous demand-responsive ferry service (ADRT) is posited as a sustainable, efficient, and user-centered mobility solution that seamlessly integrates with the city's transport network, thereby facilitating the smooth incorporation of Lynetteholm into Copenhagen's urban tapestry.

The proposed ADRT system, characterized by its autonomous operation and demand-responsive nature, is designed to double the capacity of the current Harbor Bus fleet, addressing both the anticipated residential influx in Lynetteholm and the broader transportation needs of Copenhagen's residents. This system not only promises enhanced operational efficiency and reduced environmental impact but also aligns with the city's long-term vision of achieving CO_2 neutrality and fostering a "green wave" of commuting practices.

Furthermore, the concept of "Ferry Oriented Development" (FOD) is introduced as a strategic urban planning approach that capitalizes on the untapped potential of waterways. By developing ferry terminals as focal points of urban activity, FOD encourages the formation of vibrant, interconnected communities that prioritize sustainable transport modes, thereby reinforcing Copenhagen's commitment to environmental sustainability and efficient urban mobility.

In sum, this thesis offers a comprehensive examination of the interplay between urban expansion, sustainable development, and innovative transport solutions in the context of Copenhagen's Lynetteholm project. It presents the design of a conceptual framework for an ADRT system that embodies the principles of autonomy, responsiveness, and integration, thereby contributing to the discourse on future urban mobility. This research provides a nuanced, evidence-based perspective on the deployment of smart mobility solutions in the face of rapid urban growth, offering valuable insights and recommendations for urban planners, policymakers, and stakeholders engaged in shaping the future of urban living in Copenhagen and beyond.

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Chapter 1

Introduction

1. Introduction

Cities are growing, especially capital cities in the EU see continued demand for housing as they keep on attracting people due to the dense amount of services and opportunities they foster (Pojani, 2018).
Due to this continuous growth, new urban developments, such as building on reclaimed land and constructing artificial islands on urban waterfronts are starting to become more popular and experimented with by urban developers.
In these new district developments, there may be a tendency to develop public mobility infrastructure late, as we will see in the case of Amsterdam later in the thesis, postponing investments and assuming (almost forcing) car dependency as the only mobility option - while ignoring bicycle and foot passengers.
Such new urban developments provide us with a good opportunity to experiment with, or envision at least, new, smarter, transportation options, which ultimately may reduce costs and risks for city transport agencies.
In this report we will build up on the Lynetteholm, Copenhagen, case study, which is an interesting example of a land reclamation project for the purpose of urban expansion, whereas it will still take a lot of time before its completion. Therefore, this case would provide us with enough time to study and prepare the tech and infrastructure for new smart mobility options to implement.

The next chapter will provide detailed background information about the main case study, Lynetteholm, its origins and the reasons for its construction. We will also showcase how public transportation, which has historically shaped and influenced the urban form of Copenhagen, is now asked to adapt to and service new urban areas constructed to accommodate urban growth, rather than vice versa.

We will also showcase how mobility habits of urban residents are shifting because of new lifestyle and work practices mixed with new technology more widely available. After providing the reader with this background, the research questions posed and an overview of the thesis structure, the paper will dive into a literature review on urban form, developments in traffic and transportation in cities, as well as ferry oriented development. Therby the thesis aims to extract insights and build upon existing knowledge to explore and design a waterborne transport solution for this new urban development area, Lynetteholm, and how such transport solution may influence the areas around its infrastructure.

1.1 Copenhagen's need for sustainable urban expansion

Copenhagen, a pioneer in sustainable urban development practices, is currently grappling with challenges such as housing shortages and traffic congestion amid a growing population attracted by the city's increasing allure and high living standards (Bruns-Berentelg et al., 2022). Urbanization and heightened housing demand are well-established trends in various Western metropolitan areas, including Copenhagen, where the population has experienced a significant upswing since approximately 2006, with expectations of this trend persisting for the foreseeable future.

To address this, the region's housing supply needs to expand by 5,000-9,000 residential units annually for the next 20-30 years. This entails providing around 110,000 dwellings by 2035 and over 150,000 dwellings by 2045. In addition, there will be a particularly notable demand for compact apartments catering to young individuals in the city center. Urban planning strategies could potentially yield around 270,000 dwellings, evenly distributed between the city center and the suburbs (Næss-Schmidt, 2018). One significant urban planning initiative under consideration is the creation of the artificial island, Lynetteholm, slated to be constructed by 2070 in Copenhagen's Nordhavn harbor. Lynetteholm aims to offer residences and job opportunities for approximately 35,000 people (Mørk, A., 2021).

In 2025, the city aims to reduce CO_2 emissions from 1.9 million tonnes in 2011 to 1.2 million tonnes, emphasizing innovation in the transportation sector and urban development strategies (Rode et al., 2017). This involves fostering a "green wave" of commuters through low-carbon transport alternatives, efficient mass transit, and dense housing developments (Alkhani, R. 2020). Copenhagen has been dedicated to cleaner and intelligent mobility since 2009, when it committed to becoming a CO_2-neutral city with the Copenhagen Climate Plan, unanimously adopted by the City Council in August 2009 (Reckien, 2018). This commitment has resulted in one of the lowest congestion rates in Scandinavia, with a goal for 75% of all trips to be made by bike, public transit, or on foot by 2025 (INRIX, 2018).
Consequently, any proposed solution addressing urban challenges in Copenhagen, such as the artificial island Lynetteholm, must align with the city's enduring dedication to efficient, mass transit-focused initiatives, aimed at mitigating motor traffic congestion.
These are two main challenges addressed in this thesis: the city's growing population and the new, modern transportation needs of this expanding city, already exacerbated by the difficulty to drive in and out of Copenhagen over the past decade because of the building of the Metro Cityringen, an underground transit system (Rabensteiner, K., 2013).

1.2 Lynetteholm, the new borough made of reclaimed land

In light of these developments, the Danish Government, in 2021, decided to initiate the construction of an artificial island project with a focus on urban expansion, Lynetteholm (Figure 1), set to be completed in the next 50 years (Carlson, 2021). Lynetteholm will be positioned between Refshaleøen and Nordhavn, featuring a coastal landscape facing Øresund, also known as the Sound, the strait that forms the Danish–Swedish border, separating Zealand from Scania. Situated in the Copenhagen Harbor, Lynetteholm is strategically located to address the expected population growth (Whittaker & Jespersen, 2022). The project envisions providing up to 3 million square meters of housing, potentially increasing Copenhagen's central housing capacity by 12% (Carstensen et al., 2022). The primary goal is to accommodate approximately 35,000 residents, creating a vibrant, mixed-use district on reclaimed land (Klintö, 2022). Consequently, the transportation infrastructure linking Lynetteholm to central Copenhagen must be designed to complement and facilitate the socio-economic dynamics of this emerging district, drawing insights from an analysis of the existing socio-demographics and economic patterns in the Nordhavn harbor.

Figure 1. The 275-hectare Lynetteholm artificial island project, sitting between Nordhavn and Refshaleøen. Credit: By & Havn (City & Port)

1.3 Copenhagen mobility patterns and how these are shifting due to technology

Copenhagen was chosen for this investigation to explore sustainable urban mobility due to its status as one of the global leaders in smart mobility solutions. The city has a well-established commitment to sustainable transportation and has introduced various innovative initiatives to encourage cycling, walking, and public transport, aiming to shift away from traffic reliance and automobiles. The term "green mobility," emphasizing the prioritization of bicycles, walking, and public transportation as primary modes of urban transportation, has played a pivotal role in city planning, influencing the city's urban morphology on both macro and micro scales. The promotion of the "sustainable city" concept has been actively embraced in Copenhagen.

The close proximity of Copenhagen to the water presents challenges for both individuals and goods in crossing the port. Consequently, starting in 2006, a series of bridges was constructed to facilitate bicycle travel from the harbor to the inner city. Research conducted in 2012 indicated that 70% of commuters opting for these bridges as part of their route to work preferred cycling over a faster mode of transportation. Consequently, between 2012 and 2014, the city observed a substantial rise in the share of bicycling in transport modalities, increasing from 36% to 45%. These bridges emerged as crucial links for mobility across the bay (Galal, 2023).

In addition, Copenhagen employs several smart mobility solutions through the integration of its public transportation system and technology. The city has established a unified ticketing system that seamlessly combines buses, trains, metro lines, and ferry services, offering residents and visitors an easy and convenient means of utilizing public transportation (Wolniak, 2023). Real-time data management is also utilized to inform citizens about the arrival times of the next vehicle (Eltved et al., 2021). Smart traffic management systems, monitor real-time traffic flow and adjust traffic lights to optimize the flow and alleviate road congestion (Doost, Rezaie, 2020). Furthermore, the city utilizes Internet of Things (IoT) technology, such as sensors, to enhance parking systems. These smart systems detect available parking spaces and guide drivers to the nearest open spot through dedicated apps. Other innovations in safety and accessibility ensure that public transport is both safe and accessible to everyone. This includes features like low-floor buses and tactile paving for visually impaired citizens (Bager, Mundaca, 2021), as well as systems that detect pedestrians and cyclists at intersections to alert drivers and reduce the risk of accidents.

In doing so, Copenhagen has positioned itself as a leader in global efforts to provide sustainable transportation modes, transportation efficiency, safety and accessibility, consequently improving the quality of life of residents while tackling the challenge of greenhouse gas emissions due to traffic, all at the same time.

These smart mobility solutions, however, come with a series of disadvantages as well, mainly comprising high cost of implementation, resistance to change from some residents and ongoing maintenance and upgrades of such solutions.

Knowing the landscape set out in Copenhagen in regard to smart mobility solutions, the assumption at the core of this thesis is that this city is prone to innovation and testing smart mobility solutions to improve quality of life of its citizens and optimize existing services. Such inclination for smart urban solutions, especially in the prospect of a project as innovative and future-looking as the artificial island of Lynetteholm, which could represent a fertile ground for experimentation with high-tech solutions on water too. Therefore, two globally emergent smart mobility solutions, applied in the context of waterborne mobility only, namely Autonomous Navigation Systems (ANS) and Demand-Responsive Transportation (DRT), will be discussed and proposed conjointly within one mobility solution, drawing on the user-centric functionalities of Mobility as a Service (MaaS) solutions for the city of Copenhagen to review as new possible integrations into their public transportation portfolio. This project was prompted by the anticipated population growth in Copenhagen, projected to increase from 1.4mil to 1.6mil within the next fifteen years. It goes without saying that new, flexible, and smart transportation solutions will be required to accommodate this expansion and the needs of the future residents. More so because the water body between Lynetteholm and the center of Copenhagen is already set to undergo many invasive and polluting construction works that, the integration of the island with the rest of the city should be done through multiple and sensitive slow mobility options which are oriented towards low carbon type solutions such as urban ferries, rather than bridges or tunnels, which directly promote car-oriented transit (Norris, 2023).

1.4 Research outline

In order to gather knowledge about what challenges and needs cities have in the context of urban expansions and the domain of public transportation on water, the thesis will begin by providing a literature review on the case studies of Copenhagen, Venice and Amsterdam. Starting with Copenhagen and its urban form, we will paint a clear profile of a city built on waterfronts, its needs, and how this morphology has influenced its mobility trends and urban development ambitions. Reflection upon the case studies of Amsterdam and Venice, on the other hand, will help with understanding their transport challenges and solutions, from the standpoint of cities developed on waterfronts, and translate these learnings into solutions for Copenhagen. Venice, specifically, where residents have only ever had access to mobility modes such as walking, cycling, and waterborne public transportation, is a good example from which to leverage insights about the pitfalls of such long-lived waterborne transport systems. Since waterborne transport in cities like Venice, Amsterdam and Copenhagen is the common denominator, and all three of them are some of the busiest cities in the world in terms of population inflow, needing to expand their borders decade after decade, we will introduce the concept of Ferry Oriented Development, which is a particular urban planning practice focused on the development of river banks that host ferry services and around which stations services and meeting points tend to be born.
The discourse will then examine the two smart mobility innovations aforementioned, assessing their benefits and current limitations, exploring their applicability to Copenhagen and its urban expansion project, namely Lynetteholm. Ultimately, the thesis aims to contribute to the discourse on future-looking and user-centric urban transport solutions, offering evidence-based recommendations for the adoption of ANS and DRT, combined, in urban planning, particularly in the context of accommodating rapid urban growth and expansion on water.

1.4.1 Research questions

The research questions the thesis sets to answer are the following:

Main Question: What value does an ADRT service offer when deployed in integrating urban expansion-borne neighborhoods like in the case study of Lynetteholm and Copenhagen?
Q2. In the context of urban expansion, what challenges and benefits does Ferry Oriented Development present?
Q3.What can we learn from the challenges and benefits of waterborne transport-connected cities like Venice and Amsterdam?
Q4. What are the latest transportation technologies that can facilitate the connection of waterfronts in cities?
Q5. What would be the characteristics of an integrated ADRT system as a viable transport service for Lynetteholm to be connected to the adjacent Copenhagen areas?

1.4.2. Research methods

The methods used to answer these questions encompass a systematic literature review firstly on the urban form of Copenhagen, secondly on how MaaS have evolved and transformed the urban transport landscape, thirdly on the two new technologies brought by the private sector contributing to push MaaS development forward, and lastly what learnings from Venice can be implemented to Lynetteholm. To extrapolate what value the two MaaS solutions (ANS and DRT), and their combination, could bring to the city of Copenhagen, the expected results of this thesis include the design of a conceptual transport plan that outlines the benefits, possible routes, and the monetary significance of integrating the latest technological advancements into an urban framework like Lynetteholm. This plan will engage with decision-making processes and address key considerations such as the integration and management of such services. The discussion section will explain how citizens can engage with and request these services.

1.4.3. Research relevance and expected contributions

To conclude, the purpose of this thesis is to navigate the evolving landscape of urban development and public transportation, focusing on the shift towards on-demand services that cater to the increasingly complex and individualistic needs of Western citizens. This shift is compounded by the growing intricacies of urban environments and the escalating pressures on conventional transport systems and their failures, necessitating a pivot towards technological innovation and smarter mobility solutions. This research is relevant in light of ambitious urban development projects like Lynetteholm and urban forms where waterways, and their integration into transport solutions, are central and offer new opportunities for re-imagine the future of urban mobility. The thesis aims to present a conceptual design for future mobility solutions that are not only practical and efficient for densely populated and expanding urban areas but also seamlessly integrate advanced technologies.

In essence, this thesis seeks to contribute a visionary blueprint for urban mobility that aligns with the emerging trends and demands of modern cities, offering a pathway to more adaptable, efficient, and sustainable transport solutions that resonate with the needs of future urban developments like Lynetteholm.

1.5. Thesis outline

The remainder of the thesis is structured as follows: in the research methodology we will explain what methods have been used to answer each question. Each question constitutes a building block of foundational knowledge to be able to design our ADRT solutions for Lynetteholm in the most useful and viable fashion, addressing challenges identified in the literature and case study analysis. The thesis will conclude with a discussion on the implications of such an ADRT solution in the grand scheme of the transportation services of Copenhagen and how the development of its urban form might be influenced by them. Recommendations for future research acknowledge the opportunities and benefits of waterborne transport in cities built by water and suggest to municipalities to collaborate closely with technology providers to, not only study users travel patterns to optimize current services but also to predict trends and offer new services that could result in decreased costs for transportation companies.

Chapter 2

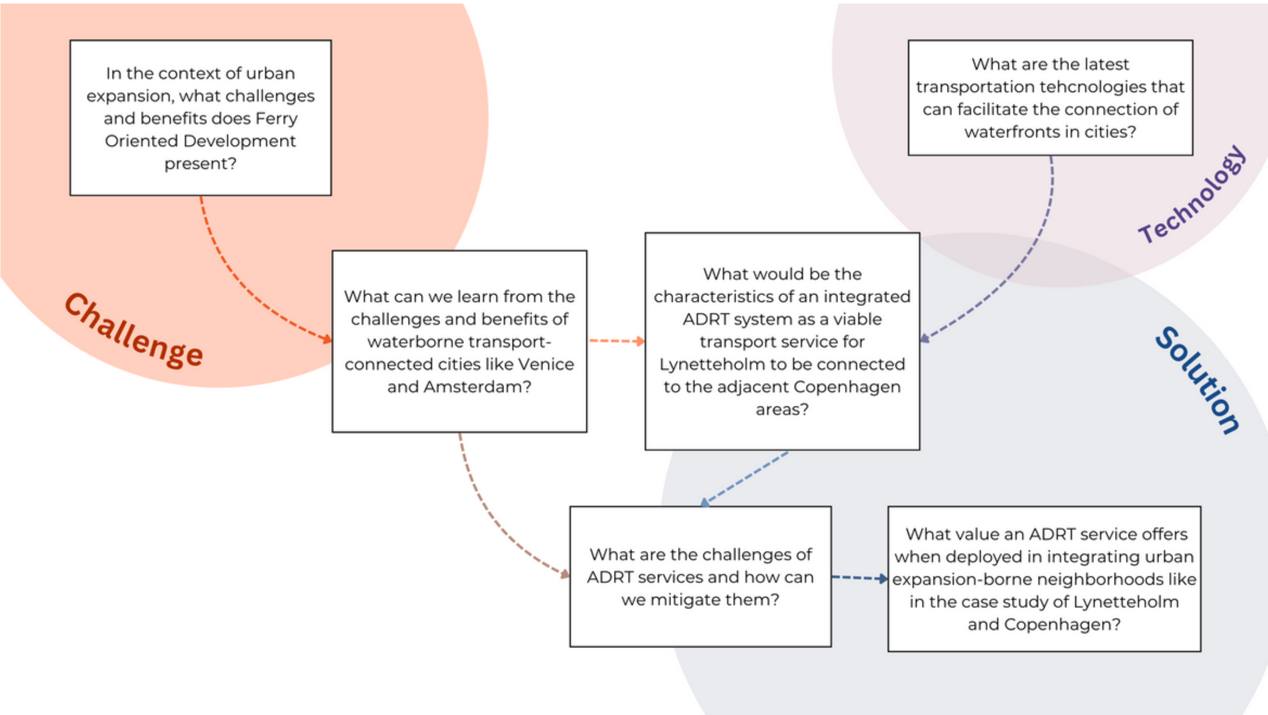
Research Methodology

2. Research Methodology

In chapter 2, we discuss the research methods in connection to the research questions we aim to answer. To this end, we will first pose the main questions the thesis aims to answer. In the remaining sections, we explain which methods we deem appropriate to answer the questions, given the constraints in terms of research effort.

2.1 Research questions and subquestions

This study poses the fundamental questions needed to design a practical transportation solution for Lynetteholm. The following diagram shows the systematic manner deployed:



2.1.1 Main research question and subquestions

In this section we present the main research questions and the research subquestions which will be answered in the remainder of this thesis. The subquestions will be tied to research methods in section 2.2.

The research questions presented in the thesis focus on three main functions:

1. To provide insights into the **challenge** of cities and their need for urban expansion on water, with the consequent need for transportation connections through water.
2. To explore what are the latest transportation **technologies** adopted by cities that can facilitate connections between their waterfronts?
3. To design an innovative waterborne transportation **solution** for the artificial island of Lynetteholm in Copenhagen, based on Venice and Amsterdam's challenges and learnings on their waterborne public transport solutions, and insights from the application of experimental transportation solutions globally.

Overarching question: What value does an ADRT service offer when deployed in integrating urban expansion-borne neighborhoods like in the case study of Lynetteholm and Copenhagen?
Which sets the context for answering questions about urban development influenced by transportation modes on water.

Challenge question: In the context of urban expansion, what challenges and benefits does Ferry Oriented Development present?
Which leads to looking into waterfront cities like the exemplary Amsterdam and Venice, and how have they dealt with urban waterborn transportation as a means to connecting residents and neighborhoods.

Subquestion: What can we learn from the challenges and benefits of waterborne transport-connected cities like Venice and Amsterdam?

From the **technology** standpoint, the question arising is: What are the latest transportation tehcnologies that can facilitate the connection of waterfronts in cities?
Subquestion: What are the challenges of ADRT services and how can we mitigate them?
Answering these two questions, will provide more clarity about what functionalities and characteristics the solution for Lynetteholm should inlcude to be able to offer a viable transport service.
Subquestion: What would be the characteristics of an integrated ADRT system as a viable transport service for Lynetteholm to be connected to the adjacent Copenhagen areas?

Finally, to design a tangible solution for Lynetteholm, the paper will provide an outlook on the value brought by a ADRT service implemented on a series of routes, and what will this mean for the economic and social development of Lynetteholm, and the areas adjacent to it.
Solution question: What value an ADRT service offers when deployed in integrating urban expansion-borne neighborhoods like in the case study of Lynetteholm and Copenhagen?

2.2 Research methods per research question and subquestion

Main Question: What value does an ADRT service offer when deployed in integrating urban expansion-borne neighborhoods like in the case study of Lynetteholm and Copenhagen?
Research method: A systematic literature review has been performed to answer the above question by identifying, selecting and synthesizing high quality research evidence on the themes of ANS and DRT, urban expansion and mobility strategies used in Copenhagen. Since the paper starts from a thorough knowledge standpoint of the topic of waterborne mobility, as well as of the advanced technologies proposed for Lynetteholm, the aim of this method is to support the design of the solution through evidence-based practice, identifying and critiquing relevant research studies. This method is highly specific and focused on the assessment of the validity of findings, to be able to base the design of a practical solution on validated concepts, problems and solutions.

Q2. In the context of urban expansion, what challenges and benefits does Ferry Oriented Development (FOD) present?

Research method: A "state of the art" literature review through the snowballing method has been performed to answer this question. Here, the snowballing method helped particularly with drawing knowledge from adjacent studies on the matter that typically would be challenging to retrieve, given the niche topic. Snowballing, in this case, provided peer reviewed papers on the benefits of FOD, which ultimately is the strongest proposition for the waterborne solution for Lynetteholm. This method is used to brief the reader about this particular urban planning practice outlining the most recent research on the subject. The learnings from the technical challenges and benefits of FOD will then be implemented in the practical design of the ADRT solution for Lynetteholm.

Q3.What can we learn from the challenges and benefits of waterborne transport-connected cities like Venice and Amsterdam?

Research method: A comparative case study has been performed to answer this question to systematically examine the cities of Venice and Amsterdam to understand their similarities, differences, and waterborne mobility challenges and strengths to offer insight to apply to the Copenhagen mobility solution in the design phase of the thesis. This approach helps in analyzing how and why specific transport solutions or policies succeed or fail, facilitating the generation of knowledge that can be applied more broadly to answer causal questions.

Q4. What are the latest transportation technologies that can facilitate the connection of waterfronts in cities?

Research method: A "state of the art" literature review has also been performed to answer this question, in a similar methodological manner as for the FOD related question. This method is used to update the reader on the current level of the advancement of a particular technology within the transportation field currently being adopted in cities. The answer to this question will be developed through a thorough and snowballing literature review that provides the reader with background information upon which a multitude of studies have built their theoretical frameworks on. The technological breakthroughs of ANS and DRT that will then be implemented in the practical design of the ADRT solution for Lynetteholm are at the core of the proposition, therefore relying on a large pool of academic studies makes the findings more solid.

Q5. What would be the characteristics of an integrated ADRT system as a viable transport service for Lynetteholm to be connected to the adjacent Copenhagen areas?

Research method: A systematic literature review has been done to answer the above question to pinpoint the most successful and useful characteristics of DRT service providers and adopt them for the design of a viable waterborne transport option to connect Lynetteholm to Copenhagen. Reports and technology blog posts have been analyzed to study the discourse about successful and failed cases of such technology implementations in cities, and with a clear idea of what works and what doesn't, the next step of the methodology section will focus on designing the ADRT transport solution.

Chapter 3
Case Studies

3.1 Case study results

In this section, we will consider a number of example cities, starting with the principally investigated one, Copenhagen and its current challenges. We will then move on reviewing challenges, solutions and their effectiveness from similar waterfront cities like Venice and Amsterdam to learn from their long-lived experience with transportation on water.

3.1.1 Copenhagen's Urban Form

Modern urban planning is characterized by numerous urban planning policies embracing sustainable measures, such as promoting energy efficient systems in order to reduce anthropogenic GHG emissions, which cities, through buildings, infrastructure and transport, produce 40–70 percent of the total global amount (Jones et al., 2009). However, with urban expansion, unsustainable development is the easier way out: urban sprawl and car centric urban planning policies augmenting road infrastructure, are a common shortcoming that many EU and North American cities are striving to steer clear from.
75% of CO_2 emissions in Copenhagen stem from road traffic alone (City of Copenhagen 2022) and together with the CO_2 emission from electricity consumption and district heating, they make up approx. 90% of the total CO_2 emission in Copenhagen Municipality in 2022. Presently, vehicles predominantly operate on fossil fuels. As a result, the city's transportation policies are geared towards reducing carbon emissions, alleviating congestion and private vehicle use, promoting multi-modal integration, and encouraging increased cycling, walking, and the utilization of public transport. As demonstrated by cities like Copenhagen, there is a growing recognition of the pitfalls of traditional car-centric approaches particularly taking into account the phenomenon of induced demand, where increased road capacity boosts vehicle usage (Schneider, 2018).
The physical shape of the city, which encompasses its density, the locations of its functions and the interconnectedness of the latter, influences how the transport networks are built and their energy usage. Studies have shown that the transportation-related energy used per-capita decreases as population density increases. Central Copenhagen boasts a densely populated urban core characterized by significant land-use diversity and the seamless integration of residential and workspaces. The city center registers a peak of 25,340 residents per km^2. Despite being much larger, London shares a similar peak residential density. Nevertheless, the substantial reliance on cars for journeys in Copenhagen (40%), in contrast to cities like Barcelona (12%), Istanbul (14%), and London (40%), underscores the need for persistent efforts to redirect the modal share from private vehicles to alternative modes (Floater et al., 2014). These figures highlight the significance of individual mobility for Copenhagen residents, notwithstanding the high urban core density and proximity to services. There's room for improvement in mass transit ridership, potentially transitioning towards more on-demand services, capturing the appeal and freedom aspects associated with car usage.
Research done by Jabareen has identified four main models of urban development aimed at delivering sustainable development policies, namely "Neotraditional development, compact city, urban containment, and eco-city". Copenhagen, and its Five Fingers urban planning approach (Figure 2), matches with the "urban containment" model, which is in principle aimed at concentrating urban development and creating green space at equidistant proximity, as well as efficient public transport running along each finger.

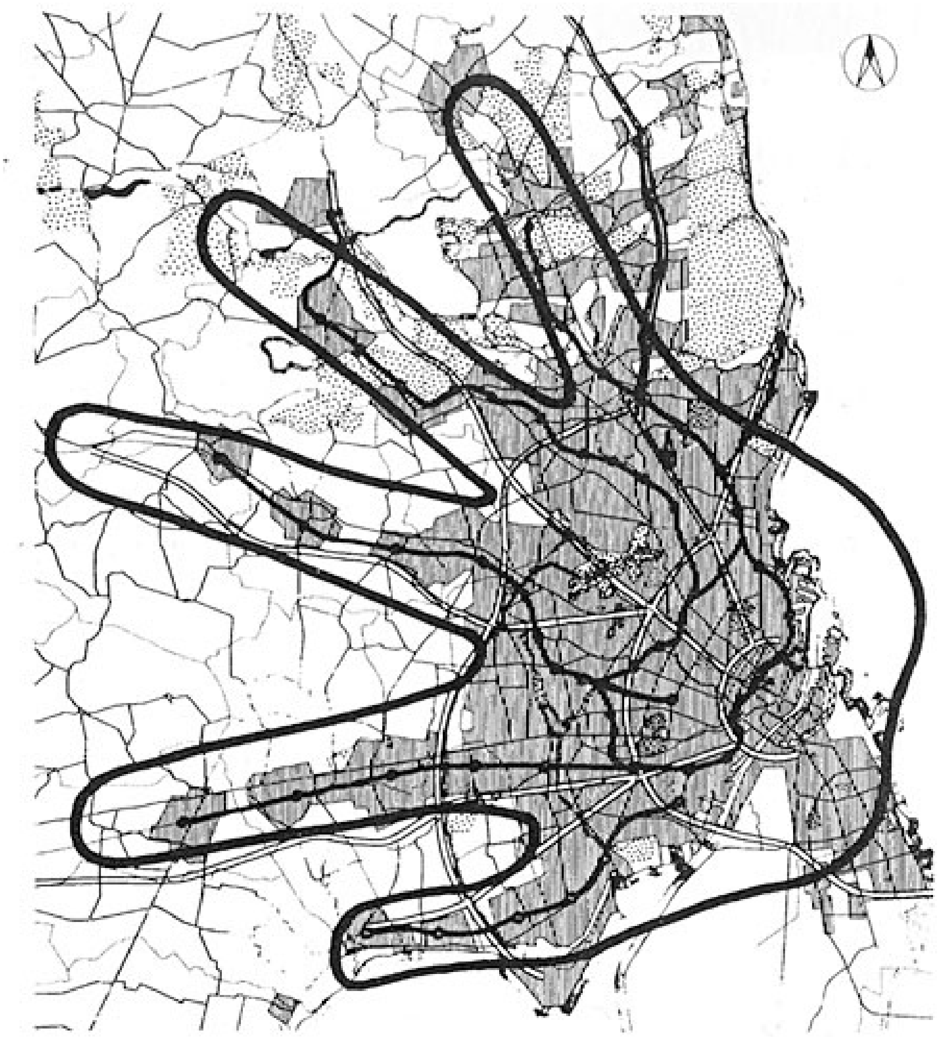


Figure 2. An illustration of the 1947 Finger Plan, which has guided development along transit corridors. Credits: Danish Design Review

Davoudi & Sturzaker highlight the efficacy of the urban containment model in fostering inward urban development, enhancing density, and aligning with sustainable transportation policies.

This approach strategically allocates infrastructure investment to designated geographical locations, stimulating their growth individually and shaping development direction. However, in this model, challenges emerge with population growth. Urban expansion beyond pre-confined areas may lack integration and suffer from insufficient planned infrastructure and green spaces. Originally designated for citizen benefits, these green spaces may narrow over time. Another drawback is the model's focus on developers and landowners, potentially neglecting end-users. Shorten (2005) underscores this issue, emphasizing the strategic disobedience of end-users who do not conform to the structured urban shape designed for them. Hence, emerging mobility connections ought to preserve human connections, fulfilling individuals' life purposes as per Kamargianni (2016), and facilitating user movement between the pre-planned "urban containment" areas and other areas that are naturally emerging and developing as the city grows, ensuring the avoidance of isolation.

Furthermore, in the context of Lynetteholm, and being aware of the drawbacks of the containment model adopted by Copenhagen, the transportation solution should provide inhabitants with high-class connections for cyclists, regular human interaction and an opportunity to enjoy the natural surroundings of the water passage that divides the two land masses. Concerns have been raised by the Danish Cyclists' Federation (Cyclistforbundet) in 2023, regarding the low investments allocated to develop suitable regional connections for cyclists to integrate Lynetteholm with the rest of Copenhagen and the Five Fingers plan. According to the Danish Cyclists' Federation, the initial agreements on Lynetteholm's development, dating back to autumn 2018, align with Copenhagen's municipal development plans since the 1990s. These plans aim to enhance the capital by prioritizing dense urban development close to the city center, following the Fingerplan principle of concentrating primary development in the metropolitan region. While this approach has the potential to positively impact cycling levels, the federation argues that significantly more funding should be allocated to cycling connections to Lynetteholm. This is crucial considering congestion challenges, the climate crisis, and citizens' desires for a well-connected city. The Federation criticizes the disproportionately low investment in high-quality bicycle connections compared to roads for motorists, stressing the need to rebalance this ratio to fulfill Lynetteholm's potential as a model of 21st-century urban development and align with the city's decarbonization goals.

Furthermore, the Federation highlights the importance of regional bicycle connections corresponding to Lynetteholm's expected population and workplace density, emphasizing that Lynetteholm's planned density warrants a more extensive network of cycle paths than currently designated. Concerns are raised regarding potential bottlenecks, particularly at Refshaleøen's narrowest point (circled in Figure 3), which could hinder southbound bicycle traffic.

Figure 3. Lynetteholm and its complementarity to the Refshaleøen neighbourhood.
Credits: News Øresund, 2021.

Bicycle-friendly cities are characterized by extensive bicycle networks spanning across various districts. The federation insists that despite the unique planning challenges posed by Lynetteholm's peninsula, the political decision to expand the capital should not compromise conditions for cyclists. They advocate for prioritizing consultation with the Finger Plan's regional cycle connections to ensure optimal conditions for cycling.
Finally, the Federation regrets the missed opportunity to establish a bicycle tunnel parallel to the Nordhavn tunnel, which could have set an international standard for cyclist-friendly infrastructure. They anticipate that Nordhavn and Lynetteholm may develop differently from central Copenhagen due to insufficient regional cycle connections, leading to primarily local cycle traffic rather than regional traffic that could reduce car usage.

3.1.2 Commonalities between Amsterdam and Copenhagen, with emphasis at Amsterdam River Connection Mobility Solution

Just as Copenhagen and Lynetteholm, Amsterdam has faced connectedness challenges with the Noord borough across the IJ river. The river runs across the city, dividing the city center area from the growing Noord borough (current population of about 96,000) (Amsterdam.nl, 2023). It is reasonable to say that the cities of Amsterdam and Copenhagen have commonalities and lessons to be learnt from each other. From the demographics perspective, in 2024, the cities have had similar population sizes, Copenhagen counts 1.4mil inhabitants, against the 1.2mil of Amsterdam. However, Copenhagen has a much lower population density, 82% lower than Amsterdam, which symbolizes how busy and cumbersome traffic and movement of people can be in Amsterdam, yet how efficient the city manages to accommodate services. The highly present cycling culture is another common ground, and according to the Copenhagenize Index the two cities are in leading position, with Copenhagen at the top of the list, followed by Amsterdam in second place. The bike-friendliness index developed in 2019 by a private professional group supported by the World Bank, assesses global cities above 600k in population size, as a means to look into urban cycling insights and benefit cycling infrastructure investment and policy making at the city level (Copenhagenize, 2020).

The morphology of the rivers crossing the cities, whose narrowest points measure around 300m for Amsterdam and 500m for Copenhagen, is also something that brings them closer to learning from each other. We will now show how Amsterdam dealt with this challenge. Data from the ferries department of GVB (the municipal public transport operator for Amsterdam) indicates that the GVB currently operates six ferry routes across the IJ river, serving over 62,000 passengers daily, totaling more than 23 million annually in 2022. This marks a significant increase from the 12 million passengers recorded in 2011, reflecting the growing significance of the Noord borough, as well as the appeal of using the ferry for connecting passengers on foot and by bicycle to the two sides of the city. With a rise in population, tourism and business activity, the number of ferry passengers is projected to reach 130,000 daily, surpassing 47 million annually by 2030. The operation of these six ferry lines, facilitated by nineteen ferries, incurs an annual cost of 10 million Euros for the GVB (GVB, 2022). This rise in demand of service is even more challenging seeing that during peak hours or special events, overcrowding on the ferries is already common and posing challenges for both embarking and disembarking passengers.

Discussions surrounding the construction of bridges across the IJ have been ongoing since the mid-19th century, with current considerations ranging from dedicated pedestrian and cyclist tunnels to cable-ways. However, proposals such as cable-ways are deemed impractical and costly, while tunnels present challenges due to their depth requirements and steep inclines.
The city council was expected to reach a decision on the matter in 2017, with potential bridge construction occurring between 2020 and 2025 at an estimated cost of €130 million, however decisions have been postponed again. Preparation for this includes the reservation of necessary land plots by the city, which is a way too valuable asset nowadays since Amsterdam population is 6 times denser than Copenhagen. Additionally, concerns have been raised by entities such as the Port of Amsterdam, which views a bridge, or the invasive construction of a tunnel, as potential obstructions to the busy, and profitable, international waterway, which is a similar situation Copenhagen faces. Finally, questions arise regarding the height of the bridge to accommodate tall container ships and the impact on cyclists' experience, as well as considerations about waiting times if the bridge needs to undergo maintenance.

Economic factors also come into play, with proposals suggesting the relocation of the Passenger Terminal Amsterdam (PTA) to the commercial port district. However, studies indicate potential negative consequences for Amsterdam's cruise ship industry, as remote port access may deter cruise agencies and passengers. This is because each cruise ship visit brings approximately €500,000 in economic benefits, with Amsterdam being one of the largest cruise ports in Europe, hosting hundreds of mega ships and about 700,000 cruise passengers each year (Koc, 2023). Therefore, the Port Authorities express concerns over bridge discussions, emphasizing that any potential delays or safety issues for logistics and economic activities are deemed unacceptable.
When looking at the metro extension perspective, for example, a total of 1.025 billion euros will be invested towards the extension of the North/South metro line to Schiphol Airport, which implies that costs and magnitude of effort and work that go into a metro extension project is significantly higher and more invasive than adding a few more stops of ferry service (Schiphol, 2023).

Another commonality Amsterdam has with Copenhagen is the underlying doctrine of urban planning reflecting the growing importance of new, peripherally-located transport oriented development (TOD) nodes which concentrated population and social and economic activity and were not unilaterally reliant on the central city. In the context of urban expansion, Amsterdam has the Ijburg island as an example to offer. In the early 1980s, IJburg, a housing expansion site for 18,000 dwelling units, built on six artificial islands raised from the IJ Lake was pervading urban development conversations. Amsterdam had sought to develop it since 1978, but construction only started twenty years later after much discussion and deliberation. The area is connected to Amsterdam via tram but the line did not reach IJburg until 2000, after the first bridge was put in place. However, its 'island' location with limited connections to the city is the root of transport bottlenecks (Alexander, 2002). This is because the interests of developers are placed ahead of strategic efforts to structure cities and regions in a more environmentally sustainable manner, which consequently limits the extent to which cities can promote TOD in practice, and may pose a key barrier for TOD in the future. The main similarity between Amsterdam and Copenhagen is highlighted by the rivers that run across the two cities and the waterborne public transport services the two cities operate to offer a mobility connection between the banks of the two rivers.

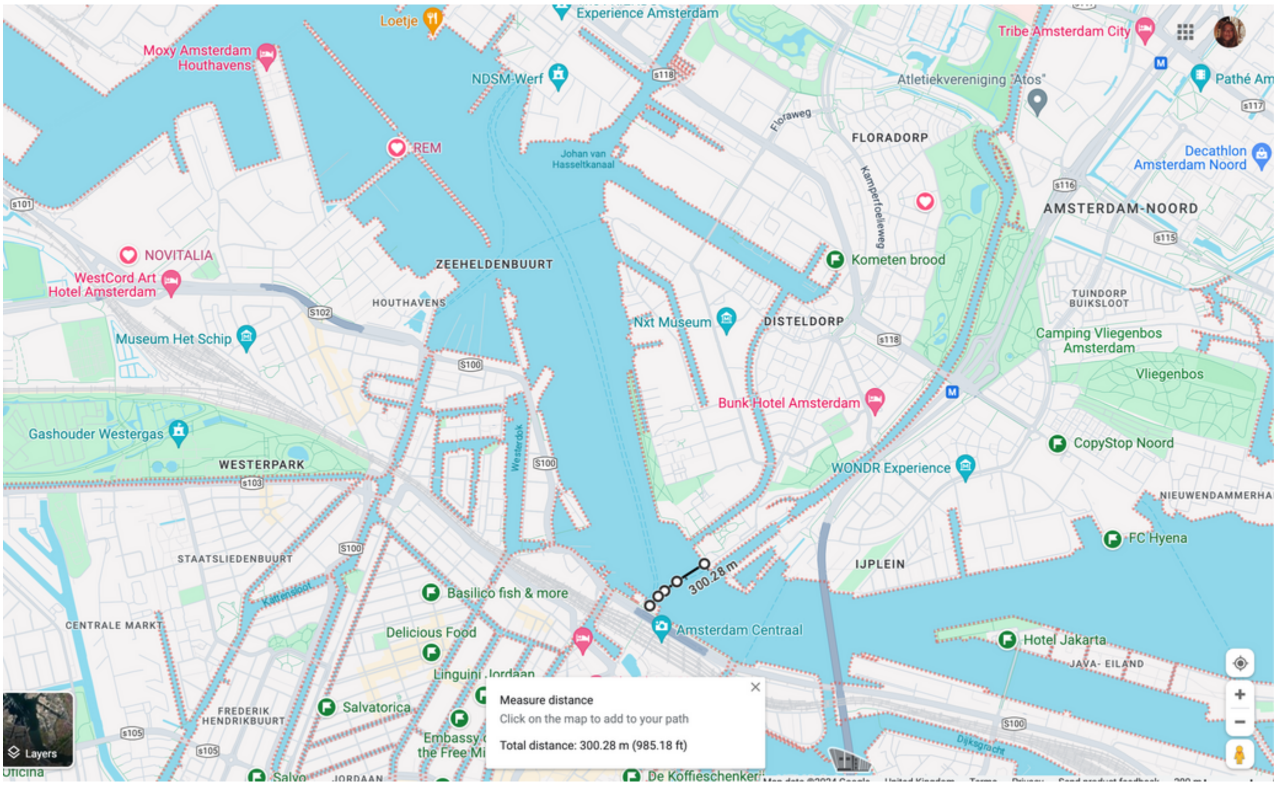


Figure 4. Shortest route from Amsterdam Centraal ferry stop to Amsterdam Buiksloterweg is 300m.

Figure 5. Longest route from Amsterdam Centraal ferry stop to NDSM ferry stop is 2.5km.

Figure 6. Shortest route from Langelinie to Lynetteholm Stop 1 is 565m.

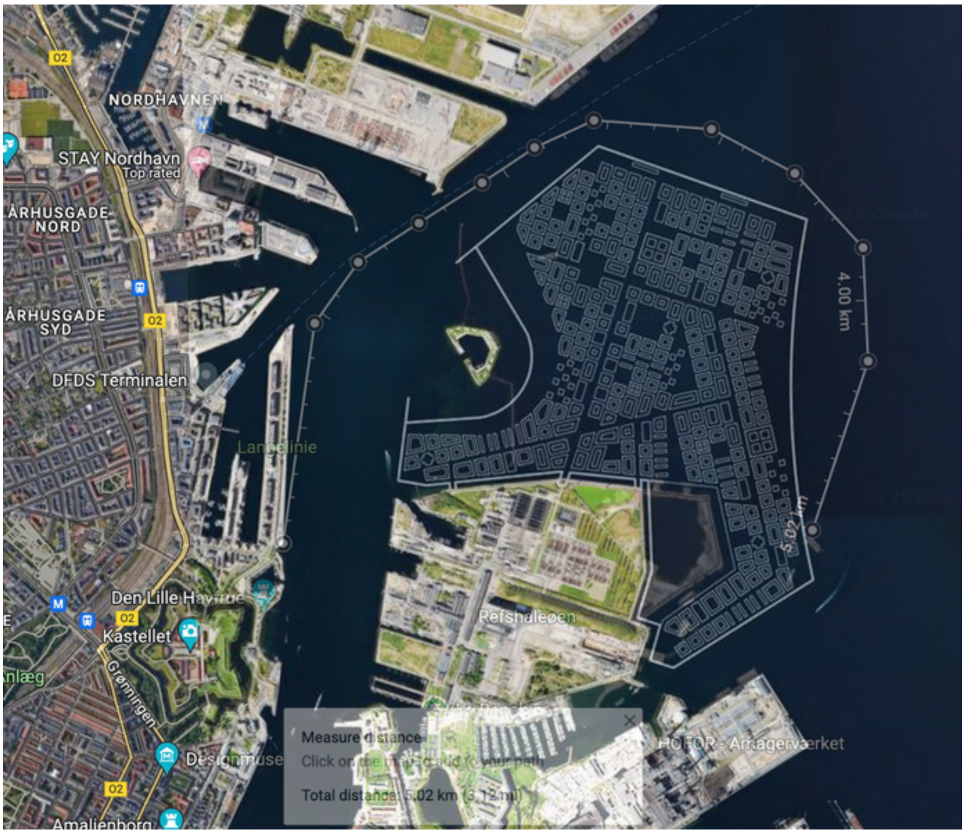


Figure 7. Longest route from Langelinie to Lynetteholm Stop 6 is 5km.

The modal split in both cities can also be compared (Figures 8 and 9), Amsterdam right, Copenhagen left). Both cities rely on cycling for almost 50% of their modal split, while car use is used 21% in Amsterdam and 27% in Copenhagen, and public transport, also similarly, is used 17% (Amsterdam) and 18% percent of the times for home-to-work commutes.

On top of that, the ferry service operating in Amsterdam has placed ferry stops in strategic locations which connect to train stations, metro stations, some of the biggest corporate establishments like Shell, Booking.com, Patagonia, etc. and some of the most densely populated and trafficked areas of the city, Noord and Centrum boroughs. However, since for Lynetteholm we do not yet know where such commercial and residential hubs will be built, we will approach the ADRT stop allocation strategy based on a study by Shen et al. (2023), which presented a practical approach influenced by queueing theory, a study of waiting lines suggesting that an equitable distribution of total traffic intensity across all bus stops could result in reduced bus delays. Thus, for this thesis, I adopted the principle of equitable distribution for ADRT stops, leading to the establishment of six evenly spaced stops covering the key areas of the island.

In addition, where it is known which locations of the already built Copenhagen will be facing Lynetteholm, ADRT stops will be strategically placed there and where the city foresees future urban developments to happen and use Ferry-Oriented Development (FOD) strategies to leverage such transportation service for the benefit of residents and services in the area.

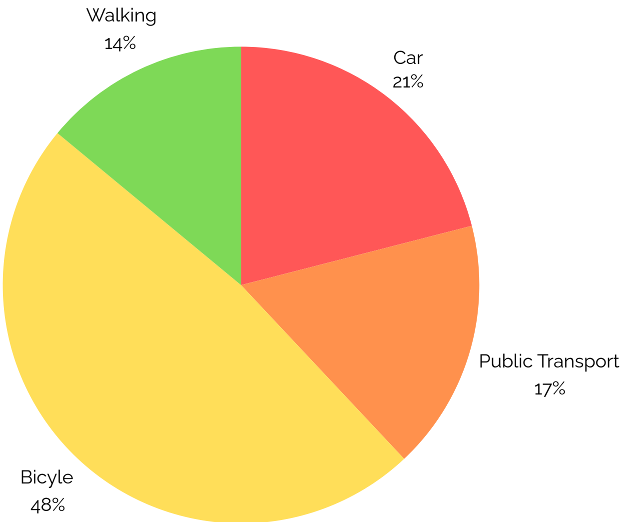


Figure 8. Modal split home to work trips in Amsterdam (2016). Credit: Knowledge Institute for Mobility Policy.

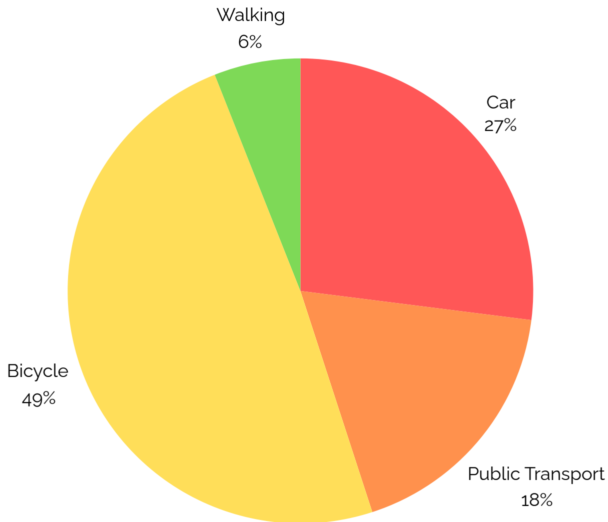


Figure 9. Modal split home to work trips in Copenhagen (2019). Credit: KK GOV.

3.1.3 Nordhavn port as an opportunity to develop an underserviced area of Copenhagen

The integration of Nordhavn with Lynetteholm in Copenhagen holds considerable significance as both neighborhoods are undergoing transformative developments. Nordhavn, a former industrial area, has been in the process of redevelopment since 2008 to meet the city's growing housing demands. The vision for Nordhavn is to create a slow mobility hub that prioritizes walking, cycling, and public transit, aiming to accommodate and provide jobs for 80,000 individuals. The area's design focuses on liveability, with a '5-minute city' concept ensuring accessibility to shops, workplaces, and public transport within a short walking distance. Additionally, Nordhavn is adopting sustainable energy solutions and aims to be resilient to climate change and changing transportation needs of the future generations of Copenhageners.

Lynetteholm, in this regard, being a newer development, presents an opportunity to experiment with innovative transportation solutions that align with the sustainability goals of Nordhavn. The proximity of Nordhavn to Lynetteholm suggests potential for collaboration in boosting economic growth and reinforcing each other's developments. As both neighborhoods emphasize waterways and canals, there's an opportunity to explore waterborne transport options alongside cycling and other slow mobility solutions. Given the low-density residential and commercial land use surrounding Nordhavn and the future Lynetteholm area, there's a clear opportunity to gather data on mobility patterns and demands to guide the implementation of efficient transportation services. This approach can ensure that as these areas develop, they can offer sustainable and user-centered mobility options that cater to the needs of their inhabitants and contribute to Copenhagen's broader urban fabric. As depicted in Figure 10, the areas surrounding Nordhavn and the cruise terminal, where Lynetteholm is slated for construction, indeed exhibit low density of residential and commercial land use, depicted in grey, while more vibrant green shades indicate high-density mixed-use areas integrating both land uses. The substantial mix of uses in the inner city of Copenhagen creates opportunities for walking and cycling trips as services will be in closer proximity, hence the focus on establishing a more densely populated city.

Not only is there an opportunity to foster collaboration between these two neighborhoods, but also policies created within the city mandate development principles such as the "station proximity principle", which requires new large offices exceeding 1500 sqm to be situated within 600m of a railway station. This principle could also well apply to the ferry stations in Lynetteholm, facilitating connections to workplaces, homes, services and intermodal changes, just like in Amsterdam. This principle implies that the underdeveloped areas around the future Lynetteholm artificial island, in terms of residential and job density, will benefit from greater accessibility and efficient overground (meaning not underground) transport connections. This, in turn, is expected to stimulate development along the riverbanks of the Copenhagen Harbour, and will draw residents to services around these stations (Floater, 2014).

In this regard, in Figure 11 it can be observed that services coverage performance in the Nordhavn area is still indeed under development, with a lack of amenities in categories such as education, leisure, and playgrounds. Thus, development in Nordhavn must prioritize the establishment of appropriate amenities around residential and commercial areas to ensure equitable distribution of services, and the appropriate transport connections (Helal, 2021).

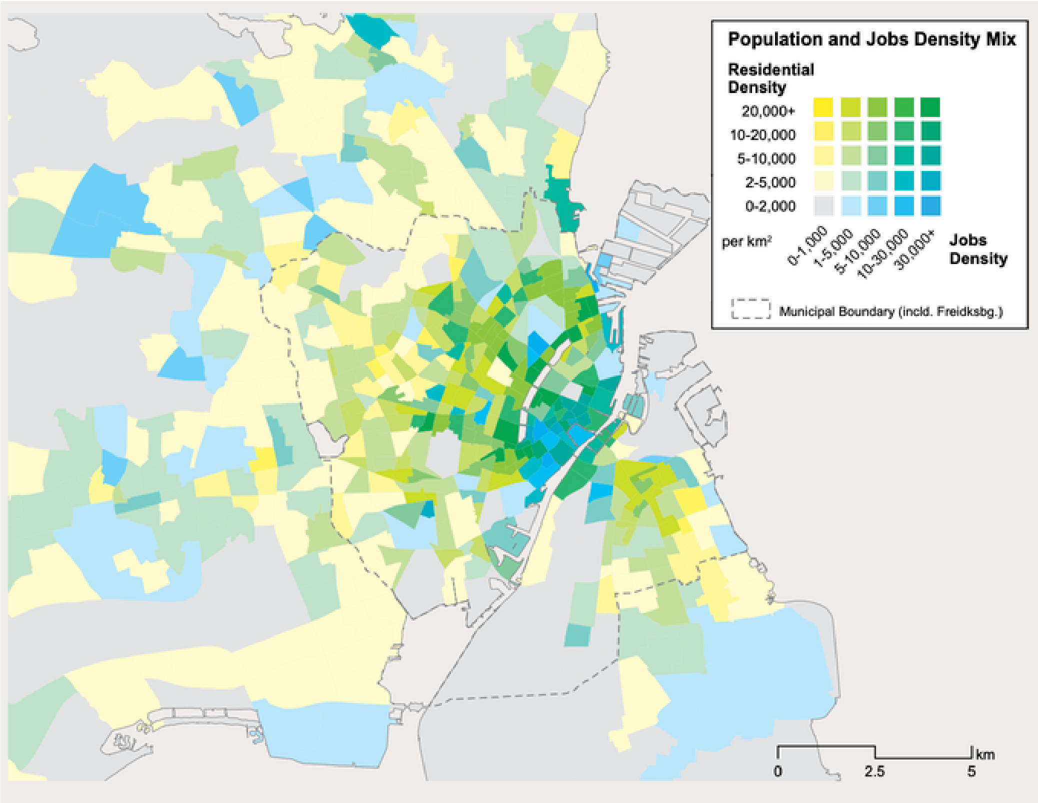


Figure 10. Copenhagen population and employment density mix 2012. Credits: LSE Cities.

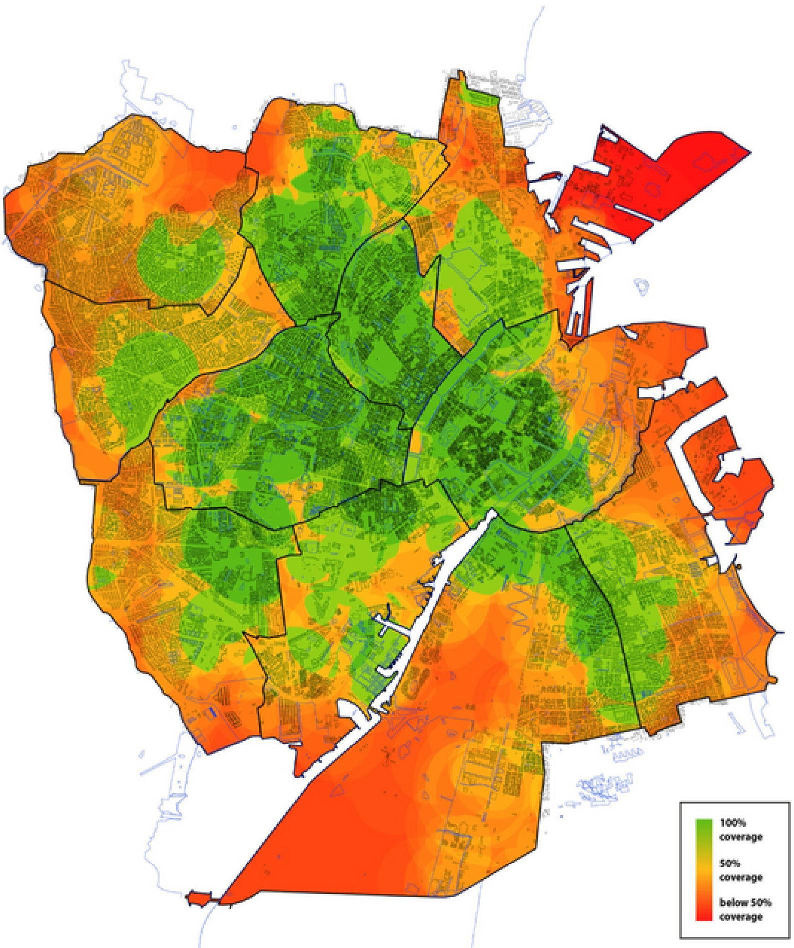


Figure 11. Performance overview map for all the districts in Copenhagen. Credits: Buro Happold.

3.1.4 Venice example, historical waterborne transportation systems and their challenges to shape a better future for insular urban contexts

In this section we will cover the characteristic of Venice, the challenges that a waterborne city faces in their daily transport service and we will highlight the lessons leant from this Italian city which can be applied to Lynetteholm.

Venice, Italy, historically belongs to water, and it has been a major hub for trade for centuries. Known as Europe's most powerful trading city, it served as a crucial maritime port in Europe and as one of the end destinations for the Silk Road commerce. Human-powered boats like rowboats and gondolas persisted into the 19th century until the introduction of steam-powered boats, the vaporetti, in the 1880s, offering a faster way for residents to move around. Venice, like other port and waterborne cities with narrow lanes and often congested waterways, especially with the large influx of tourists, lacks typical traffic management measures such as lanes and traffic lights. Unlike other cities where infrastructure can be expanded to ease congestion, Venice's unique layout, bounded by its historic canals and buildings, offers little scope for such expansion. Similarly to Copenhagen, which actively chose so, Venice is experiencing its own urban containment urban form, due to the limited expansion capacity of the island. Traffic congestion has escalated over time, with some waterways experiencing over a thousand vessels passing daily (Lilliquist, 2018).

In contrast to many large cities, Venice is experiencing a decline in its resident population, now falling below 50,000 as of 2023. Despite this, the city saw an average daily tourist count of 57,430 in 2013, with numbers soaring to 90,000 during peak summer times. The year 2019 marked a record with 5.5 million tourists, a figure that has since been exceeded by 2023. Venice finds itself in a challenging position, heavily reliant on yet overwhelmed by its tourism sector. This influx of visitors significantly impacts local traffic, a common issue in places with a high number of non-residents, with Venice being a prime example. According to "Impacts of Tourism", tourists reduce the walking pace of Venetians by around 16%. Moreover, all goods entering Venice, half of which are estimated to serve the tourist demand, contribute to the considerable traffic of motorboats along the canals.

Venice's traffic patterns differ significantly from those of other similarly sized cities, largely influenced by unique commuting habits and tourist activities. Unlike in most cities where peak traffic coincides with work commutes, in Venice, the majority of residents walk or use water buses, minimizing their impact on boat traffic. Instead, the delivery of goods to stores, constituting 36% of waterway traffic, and tourist transportation, accounting for 40%, dominate Venice's traffic flow (Lilliquist, 2018). Consequently, the city's peak traffic periods don't align with typical before-and-after work patterns seen elsewhere. The primary mode of public transport is the Vaporetti, or Venetian water buses, provided by the public transport company ACTV carrying 95 million passengers annually. Other available means include water taxis, Alilaguna (airport water buses), and traghetti, which are used specifically for crossing canals. Unlike road-based cities where private cars are the main contributors to traffic, in Venice, private motor boats play a smaller role in the overall traffic volume. To this last point, Lynetteholm could take example from Venice and rely on waterborn public transportation to reach the city centre of Copenhagen, integrating cycling and ferries, steering clear from car use. The operation of the vaporetto system shares many similarities with traditional bus or metro systems: ticketing, stops and schedules. However, passengers using the water bus service need to stay adaptable and alert, as routes can unexpectedly change and may also vary with the seasons. Which is why, digitisation and a better user interface through which technologies inform users about the next vehicle available would help with service optimisation.

Venice struggles with multiple traffic-related challenges, among which water pollution and 'moto ondoso' or wave motion stand out, adding complexity to issues of congestion and air pollution. Moto ondoso, a phenomenon unique to Venice, plays a significant role in the degradation of canal walls and is primarily attributed to the advent of gas-powered boats in the 1950s. The wake force generated by motor boats navigating the canals and the adjacent lagoon have inflicted considerable damage on buildings and canal walls, as noted by Broggi (2012), compromising the stability of Venice's architectural heritage.

The extent of damage caused by moto ondoso remains a subject of debate among experts, yet a consensus exists that it accounts for at least 50% of the damage to canal walls, the rest of the damage accounts for natural degradation.The transition from traditional rowboats to motor boats has undoubtedly enhanced the efficiency and speed of transportation within Venice. However, this technological evolution has been accompanied by environmental repercussions, posing significant challenges to the city's delicate ecological and urban fabric. Therefore, this teaches us that technological innovations should play the long game and pay more attention to how they develop in the future, the consequences brought to the environment and the socio-economic landscape of urban contexts.

Studies have been conducted to understand and mitigate this issue. Students from Worcester Polytechnic Institute, conducted a research titled “Boats Are Waking Me Crazy: An Analysis of Boat Traffic and Moto Ondoso in Venice,” which offers recommendations for systemic enhancements, projecting a potential reduction in moto ondoso by 57%.

The study emphasizes the reconfiguration of taxi and cargo boat operations, which constitute a combined 82% of the city's water traffic—46% from taxis and public transportation, and 36% from cargo vessels. The students proposed the optimization of taxi boat routing. Under the current system, taxi boats are obligated to return to their original stands post passenger drop-off, resulting in approximately 33% of their operational time spent in transit without passengers. This practice not only heightens congestion but also significantly contributes to moto ondoso. The recommendation to revise the taxi dispatch system, enabling the pick-up of passengers at drop-off points rather than returning to the original stand, is estimated to reduce moto ondoso by 14%. Implementing such a measure could substantially refine the efficiency and ecological footprint of Venice's waterborne public transportation system. Analogically, this learning contributes to the case of the proposed ADRT service for Lynetteholm, where the transportation service has been optimised by the demands and travel patterns of passengers, making pick-up and drop-off as tailored and as efficient as possible.

Another issue Venice faces is public safety. A series of technological upgrades have been introduced to the main public transport fleet by 2006. The Vaporetto fleet was fitted with GPS, enhancing route and speed compliance monitoring. The SALOMON system was also introduced as on-board tech for precise location tracking and speed regulation via instant alerts. Finally, the ARGOS system was also launched by 2006, utilizing cameras and vision tech for comprehensive Grand Canal monitoring, aided by SALOMON and GPS data for precise positioning. ARGOS's multi-camera survey cells enable detailed tracking of boat movements, assisting Venice's authorities in managing traffic and enforcing regulations.

Despite all of this, a tragic event on August 17, 2013, when a gondola carrying a German family collided with a reversing vaporetto, resulted in the death of the 50-year-old German father, a law professor. This event prompted calls for even stricter traffic and speed regulations. In addition, after gaining international attention, the incident had the mayor of Venice introduce 26 new safety measures aimed at preventing such accidents within the city's waterways. Among the new regulations were bans on using mobile phones while operating any vessel and the removal of unauthorized docking points to ease boat navigation.

In the following chapter, we will explore how the challenges identified in Venice—ranging from safety and transportation inefficiencies to pollution and service reliability issues—can be proactively addressed in the development of Copenhagen's new artificial island, Lynetteholm. We will introduce a "Demand Responsive Transport" (DRT) waterborne solution equipped with "Autonomous Navigation Systems" (ANS), designed to ensure safer, more efficient, and reliable operations around the clock for Lynetteholm.

Chapter 4

Introduction to Literature Review

In this chapter, we show the results of the literature review. This review aims to answer the following research questions:

Main Question: What value does an ADRT service offer when deployed in integrating urban expansion-borne neighborhoods like in the case study of Lynetteholm and Copenhagen?

Q2. In the context of urban expansion, what challenges and benefits does Ferry Oriented Development present?

Q3.What can we learn from the challenges and benefits of waterborne transport-connected cities like Venice and Amsterdam?

Q4. What are the latest transportation technologies that can facilitate the connection of waterfronts in cities?

Q5. What would be the characteristics of an integrated ADRT system as a viable transport service for Lynetteholm to be connected to the adjacent Copenhagen areas?

4.1 Literature review methodology

After having introduced the case study of Copenhagen and Lynetteholm, the example cases of Amsterdam and Venice as well, and the challenge at the base of the waterborne mobility solution that we will propose to the Municipality, we will, in the following chapter provide the reader with a literature review on city-agnostic notions and concepts that will be at the basis of the theoretical and technological core of the solution proposed.

The methodology for this survey involved thematic analysis, covering themes such as
the increasing interest of modern, compact cities in MaaS to meet the digital and mobility demands of their citizens, and a detailed examination of ANS and DRT within the MaaS context. By investigating the current real-world applications of these technologies, the study aims to devise an efficient, evidence-based transport solution for Lynetteholm, thereby addressing the identified research gap. The identified gap entails the absence of studies explicitly addressing the potential demand for DRT services within a Mobility as a Service (MaaS) framework, especially when combined with ANS in public waterborne transportation systems. Currently, no MaaS schemes comprehensively incorporate DRT systems. Through an exploration of relevant case studies, we will outline the benefits and limitations of these technologies, which will be instrumental in formulating a pragmatic transportation solution for Lynetteholm, aiming to contribute to the dialogue with evidence-based recommendations for integrating these technologies into urban infrastructures.

Focusing on peer-reviewed research articles published in English, this search was carried out through Google Scholar, which provides access to a range of databases such as ScienceDirect, Scopus, Web of Science, Wiley Online Library, and the Directory of Open Access Journals (DOAJ). To ensure a comprehensive literature review, we also included edited or authored books, articles available in other languages (with English translations), grey literature like government or industry reports, non-academic research, and editorial papers. The search strategy was tailored to cover the various themes mentioned above utilizing targeted keywords and Boolean operators to refine the results. In the appendix of this thesis, the reader can find a table with the keywords, Boolean operators, aim of research and which questions will be answered by each chapter of the literature review.

4.2 Ferry Oriented Development

Given the waterborne nature of the location where Lynetteholm's construction has been envisioned, and the development needs of said area, this thesis aims at exploring what type of benefits could waterborne transportation, and relative ferry oriented development (FOD), bring to the areas hosting such services. Research by Leung et al. (2017) published in the Island Studies Journal identifies key factors contributing to the success of ferry-connected cities, and especially urban islands, and explores the potential impacts of enhancing ferry access in waterfront areas. This section of the literature review will be exploring such concepts and their benefits.

FOD is considered to be a strategic approach to urban planning which leverages the untapped potential of waterways through the development of ferry terminals (Leung, 2017). To strengthen the proposition of our DRT and waterborne mobility solution for Lynetteholm, the explanation of FOD seems appropriate.

(Urban) Island studies is an expanding research area that views islands as unique urban development cases, defined as land surrounded by water (Eichhorn, 2016). Initially, maritime advancements connected these lands through water transport, with ferries being favored for their minimal infrastructure needs. However, as water transport became less efficient, cities started linking islands through permanent fixtures like bridges or by extending land through reclamation.

Despite the emergence of fixed links, ferry systems have continued to develop and integrate with these structures in cities like London, New York, Brisbane, and Sydney. These ferry systems have managed to complement fixed link transportation, contributing to the revitalization of waterfront spaces (Fox, 2016; Tanko & Burke, 2016; Weisbrod & Lawson, 2003). This integration has led to the rise of Ferry-Oriented Development (FOD) (Sipe & Burke, 2011), drawing from the concept of Transit-Oriented Development (TOD) (Cervero, 2004), which has influenced Copenhagen's urban planning since the implementation of the Five Finger Plan in 1947. This plan, aligned with railway lines, has facilitated accessible transit to Copenhagen's central business district, guiding urban growth along these transport corridors.

Ferries are uniquely attractive compared to other forms of transit due to the innate human fascination with water, making waterborne transport often more favored, when multiple transport options are available (Kamen & Barry, 2011; Soumoy & Sweeny, 2000; Tanko & Burke, 2016). Strategically placing residential or commercial areas close to ferry docks effectively increases the number of ferry users, and vice versa. Urban waterfront projects are increasingly integrated with new ferry services and developers might fund ferry terminal infrastructure to secure a ferry stop near their projects. Conversely, the value added to properties by proximity to ferry services has been proven in cities like New York and Brisbane, with research showing a property value increase of about 4%-8% if within 400 meters of a ferry terminal.

Learning from other waterfront cities shows that successful public transport hinges on seamless intermodal connections, creating a network that minimizes time and costs for users (Curtis & Scheurer, 2010; Dodson et al., 2011). In contrast, Hong Kong's ferry services have seen limited growth, largely due to the unappealing waterfront uses and the scarce transfer options at ferry terminals. Similarly, Bangkok has largely excluded ferry services from its integrated transport planning. Attempts at new ferry services like Shanghai's 'River Bus' (Lan, 2016) and Taipei's 'Blue Highway' (Hsiao et al., 2015) have also struggled, partly because they weren't incorporated into broader land use and fare integration strategies.

Such failures teach us that successful ferry services depend on proximity to piers, availability of connecting transport modes, integration with municipal transport planning, and strategic placement of terminals in key commercial and residential areas (Wong, 1998).

On the other hand, there are arguments against FOD that we aim to address while designing the DRT service for Lynetteholm. Island populations may be restricted by transportation challenges, such as limited availability of stops, canceled routes for breakdowns and necessary maintenance or bad weather conditions (Knowles, 1996). Therefore, the lack of transport service implies the risk of isolation, which lead to scarcities in essential goods like food, pushing up the cost of living for island dwellers (Calderwood & Freathy, 2011). These issues are often cited to support the construction of fixed connections such as bridges or the use of land reclamation for roads or railways, which usually necessitate a specific population size or development stage to offset the investment (Grydehøj, 2015). The development of the fixed connections when supporting car traffic, though, will exacerbate the use of cars, therefore, we propose to discard this option as a sustainable connection for Copenhagen and Lynetteholm.

4.3 MaaS and its integration into Public Transportation

The advent of digitalization has facilitated the emergence of new mobility solutions, such as Mobility-as-a-Services (MaaS). MaaS, currently in pilot stages globally, promise to address the challenges of urban congestion, pollution, and parking scarcity, offering more sustainable transit options. These initiatives aim to enhance urban mobility, making travel within densely populated areas more convenient and efficient. MaaS comprises two main elements: shared transportation services, encompassing various modes of transport, and integrated functionalities for finding, booking, and paying for services.

Some examples of MaaS platforms that exhibit these functionalities are:
The 9292 App in the Netherlands, facilitates comprehensive travel planning across various modes of public transport in the Netherlands, including trains, buses, trams, metros, and ferries, as well as options for bicycles, e-bikes, scooters, and rental bikes. It offers real-time updates and alternative suggestions in case of disruptions, alongside the convenience of purchasing e-tickets directly through the app for a seamless journey across multiple transport service providers. The app also integrates personal preferences like walking, cycling, or scooter use at trip endpoints, providing tailored travel advice and information on bicycle rental locations.

The Whim app, in Finland's capital, is also working on a shift in urban mobility with its ambition to render private car ownership redundant by 2025. It integrates various transportation modes, such as trains, taxis, buses, carshares, and bikeshares, into a single platform, offering Helsinki residents a single solution for journey planning and payment. Through Whim, users have the flexibility to select their preferred transportation method or combine multiple modes for seamless door-to-door travel, with payment options including a monthly subscription or pay-as-you-go.

Similarly, in Copenhagen, the DOT Ticketing App enables users to buy travel tickets and passes within Zealand, Lolland, Falster, and Møn, offering real-time tracking for trains, buses, and metros. However, it lacks integration with on-demand transport services, highlighting an opportunity for expansion in this area.

As seen in the Helsinki example, the integration of such functionalities into one single platform allows for interoperability, door-to-door travel estimation and ride convenience, and inclusion of multiple transportation modes and services for the user to understand which is the best option available for them in real time. Transitioning from unimodal travel information systems to integrated multimodal information and booking services represents an important shift to viewing mobility as a commodity, which means that it becomes a basic need that can be easily bought, or rented, and easily exchanged or given back to the next user.

Another crucial factor characterizing MaaS is the sharing of data. Governments require insights to effectively manage the use of public services. Collaborations between the public and private sectors are pivotal in achieving societal objectives and providing an attractive alternative to private car ownership and use. Enabled by advancements in mobile internet connectivity and smartphone technology, MaaS embodies nine core characteristics outlined by Jittrapirom et al. (2017), including multiple tariff options, and demand-oriented services. The overarching vision of MaaS is to envision the entire transport sector as a cooperative, interconnected ecosystem, catering to the diverse needs of customers (Hietanen, 2014).

Urbanization and digitalization trends are reshaping how people access goods, services, and opportunities in society (Lyons et al., 2017). Changes in travel patterns and demand, as highlighted by the Commission on Travel Demand in the UK (Marsden et al., 2018), are evident. More specifically, city center traffic has declined in the UK, with cities like Manchester and Bristol cited as examples, while motorway traffic, outside and in between cities, has increased. Shopping trips have decreased by 30% over the past decade, coinciding with the rise of online shopping. Cycling rates are on the rise, while per-person car travel distances have decreased across England. Young people are delaying learning to drive and making fewer car trips, as noted by Chatterjee (2020), who found significant decline in the number of 17–20 year-olds holding a full driving license in the UK, from 48% in 1992 and 1994 to 29% in 2014, attributing this trend to factors like income uncertainty and income ranges.

Despite the excitement surrounding Mobility-as-a-Service (MaaS) its impact is yet to be fully realized. Pangbourne et al. (2018) argue that the prevailing discourse on MaaS is overly optimistic and technologically deterministic. While MaaS is gaining visibility, especially in the transport sector, it has not yet sparked a mobility revolution. Only a limited number of pilot projects and schemes have been implemented, with few experiencing full-scale adoption and realizing the anticipated public benefits (Smith et al., 2018). Jittrapirom et al. (2017) provide a comprehensive overview of global MaaS examples, identifying 12 schemes that embody the key features of MaaS, with most emerging after 2014. However, MaaS remains a niche development, as emphasized by transition theory (Geels, 2012). While niche developments can signal the beginning of a fundamental transition, the entrenched nature of existing transport regimes may hinder their widespread adoption (Köhler, et al., 2019). Achieving regime change necessitates disrupting the status quo through governance, regulatory, and procurement reforms on the supply side, as well as changes in individual and organizational preferences and behaviors on the demand side.

However, such disruption should not compromise efforts to promote active travel, public transport usage, and the reduction of private car reliance, as raised by authorities such as Transport for London and the UK Department for Transport. Similarly, Pangbourne et al. (2020) argue that portraying MaaS as unrestricted freedom for individual consumers conflicts with the challenge of meeting simultaneous demands within a finite transport network. Such challenge to meet demands within a finite transport network though is a recurrent challenge for cities as they expand and Hensher et al. (2020) highlights the the benefits of MaaS comprise the tailoring aspect to individual user needs, which could help current public transport infrastructure if vehicle utilization and occupancy levels are not optimized.

To conclude, MaaS is widely seen as an optimistic integration into the traditional public transportation services, where digitisation could help with the optimisation of travel booking from the user perspective. From the governmental perspective, it may result in heavy investments and R&D pilots, which ultimately may result in optimized service. Cities such as Copenhagen, where public transportation services are already unified under one scheduling, booking and purchasing system, could be the perfect piloting ground for more technological MaaS solutions, such as ANS and DRT, further discussed in the next chapter.

4.4 DRT & ANS

4.4.1 Demand Responsive Transport

This thesis will base the design of an autonomous demand-responsive ferry service for Lynetteholm on a high-level conceptual framework developed by the Transit Analytics Lab (TAL) of the University of Toronto (Figure 12) (Klumpenhouwer, et al., 2020). On-demand transit will be addressed as Demand Responsive Transport (DRT) in this thesis. DRT is known as flexible on-demand transport, representing an innovative alternative, or support, to traditional public transportation, functioning akin to an Uber for public transit. This paragraph will delineate the specific differences (and commonalities) between the different types of transit services used in cities. As seen in Figure 12, the TAL model delineates four tiers of transportation solutions: Ride Hailing, Ride Sharing, On-demand Transit, Fixed Route Transit. Each is defined by specific parameters: Stop Service, Route Planning, Journey Durations, Connectivity, and Sharing Extent (Klumpenhouwer, et al., 2020).

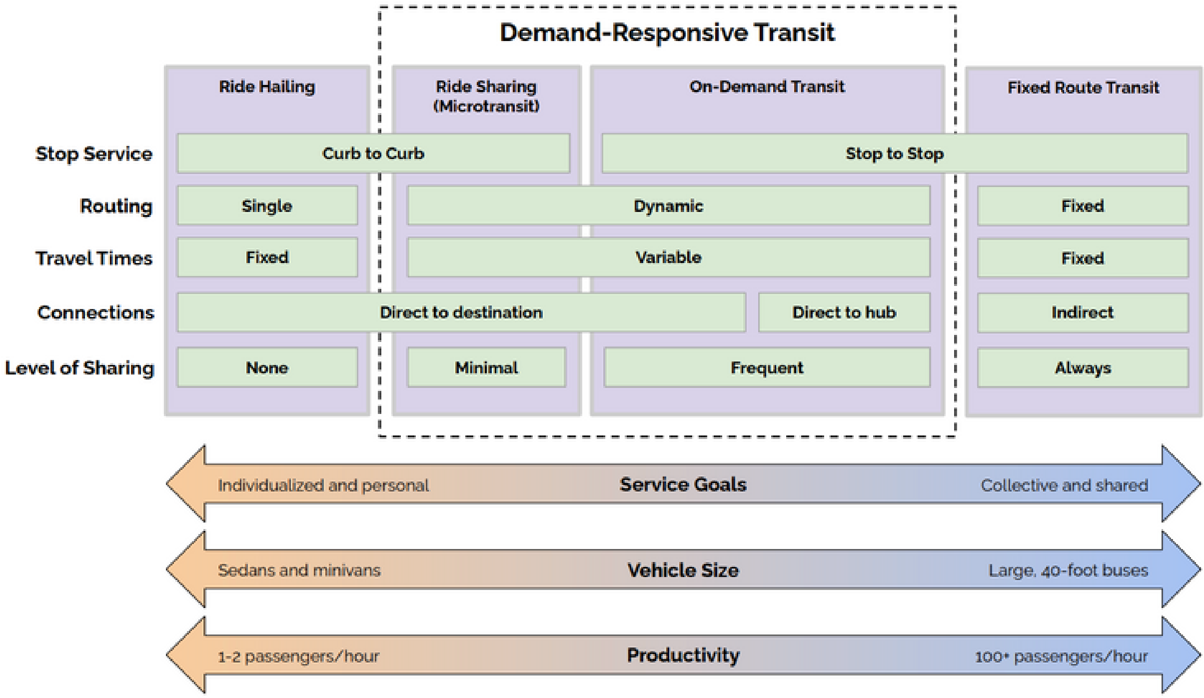


Figure 12. High level conceptual framework of transit and ride hailing services. Credit: University of Toronto, Transit Analytics Lab (TAL).

For clarity, when talking about fixed-route transport systems, we include buses, vans, and light rail, and ferries that follow specific paths and schedules in cities, having set timetables and stops where passengers get on and off. According to TAL, the core differences between micro transit (e.g. Uber provides ride hailing services) and macro and mass transit (e.g. public transport) are the Stop Service and the Level of Sharing parameters, which, as seen in Figure … represent the two biggest net divides. While still offering the flexibility for passengers to board on the spot and rely on onboard payment systems through a stop-to-stop pick up/drop off approach, DRT mainly facilitates and employs on-demand rides technology common to microtransit and ride-hailing services, which instead use the curb-to-curb pick up/drop off approach. DRT's primary benefit is, therefore, its frequent sharing of vehicles, surpassing the sharing frequency found in micro-mobility, thereby enhancing operational efficiency and fostering a more communal service through the use of larger, collectively used vehicles. This also represents a nuanced distinction from public transit, with DRT prioritizing regular vehicle sharing, while fixed-route systems aim to achieve full vehicle occupancy.

According to TAL, reasons for DRT adoption by local transit agencies are challenges with low ridership in specific areas or fixed routes, and therefore a need for insights into the economic viability of existing and new routes, or an overall need for operations optimization. DRT also responds to the public transport sector's challenges in innovation due to lengthy procurement processes, infrequent contract renewals, and limited budgets. Thus, such agencies are increasingly recognizing the need for experimentation and integration of DRT solutions by supplementing, complementing, or ultimately replacing current services and routes with these.

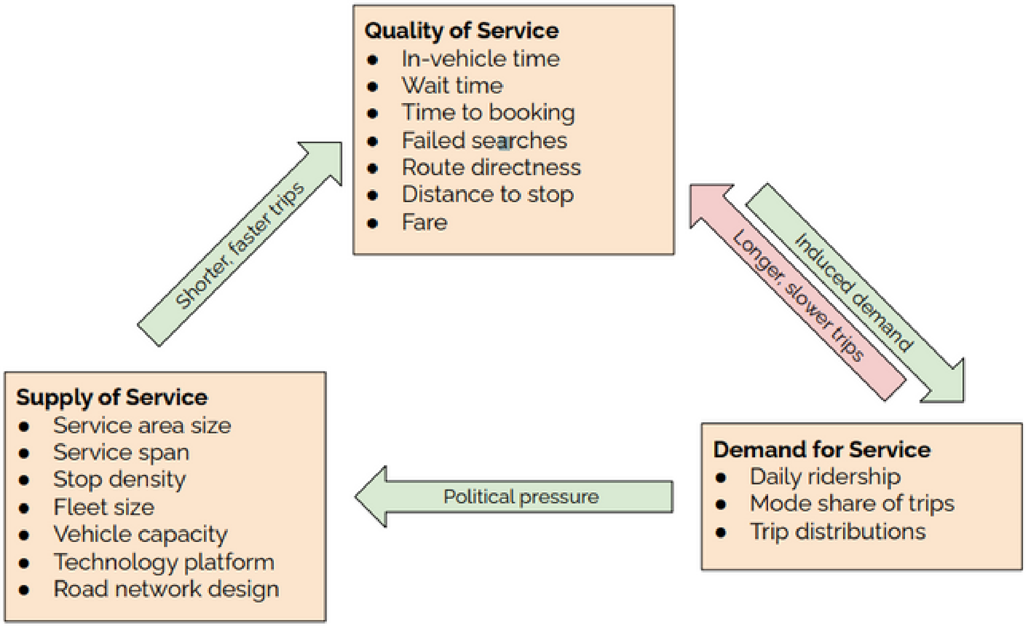


Figure 13. List of demand, supply and quality of service variables kept in consideration for transport solutions. Credits: Klumpenhouwer, et al., 2020.

DRT services are also highly sensitive to three main elements (demand, supply and quality of service) for them to be viable. Demand is shaped by sociodemographic elements, urban design, physical accessibility, and the daily activities and trips performed by the users. Supply, on the other hand, covers operator-controlled factors such as service area size, fleet size, stops density, vehicle capacity, which technology platform users are interfacing with and how seamlessly. Finally, quality of service includes travel and wait times, ease of booking trips, route design, fares and stop proximity. Quality of service is important from the user perspective, especially if DRT is implemented within an urban setting in the fashion of a short-term pilot, and it is assessed based on factors like reliability, responsiveness, and customer care. While traditional transit can handle slight demand surges without quality loss, DRT may find it challenging to keep up with quick demand spikes. A solution is to set a target service quality and adjust service supply accordingly.

As mentioned above, when it comes to deploying DRT, public transport agencies look at supporting their operations through three different support frameworks (Figure 14):

Figure 14. Three implementation frameworks in which DRT can support fixed route services. Credits: Klumpenhouwer, et al., 2020.

A supplementary system introduces a transportation service to previously unserved areas, linking them to existing fixed-route networks through transfer points where passengers can switch from DRT to conventional public transport. This approach is often adopted in newly developed areas such as neighborhoods, wards, or rural regions needing expanded services, marking their initial introduction to transport services. Additionally, it can be applied in areas with established daytime transport services that lack night-time coverage, leading to the introduction of DRT to meet off-hours demand. Implementing DRT in these new or underserved times and places allows operators to better understand unique ridership patterns, facilitating more informed service planning.

In a complementary system, a Demand Responsive Transit (DRT) service substitutes one or several underperforming routes, supplementing higher-demand fixed routes to prevent them from becoming overwhelmed. In this setup, the DRT operates in areas that both border, intersect and overlap with existing fixed routes, providing a supportive and integrated service solution.

When a DRT replaces a fixed-route with its own primary service area, all fixed route stops are accessible via DRT, which is particularly useful at night or on weekends when travel patterns are unpredictable and fixed-route services might not be as efficient. This approach helps at moments and locations where the fixed-route efficiency is low, offering insights into travel demand for future planning purposes. By observing which DRT stops are most used, cities can adapt and establish permanent routes based on actual usage, avoiding unnecessary investment based on speculative data. This method reduces the guesswork in transport planning, relying on actual rider behavior data to guide investment decisions.

On an even higher implementation level, when examining the context of socio-technological transitions within the multi-level perspective framework (MLP), research places DRT as niche representing a novel (flexible) mobility service, in a landscape that encompasses the evolving perception and demand for flexible service provisions (Meurs et al., 2020). Advancements in the IT and wireless network sectors have created a niche for demand-based public services utilizing interactive platforms, often facilitated through smartphone applications. This responds to the significant rise in smartphone-centric lifestyles, where applications cater to various needs. A regime with the MLP and DRT contexts refers to the regulatory framework governing (public) transportation, which is undergoing changes such as alterations in public service contracts or concessions through tendering procedures. The socio-political landscape of a city where DRT is ideally applicable is characterized by socio-demographic shifts such flexible lifestyles, evolving attitudes towards car ownership detachment, with DRT contributing to increasing such digitalization and integration trends, facilitating the advancement of MaaS and intermodal transport shift.
However, despite the widespread interest and implementation of DRT services globally, their success has been limited, with 70% of services ceasing operations within three years (Currie and Fournier, 2020). It is essential to recognize that among these discontinued services, some were initially introduced as predefined fixed-duration pilots, often due to budget constraints. Additionally, DRT service operations are typically expected to be self-sustaining, as they are often provided by private companies permitted by local governments to conduct pilots, which can pose public or political challenges (Klumpenhouwer, et al., 2020), such as high prices, or lack of full and equal integration across the public transport network.

High DRT fares compared to regular public transport were a significant factor in some DRT system failures, as Enoch et al. (2004) noted. Currie and Fournier (2020) also discussed the closure of Bridj and Chariot in the U.S., suggesting their perceived success was more due to media hype rather than actual performance, with high costs not widely reported as a cause of failure. Despite these setbacks, the launch of pilot DRT projects in over 900 cities in recent years indicates a potential for DRT to fill the gap between efficient public transit and the convenience of personal transport.

Lessons gleaned from the Viavan DRT pilot study in Helsinki, conducted between 2019 and 2020, underscore the importance of integration within the MaaS platform for ordering and payment. This integration is vital for complementing existing mobility ecosystems and familiarizing users with alternative modal shift options. Ensuring high-quality training and service is equally important, as it takes time for individuals to adjust to new habits and reconsider rooted behaviors such as car usage. Therefore, the duration of such pilot initiatives is significant in allowing sufficient time for user adaptation, and it should be reassessed, in conjunction with exploring potential subsidy models, similar to those for conventional scheduled public transportation services. This is why adopting DRT in a complementary fashion will bring benefits to the case of Lynetteholm if paired to a transportation solution on water promoting the already strong cycling habits of the residents, and the decarbonisation goals of the city of Copenhagen.

4.4.2 Autonomous Navigation System and their Applications

On this note, transportation contributes significantly to greenhouse gas emissions, accounting for 25% to 33% on average of the total output of a city. Smart urban mobility, which involves the use of sustainable vehicle technologies and intelligent transport systems linked via cloud computing and big data networks, is emerging as a crucial aspect of modern urban policies aimed at mitigating the negative impacts of transportation. In simpler terms, smart urban mobility combines urban traffic services with advanced technologies. One of the most sophisticated examples of this is the autonomous vehicle (AV), also known as a self-driving car, operated by autonomous navigation systems (ANS).The idea behind AVs is to automate driving tasks using automation, electronic and mechanical systems, reducing or eliminating the need for human drivers. ANS, on the other hand, represents an integration of sensors and computational algorithms. This system presents a series of functionalities for the autonomous operation of these vehicles in diverse navigation environments. Central to its operation is the ability for autonomous perception, which involves the real-time analysis of environmental data to identify navigable pathways and potential obstacles. Path-planning algorithms within the ANS enable the vehicle to compute the most efficient and safe routes, taking into consideration the dynamic nature of roads, waterways and airways. ANS are rigorously tested under various conditions, to execute tasks such as route adherence, obstacle avoidance, and maintaining formation with leader/follower dynamics during both diurnal and nocturnal operations.
The concept of automated navigation dates back to the early 20th century, focusing initially on basic functions like speed and lane control. However, the past decade has seen a surge in technological progress, driven by the Digital and 4th Industrial Revolutions (Bloem et al., 2014).

The initial idea of a self-driving vehicle was showcased by General Motors back in 1939. Between 1964 and 2003, the United States, Europe, and Japan saw numerous research and development programs, propelled by collaborations between government bodies and academic institutions (Kasap, 2022). These efforts focused on creating automated convoys of buses and trucks, highly advanced vehicle systems, and technologies for recognizing driving scenes through video processing. In 2004, the pace of autonomous vehicle (AV) research quickened significantly with the introduction of the Defense Advanced Research Projects Agency's (DARPA) Grand Challenges in the US (Helldin, 2014). These challenges led to the development of AVs capable of navigating desert terrains in 2005 and urban settings in 2007, through DARPA's Urban Challenge. Since then, research and development have rapidly progressed in both university labs and the corporate world. For example, Volvo embarked on its autonomous driving project in 2006, showcased a fully autonomous test vehicle in 2017, and aims to release a completely independent AV by 2021. Google ventured into the realm of AVs in 2009, and by 2017, its AV fleet, known as WAYMO, had logged three million miles in four US states. In 2014, TESLA announced its vehicles would achieve near-full autonomy, and currently, all TESLA models come with self-driving features (Pires, 2019). By 2020, automotive giants like Audi, BMW, Mercedes-Benz, and Nissan anticipated launching their own AVs.

A 2017 Bloomberg report examined how cities worldwide are gearing up for the shift towards AVs. The report identified 36 cities engaged in AV testing or planning to do so, while another 18 cities were exploring the regulatory, planning, and governance aspects of AV integration without initiating pilot projects (Aoyama, 2021). The testing primarily occurs in controlled environments such as tech parks, college campuses, urban redevelopment areas, highways, and sites of former international events, rather than in complex cityscapes. This indicates that, despite the ongoing trials, the challenges of navigating AVs through intricate urban environments remain largely unaddressed. Reasons for this slow adoption of the technology is that ANS can be integrated according to different levels of autonomy, and AV usually convey the idea that the vehicle is unmanned and such idea can be scary and not socially accepted.

What also doesn't help with the most seamless integration of AVs into our daily lives is the wide pool of different transportation modes and their specific regulations, taxonomy and classifications for autonomy levels (Vagia, 2019). For example, aviation, automotive, rail, and maritime and inland sailing. Each mode has its own, unstandardised, rules.
Levels of autonomy often look at the division of navigation responsibility between human and the automations system. Among the numerous classifications available, the most widely accepted taxonomy for autonomous systems is based on five levels of autonomy:

Level 0: No automation involved.
Level 1: The system can manage movement authority and a desired speed profile. It can also identify risks not related to the railway, like side winds, and these risk assessments are relayed to the driver.
Level 2: The operational system integrates with onboard and Automatic Train Protection (ATP) or supervisor systems. Speed adjustments suggested by external risk detection systems are communicated to the Automatic Train Operation (ATO) system.
Level 3: The driver's role shifts to that of an onboard monitor, intervening only when necessary.
Level 4: The train operates autonomously, without any onboard personnel required.

For the purpose of this research and the smart mobility solution that is sought to be proposed to the city of Copenhagen, we will now focus on ANS for navigation in inland waterways and urban environments. Accordingly, we will adopt the Central Commission for the Navigation on the Rhine proposed definition of autonomy, which is similar to the one proposed for cars:

CCNR's suggested levels of autonomy:
Level 0: No automation, for example, navigating using radar assistance.
Level 1: Assistance with steering, such as a turn rate controller or a track-pilot system.
Level 2: Semi-automation, with some aspects of steering and propulsion automated. The boat-master has other tasks.
Level 3: Conditional automation, where automation supports all navigation tasks, including avoiding collisions. The boat-master steps in as needed.
Level 4: Advanced automation, with complete automation and backup handling for all scenarios within specific conditions, like navigating through locks. The boat-master deals with other situations.
Level 5: Complete automation, with no human needed for boat operation.

Inland passenger vessels' operations, while they can be compared to the one of trucks, which ride in allocated and reserved lanes, also have less issues with unpredictable events and they carry passengers. Carrying passengers, according to current regulation landscapes, demands for keeping a human operator to rely on in the system. This is because transporting passengers necessitates having trained staff on board to manage emergencies and potential evacuations. Ensuring passengers can board and disembark safely also presents a challenge. On the subject of safety, the way humans interact with automated systems varies significantly across different modes of transportation. Vessels, for example, travel at slower speeds and navigate in more regulated environments than cars, which face unpredictable traffic and sudden human presence. This slower pace gives the operator more time to assess their surroundings and respond when necessary, which makes it easier to design autonomous navigation interfaces with which they can interact.

Another important point to consider when studying inland ANS, is the environment they operate in. Looking at Lynetteholm and the morphology of the area where it will be constructed, the environment where the proposed autonomous vessel will navigate can be compared to contained and protected environments such as inland rivers, harbors and ports, urban canals, etc. where the complexity of operations, environmental factors, and occurrence of unexpected objects are relatively low.

Lastly, different AV may receive varying levels of societal acceptance, which depends on factors like the potential for causing harm, perceived usefulness, the risk to bystanders, and public familiarity. For example, the risk associated with autonomous cars is seen as higher due to their prevalence and potential for systematic errors. In contrast, large ships, though capable of significant damage, are considered medium risk because they are fewer and operate in less crowded spaces. Vehicles perceived as highly useful or those posing risks primarily to professionals in controlled environments may face less scrutiny. Familiarity also plays a role, with vehicles well-known to the public, like cars, which might face reduced acceptance in the event of accidents or hazardous situations, as many people might perceive a greater personal risk.

The combination of the two can be possible, however socio-demographics and the perception of the users is still crucial, as this constitutes of the three main cores for the viability of the service, which is demand. A study done by Golbabaei et al. in 2023 on ANS and DRT in South East Queensland, Australia, indeed investigated how socio-demographic factors influence attitudes towards Autonomous Demand Responsive Transit (ADRT) as a complement to traditional public transport. Findings indicate the main benefit of autonomous shuttle buses (ASBs) is seen as reducing congestion and emissions, with the main concern being technology reliability. In the study, full-time male workers were more familiar with autonomous vehicles, while women and those from lower-income households were less likely to have used one. Younger individuals, those with higher incomes, and those without a driver's license viewed ASBs more positively, but men and full-time workers without a license worried more about traffic accidents. Those with less education and living in peri-urban areas were more concerned about fares.

To encourage ADRT adoption, it's crucial for policymakers to enhance positive perceptions and address concerns. Ensuring reliable and convenient ADRT services is key to overcoming user hesitations. Features like information screens and easy access can help mitigate the lack of a driver. Deploying ADRT in controlled environments rather than regular urban traffic, such as dedicated lanes or areas lacking public transit, may be more acceptable.
Nevertheless, in the context of Lynetteholm, which is set to be built by the year 2070, the regulation landscape may change and technologies such as ANS or ADRT will be more widely adopted. Therefore, in the methodology section, the recurrent assumption will be that, within the context of socio-technological transitions, these niche technologies would have established themselves in markets, with mainstream users cases demonstrating the technical, social and economical viability of the technology, and the relevant infrastructure been developed and standardized across transportation networks of cities and waterways.

For the purpose of this thesis, to develop a DRT service that incorporates ANS, it's necessary to merge theoretical concepts with practical applications. Thus, for this study, we will use Roboat, a Dutch startup specializing in ANS for inland vessels, as a commercial case study to base the ADRT service on.

4.4.3 Roboat, example of a company providing ANS to the waterborne transport market

The growing needs in environmental monitoring, search and rescue operations, hydrological studies, and national defense have sparked significant interest from the commercial, scientific, and defense sectors in the development of advanced unmanned surface vehicles (USVs) (Mohsan et al., 2023). Furthermore, USVs hold potential for reshaping urban transportation in densely populated coastal and riverside cities like Amsterdam and Venice, where the current road and bridge network is under considerable strain. Traditionally, in cities with extensive networks of canals and rivers, boats were the primary means of transporting goods and people. However, over the past few decades, this mode of transportation has largely been replaced by trucks, vans, and cars, leading to environmental degradation and reduced quality of life in these urban areas. Introducing a fleet of autonomous boats could alleviate this pressure by transferring the movement of goods and people to waterways, thereby encouraging less car usage and easing urban traffic congestion. A 5-year collaboration with the Massachusetts Institute of Technology (MIT), researchers from Delft University of Technology (TU Delft) and Wageningen University, and the Amsterdam Institute for Advanced Metropolitan Solutions, resulted in Roboat spinning off becoming a company based in Amsterdam aimed at advancing autonomous technology in urban water settings.

Among the many use cases explored, at the moment of spin off, the focus shifted toward autonomous water taxis, or buses, as a proposition to the city of Amsterdam to alleviate congestion on roads and provide locals and tourists with flexible and on-demand waterborne transportation. However, navigating autonomous boats through Amsterdam's highly trafficked canals presents numerous challenges such as sensing the environment, planning movements, avoiding obstacles, plotting predictive paths, and coordinating with other vessels. Therefore, Roboat is equipped with a variety of sensors (including LiDAR, an Inertial Measurement Unit (IMU), and an RGB camera), along with a WiFi router and adapter, battery, computer, microcontrollers, and runs on Robotics Operating System (ROS) middleware (Wang, 2019). The integration of LiDAR and camera technologies allows Roboat to measure distances to objects and identify them, facilitating obstacle avoidance during navigation (Leslie, 2022). This sensory data is crucial for Roboat's navigation system, enabling it to chart a collision-free course in real-time. This is achieved through a Non-linear Model Predictive Controller (NMPC), which takes into account the boat's intended path, its dynamics, and the forces exerted by its thrusters (Johnsen, 2019).

To conclude, in line with Copenhagen's smart city character, technologies like Roboat, not only can deliver self-sailing capabilities, but their sensors also allow them to serve as dynamic environmental monitoring tools. Such sensors can gather data on various environmental factors, including water and air quality, as well as weather conditions, while moving around the city (Johnsen, 2019). This smart mobility solution offers the advantage of collecting detailed environmental data across different locations, while performing its transportation tasks, unlike fixed monitoring stations. The insights gained from Roboat can help city officials make informed decisions regarding environmental and public health matters. In the context of Lynetteholm, after the highly intensive construction works that will happen to make the artificial island possible by 2070, it would be wise to put in place environmental quality monitoring tools.

4.5 Discussion of the case studies and literature review

In this paragraph, we will discuss the meaning and relevance of the case study studies analyzed through the literature review and what learnings they bring for the next section of the thesis, the design of the waterborne mobility solution for Lynetteholm. Through the use of technology and flexible waterborne mobility strategies, cities like Venice and Amsterdam have been able to serve their high-density cities and busy river crossings in an efficient way, setting the example for new urban development projects such as Lynetteholm.

In the case of Amsterdam, many transportation options have been assessed by city authorities, studies, reports, and discourse, however the busy nature of the River Ij and the highly populated city of Amsterdam impede the commitment of the construction of a fixed infrastructure solution like a tunnel or a fixed bridge over the river. The reason is that such actions would disrupt the highly profitable and already delicate ecosystem of the River and Port activities and logistics in Amsterdam, which could signify costly losses to Amstedam's economic activities. Another learning that can be drawn from the case of Amstedam is that it abides by the urban containment form, just as Copenhagen, for what concerns transport oriented development. That means that local planners look to design urban areas and expand the city in relation to immediate transport hubs or stations to allow residents movement seamlessly, which in the case of Lynetteholm is a good opportunity, because, as mentioned before, it will be a brand new neighborhood, therefore and urban planning strategies have plenty time and space to be steered towards accommodating flexible transport for the area. Finally, it resulted that often, the interests of developers are placed ahead of strategic efforts to structure cities and regions in a more environmentally sustainable manner. This situation currently limits the extent to which cities can promote TOD and, ultimately FOD in practice. However, studies have also shown that waterfront cities, if they include FOD in their transportation development planning, with relative ferry stations in residential and commercial areas, are more likely to see property value go up 4 - 8% if within 400 meters of a ferry terminal a few years from the implementation of the transportation service, which is a positive incentive for the adoption of FOD, alongside reduced infrastructure investment costs and its higher flexibility.

When taking the Venice example, on the other hand, we understand that leveraging technology and data collection to optimize current services and foresee the transportation demand and patterns of citizens is important to be able to accommodate densely populated cities to cope with the high amounts of travelers. This is because the waterborne transport system of Venice is one of the oldest and most established in the world, since the city has never had a different transport modality but by water, however, it now important for the city to innovate due to the high influx of tourists and the toll that high traffic is placing on the safety of the travelers, the infrastructure condition of the canal walls and the pollution levels of the water.

An important takeaway from the literature review on FOS, is that waterfront cities that successfully manage to integrate the ferry systems through intermodal connection, increase the attractiveness of they waterfronts, increase the property value of their commercial and residential areas, and most importantly manager to minimize travel time and costs for users. Integration into the existing network of the public transit should happen through digitisation and the availability of scheduling, paying for and tracking a service on MaaS platforms, to not exclude ferry transport from the rest of the available options of the user.

Another notion emerged from the review was that new technologies in the public mobility domain in cities are challenging to be adopted due to long procurement processes and short piloting periods. Trust in such technologies also must be established and this requires time. At the governmental level, it may result in not so low investments and high risks being taken. However, cities such as Copenhagen, where public transportation services are already unified under one scheduling, booking and purchasing system, could be the perfect piloting ground for more technological MaaS solutions, such as ANS and DRT, especially given the generous timeline available before the completion of the island.

.4.6 Literature Review Conclusions

The literature review conducted for this thesis has elucidated several critical factors influencing the successful implementation of Demand Responsive Transport (DRT) systems, particularly in emerging urban landscapes like Lynetteholm. These insights are foundational in constructing a nuanced perspective on the optimal integration of DRT within the urban mobility framework, aiming to elevate the overall transportation experience for city dwellers.

Central to the discourse on DRT systems is the principle of seamless integration with the broader public transport network. This synergy is vital for augmenting urban mobility and precluding potential competitive frictions between varying transport modalities. The proximity of DRT stops, including ferry piers, to residential and commercial hubs is a significant determinant of user convenience and system efficiency. Ensuring these stops are within a comfortable walking distance from key destinations not only encourages the use of DRT but also complements the city's sustainability goals by promoting pedestrian movement.

Drawing from seminal works by Curtis & Scheurer (2010) and Dodson et al. (2011), the literature review highlights the imperative for DRT systems to facilitate unhindered access across the transportation network. The design and operational strategies of DRT should empower users to traverse the cityscape with minimal temporal and financial expenditure, thus democratizing urban mobility. Such network effects amplify the utility of DRT, making it an attractive alternative to private vehicle ownership and a catalyst for sustainable urban living.

The literature posits that DRT's efficacy is markedly enhanced when it is integrally considered within the centralized municipal transport planning discourse. This inclusion ensures that DRT services are not peripheral solutions but are core components of the urban transport strategy, tailored to address specific mobility needs and complement existing infrastructure. Insights from Yeoman et al. (2007) inform the nuanced approach required to balance the economic impacts of tourism on urban transportation systems.

The literature suggests the potential for delineating resident-exclusive DRT routes on Lynetteholm, thereby mitigating tourist-induced congestion and preserving the quality of transit services for local inhabitants. The strategic positioning of DRT stops, particularly in relation to vibrant activity centers and prime residential locales, emerges as a pivotal theme in the literature. Ensuring a dense network of conveniently located stops enhances the service coverage and accessibility, making DRT a viable and preferred mode of transport for a broad user demographic.

Collectively, these factors underscore the multifaceted benefits of DRT systems in fostering a more connected, sustainable, and user-centric urban transportation ecosystem. Enhanced communication channels between riders and service providers facilitate real-time feedback and service adjustments, ensuring that DRT remains responsive to evolving community needs. The ability to adapt service parameters dynamically, in response to changing demand patterns or special events, introduces a level of operational flexibility previously unattainable with traditional fixed-route systems. Moreover, the engagement with rich rider data through targeted surveys and interactions paves the way for a more personalized and satisfying user experience.

In the broader context of urban expansion and waterfront development, these insights contribute to addressing the critical challenge of crafting viable transportation solutions that bridge newly developed areas with established city centers. The exploration of cutting-edge transportation technologies and the design of innovative waterborne solutions, informed by global best practices and localized challenges, hold the promise of reshaping Lynetteholm's mobility landscape. Through this academic inquiry, the thesis aims to not only elucidate the potential of DRT in enhancing urban connectivity but also to chart a course for future practical applications in the realm of smart urban transportation. Linking literature review insights to the objective of answering research questions has revealed many points that we will take into consideration when designing our ADRT service for Lynetteholm.

Chapter 5

Design of a ADRT services through an adaptation of the TAL framework on transit and ride hailing services

This thesis will base the design of the autonomous demand-responsive ferry (ADRT) service for Lynetteholm on a modified high-level conceptual framework developed by the Transit Analytics Lab (TAL) of the University of Toronto (Figure 14).

5.1 Towards a modified conceptual framework for ADRT service design

The adaptation will be led by the motif that the solutions will be pitched to the municipality of Copenhagen, and not to the end-user (i.e., residents, travelers). Therefore, the framework proposed by TAL will be taken as a basis for this thesis framework, adding an extra parameter and transport solution column that will help with the envisioning of how adding autonomy will impact operations.

The design of such ADRT service is particularly relevant in the context of rapid urban expansion and growth, aiming to contribute to the dialogue with evidence-based recommendations for integrating these technologies into urban infrastructures. A notable gap has been identified in existing literature on the absence of studies explicitly addressing the potential of DRT services within a Mobility as a Service (MaaS) framework, especially when combined with ANS in public waterborne transportation systems, and this thesis will attempt at filling this gap. To clarify, DRT is considered as part of the public transit offer, ride hailing is purely companies like Uber that ride with one booking-user (or a group) on, not sharing the ride with other users (not carpooling, which is ride sharing)

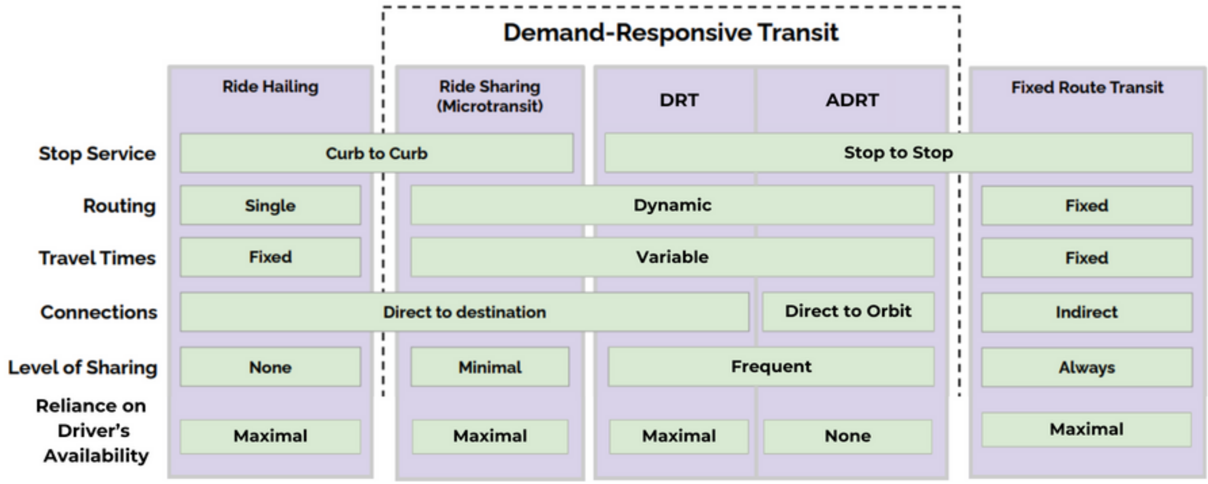


Figure 15. Modified conceptual framework for ADRT service design. Credit: University of Toronto, Transit Analytics Lab.

According to this framework, transit agencies may face challenges such as low ridership, a need for operations optimization, or insights into the economic viability of existing and new fixed route services. Therefore, such agencies are looking at supplementing, complementing, or replacing these current services and routes with technology that is able to provide such support.The TAL model delineates four tiers of transportation solutions (Ride Hailing, Ride Sharing, On-demand Transit, Fixed Route Transit), each defined by specific parametres: Stop Service, Route Planning, Journey Durations, Connectivity, and Sharing Extent.

In the adapted version of the Transit Analytics Lab (TAL) model, we introduce an Autonomous Demand Responsive Transport (ADRT) category, distinguishing it from traditional DRT primarily based on the reduced dependency on human operators. This innovation in the model underscores the pivotal role of ADRT in alleviating the operational challenges associated with driver availability during peak periods, holidays, night shifts, and times of slow recruitment. The essence of ADRT lies in its autonomous nature, eliminating the need for a conventional driver or captain. Instead, the system necessitates the presence of an individual trained for emergency response, negating the requirement for a sailing license. This shift is predicated on the autonomous system's certification, with an anticipation that by 2070, regulatory frameworks will have evolved to fully embrace and integrate such autonomous technologies within the urban mobility landscape.
A notable distinction to be addressed pertains to the 'connections' parameter within the ADRT framework, which transitions from direct-to-destination to direct-to-Orbit. The term 'Orbit' is employed to denote a service hub, which, in the context of this study, refers to a pier acting as a convergence point for various transportation modalities, including metro, bus, and train stations (just like in Figure 16) Moreover, this hub is situated within close proximity to essential services and facilities such as shopping centers, healthcare institutions, educational establishments, and libraries. Thus, an 'Orbit' embodies a central node where transportation, services, and employment opportunities are aggregated, facilitating efficient micro mobility and intermodality.

Figure 16. The orange circles highlight the major metro lines on the Langelinie side that act as intermodal connections (or "Orbits") for the Lynetteholm residents to shift to once they have gotten off the ADRT service. Otherwise, they can continue their journey cycling or walking.

For clarity, when talking about fixed-route transport systems, we include buses, vans, and light rail, and ferries that follow specific paths and schedules in cities, having set timetables and stops where passengers get on and off. Therefore, when the TAL framework is expanded to incorporate ADRT service, this extends onto the broader spectrum of transport services, indeed applicable to various vehicles including cars, boats, and buses. This innovation merges autonomy with the on-demand model, addressing urban transportation challenges such as driver shortages and the need for extended service hours, including nighttime and underserved areas. The framework's versatility allows for its application to both waterborne and road transit solutions.

For instance, considering the fixed-route transit solution within the context of Copenhagen's Harbour Bus, we observe the following characteristics: 1. Service operates on a stop-to-stop basis. 2. Routing remains fixed. 3. Travel times are predetermined, adhering to a set schedule. 4. Connections are indirect, akin to transferring from a metro to a bus on land. 5. High level of vehicle sharing, as the Harbour Bus is an integral component of the public transport network. 6. Dependence on the driver's presence is significant due to regulatory requirements and the necessity of a captain onboard.

Conversely, when this framework is applied to waterborne systems like the Rotterdam water taxi, a service that accommodates both shared and private bookings, we see a shift towards a more flexible model. Operating from pier to pier, similar to curb-to-curb ride-hailing services, the water taxi in Rotterdam offers a level of convenience and accessibility comparable to that of an Uber on the road, illustrating the framework's adaptability to different transit contexts.

Moreover, adhering to a stop-to-stop pick up/drop off approach through a gated access and egress system, DRT, facilitates and employs on-demand rides technology common to microtransit and ride-hailing services, which instead use the curb-to-curb pick up/drop off approach. DRT's primary benefit is, therefore, its frequent sharing of vehicles, surpassing the sharing frequency found in micro-mobility, providing reliable and familiar stops but not according to schedule, rather on demand, thereby enhancing operational efficiency and fostering a more communal service through the use of larger, collectively used vehicles. This also represents a nuanced distinction from public transit, with DRT prioritizing regular vehicle sharing, while fixed-route systems aim to achieve full vehicle occupancy.

5.2 Characteristics of the ADRT service for Lynetteholm

5.2.1 High level design dimensions

In examining the high-level design dimensions of the proposed service, we focus on answering the following high level design questions:

WHO: The intended service is designed to cater to the inhabitants of Lynetteholm as well as commuters from neighboring districts. Based on Copenhagen's transportation modal split, data indicates that 18% of working-age residents (individuals between the ages of 18 and 65, accounting for 72% of Copenhagen's total population) prefer public transport for their daily commute to work. Extrapolating these statistics to the context of Lynetteholm suggests that out of an estimated 25,200 working-age individuals residing in the area, approximately 4,200 might utilize public transportation on a daily basis, inclusive of ferry services like the Harbor Bus.

WHAT: The resources at disposal for this initiative encompass the expansive network of Copenhagen's waterways, the feasibility of pier construction, and the already established modes of transportation within the city. A significant asset is the local population's familiarity with water-based transport and cycling, coupled with a well-integrated system of intermodal mobility. These elements collectively provide a robust foundation for the introduction and integration of the proposed service into the existing urban fabric.

WHERE: The ideal location for deploying the service includes the Copenhagen harbor area, designed to complement the existing Harbour Bus system and guarantee a base level of ridership. Concurrently, the peripheral regions of Lynetteholm present an experimental testing ground for innovative service models, providing an opportunity to evaluate their effectiveness in less established areas before broader and fixed implementation investments.

WHEN: The proposed service operates on a 24/7 basis, addressing both constant demand and the specific requirements of nighttime travel. The ADRT service is strategically designed to facilitate the seamless, rapid, and dependable integration of the newly developed Lynetteholm neighborhood, ensuring its accessibility and livability from the onset of its inauguration to residents.

WHY: The principal objective of this service is to optimize cost-effectiveness by aligning the operation of on-demand vessels with peak demand periods, and minimizing their operation during low-demand intervals. A key aim is to diminish the reliance on personal vehicles within the area. Secondary objectives include increasing ferry ridership and broadening the scope of service coverage. Tertiary goals encompass the collection of pertinent data, experimentation with automated dispatch systems, enhancement of the user experience, minimization of environmental footprints, and provision of services to underserved regions, commonly referred to as transit deserts.

HOW: Realizing these goals through an ADRT system necessitates the establishment of a reliable booking system, cohesive integration with existing public transportation infrastructure and planning methodologies, and the utilization of user-friendly digital platforms. Special emphasis should be placed on servicing areas that exhibit considerable demand for transportation, ensuring coverage and accessibility satisfaction.

5.2.2 Integration within the existing transport systems of Copenhagen

The conceptualization of an ADRT ferry service for Lynetteholm is strategically designed to complement the existing "Harbor Bus" network operated by Movia in Copenhagen. The current Harbor Bus infrastructure encompasses 3 ferry routes with 11 stations and maintains a fleet of 6 harbor buses. The proposed ADRT service enhances this arrangement by introducing an additional 6 stops and doubling the harbor bus fleet to a total of 12 vessels. This expansion is tailored to meet the evolving mobility requirements of the Lynetteholm community, ensuring comprehensive coverage and accessibility. Explanation of these choices will follow in later paragraphs about the service details.

Opting for larger vessels is a deliberate decision aimed at maximizing efficiency and catering to a broader passenger base, thus presenting a viable alternative to traditional metro or car travell. This approach resonates with the city's broader transport goals, emphasizing mass transit solutions over individual vehicle use. The choice against smaller vessels, which would necessitate a larger fleet due to their limited capacity, is based on several considerations. Smaller vessels would require more resources for construction and maintenance, including a higher number of batteries and increased material usage, and increased waste material at the end of the fleet life cycle. Additionally, the operational expenses (opex) would escalate with the need for a larger workforce to maintain the vessels and the autonomous systems aboard each vessel.

By contrast, the ADRT model emulates the public ferry service framework, with the added advantage of online booking and demand-responsive routing. Unlike a curb-to-curb service that operates with flexible stopping points, the ADRT service maintains fixed stops, allowing for predictable travel times and controlled boarding processes. This model strikes a balance between operational efficiency and user convenience, aligning with the municipality's vision for a sustainable and efficient urban transport system.

5.2.3 Autonomy Level

The proposed autonomous demand-responsive ferry service within the modified Transit Analytics Lab (TAL) framework incorporates the highest level of automation, Level 5, as defined by the Central Commission for Navigation on the Rhine (CCNR) for inland waterway transport. This level of autonomy ensures that vessels can navigate freely in open or canalized waterways, possibly navigating through lock systems autonomously. At this advanced stage, the automation system is capable of independently managing all routine and emergency navigational tasks, underscoring the adaptability of the TAL framework to encompass various transportation modalities, each characterized by their respective autonomy levels tailored to the specific mode of transport.

5.2.4 Stops Design

Figure 17. Copenhagen's existing Harbour Bus (in red) routes, being complemented by the ADRT (in orange) routes.

This study presents a novel methodology study by Shen (2023), introducing an innovative approach grounded in queueing theory, which is the mathematical examination of queue formations, advocating for the equitable distribution of traffic load across all berths to minimize bus delays. Motivated by these findings, I applied the principle of balanced distribution to the arrangement of ADRT stops.

Analyzing the geographic layout, I ensured a direct linkage between Stop 1, a pivotal node with extensive intermodal connections including bus, metro, and train services, and Stop 2, which addresses the traffic congestion in Refshaleøen—a noted bottleneck due to limited cyclist pathways to the southern districts from Lynetteholm. Stop 3 aims to integrate with Orientkaj, a newly established station serving the Nordhavn redevelopment, already equipped with ferry docking facilities. Stop 4 is strategically positioned to serve Nordhavn's residential area, while Stop 5, located at the rear of Lynetteholm, offers a tranquil ferry ride for those preferring to avoid cycling through the entire island. Finally, Stop 6 closes the loop at Lynetteholm's southern tip, facilitating movement between Stops 4 and 6. We welcome feedback on this layout, particularly concerning the necessity and efficacy of the proposed number of stops.

5.2.5 Service Supply

Our fleet comprises six state-of-the-art autonomous ferries, each designed to carry 50 passengers, effectively doubling the existing fleet capacity. These ferries are equipped with an advanced navigation system (ANS) integrated during their manufacturing at the shipyard. The ANS encompasses features such as autopilot, autodocking, automooring, collision avoidance, redundancy for single point failure, and sophisticated path planning, ensuring the highest standards of safety for round-the-clock operation.

The procurement involves six Roboat autonomous ferries tailored for Lynetteholm, costing €500,000 each. A collaborative manufacturing agreement with a shipyard includes a profit margin, bringing the retail price to approximately €650,000 per unit. The total investment for the fleet amounts to €3.9 million. Additionally, the construction of six new piers incurs a cost of €200,000 each, culminating in a total infrastructure expenditure of €1.2 million. These costs encompass landside access, integration with existing infrastructure, wave mitigation solutions, pontoons equipped with restraint systems, facilities for passenger embarkation and waiting areas, along with essential cabling and networking for operational efficiency.

Given the autonomous nature of the ferries, no skippers are required for operation, anticipating that by 2070, both regulatory frameworks and societal acceptance will align with such technologies. Should manual oversight be necessary, a rotation of 18 skippers, changing every 8 hours to cover the 24-hour service, would incur a salary expense of €85,000 each, totalling €1.530 million annually. Additional operational costs include maintenance (€500,000), insurance (€100,000), administrative overheads (€200,000), and electricity (€100,000), leading to a total annual operating expense of €2.430 million.

The ferries operate at a speed of 8 knots, enabling them to cover 1 kilometer in approximately 4 minutes. The service is designed to function continuously, with ferries scheduled to arrive at each stop every 10 minutes, providing a reliable and efficient transport solution.

In addressing the concept of failed boarding probability within the context of an on-demand ferry service, it's crucial to consider the operational capacity of each vessel and the implications for passenger boarding. With a defined capacity of 50 passengers per vessel, the service must ensure efficient utilization while minimizing the occurrence of failed boarding instances, where passengers are unable to board due to capacity constraints.

The proposed system incorporates an advanced booking mechanism, akin to those used in modern train services, where passengers can secure their spot on a specific ferry departure. In the event that a particular service reaches its full capacity, the system proactively informs the user and offers alternative departures from the same or nearby locations, thereby optimizing passenger flow and reducing the likelihood of service denial.

A key aspect of the service design is the anticipation of peak demand zones, particularly on the western side of Lynetteholm, where a higher concentration of commuters is expected due to proximity to major cycling routes and destinations. This geographic demand distribution necessitates a dynamic allocation of ferry services, ensuring that vessels are more readily available on the busier western side during peak times.

This strategic approach to ferry deployment, informed by real-time demand data and commuter patterns, allows for a more flexible and responsive service. By reallocating vessels from less congested eastern stops to busier western ones during peak hours, the system can effectively accommodate fluctuating demand and reduce the likelihood of failed boarding.

In summary, the design choices regarding ferry capacity, advanced booking mechanisms, and dynamic vessel allocation are driven by the need to provide service efficiency and passenger satisfaction for Lynetteholm. Since the ADRT will be on demand, the precise data will of course be obtained if this solution will ever be implemented.

5.2.6 Service Demand

Our projected ridership accounts for the 24/7 operation and recognizes the variance in demand, with a notable decrease during nighttime hours, affecting the overall hourly ridership average.

Assuming a workforce population of 4,200 individuals on Lynetteholm who might opt for public transport based on Copenhagen's modal split, and considering the ferry's capacity of 50 passengers, we estimate about 84 total ferry rides are needed per day to deal with demand. Distributed across six ferries, this equates to approximately 14 rides per ferry, complementing the municipal ferry service of Copenhagen in the more central parts of the river. Given the early stage of Lynetteholm's development, the on-demand ridership data remains speculative, pending further demographic and service usage analysis.

For operational efficiency, a ferry traveling at 8 knots will cover the shortest route from Langelinie (Stop 1) to Lynetteholm (Stop 2), approximately 1 km, in about 4 minutes. Consequently, the longest route from Stop 1 to Stop 6, spanning 5 km, would necessitate a one-way travel time of 20 minutes, extending to 40 minutes for a round trip, inclusive of boarding and disembarkation. The introduction of autonomous features like autodocking and optimized routing is expected to maintain consistent travel times and minimize operational delays associated with manual navigation.

Regarding service frequency, a single round trip on the 1km route, accounting for boarding and egress, is projected at roughly 15 minutes. This translates to four round trips per hour, enabling one ferry to transport up to 400 passengers in 8 one-way trips. With six ferries operational, the total hourly capacity reaches 2,400 passengers. During peak hours, spanning 20 hours from 7:30 to 9:30, this fleet composition is anticipated to meet the commuting needs of the 4,200 residents.

Service frequency calculations are based on the formula that if a route spans x km, the travel time would be 4x minutes. Factoring in additional time for boarding and other logistics, the total round trip time, T minutes, dictates the service frequency, with a maximum of 60 minutes / T. Hence, the capacity is determined by the equation 50*(60 / T)*N_vessels.

To optimize passenger wait times and align with competitive on-demand services, a proposed service interval of 10 to 15 minutes is suggested, averaging a 15-minute wait. A 15-minute wait is simply the time the user will need to wait from the moment of the booking of a ride to the moment a ADRT ferry arrives at the allocated pick up station. This approach is designed to both complement and enhance the existing public ferry service, drawing on comparative analyses such as the study by Insardi and Lorenzo (2020) on Uber service 7.5minutes waiting times, to ensure the ADRT system remains attractive and efficient for Lynetteholm residents.

5.2.7 Service Quality

The fare for the service is established within a spectrum, commencing from the baseline DOT ticket price of 24 DKK, equivalent to €3.30 based on the conversion rate as of March 2024, extending up to a ceiling of €10 for on-demand trips with occupancy levels below 50% per singular journey. This pricing model is crafted to accommodate the varying demands of passengers while ensuring the service remains economically viable. The design of the service prioritizes seamless integration with the existing urban mobility framework, ensuring straightforward access to public transportation, cycling infrastructures, and pedestrian networks.

Service frequency is a crucial parameter that significantly influences the system's reliability and the user experience. It denotes the regularity with which ferries arrive at each stop, impacting both the average waiting time for passengers and the system's overall robustness. Higher service frequency reduces the average waiting time, enhancing passenger convenience and making the service more attractive compared to other modes of transportation. Conversely, lower frequency can lead to increased waiting times, potentially deterring users from opting for the service, particularly during peak hours or in adverse weather conditions.

The robustness of the ferry service, or its ability to maintain consistent operations under varying conditions, is closely tied to its frequency. A system with high service frequency can more effectively manage unexpected events, such as a vessel being unable to board passengers due to capacity issues or technical problems. In such scenarios, the presence of subsequent ferries arriving in short intervals ensures minimal disruption to the service, maintaining its reliability. Furthermore, service frequency must be carefully planned to balance operational costs with user needs. An overly frequent service may lead to underutilization of resources during off-peak hours, whereas infrequent service may not meet peak demand, leading to overcrowded vessels or long waiting times.

Incorporating dynamic scheduling and real-time data analytics can enhance the system's responsiveness to varying demand levels throughout the day, optimizing service frequency and ensuring a balance between cost-efficiency and user satisfaction. This approach allows the service to adjust frequency based on actual usage patterns, improving the overall efficiency and reliability of the transportation system. In summary, service frequency is a vital factor in determining the effectiveness and appeal of an on-demand ferry service. It influences the average waiting time, affects the system's ability to cope with unforeseen circumstances, and plays a significant role in operational planning and resource allocation.

Finally, guarantee resilience against breakage and diverse meteorological conditions, the vessels are engineered to standards observed in cities renowned for their robust maritime infrastructure, such as Hamburg. In the event of malfunctions, the service's operational framework is designed to maintain efficiency through reduced fleet deployment, offset by advanced software solutions to minimize disruption.

The ADRT service is conceived to complement the existing Harbour Bus operations within the harbor precinct, while simultaneously introducing supplementary routes to gauge emergent demand patterns from the developing urban sectors of Lynetteholm. This dual approach enables municipal authorities to make informed decisions regarding future infrastructure investments, particularly in discerning the potential for establishing fixed route services based on the preferences and needs of Lynetteholm's populace.

The service is calibrated to align with peak urban transit periods, transitioning to an on-demand model during periods of reduced activity and extending its availability into the nocturnal hours, thereby addressing the gap left by the daytime-centric Harbour Bus schedule. This strategic operational model ensures continuous and adaptive mobility support, tailored to the dynamic rhythms of urban life in Copenhagen.

Considering the ferry's capacity is limited to 50 passengers per journey, the system is designed to prevent overbooking, akin to railway services. Should a passenger attempt to reserve a spot on a fully occupied ferry, the booking system will indicate the unavailability for the selected time slot, simultaneously offering alternative departures at proximate times or from nearby stations, ensuring passenger convenience and system efficiency.

Anticipated peak demand suggests heightened activity on Lynetteholm's western front, attributed to the propensity of cyclists to gravitate towards the closest ferry point aligned with their ultimate destination. This behavioral pattern allows for strategic deployment of the fleet, optimizing vessel availability on the eastern side during peak periods to accommodate the concentrated demand on the western side. The system's inherent flexibility facilitates reallocation of resources to meet demand surges, ensuring operational resilience.

The proposed DRT service is meticulously designed to reflect the established Copenhagen transport network, ensuring a smooth transition for users and maintaining coherence with the city's mobility ecosystem. The inclusion of bicycles, strategic placement of stops at activity-rich "orbits" or hubs, and the integration of advanced booking and payment technologies underscore the service's commitment to offering a contemporary, adaptable, and user-centric ferry solution. This approach not only enhances the utility and appeal of the DRT service but also reinforces Copenhagen's vision of a connected, efficient, and sustainable urban mobility landscape.

Chapter 6

Discussions, Limitations, and Conclusions

6.1 Discussions and Limitations

Incorporating an ADRT system into urban mobility, particularly in waterfront areas like Lynetteholm, offers a forward-thinking approach to addressing transportation needs. This section explores the design rationale, highlights limitations, proposes areas for future research, and draws parallels with other metropolitan contexts.

The proposed ADRT service is designed with a capacity of 50 passengers per vessel, optimizing space while ensuring efficient service delivery. This capacity mirrors the constraints of physical space and operational feasibility, akin to how trains operate with set capacities. The booking system's design to indicate full capacity and suggest alternative timings or nearby departure points is rooted in enhancing user convenience and managing demand effectively.

The anticipation of higher demand on Lynetteholm's western side, where bike commuters converge, informed the strategic placement of ferry stops. This decision is underpinned by the intention to provide accessible service to the largest number of users while mitigating potential bottlenecks. The system's flexibility allows for repositioning of the fleet in response to fluctuating demand, demonstrating an adaptive approach to urban transit that aligns with contemporary mobility trends.

This study's scope is inherently limited by speculative elements, given the future-oriented nature of Lynetteholm's development and the ADRT system's implementation. Key assumptions include the adoption rates of ADRT, regulatory acceptance of autonomous vessels by 2070, and the projected urban development of Lynetteholm. Moreover, the reliance on real-time data for demand-responsive service optimization introduces complexities related to data privacy, security, and the robustness of the underlying technological infrastructure. The scalability and adaptability of ADRT in response to unpredictable urban growth patterns present additional challenges that warrant further investigation.

Future research could delve into the empirical validation of these assumptions, examining user acceptance, regulatory evolution, and the practical implications of integrating ADRT within existing urban fabric. Additionally, exploring the scalability of ADRT to other urban settings and its adaptability to varying urban forms and mobility cultures would provide valuable insights.

The potential of ADRT in practical scenarios remains an area of uncertainty, with operational challenges such as waiting time when demand fluctuates, system reliability under adverse weather conditions, and user adaptability posing critical questions. The integration of ADRT could potentially influence urban form, encouraging development patterns that prioritize waterway access and promote a shift towards less car-dependencies. Lessons that can be learnt from Venice include safety concerns, heavy traffic management and the preservation the environment through les wake possible, which is not often regulated in Venice, and solutions such as ADRT can have a specific set of rules including speed, routing, times and which users can book the service, which will make the service safer.

6.2 Conclusions

Expanding upon the conceptualization of system for Lynetteholm, this conclusion delves deeper into the nuanced dynamics of on-demand services, the implications of real-time data usage, and the tailored application of ADRT in the context of Copenhagen, drawing comparisons with Venice and Amsterdam.

The essence of on-demand transport services, such as the proposed ADRT, lies in their reliance on real-time data to make operational decisions. This characteristic fundamentally distinguishes them from traditional transport systems, which often operate on schedules and projections derived from historical data. In rapidly evolving urban environments like Lynetteholm, where demographic and infrastructural landscapes are subject to significant changes, the ability of ADRT systems to adapt to real-time demand becomes invaluable. This dynamic nature ensures that the service remains efficient and responsive, catering to the immediate needs of the community rather than relying on potentially outdated predictions. However, this reliance on real-time data also introduces a layer of complexity, as projections based on past trends may not always align with future realities, especially in long-term projects where urban and societal transformations are anticipated.

Reflecting on the experiences of Venice and Amsterdam offers pertinent insights into the integration of waterborne transport solutions within urban settings. Venice, with its intricate network of canals, faces challenges related to high tourist volumes, frequent canal cruises, traffic congestion, and environmental concerns. These issues underscore the need for a transport solution that can mitigate such challenges while enhancing the urban experience for both residents and visitors. The introduction of ADRT in a context like Venice could, theoretically, offer a more regulated, efficient, and less intrusive alternative to traditional waterborne transport, given its digital and autonomous nature. Amsterdam, known for its extensive canal system and a strong emphasis on cycling and pedestrian pathways, presents a different set of considerations. Here, the integration of ADRT could complement the existing transport ecosystem, providing a flexible link between various modes of transport and catering to the city's unique urban form.

One of the most compelling advantages of ADRT systems is their capacity for customization. Given their digital framework, ADRT services can be designed to cater to specific user groups—be it residents, employees of a particular sector, individuals of a certain age group, or even tourists, under controlled conditions. This level of specificity allows for the creation of a complementary service that supports, rather than competes with, existing public transport infrastructure. In the context of Lynetteholm, this could mean designing ADRT services that prioritize the mobility needs of the island's future residents, ensuring seamless integration with Copenhagen's broader transport network while addressing the specific challenges of a newly developed urban area.

In conclusion, the exploration of an ADRT system for Lynetteholm not only contributes to the discourse on smart, sustainable urban mobility but also offers a template for other cities facing similar expansion challenges. By harnessing the potential of real-time data and tailoring services to meet the specific needs of diverse user groups, ADRT can pave the way for a new era of urban transport that is adaptable, efficient, and harmonious with the evolving landscapes of modern cities. The lessons drawn from Copenhagen, Venice, and Amsterdam further enrich this discourse, providing valuable perspectives on the integration of innovative transport solutions within varied urban and cultural contexts.

Chapter 7

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Appendix A

For practicality, the reader is welcome to visit this link to explore how the literature review has been performed:

https://docs.google.com/spreadsheets/d/1MT7HABfHOkjr-KwkLOLk9Hi-vSVSEbLpTThblbqb8P0/edit?usp=sharing