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Lessons learned from the trial operation of an autonomous urban passenger ferry

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A R T I C L E I N F O

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A B S T R A C T

Cities worldwide consider autonomous passenger ferries a sustainable way of transporting passengers across and along waterways. Since 2016, a university-led effort to develop autonomous urban passenger ferry prototypes has been underway in Trondheim, Norway. The work culminated in what is considered the world's first trial operations of an autonomous urban passenger ferry open to the public, where the ferry milliAmpere2, over three weeks, completed almost 500 trips and transported more than 1500 passengers over a 100-meter crossing. During the trial period in September and October 2022, several quantitative and qualitative data samples were collected to understand passengers' and safety operators' perceptions of trust and safety onboard autonomous ferries. This article briefly presents the autonomous ferry and its autonomy system and provides details about the trial operation, the area of operation, and the data samples collected. It concludes with lessons learned from the trial operation that can be useful for other researchers who study autonomous ferries and their interplay with operators, passengers, and other stakeholders.

Introduction

In Roald Dahl's classic "Charlie and the Chocolate Factory," the eccentric factory manager Willy Wonka takes Charlie and his grandfather on a glass elevator ride. This elevator can move in any direction and escort passengers to any place in the factory. Similarly, we envisioned an automatic water elevator that could take passengers, at the press of a button, across city waterways efficiently and sustainably. This resulted in the design of the autonomous all-electric urban passenger ferry *milliAmpere2*. This article reports on the preparations, execution, and lessons learned from a three-week trial operation of the ferry in Trondheim, Norway.

Deployment of traditional, crewed ferry services for urban mobility in Norway is hindered by two factors: crew cost and an increasing national shortage of certified crew (Bull et al., 2023). This has resulted in conventional ferry services being dominated by larger vessels with infrequent departures and few routes. To provide high levels of service, these should be replaced by a larger number of small ferries, which will provide more frequent departures, more routes, and more flexible fleet deployment (Smogeli et al., 2023). Autonomy is expected to eventually reduce the need for certified crew, thereby reducing operational costs and enabling the deployment of waterborne urban mobility networks (ibid.). Therefore, autonomous ferries undergoing gradual crew replacement may, in the long term, prove economically feasible (Kooij and Hekkenberg, 2021; Dantas and Theotokatos, 2023). However, as Ghaderi (2019) point out, such operations will rely on highly skilled operators and investment in remote control infrastructure – factors that suggest higher initial costs than conventional ferries.

An autonomous urban passenger ferry is a type of ferry that is capable of operating without a human operator onboard (Reddy et al., 2019; Smogeli et al., 2023). It uses a combination of exteroceptive sensors such as radar, lidar, and cameras to interpret its surroundings

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and a range of other sensors and technologies to navigate, avoid obstacles, and maintain a safe course (Eriksen, 2019; Thyri, 2022). It can operate independently using pre-programmed routes and algorithms with remote supervision from a land-based control room operator. Owing to their small size and scalability, autonomous ferries open new possibilities for on-demand mobility across and along urban waterways such as harbor fronts, rivers, canals, and lakes. A helpful analogy, as mentioned above, is that of a "water elevator" that, like connecting floors in a building, makes moving along waterfront areas straightforward and accessible. In the eyes of city developers, autonomous ferries transform bodies of water from hindrances to opportunities. They circumvent the need for bridges and other inflexible and resource-heavy infrastructure that may lead to circuitous routes and congestion, instead creating a new constellation of mobility networks. According to the United Nations, the population of urban dwellers outnumbered rural inhabitants for the first time in 2007, and the shift in balance continues steadily (United Nations, 2019). In December 2022, the world's population reached eight billion, which may be seen as indicative of the strain on urban mobility in waterfront cities worldwide. Despite the favorable opportunities and increasing attention, many questions remain unanswered about autonomous ferries. Will passengers react to autonomous ferries with skepticism or openness? Will the safety operators, who are needed in the initial phase of operation, be forced to take over manual control to prevent accidents due to faulty automation, misbehavior of passengers, or hazardous interaction with other traffic? And if so, how often? The most important factor at stake is passenger safety, which must be demonstrated before the technology is ready for public use.

Another open question is the regulations for autonomous ferries. The Norwegian Maritime Authority has published guidance regarding unmanned or partly unmanned operations (Norwegian Maritime Authority, 2020a,b). These are leaning on similar guidelines from the International Maritime Organization (2013). In short, the guidance say that one can get approval based on proofs that the solution is as safe as – or safer – than conventional operation.

Many research groups around the world are investigating the viability of autonomous urban passenger ferries. Two examples are the RoBoat from MiT in Amsterdam (Wang et al., 2019) and the GreenHopper from DTU in Aalborg (Enevoldsen et al., 2022). Commercial initiatives are also found, such as Zeabuz and Hyke, where the first started commercial operation in June 2023. The milliAmpere2 ferry at NTNU, borne from the milliAmpere test ferry (Brekke et al., 2022), is another example, which will be presented in detail later in this article.

The majority of research on how people perceive and interact with Artificial Intelligence (AI) systems, Robots, and Autonomous Vehicles (AVs) is conducted using in-lab and simulation methodologies (Pan et al., 2017; Hock et al., 2018; Jung and Hinds, 2018). Even though this research is instrumental in creating the foundation for Human-AI interaction research and keeping the participants safe during the studies, there is a growing criticism of whether those methodologies can capture the complex social contexts in which AI systems are increasingly placed (Jung and Hinds, 2018; Verma et al., 2019; Meurer et al., 2020). Specifically for AVs, real-world testing allows for the investigation of environmental, socio-technical, and human factors that may influence the target population's acceptance of these technologies. Both the EU (European Commission, 2018) and the US (US Department of Transportation, 2018) have published policy documents on Autonomous Transportation in which public demonstrators of autonomous vehicles is emphasized as a method to increase trust perceptions among the general public. Even though the need for "in-the-wild" testing is emphasized, it is not clear how one should perform a multifaceted evaluation of the deployment of autonomous vehicles into an urban transportation system.

From September 21 to October 9, 2022, the milliAmpere2 test ferry underwent a three-week public trial (see Fig. 1). This marked the first-ever trial operation of an autonomous urban passenger ferry open to the public. It allowed researchers to study the questions surrounding

Fig. 1. The autonomous urban passenger ferry milliAmpere2 during its trial operation in September and October 2022 in Kanalen, Trondheim, Norway. The traditional ferry service "Ferry Man" is to the left. (Photo: Kai T. Dragland, NTNU).

how autonomous urban passenger ferries would be met in the public eye. This paper presents details about how a large-scale deployment of an autonomous urban ferry was set up in order to provide methodological insights that may be of use to others in conducting real-world evaluations with their own autonomous vehicles. It is a method article and does not report on specific results from the data collected.

This study can be regarded as a sociotechnical experiment where alternative technologies are being tested in society and with real actors. By doing so, the transition towards sustainability is slowly shaped through demonstration and learning by implementing such experiments. Within the context of sustainability transition, an experiment is defined as "an inclusive, practice-based and challenge-led initiative designed to promote system innovation through social learning under conditions of uncertainty and ambiguity" (Sengers et al., 2019, p.161). The experiment with the autonomous ferry was initiated within a constrained environment where the ferry was built, functionalities were tested, and it gradually was put to the test with various users and within expanding boundaries. Therefore, it can be characterized as a Niche Experiment (Sengers et al., 2019).

The rest of the article is organized as follows: First, we present related work on trial operations of autonomous mobility systems. Then, we present the context of the trial operation, including the milliAmpere2 ferry and the area of operation. Then, we go into detail on various dimensions related to the trial operation, such as operating hours, personnel involved, docking, charging, safety, and information to the public. Furthermore, we present details on the data collection protocol and give an overview of the research data collected during the trial operation. Finally, we provide lessons learned from the trial operation that can inform research institutions, industry, maritime authorities, and municipalities about how to plan and conduct trial operations of autonomous urban waterborne transport.

Related work

In related literature, only a handful of instances can be found in which passenger perceptions of autonomous ferries are explored. A notable example is the study by Munim et al. (2022) that examined the public's attitudes toward the safety of autonomous ferries using an online survey in Norway. Their results showed that people remain skeptical about fully autonomous ferries without operators on board and that those perceptions vary based on demographic factors. The questionnaire used in this study was based on the work by Goerlandt and Pulsifer (2022), who also explored safety perceptions of autonomous ferries.

Similarly, the results of this study showed that perceptions of safety were higher for lower levels of automation and that this was moderated by demographic factors. Both studies provided valuable insights into passenger safety perceptions of autonomous ferries. Yet, they also share the same limitation of collecting data from people who never had first-hand experience with autonomous ferries.

Even though the study by Goerlandt and Pulsifer (2022) sampler a narrower selection, they made more efforts to contextualize the scenario to a specific geographical location. This led to numerous comments from participants mentioning how their safety perceptions would be influenced by the environmental conditions in which the ferry would operate. Those two examples mentioned above highlight the need not only for more research on public perceptions of autonomous ferries but also on the importance of real-world and highly contextualized studies that would unveil the whole spectrum of considerations that could influence the adoption of those vehicles.

Due to the limited amount of research on autonomous ferries, we have also included other types of vehicles. We decided to concentrate on autonomous public transportation since the role of passengers in autonomous cars is still relatively active and requires more control compared to ferries. Several studies have been conducted on public engagement with autonomous passenger vehicles, specifically autonomous buses. However, conducting public trials for such vehicles is a complex process that requires researchers to customize their methodologies based on their specific objectives and conditions.

Studies have looked at public trials of autonomous vehicles in special environments so that the trials would not harm other road users. Salonen (2018) reported from a public trial of an automated minibus in Vantaa, Finland, which transported more than 19,000 passengers during the trial period. The automated minibus operated on a dedicated road, which was not accessible to other road users. Classen et al. (2021) also conducted a public trial of an automated minibus on an empty road in Florida, US, which focused on how elderly people perceive automated buses. Mirnig et al. (2020) reported a public trial of an automated minibus, which focused on how pedestrians and other car drivers perceived and interacted with the automated minibus. The public trial was conducted at a driving test center in Salzburg, Austria.

Some public trials of autonomous vehicles were conducted in semi-dedicated environments. Using this approach, the public trials could still be conducted within environments that were familiar to the researchers, but also provided the opportunity for other people to try the autonomous vehicles and observe the public trials. Christie et al. (2016) reported a public trial of an automated minibus, which was conducted in Lausanne, Switzerland. A total of 1600 passengers were transported by the automated minibus during the trial period. The public trial was performed within the EPFL campus environment, and thus many of their passengers were either employees or students at EPFL. Nordhoff et al. (2018, 2019, 2020) reported three different public trials of an automated minibus, which were all conducted in Berlin, Germany. Although both public trials were conducted within the EUREF campus environment, the minibus shared the road with other road users, e.g., pedestrians, cyclists, and cars.

Finally, one has the public trials of autonomous vehicles that were conducted on public roads. This approach allows researchers to observe how the public perceives and interacts with autonomous vehicles in a real-world setting. Bernhard et al. (2020) tested their automated minibus on a public road in Mainz, Germany. More than 900 passengers were involved in the public trial. Launonen et al. (2021) conducted a public trial of an automated minibus, which focused on the public perception of the automated minibus in winter conditions. It was conducted on a public road in Lapland, Finland, involving 70 passengers. Mason et al. (2022) also conducted a public trial of an automated minibus on different road conditions in Iowa, US. The public trial involved 85 passengers, and the journey included highways and gravel roads. Yan et al. (2022) conducted a public trial in Tianjin, China, where three automated full-scale buses operated simultaneously. More than 500 passengers managed to try the automated buses during the public trial.

When we sum up the related work, we see that more research is needed on autonomous waterborne mobility systems. A few existing studies were performed with non-representative users who had not tried autonomous ferries in real life.

Context

This section describes the milliAmpere2 ferry, the autonomy system, and the area of operation for the public trial.

The milliAmpere2 ferry

The milliAmpere2 ferry was designed in 2019, first launched in 2020 for testing, and officially commissioned in September 2022. The ferry was built as a university research infrastructure designed for the development and evaluation of new algorithms and systems within vessel control, dynamic positioning, docking, and anti-collision, as well as understanding passenger acceptance and trust.

General characteristics

The ferry milliAmpere2 (see Fig. 2) is an 8.65-meter-long and 3.5-meter-wide ferry that comfortably fits 20 passengers. However, due to regulations, the maximum number of passengers allowed onboard is 12 (Norwegian Maritime Authority, 2020a,b). A centered-positioned bench allows the passengers to sit down during the journey. When docking, a latch lowers and lets the passengers disembark. The ferry has a wide monohull, designed for high stability. The ferry is powered by four electric azimuth thrusters, each with 10 kW capacity, giving it a maximum of 40 kW propulsion. The ferry has a maximum speed of 5 knots, limited by software, and its operating speed is 3 knots. The ferry is powered by 48 V DC lead batteries, distributed over two independent and redundant battery cells, each with a total capacity of 24 kWh. The ferry has a displacement of about 6 tonnes and is made of aluminum. The propulsion and energy system are divided into two redundant systems, each with two of the four thrusters and two of the four battery packs. This increases the ferry's reliability in case of a single-point failure.

Control system

The ferry is controlled using an industry-standard dynamic positioning system (DP2) delivered by Marine Technologies. In manual mode, the ferry is driven via an operator terminal with a touch panel and a joystick, with an identical backup terminal in case of failure. Two emergency stop switches cut the power to the thrusters while the DP and other systems are unaffected. The ferry can be operated in DP mode using software located on the control terminal.

Sensors and technical equipment

The milliAmpere2 is equipped with various sensors and technical equipment for its autonomous and remote operation, as listed in Fig. 3. The eyes of the ferry include several cameras, lidar, radar, and ultrasonic distance sensors. For remote monitoring and control the ferry is connected to a remote-control center (Alsos et al. 2022b) located about 1.4 km from the area of operation. It is outside the scope of this article to present all the details about the sensor rig and technical equipment. For more details on the design of milliAmpere2, the reader is directed to Eide et al. (2024, Manuscript submitted for publication) and Mustvedt (2019).

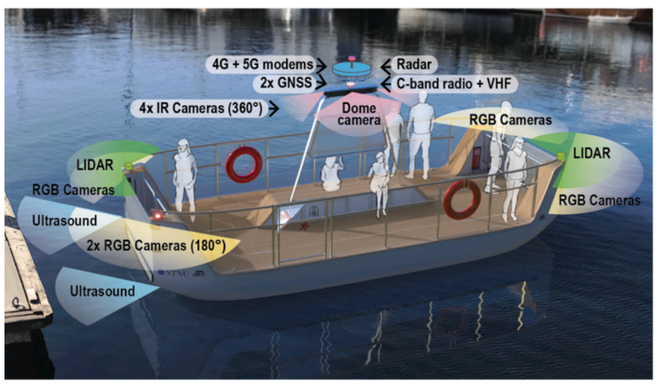
Before the trial operation started, we installed additional equipment and displays on the deck for monitoring the systems. In addition, we also temporarily installed a tent in order to provide weather protection for the equipment on deck.

Autonomy system

The ferry has an autonomy system on board that ensures automatic crossing (following a preprogrammed route), docking, and collision

Specification	milliAmpere2
Length (LOA)	8.65 m
Beam	3.50 m
Draught	0.3 m
Air draught	3.5 m
Displacement	6 tonnes
Max. pax.	12
Propulsion	4 azimuth thrusters
Operation speed	3 knots
Max. speed	5 knots
Energy	Electric 48V DC
Batteries	Lead-Acid VRL 48 kWh
Power	4 x 10 kW
Sensors	IR camera, camera, RADAR, LIDAR, ultrasonic

Fig. 2. The milliAmpere2 and some of its main specification. (Photo: Kai T. Dragland, NTNU).



Sensors onboard milliAmpere2
1 RTK GPS compass with cm accuracy
1 backup GPS system (Saab)
1 pc IMU (X-sens)
2 Lidar (Ouster)
4 IR cameras
8 RGB machine vision cameras
2 CCTV cameras
1 dome camera
4 ultrasonic distance sensors
1 maritime radar type Simrad Halo 24
1 anemometer (ultrasound)
Battery monitoring system (Anda-Olsen)

Fig. 3. The sensors onboard milliAmpere2 (Illustration: Petter Mustvedt and Jooyoung Park).

avoidance in case of crossing traffic. To comply with current regulations, the ferry was crewed by a safety operator during the trial who was instructed to take over control if necessary. This mode of operation aligns with "Degree One" autonomy as defined by the International Maritime Organization (IMO), described as a vessel with "automated processes and decision support." (International Maritime Organization, 2021). This degree of autonomy is distinguished by the trial phase accommodation of personnel on board who are ready to take control of the primarily unsupervised automated control system.

With the help of the sensors (camera, IR, radar, lidar, and ultrasound sensors), the autonomy system onboard milliAmpere2 tracked objects and formed a situational picture of the traffic situation. If there was crossing traffic and a risk of collision, the ferry lowered its speed and remained stationary on the DP until the traffic had passed and the area was cleared for further travel. Thus, the implemented autonomy system was defensive. The autonomy system used was delivered by Zeabuz, which is a company spun out of NTNU's research on autonomous ferries.

Area of operation

This section describes the background, context, and area of operation for the trial operation.

Societal and cultural context

With regard to the implementation and testing of advanced technologies, Norway stands in a unique position. The country has a unique culture of trust in the authorities that makes it stand out from other Western countries (OECD, 2024). The high level of trust in authorities spills into other echelons of the society, meaning businesses, developers, research organizations and other people. This renders Norwegians more likely to trust the technologies that are introduced and implemented (Innbyggerundersøkelsen, 2021). Having benefitted from large-scale investments and progress in digitalization, Norway also advances other countries in the digitalization culture and digital infrastructure. This makes autonomous technologies more acceptable in this society that is already used to various advanced technologies of Industry 4.0 being part of their normal daily lives.

In addition to that, the low population of Norway and the emerging challenges such as the aging population mean that the Norwegian society must prepare for shifting employment patterns and use autonomous technologies to fill the gap for the low number of employees and an expensive workforce in certain sectors such as maritime transport. The country has an open mind in embracing technological advancements and trusts that the regulatory bodies will ensure the societal interest as a priority.

Geography

Trondheim is a Norwegian city with about 200,000 inhabitants. The *Nidelva* river meanders through the city. *Kanalen*, a canal created by an old riverbank (Bratberg, 1996), divides parts of the city, creating an island connected to the mainland with an underwater tunnel and a total of 7 bridges: 2 for trains, 2 for pedestrians and cyclists, and 3 for mixed traffic (see Fig. 4). The railway and pedestrian bridges at the western canal outlet bridge are not as trafficked as the eastern bridges. Therefore, these western bridges will usually be opened to accommodate boat traffic. The bridges are placed relatively close to each other, except for one stretch where the distance is more than one kilometer. This creates a long detour for pedestrians. On the old riverbank is now built a railway station, a container terminal, several quays, and several office buildings. The canal hosts many leisure boats and a local veteran boat association.

Fig. 4. The northern part of the city of Trondheim and the old riverbank that is now an island connected by seven bridges. The location of the bridge is marked on the map. The arrows indicate where ships can pass through opening bridges. (Map: Norgeskart).

History

In the early days, until 1965, before the construction of new bridges allowed people to cross the canal easily, a transport service called *Fløttmannen* (the "Ferry Man") operated in Trondheim (see Fig. 1). The Ferry Man transported people over the canal in a small traditional rowboat. Now the Ferry Man only operates during summer months as a tourist attraction.

In 2015, as a response to the municipality's plans to build a new pedestrian bridge over the canal (at the same location as the area of operation), several boat associations protested as it would be very hard to leave the canal because they would have to cross five heavily trafficked opening bridges with very limited opening hours, instead of passing only two bridges that have less traffic and more flexible opening hours. As a response to this, one of the boat association members, who is also an employee at NTNU, proposed an autonomous ferry service over the canal that could replace the bridge. Funded by the NTNU, the 5-meter long and 2.8-meter wide *milliAmpere* ferry was designed, built, and commissioned in 2016 (Brekke et al., 2022). This ferry was not used for passenger transport, only for testing the sensors and the autonomy system. Based on the experiences and technological development from milliAmpere, the milliAmpere2 ferry was designed in 2019, built in 2020, tested in 2021, and commissioned in 2022 (Alsos et al., 2022).

Operation conditions

The ferry operated in the canal between *Ravnkloa* and *Fosenkaia*, a closed harbor with a maximum width of about 100 m (see Fig. 5). At each end, there is a permanent floating dock that is independent of the tide difference, which on average is 2 m and almost 3 m during peak tide.

The traffic conditions in the narrow canal during summer months are relatively heavy, with several tourist operators, fishermen, leisure boats, etc. At the Ravnkloa side, at least two tourist vessel operators use the same floating dock as milliAmpere2. Two of the tourist boats are more than 20 m long and have a relatively large turning circle in the middle of the operating area of milliAmpere2. At the Fosenkaia side, the floating dock is filled with large veteran boats. The speed limit in the canal is 5 knots.

The current in the canal varies based on the tide and the water flow in the Nidelva River and it can reach up to about 2 knots (1 m/s) (Fig. 2, right). At the Fosenkaia side, near the northern outlet of the canal, the current can be strong, making it a bit challenging for boats to navigate and dock.

During the period of the trial operation, which lasted from 21 September 2022 to 9 October 2022, the weather varied significantly,

Fig. 5. The area of operation, canal outlets, traffic flow, river current directions, and interview areas. (Map: Norgeskart).

ranging from sunny weather to heavy rain and wind. At a latitude of 63.4 degrees North, the temperature in Trondheim during the trial operation varied between five and thirteen centigrade according to the historical weather data from the Norwegian Meteorological Institute (2024).

Trial operation

The ferry operation started on 21 September 2022 with a commissioning ceremony, where invited guests and the public could cross the canal with the ferry. The regular trial operation started one day after the ceremony and lasted for three weeks from Thursday to Sunday between 10:00 and 18:00. There were no scheduled trips since the ferry operated on demand, i.e., the ferry would leave as soon as there were passengers onboard or else be waiting on the other side.

Onboard safety operator

On board, there was a safety operator to ensure the safety of the passengers and to ensure that the ferry complied with the International Regulations for Preventing Collisions at Sea (COLREGS; IMO, 1972). The operator had the opportunity at any time to take over manual control using the DP system and to operate the hatches manually if needed. The operator also had the safety responsibility onboard and would inform, guide, and assist passengers in case of any emergency situations, especially if evacuation became necessary.

The operators had a professional nautical background with a Deck Officer Class 5 (Pleasure boat) or higher certificates in addition to necessary safety training (IMO50) and STCW Crowd and Crisis Management certificates. The five safety operators on the team rotated on 4-hour shifts. Four of the safety operators were hired by the transport company Torghatten, and the last one worked at NTNU. The experience of the operators ranged from recently graduated to almost 50 years of experience with onboard passenger ferries and cruise ships.

In addition to the safety operator, there was always at least one technician onboard who monitored the autonomy system, logged evasive maneuvers and unexpected events, and took measures if a technical failure occurred, such as false object detection or malfunction. In addition, they cleaned and maintained the sensors and troubleshot and debugged the autonomy system before and during the operation.

The technicians were put on duty by Zeabuz, the company that developed the autonomy system running onboard the ferry.

Docking

On the Ravnkloa side, the ferry docked directly with its front towards the floating dock, while on the Fosenkaia side, a special floating dock was installed (see Fig. 6, left). This special dock is made ready for a future inductive charger and a latching mechanism to hold the ferry fixed to the dock.

As soon as the ferry reached the dock, the latch would open and create a walkway over to the floating dock (see Fig. 6, middle and right). The docking process, which started about 2 m from the dock, took between 20 and 60 s depending on the wind and current conditions at the time.

Undocking

To leave the dock, passengers had to push a button to start the ferry. The hatch would then automatically close, and the ferry would depart afterwards.

Charging

The ferry is designed for inductive charging through 4 inductive panels below the hatch on each side. However, during the trial operation, the inductive panels were not installed yet, and the ferry needed to be charged by connecting a cable twice every day for about 30 min. The operation was paused during the charging period. A sign was used to inform passengers waiting that the ferry was taking a charging break.

Safety

Safety was highly important during the trial operation. Before the trial operation, a detailed risk analysis was conducted. The ferry followed the current safety regulations for its size and had the safety equipment as presented in Fig. 7.

In case of an emergency the ferry will (1) go to the nearest dock, (2) emergency stop on DP, or (3) emergency stop by automatically dropping anchor. If passengers need to be evacuated, the Trondheim Fire and Rescue Service was prepared to respond with fast-moving vessels about 1.1 km and less than 5 min away from the trial operation area. In addition, the research team had small boats available next to the dock, prepared to go out if needed.

The operator could take over the control at any time if the autonomy system did not make the desired maneuver on the ferry. A portable VHF radio was on board for the operator to communicate with other vessels. Otherwise, the short distance for the area of operation allowed the operator to use visual communication. Prior to the trial operation, the research team was in close dialogue with the Norwegian Maritime Authority to make sure safety was in order.

Signs and information to passengers and public

To attract passengers to the ferry service and to inform them about the trial operation and the research study, we used media and created signposts and information signs as described below.

Press, media, and social media

To inform the citizens about the ferry service, an op-ed about the ferry service was written and published in the regional newspaper the day before the grand opening and official commissioning (Alsos et al., 2022a). In addition, a press release was published, and local, regional, and national media were invited. The opening attracted significant media attention that resulted in media coverage in more than 40 national and international media (e.g., Wang, 2022), which helped spread the word about the new ferry service. We also posted information about it on social media and the university intranet.

Signposts and street signs

In addition to media, we produced signposts, which were installed on the light poles around the city, and street signs that directed citizens to the ferry service. In addition, we spray-painted signs on the ground in the vicinity of the docks. Permission to set up the signs was given by Trondheim Municipality or Port of Trondheim, depending on who owned the area. Near the entrance to the docks, a red, highly visible tent was placed to protect the data collectors, questionnaires, and recording equipment from the diverse weather conditions (See Fig. 8).

Information to passengers

At the entrance of the docks, we placed a poster explaining how the ferry and its sensors worked. Onboard the ferry, a sign was displayed with the safety plan showing the location of safety equipment and emergency exits.

Method

In this section, we describe the data we collected and how we collected it during the trial operation.

Data collection

The data collectors were staff, postdocs, Ph.D. students, research assistants, and students associated with the Shore Control Lab (Alsos et al. 2022b). A team of 13 data collectors, wearing blue vests with the university logo and name tags, worked 4-hour shifts, with about 2–6 data collectors on each shift depending on the passenger traffic. The data collection took place near the dock entrances at Ravnkloa and Fosenkaia (Fig. 5).

Data collector protocol

The data collectors followed the following procedure:

For public and bystanders

Many citizens were either curious about what was happening and seeing the staff in university vests, or they knew about the ferry from social media and word of mouth or reading the posters and sign. Therefore, the data collectors used the following procedure:

For the public and bystanders

(1) Inform passers-by about the ferry service.
(2) Invite them to take the ferry.

Fig. 6. The special dock at Fosenkaia (left) and how the latch worked (middle and right). (Photo: Kai T. Dragland, NTNU).

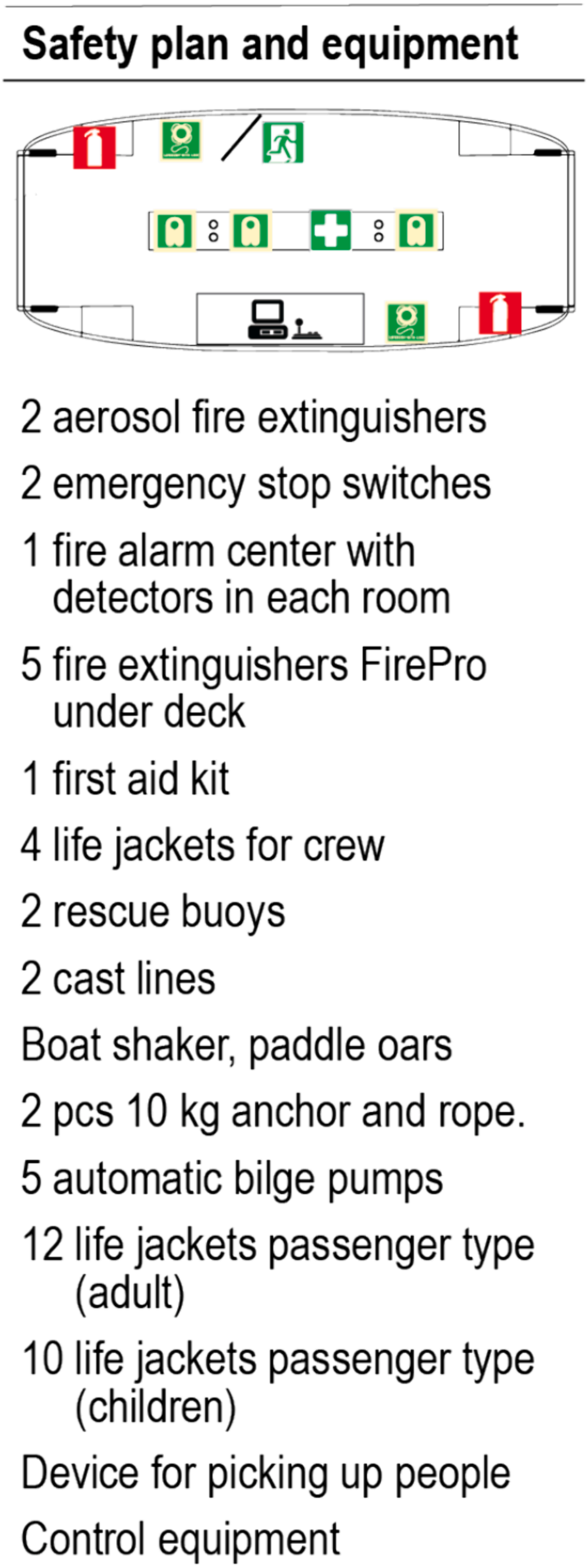


Fig. 7. Safety plan and equipment on milliAmpere2.

For embarking passengers

(3) Hand the passengers a clipboard with the *before-trip* questionnaire and ask them to fill it.
(4) Give a sticker, which contains a unique ID, to each passenger and ask (or help) the passengers to attach the sticker on their clothes.
(5) Collect the before-trip questionnaire and write the unique ID shown on the sticker on the questionnaire, as well as the time and date of the trip.
(6) Guide the passengers to wait on the dock.

For disembarking passengers

(1) Give the passengers a clipboard with the after-trip questionnaire and ask them to fill it out.
(2) Ask the passengers to take the sticker from their clothes and attach it onto the after-trip questionnaire.
(3) If the situation allows, for example, few passengers or more staff are working, ask the passengers to participate in an interview.
(4) If the passengers accept, conduct and record the interview with a voice recorder. Start the recording by saying the passenger ID and date.
(5) After the interview, ask permission from the passengers to save and use the recordings for research. If the passengers do not accept, delete the recordings immediately.
(6) Note down special conditions in an observation log, including passing traffic, weather conditions, e.g., rain and wind, and anything that could influence the ferry trip experience.
(7) At the end of the day, take the questionnaires and voice recorders into a safe storage space.

Later, the questionnaires were digitized, and the voice recordings of the interviews were transferred to a secure data server. Only NTNU devices were used, and the safe storage was accessible to the staff only.

Safety operator and technician protocol

A protocol was developed for the safety operators to instruct them on how to behave on board the ferry to reduce the influence that they could have on the passengers' behaviors. The protocol instructed the safety operators to (1) invite the passengers to push the button to start the ferry and (2) stay away from the onboard controls during the operation to show that they were not controlling the ferry. Initially, the protocol also instructed them not to interact with the passengers, but this instruction was found impossible to follow, because the passengers were seeking information and had so many questions.

Research ethics

The study was approved by Norwegian Agency for Shared Services in Education and Research (Sikt; Project no. 340097). The participants were made aware that they could refrain from the study at any time without any consequences. None of the participants were paid or rewarded in any way. All data were collected and safely stored on university equipment and file servers in accordance with the data management plan approved by Sikt.

Operation scenarios

During the trial operation, we used two different operation scenarios: *normal operation* and *kayak intervention.*

During the trial operation, the ferry crossed the canal under normal traffic conditions. We had no control over the traffic and did not take any precautions other than informing the tour operators and the port authorities about the trial operation. In 49 cases the autonomous ferry interacted with other boats of different sizes, e.g., kayaks, fishing boats, tour boats, and leisure boats, 396 of the remaining trips were classified as normal operations.

Fig. 8. Signposts, street signs (a, b, d, e) and the interview area at Fosenkaia (c). (Photos: Jooyoung Park).

For some trips during the last week, we deliberately sent a kayaker towards the ferry to interrupt its operation (see Fig. 9). The purpose of this kayak intervention was to investigate the passenger's perception of vulnerable traffic in the canal. A special interview guide was developed for the passengers who experienced the kayak intervention. This was done in 43 out 235 cases in the last week of the trial study. For more details about the kayak intervention, we direct the readers to future publications.

Data samples

During the trial operation, data samples were collected from both the ferry itself and different stakeholders related to the ferry, such as passengers, safety operators, technicians, and other boat drivers in the canal. The purpose of this section is to give a brief overview of the data collected. However, it is outside the scope of this article to discuss the details of the data, data analysis, or results. For more details on the analysis and results, we direct the reader to forthcoming articles about the trial operation.

System log data

During the operation of the ferry, the system logged data 4 times per second. The log followed the NMEA 0183, which is a combined electrical and data specification for communication between marine electronics such as GPS receiver, gyrocompass, autopilot, echo sounder, sonar, anemometer, and other types of instruments (National Marine Electronics Association, 2023). The log gave us data such as time, position, heading, roll, pitch, speed over ground, actual track, wind, battery status, and sensor fusion system status. This allowed us to calculate the speed and travel time of the ferry, monitor battery status, calculate power consumption, and record any deviations from the planned trajectory or stops that occurred.

Onboard CCTV recordings

The four CCTV cameras on board milliAmpere2 recorded videos of the waterways on all sides of the ferry. The passengers were usually not observed by these cameras. In addition, there was a downward-pointing 180-degree dome camera at the top of the mast that recorded video of the deck and area around the ferry (see Fig. 10). The purpose was to observe how the ferry interacted with other traffic during the trial and to analyze unexpected events that occurred.

Additional video recordings

We equipped the ferry with onboard CCTV and three GoPro 10 cameras for an ultra-wide view of on-deck activities and passenger interactions (see Fig. 11). Informed consent for recording was secured at boarding, and all data was securely stored. This setup also had the capability to live stream and remotely monitor the trial in a Remote Control Center (ROC) at the Shore Control Lab (SCL) (Alsos et al. 2022b). However, this feature was not utilized during the trial operation, as we made the decision to prioritize other aspects and conserve the network bandwidth for other more essential functions.

Technician's logbook

The technician on duty who overlooked the technical system onboard logged every expected and unexpected stop during a trip, as well as any other interesting observations and unexpected events that occurred. A total of 112 events were logged. The number of log entries and their degree of detail varied significantly with the technician on duty. Examples of events were ghost tracks, late detections, manual takeovers, complex tracking situations, too-fast dock approaches, dock lateral errors, strong wind gusts that challenged the DP system, etc. The log gave the technical team important information about the system's performance, and this was used to finetune the autonomy system during the days when the ferry was not operating.

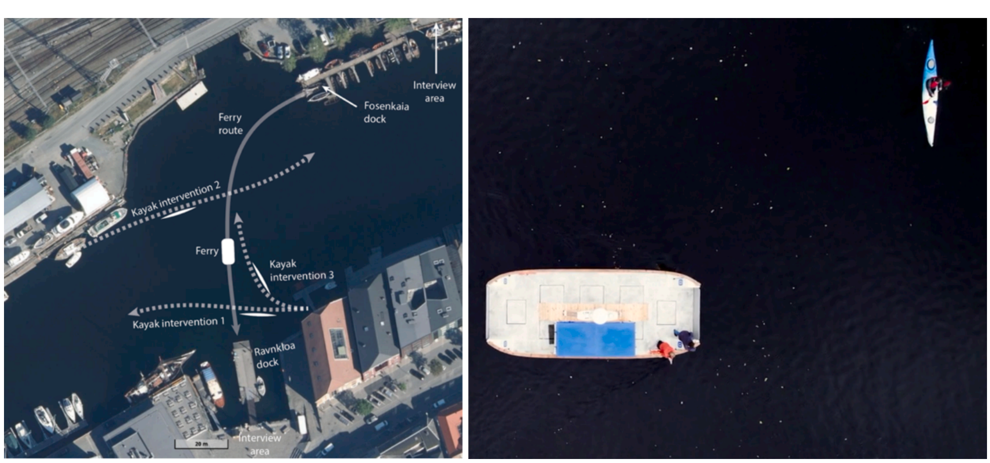


Fig. 9. The kayak intervention study and how the kayak approached the ferry. (Map: Norgeskart, Photo: Magnus Rønningen Hansen, Berre).

Fig. 10. A snapshot from one of the onboard CCTV cameras during a kayak intervention and dome camera during normal operation. (Photo: Felix M. Petermann).

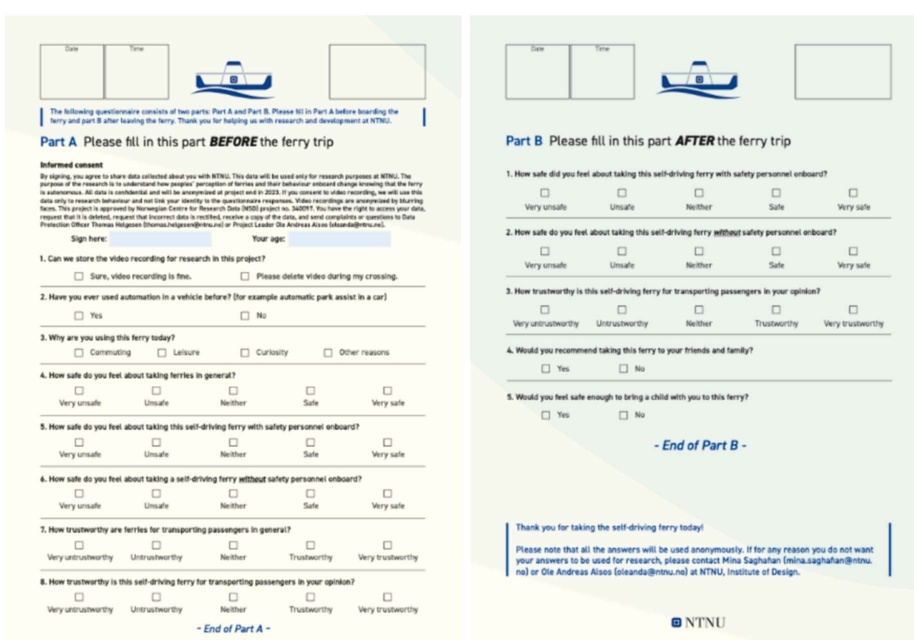
Fig. 11. Additional video recordings from the ferry. (Photo: Felix M. Petermann).

Technicians' debriefing workshop

About a week after the trial operation was finished, all the technicians who had overseen the ferry trial (N = 15), as well as some of the researchers responsible for the trial operation (N = 6), participated in a debriefing workshop. The purpose of the workshop was to discuss and document the performance and improvements of the following topics: (1) the autonomy system (sensing, situation awareness, motion planning, and system integration), (2) the ferry as a DP system, (3) the onshore and remote infrastructure (docking, charging, remote operation center, communication infrastructure), (4) passenger management, experiences and communication, (5) data gathering and (6) regulatory processes. The result of the workshop was a number of challenges and suggested solutions to the topics above. In total, there were documented 148 solutions/improvements in 27 subtopics.

Onboard observations

The data collectors would occasionally join the ferry trips and blend in with the passengers to observe their behaviour. No notes were taken by the data collectors on the ferry to avoid influencing the passenger behaviour by making it obvious that they are observed (also known as the Hawthorn effect (McCarney et al., 2007)). Immediately after the ride researchers would note down interesting observations that were discussed during a debriefing session. They also asked the safety operator and technician about any interesting observations or unexpected events,



Date | Time

The following questionnaire consists of two parts: Part A and Part B. Please fill in Part A before boarding the ferry and part B after leaving the ferry. Thank you for helping us with research and development at NTNU.

Part A Please fill in this part ***BEFORE*** the ferry trip

Informed consent

By signing, you agree to share data collected about you with NTNU. This data will be used only for research purposes at NTNU. The purpose of the research is to understand how peoples' perception of ferries and their behaviour onboard change knowing that the ferry is autonomous. All data is confidential and will be anonymized at project end in 2023. If you consent to video recording, we will use this data only to research behaviour and not link your identity to the questionnaire responses. Video recordings are anonymized by blurring faces. This project is approved by Norwegian Centre for Research Data (NSD) project no. 340097. You have the right to access your data, request that it is deleted, request that incorrect data is rectified, receive a copy of the data, and send complaints or questions to Data Protection Officer Thomas Helgesen (thomas.helgesen@ntnu.no) or Project Leader Ole Andreas Alsos (oleanda@ntnu.no).

Sign here: Your age:

1. Can we store the video recording for research in this project?
☐ Sure, video recording is fine. ☐ Please delete video during my crossing.

2. Have you ever used automation in a vehicle before? (for example automatic park assist in a car)
☐ Yes ☐ No

3. Why are you using this ferry today?
☐ Commuting ☐ Leisure ☐ Curiosity ☐ Other reasons

4. How safe do you feel about taking ferries in general?
☐ Very unsafe ☐ Unsafe ☐ Neither ☐ Safe ☐ Very safe

5. How safe do you feel about taking this self-driving ferry with safety personnel onboard?
☐ Very unsafe ☐ Unsafe ☐ Neither ☐ Safe ☐ Very safe

6. How safe do you feel about taking a self-driving ferry *without* safety personnel onboard?
☐ Very unsafe ☐ Unsafe ☐ Neither ☐ Safe ☐ Very safe

7. How trustworthy are ferries for transporting passengers in general?
☐ Very untrustworthy ☐ Untrustworthy ☐ Neither ☐ Trustworthy ☐ Very trustworthy

8. How trustworthy is this self-driving ferry for transporting passengers in your opinion?
☐ Very untrustworthy ☐ Untrustworthy ☐ Neither ☐ Trustworthy ☐ Very trustworthy

- End of Part A -

Date | Time

Part B Please fill in this part ***AFTER*** the ferry trip

1. How safe did you feel about taking this self-driving ferry with safety personnel onboard?
☐ Very unsafe ☐ Unsafe ☐ Neither ☐ Safe ☐ Very safe

2. How safe do you feel about taking this self-driving ferry *without* safety personnel onboard?
☐ Very unsafe ☐ Unsafe ☐ Neither ☐ Safe ☐ Very safe

3. How trustworthy is this self-driving ferry for transporting passengers in your opinion?
☐ Very untrustworthy ☐ Untrustworthy ☐ Neither ☐ Trustworthy ☐ Very trustworthy

4. Would you recommend taking this ferry to your friends and family?
☐ Yes ☐ No

5. Would you feel safe enough to bring a child with you to this ferry?
☐ Yes ☐ No

- End of Part B -

Thank you for taking the self-driving ferry today!

Please note that all the answers will be used anonymously. If for any reason you do not want your answers to be used for research, please contact Mina Saghafian (mina.saghafian@ntnu.no) or Ole Andreas Alsos (oleanda@ntnu.no) at NTNU, Institute of Design.

NTNU

Fig. 12. Questionnaires filled out by passengers before (left) and after (right) the ferry trip.

either from the passengers onboard, or from the traffic in the canal.

Passenger survey

A passenger survey was conducted to gather data on the public's experience with the autonomous urban ferry. The final questionnaire was divided into two parts: before-trip (seven questions) and after-trip (five questions) (see Fig. 12). It assessed passengers' previous experience with automation, trust, and safety perceptions towards ferries, and their willingness to recommend and use the service with family members. Responses were collected via paper forms, tablets, and smartphones. From 925 collected responses, after excluding minors and incomplete entries, 884 unique responses were analyzed.

Interviews with passengers

Semi-structured passenger interviews were conducted to gather insights into the experiences with the autonomous ferry service, focusing on trust, safety, convenience, and potential impacts on society and the environment. The initial interview guide was broad to scope out areas of interest, which was then refined into more focused questions in subsequent weeks based on passenger feedback and trial observations. The interviews also explored how passengers perceived the ferry's interaction with surrounding traffic and other waterway users. Over three weeks, 164 interviews ranging from 1 to 15 min were conducted, with the findings securely stored for analysis.

Interviews with other stakeholders

We interviewed various stakeholders involved with the autonomous ferry. Safety operators discussed their experiences and any control takeovers during the trial, with interviews averaging 15 min and one extended session lasting an hour. Additionally, 30 Norwegian Maritime Authority (NMA) employees, after riding the ferry, provided feedback on autonomous ferry challenges, opportunities, and regulatory implications, with 5 employees interviewed in-depth. Tourist boat operators, sharing the waterway with the ferry, were also interviewed about their experiences and perspectives on autonomous maritime transport.

Overview of data samples

In total, we collected 12 different data samples. These were of varying degrees of detail and quality, but together they gave a holistic overview of the performance of the system and the perceptions and opinions of a broad spectrum of stakeholders of autonomous passenger ferries. The data samples are summarized in Table 1.

Lessons learned

During the three-week trial operation of milliAmpere2, we conducted almost 500 trips and had more than 1500 passengers onboard. The 12 data samples gave us a broad and rich data set that allows us to analyze the trial operation from both technical and sociotechnical perspectives. This section presents the most important lessons learned from the trial operation, which may have value to other researchers conducting similar trials with other public transport carriers in different contexts.

Start with explorative and broad research objectives and finetune these throughout the process

The aim of explorative research is to find possible new areas of research and provide a starting point for possible analysis and more learning, as well as for exploring existing research areas but with the aim of producing new hypotheses that can be examined and verified in the future (Swedberg, 2020). New forms of research can also be explored to improve knowledge-making and knowledge-sharing. In multidisciplinary research, such as this trial, which is at the crossroad of technology interacting with human operators and the society it is embedded in, an explorative research study is a valuable toolkit to fulfill all three

Table 1
Overview of the data samples, their purpose, dataset, and data points.

Data	Purpose	Data set	Data points
System log	Measure the performance and status of the system	Timestamped log with speed, trip duration, power consumption, number of stops, maximum speed, number of crossings, equipment status, sensor readings, etc.	More than 5 million data points from 59 different data types
CCTV recordings	Observe ship traffic and unexpected events	Video recordings from different angles outside the ferry	4 of 12 days video from 5 cameras
GoPro recordings	Observe ship traffic, unexpected events, and passenger behaviour	Video recordings from different angles outside and onboard the ferry	3 days of video from 3 cameras
Technician's logbook	Identify unexpected events. Compare the different viewpoints of technicians and passengers. Compare workshops with technicians. Triangulation.	Log entries describing stops, unexpected events, traffic in the canal, close calls, etc. Log entries suggesting improvements	110 log entries
Technicians debrief workshop	Identify problems, unexpected events, and improvement suggestions	List of problems and ideas for solutions	173 list entries within 5 topics
Onboard observations	Collect data on passenger behavior before, during and after trip	Observation notes	Qualitative description
Interviews with passengers	Collect data on perception of trust, safety, employment, urban planning, transparency, usability,	Transcribed interviews	164 interview
Interviews with boat drivers in the canal	Collect data on the view and perspectives of other traffic	Transcribed interviews	4 interviews
Interviews with safety operators	Collect perspectives on manual takeover, unexpected events, skills, training, employment,	Transcribed interviews	6 interviews from two samples
Interviews with NMA	Collect data on regulations, challenges and opportunities with autonomous ferries	Transcribed group interviews	2 interviews, 5 persons
Passenger survey before trip	Understand passengers' expectations	Questionnaire data	884 surveys responses

(*continued on next page*)

Table 1 (*continued*)

Data	Purpose	Data set	Data points
Passenger survey after trip	Collect data on perceptions, opinions, and acceptance	Questionnaire data	884 surveys responses

aims mentioned above. Therefore, in addition to bringing tentative hypotheses and new research ideas to the surface within the realm of autonomous urban ferries, we aim to improve explorative research study methods by sharing how it was done and how it can be improved for this context. Such studies may include fieldwork, case studies, interviews, logs or diaries, and statistical data to find trends and map influential factors and actors.

In our case, the public trial lasted for an extended period with many passengers. It would be a missed opportunity if we focused on one research objective only. Our research protocol gave us the flexibility needed to start with broad and explorative research objectives and then adjust these based on the data that we already collected. The focus was primarily on the passengers' evaluation of the ferry, through qualitative and quantitative data collection, such as interviews and questionnaires. In addition, we mapped the passenger-ferry interaction, operator-ferry interaction through system and technician logs, and passenger-operator interaction through observation. The combination of pre-planned field observations, and in-situ data collection allowed us to capture the factors and actors, those who were affected by the autonomous ferry directly and indirectly. This also helped us to adjust our follow-up data collection process by improving the interview guide and expanding our data collection and logging capacity. In doing so, we also realized how we could conduct our research better and in a more effective way.

Depending on the duration of the public trial and the possible number of passengers, we recommend other researchers to start with explorative and broad research objectives and finetune these throughout the process. This approach would enable other researchers to investigate multiple research objectives from one public trial.

Understand the context and area of operation

We learned that the context and area of operation had significant influences on our public trial, and thus we recommend other researchers to understand the context and inspect the area of operation multiple times before conducting their trials. During the inspections, researchers need to pay attention to the types of vessels that travel through the operation area because they may affect the ferry trips and then consequently affect the passenger experience as well. They also need to pay attention to the existing infrastructure in the operation area to identify any accessibility issues.

Depending on where the operation area is located, researchers may need to acquire permission to use it. In our case, the operation area is owned by the Trondheim Municipality and Port of Trondheim, and we had to apply for permission several months before the public trial. Since acquiring permission can be a lengthy process, we recommend that other researchers apply for permission well in advance.

Depending on the operation area, there may be multiple stakeholders that should be involved or informed when planning or conducting the public trial. In our case, we had to communicate our plan and objectives with the municipality, port authorities, Coastal Federation, and businesses in the area. Such communication was important to ensure that our public trial did not have any negative impacts on their activity and business in the area.

At last, we identified potential hazards and assessed risks (HAZID) associated with the ferry and the data collection process. This helped us to mitigate risks and create a contingency plan. We recommend that researchers perform a systematic and structured HAZID before conducting the research.

Like any kind of user study, we recommend other researchers conducting pilot tests to check whether their protocols are appropriate for the characteristics and constraints of the operation area. Researchers should also pay attention to the number of people that may exist around the operation area since this could influence passenger handling and how data collection should be administered.

Be prepared for tactical adaption of the research protocol

We spent extensive time and effort on planning, reviewing, revising, and piloting the research protocol and data collection tools, such as questionnaires and interview guides, cameras and recorders. However, when putting the protocol into action, we found several challenges that we quickly had to solve. For example, we originally developed Norwegian and English versions of the questionnaires and interview guides. However, because of the arrival of several large cruise ships to Trondheim with German tourists – many of whom were not fluent in English – we quickly translated and printed new questionnaires into German and asked a German-speaking data collector to interview these passengers.

The duration of the trial operation, which lasted three weeks, led to another unexpected issue. After the first week of data collection, we realized that we already had enough data to make significant conclusions on our initial research questions. This allowed us to change the direction of the research trial as new research questions emerged by changing the interview protocol.

One of our research aims was to see how passengers reacted to the ferry's response to other traffic in the canal. However, we discovered that it was hard to control when kayakers and boats intervened with the ferry. As a response, we designed a controlled intervention study where one of the data collectors would intercept the ferry with a kayak to induce passengers' reflections on vulnerable traffic encounters.

The examples above demonstrates that a research protocol must have a certain flexibility and that a research team should have additional resources and capacity to take advantage of opportunities that appear during the research.

Be aware of biasing factors

Most passengers reported during the interviews and in the questionnaire that they trusted the ferry. We suspect that some of this trust could be contributed to the presence of the university logo on the ferry, the presence of researchers with blue vests and name badges, and a friendly and service-minded safety operator. In addition, we believe that several factors related to the area operation contributed to a low perceived risk and high level of trust: short travel distance, closed waters with no waves, high presence of people and other boats in the area, and a low operation speed. Finally, we believe that many of the potential passengers who initially did not trust the ferry instead took the detour across the nearest bridge.

One of the lessons learned was, even though the ferry was self-driving, how important the safety operator was for the passengers' trust and perceived safety. The safety operator welcomed the passengers on board and encouraged them to press the start button. The safety operator also answered questions about how the ferry worked and informed them what happened when the ferry occasionally stopped for other boats or took a long time to dock. We attempted to reduce these biasing factors by designing a protocol that gave the safety operators detailed instructions on how to behave to reduce their effect on the passengers' behavior. However, we quickly discovered that the safety operators did not follow all the instructions, since it was very hard for them to not interact with the passengers. This was partly due to them being professionals and service-minded, as well as the fact that they received many questions from the passengers. Based on this, we recommend researchers identifying and taking biasing factors into account when designing the research protocol and analyzing the results.

Prepare well for efficient data collection

We used cameras to collect data about the ferry's surroundings and sound recorders to interview the passengers. Both devices were running on batteries, and the data were stored on their memory cards. Empty batteries and full memory cards occasionally caused lost data, and we quickly created routines to have fresh batteries and empty memory cards ready. With this in mind, we advise researchers to consider the limitations of the equipment used for collecting data to ensure data collection can proceed without any disruption.

Conducting a public trial for a long period, as we did, requires a large team of data collectors. In our case, we had to hire additional data collectors, as it was not possible for our research group to carry out the entire public trial by ourselves. We recommend the recruitment be done well in advance to make sure the data collectors are available for the public trial and have the right training, personality, and language skills for handling and interviewing passengers. Once recruited, we recommend making a data collector rotation to ensure there it is enough manpower at any given time during the public trial.

To make sure the collection of data during a public trial could go smoothly, work needs to be done before and after the data collection. For example, before starting, researchers need to print enough questionnaires, bring all the data collection equipment, and set up the data collection area. After the data collection is finished, researchers need to dismantle the data collection area, safely store the filled questionnaires, transfer the data from cameras and sound recorders, store data according to the data management plan, and prepare recording equipment for the next day. We recommend other researchers to delegate responsibility within the research team, so that it is clear who is responsible for certain tasks on certain days.

We spent considerable effort in developing digital questionnaires so that we could use tablets or the passengers' own smartphones to collect data. We expected this could save us much effort in digitalizing the collected data afterward. However, on the first day of the trial operation, we realized that the passengers preferred paper, and it was much easier and more efficient to collect data through paper-based questionnaires since paper never run out of battery and do not need instructions. This allowed us to collect data much faster on the dockside, especially when the passengers arrived at the trial operation area in large groups. We also observed that very few passengers declined to fill out the questionnaire. Thus, the response rate was close to 100 %. We therefore recommend other researchers to prioritize conveniency for passengers.

Initially, the paper questionnaires were provided on paper clipboards that the passengers had to bring with them across the canal. This decision was made since it would be easier for the data collectors to match the before-trip and after-trip questionnaires from each passenger. However, we observed that they were distracted by the paper clipboards. Considering this, we decided to collect the before-trip questionnaire before the passengers departed and provided the after-trip questionnaire after they arrived on the other side. Because of this, we had to invent a tracking system so that we could link the before-trip and after-trip questionnaires. Our initial tracking system was to use the combination of origin, destination, time, and queue number as a unique and anonymous identifier for each passenger. However, this tracking system gave us many before-trip and after-trip questionnaires that could not be linked to the same person. To mitigate this issue, we implemented the sticker system as described in *Method*. This worked very well since it was easy for us to link the before-trip and after-trip questionnaires by using the numbers printed on the stickers, which were attached to the passengers' clothes. The tracking system was privacy compliant, and we therefore recommend other researchers to adopt a similar approach when collecting data from passengers before and after using the autonomous vehicle.

Plan for various weather conditions

Based on our public trial, we learned that weather conditions significantly influenced the data collection. During good weather, there were too many passengers for the data collectors to handle, while we had almost none when the weather was at its worst (Fig. 13). We learned that weather protection is important since the current milliAmpere2 had no roof for the passengers and that the data collection area should be protected. The tents that we used were not sufficiently weatherproof, and several times we had to run after blown-away paper questionnaires or protect the recording equipment from the rain. Strong wind noise also corrupted some of the interview recordings. On the positive side, we were able to collect data from "all seasons" except winter. Based on these experiences, we recommend researchers to consider all possible weather conditions before conducting a public trial.

Explore passenger diversity and accessibility

We had a wide distribution of passengers onboard during the three-week trial, including children, seniors, tourists, and commuters. While their age distribution generally matched that of the population in Trondheim, it was skewed towards a younger demographic (Veitch et al., 2024). The youngest passenger was five months old and the oldest was 96 years. We also had dogs, bikes, cargo bikes, strollers, and walkers onboard. Due to difficult access to both docks, with cobblestone on one side and a steep gangway on the other side (Fig. 14), we did not have passengers in wheelchairs onboard. Therefore, accessibility was a topic we could not explore in detail in the trial operation. However, the water level at the trial operation area was significantly influenced by the 2-meter tide difference. During the low tide, the access ramp to the floating dock on the Fosenkaia side became very steep, which posed a challenge for some of the passengers to embark and disembark off the ferry on the Fosenkaia side. This highlights the need for a tide-adaptive infrastructure to ensure passenger comfort and accessibility. We therefore recommend other researchers to explore passenger diversity and accessibility.

Use mixed-methods and plan for data triangulation

The interviews of the other voices, such as other boat drivers in the canal, safety operators, and representatives from the Norwegian Maritime Authority (NMA) gave us complementary perspectives on the perceptions of nearby ships, the performance of the ferry, the autonomous waterborne mobility, and regulatory issues. Therefore, we recommend that data is collected from multiple perspectives and not only passengers.

By itself, each of the 12 data samples we collected had different characteristics, details, quality, and significance (Table 1). However, when viewed together, merged, and triangulated, we expect the data to give us a detailed, meaningful, and comprehensive view of public perceptions of the milliAmpere2 ferry. Fig. 13 above shows an attempt to visualize some data samples with contextual factors, such as weather, tide, etc. Such visualizations can be useful to understand and explain usage patterns. We recommend other researchers to use a mixed-method approach and to use data triangulation when conducting trial operations of autonomous vehicles.

Consider the technological capabilities, performance, and limitations

In general, the technical performance of the milliAmpere2 ferry was good. One of the reasons for this was that we used a well-proved, commercial, and industry-standard DP system, as well as an autonomy system developed by a spinoff company based on the autonomy research at NTNU. However, there were situations, such as false track detection and unexpected stops, where the safety operators had to take over control of the ferry. Such situations happened several times at the

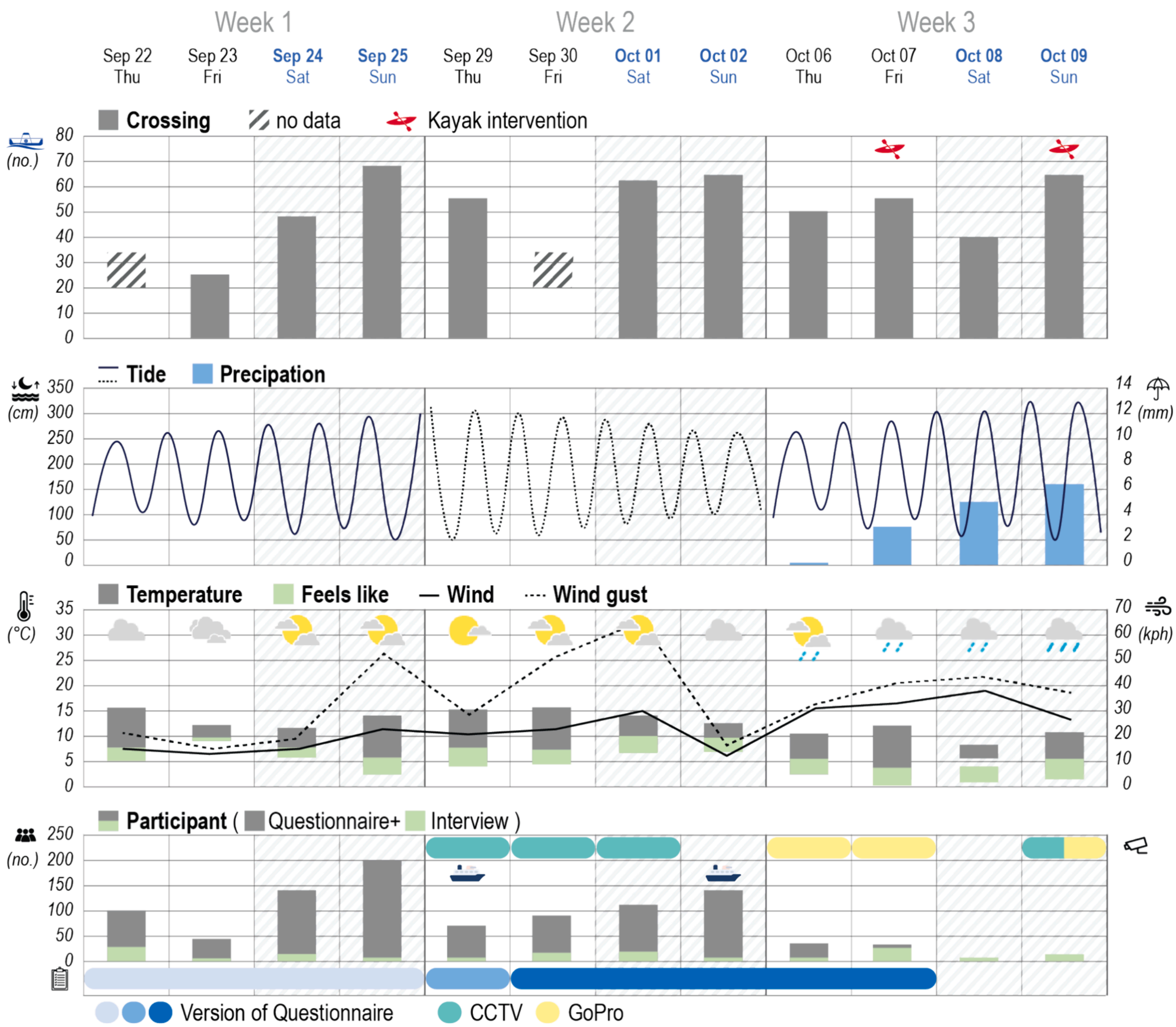


Fig. 13. Overview of the trial period, data collected, and variables of the environment. (Illustration: Jooyoung Park).

Fig. 14. Accessibility issues at the docks. Cobblestone (a) and steep gangway at Ravnkloa (b) and at Fosenkaia (c&d) during low tide. (Photo: Kai T. Dragland, NTNU).

beginning of the trial period and decreased to almost non-existent towards the end of the trial period. It is important to note that the safety operators did not have to take over the control due to dangerous situations, but only because the sensors were failing during heavy rain or false tracks due to stern waves or objects, e.g., leaves from trees floating in the operation area.

In our trial schedule, we had two days without operation to be able to find and fix issues that were discovered during the previous days and to make changes in the research protocol. We therefore recommend other researchers to add slack in the schedule to improve the performance of their autonomous system and to refine the research protocol. Further, we believe it is important for researchers to consider the technological capabilities and limitations of the autonomous vehicle to minimize the number of disruptions during the public trial. For example, the ferry had to be charged periodically and we had to stop the operation when the ferry was being charged. Therefore, we charged the ferry whenever there were no passengers so that the ferry would always be running when there were passengers. In addition, it is also important to have a backup plan in case of technical issues with the ferry, for example, having technicians available to fix technical issues.

Create a dissemination plan for sharing results and data

Conducting a public trial of an autonomous vehicle can generate a large amount of data. Having a dissemination plan can help prioritize what kind of data should be analyzed and what level of details should be provided to the intended audience. We also recommend publishing the data collected in an open-access database (such as Veitch et al., 2024) so that other researchers can access, review, and reuse the collected data.

Discussion

The trial operation of the milliAmpere2 ferry was to our knowledge the world's first operation of an autonomous urban passenger ferry open to the public over an extended period. It was, at the same time, one of the largest studies of the interplay between passengers and autonomous ferries, with observations of almost 500 crossings with more than 1500 passengers, questionnaires from 884 unique passengers, and 164 interviews from various stakeholders. Some key success factors were good timing, collaboration between professionals and students from a broad range of disciplines and study programs, and partnerships with various stakeholders.

In this paper, the main contribution to the research community is to describe the material and method of the trial operation; a detailed account of the autonomous ferry we used, the area of operation, how we planned and conducted the trial, how we collected data, and the lessons we learned. In this way, we hope that other researchers who plan to conduct similar studies can learn from our protocol and avoid potential mistakes and pitfalls. Our aim was to make a general research protocol that can guide researchers to conduct trial operations of autonomous passenger ferries.

Comparison with other public trials of autonomous passenger vehicles

Many studies presented in *Related Work* involved only passengers to investigate the public perception of autonomous passenger vehicles, even though some of them were conducted on public roads. Considering that there are other groups of people that may be present in the same environment as autonomous passenger vehicles, it is important to consider the perception of other groups of people as well. Among the studies presented in *Related Work*, Mirnig et al. (2020) was the only public trial that focused on the perception of other road users, e.g., pedestrians and other car drivers. Following the EU guidelines for trustworthy AI systems (European Commission, 2019), it is important to consider other groups of people when developing and testing AI-based systems. In the public trial of milliAmpere2, we not only managed to investigate the public opinion on the autonomous ferry from the passengers' perspective but also from other stakeholders' perspectives, including safety operators, technicians who monitored the ferry, engineers who programmed the system, the designers, the Norwegian Maritime Authority, and other boat drivers (see *Method*).

Most other studies investigating public perceptions of autonomous ferries (e.g., Goerlandt and Pulsifer, 2022; Munim et al., 2022) have done so with a narrow target group who have never tried such a ferry. In contrast, we collected data before, during, and immediately after the passengers had taken the ferry. This strengthened the validity of the data.

A major similarity between other public trials of autonomous passenger vehicles presented in *Related Work* and the public trial of the milliAmpere2 ferry is the presence of safety operators. This role is essential in such public trials to ensure the well-being of the participants and that other groups in the trial area are not harmed. However, as mentioned in the *Lessons Learned* section, the presence of the safety operator could affect the passengers' experience since the safety operator welcomed the passengers and answered all questions from the passengers. Among all the studies presented in *Related Work*, the public trial reported by Nordhoff et al. (2020) was the only public trial where the safety operator pretended to be an observer. Therefore, their passengers were not aware of the presence of the safety operator onboard the automated minibus.

Due to the novelty and explorative nature of this research, it was important to collect a wide range of data from all possible viewpoints to have a better understanding of the phenomenon at hand. In this context, data were collected from both locals and tourists, people of different ages, occupational and educational backgrounds, and people who were either technology enthusiasts or skeptics but nevertheless willing to try the autonomous ferry. Within our specific context, the data can shed light on acceptance of autonomous ferries based on how safe and trustworthy the public perceives them to be. Furthermore, the interviewees discussed and shared their own perspectives, predictions, and design possibilities. This means that the data collected is contextually rich and can be used to explore multiple trajectories in this novel context. This is aligned with our explorative research study objectives.

In *Related Work* we present some studies that conducted public trials of autonomous passenger vehicles. In those public trials, the data were collected from the passengers through questionnaires (e.g., Bernhard et al., 2020), interviews only (e.g., Nordhoff et al., 2019), or both (e.g., Launonen et al., 2021). In the public trial of the milliAmpere2 ferry, we managed to collect data from the passengers as well as from the autonomy system of the ferry, the surrounding environment, and other non-passenger stakeholders (see data collection section). Moreover, comparing the data from the autonomy system and the notes taken by the technicians and safety operators could also help us better understand the ferry's performance and behavior under different operational conditions.

Future research

This study was part of a series of planned trial operations, where we gradually want to move towards a team of operators monitoring a fleet of autonomous ferries from a land-based control center. However, to reach that goal, we need to move forward in small, controlled, and safe steps.

Our short-term plan is to conduct a new trial operation during the summer of 2024. This time we will try out new technical solutions, such as automatic passenger handling and passenger information screens, to allow us to move the safety operator from the ferry to a local operation center in the immediate vicinity of the area of operation. In parallel, we will collect data from Estelle in Stockholm, an autonomous urban ferry that was the first commissioned in commercial operation (since June 2023). The next step is to move the safety operator into the Shore Control Lab (Alsos et al. 2022b), an experimental remote-control center located in Trondheim. The last step is to let a team of operators simultaneously monitor and control a fleet of ferries.

Will we ever be able to replace the safety operator with buttons, information screens, and automatic voice prompts? In the same way that elevator operators disappeared from the elevators due to automation and better elevator user interfaces, we believe that the safety operator on board can be moved to shore when the technology is mature, reliable, and tested. Until then, as well as in the start-up phase of urban mobility services without personnel on board, we believe it is important to have a safety operator on board.

Conclusions

In this article, we presented the trial operation of the milliAmpere2 ferry, the world's first public operation of an all-electric autonomous urban passenger ferry. To date, the trial is the largest of its kind, investigating the interplay between passengers and autonomous ferries, with observations of almost 500 crossings and more than 1500 passengers.

The main contribution of the study to the research community is a detailed description of the material and method of the trial operation. This includes a detailed account of the autonomous ferry we used, how we conducted the trial, how we collected data, and the lessons we learned. In this way, researchers conducting similar studies can learn from our protocol and avoid repeating potential pitfalls.

CRediT authorship contribution statement

Ole Andreas Alsos: Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mina Saghafian:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Erik Veitch:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Felix-Marcel Petermann:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Taufik Akbar Sitompul:** Investigation, Writing – review & editing, Writing – original draft. **Jooyoung Park:** Visualization, Investigation. **Eleftherios Papachristos:** Formal analysis. **Egil Eide:** Software, Resources, Project administration, Funding acquisition, Conceptualization. **Morten Breivik:** Resources, Project administration, Funding acquisition, Conceptualization. **Øyvind Smogeli:** Software, Resources, Project administration, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The trial operation was funded by Trondheim Municipality, NTNU through the Pro-Rector for innovation, as well as the strategic research areas NTNU Oceans, NTNU Digital, NTNU Energy and NTNU Sustainability. It was also funded by the Norwegian Research Council through the projects SFI AutoShip (grant number 309230) and MIDAS (331921). In addition, the trial was supported by Trondheim Harbor and The Coastal Federation (Kystlaget).

The authors Eide, Breivik, and Smogeli have financial interests in the NTNU-spinoff Zeabuz.

Data availability

Data will be made available on request.

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