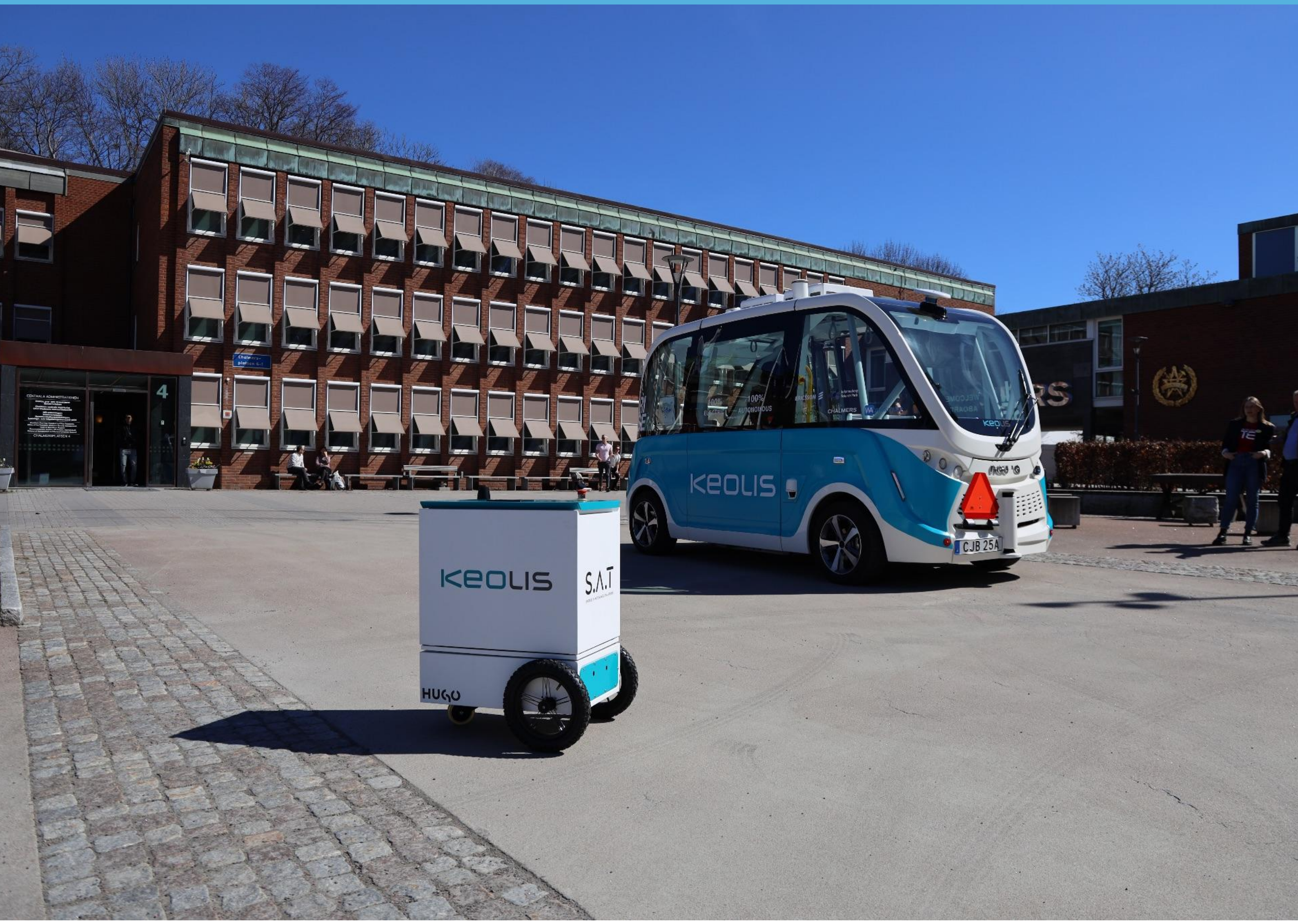
DRIVE SWEDEN



SAT- Synergies in Autonomous Transportation

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1. Summary

The SAT project is divided into five parts: business models, urban development, transport efficiency, digital interaction between traffic types (bus/robot) and user perspective.

In order to be able to carry out tests, the Hugo robot has been adapted for testing on the Chalmers campus, both to be able to deliver mail unmanned and to be able to travel with the autonomous bus.

Business models: business models and policy were evaluated to demonstrate the values and costs that a collaborative autonomous transport system is expected to generate.

Urban development: Opportunities, challenges and solution proposals for the implementation of automated last-mile freight and passenger transport from an urban development perspective. A particular focus was to identify possible synergies with coordinated system solutions of the two Transport Act, as opposed to treating them separate.

Transportation efficiency: conducted a comprehensive evaluation of integrating freight delivery by automated robots with autonomous public transportation. The primary objective is to assess the feasibility and to reduce energy consumption for the entire transport sector, including freight and passenger transport.

Digital collaboration: Communication between the autonomous bus and the robot was achieved through MQTT clients (Ericsson), which provide battery status and position updates.

User perspective: The result is (i) a concept for an automatic logistics system that uses delivery robots and which describes how this should be able to pick up, transport and deliver packages and mail completely unmanned, and (ii) a concept that gives suggestions for how a delivery robot should act and where in the traffic environment it works best – together with pedestrians, cyclists and/or motorists.

2. Swedish Summary

SAT-projektet är uppdelat i fem delar: affärsmodeller, stadsutveckling, transporteffektivitet, digital samverkan mellan trafikslag (buss/robot) och användarperspektiv.

För att kunna göra tester har Hugoroboten anpassats för testning på Chalmers campus, både för att kunna dela ut post obemannat och kunna åka med den autonoma bussen.

Affärsmodeller: affärsmodeller och policy utvärderades för att visa på de värden och kostnader som ett samverkande autonoma transportsystem förväntas generera.

Stadsutveckling: Här analyserades möjligheter, utmaningar och lösningsförslag för implementering av automatiserade last-mile gods- och persontransporter ur ett stadsutvecklingsperspektiv. Ett särskilt fokus var att identifiera möjliga synergier hos samordnade systemlösningar av de två transportslagen, i motsats till att behandla dem separat.

Transporteffektivitet: genomförde en omfattande utvärdering av att integrera godsleveranser av automatiserade robotar med autonom kollektivtrafik. Det primära syftet är att bedöma genomförbarheten och att minska energiförbrukningen för hela transportsektorn, inklusive gods- och persontransporter.

Digital samverkan: Kommunikationen mellan den autonoma bussen och roboten uppnåddes genom MQTT-klienter (Ericsson), som ger batteristatus och positionsuppdateringar.

Användarperspektiv: Resultatet är (i) ett koncept av ett automatiskt logistiksystem som använder sig av leveransrobotar och som beskriver hur detta skall kunna hämta, transportera och leverera paket och post helt obemannat, och (ii) ett koncept som ger förslag på hur en leveransrobot skall agera och var i trafikmiljön den fungerar bäst – tillsammans med gångtrafikanter, cyklister och/eller bilister.

3. Background

- **Why was the project initiated?**

The project was initiated in order to explore the possibilities of implementing autonomous vehicles in an existing urban environment and examine potential combined operations between these vehicles, it is also relevant to assess the feasibility of integrating autonomous vehicles into a delivery chain spanning various destinations and determine whether this can be accomplished in a fully autonomous manner. During these tests, data analysis will also be conducted to evaluate the efficiency, emissions reductions, and time savings compared to current methods.

The aim has been to show that interaction between a delivery robot and a self-driving vehicle is possible. The underlying idea can be summarized as increasing the delivery robot's range and shortening the delivery time by carpooling with self-driving vehicles. It has been shown to be possible

The rationale behind the workpackage 6 (user perspective) was twofold:

(i) Last-mile delivery (LMD) is considered the most inefficient phase in transportation of parcels and therefore also stands for a big part of the total transportation costs. Therefore, it is important to research possibilities to increase efficiency, and;

(ii) in an earlier study it was found that merely introducing a bot for transportation of parcels in the current logistic system at a campus led to a sub-optimal logistic system, increasing for instance the involved personnel's perceived workload. The reasons were primarily that the personnel had to stand and wait for the bot to deliver parcels, taking time from other tasks but also that the solution meant adding new tasks since the personnel had to assist the bot in opening/closing doors as well as loading/unloading the bot as the bot could not carry out these things by itself. This was deemed the consequence of the bot not being introduced as part of an overarching logistic system solution, supporting automated parcel deliveries during the last-mile. The findings motivated further research into what is required from a logistic system to support automated LMD at a campus.

- **Challenges and needs?**

The challenges inherent in this project revolve around optimizing the efficient utilization of the available resources. In earlier stages of the project, we encountered obstacles in facilitating the robot's capacity to navigate extended distances with optimal performance. We were cognizant of the inherent limitations within the robot's hardware and software domains. On one hand, the robot's lack of full autonomy necessitated manual intervention. On the other hand, subpar motor performance and insufficient CPU capacity impeded the realization of this objective, thereby adversely affecting overall performance.
To surmount these challenges, it is imperative that we explore novel solutions incorporating enhancements to both hardware and software components.

To make a logistic solution for the robot and AV to find each other
To board the robot on the shuttle

One challenge is to develop a logistic system that utilizes the possibilities that delivery bots enable. Therefore, there is a need to understand what aspects affect user experience and acceptance.

- Contribution to Drive Sweden's mission

Development of an autonomous robot and its interaction with other autonomous systems (i.e; the Keolis bus). This showed how multiple self-driving systems can contribute and complement each other when striving towards a zero-emission, automated public transport service.

It contributes in two ways, of which both relate to sustainability. First and foremost, by increasing the efficiency in the last-mile we can support a transition to a more sustainable logistic chain (in terms of resources needed), and finally, by considering people's experience and acceptance, the chance of a successful implementation increases.

WP2 (business models)
Autonomous deliveries constitute a network service, and the built environment, along with public transportation, form part of an emerging network of potential delivery routes and locations. It is challenging for actors involved in a network without formal collective ownership to demonstrate the value generated by their collective contributions. Economic, environmental, and social values created at the systemic level are difficult to capture in accounting terms and are rarely considered at the organizational level. Therefore, the business models of the network participants need to ensure that all actors have the correct incentives to act for the improvement of efficiency in the network and, consequently, the overall transportation system. Yet, it is uncertain how the actors within the system can and will cooperate to implement and scale up autonomous solutions.

There is a high and rising interest from the city development sector regarding how the implementation of self-driving vehicles will affect city planning, and vice versa. But there is little knowledge about what this implies in terms of key challenges and opportunities. Therefore, work package 3 had a threefold purpose: firstly, to contribute to solution proposals regarding implementation from an urban development perspective (project result objective 3), secondly to engage stakeholders in the real estate and urban development area and give them opportunities for learning and influence, and thirdly to bring together actors from different sectors to create new forms of cooperation opportunities.

The work in WP3 (urban development) addressed many different issues in addition to city planning, which was the main focus of AP3: primarily challenges with new business models, the need for digital solutions and the importance of policy development. Contributions have thus been created for several of Drive Sweden's thematic areas and effect logic.

The workshops in WP3 (urban development) have also brought together a wide range of actors from business, academia, and public actors, but the mix of disciplines and industries is also large with representation from: property owners, researchers, municipal traffic planners, traffic strategists, private property developers, urban developers, vehicle developers, community planners, telecom business developers, civil servants, traffic operators, innovation leaders.

WP (transport efficiency)
Last-mile Deliveries (LMD) refer to the supply chain's final leg, typically involving the trip to the retail or the final consumers. An efficient LMD is vital for a country's vibrant economy and quality of life. Also, LMD is not only the most expensive part of the supply chain but also plays a crucial role in local pollution, emissions, noise, and the safety of urban dwellers. In recent years, there has been rapid growth in LMD traffic due to the higher share of e-commerce, and home deliveries, augmented by the pandemic. The trends mentioned above in LMD have resulted in additional challenges to achieving sustainable urban last-mile deliveries across the globe. The existing strategies to enhance LMD performance are demand management, better emission standards for vehicles, transport management, and routing (Wang, Zhang et al. 2016, Holguín-Veras, Amaya Leal et al. 2018, Holguín-Veras, Amaya Leal et al. 2018, Ranieri, Digiesi et al. 2018). However, Automated Vehicles (AV), which include robots and drones, are less studied, and are one of the emerging technological advancements with a vast potential to revolutionize the LMD for a better future (Kalahasthi, Sánchez-Díaz et al. 2021).

The existing research primarily focuses on achieving the sustainability of freight and passenger transport separately instead of treating the transport sector as a single entity. Though slowly, the focus is shifting towards inclusive sustainability, i.e., combining freight with passenger transport, primarily aimed at utilizing the excess capacity of public transit during off-peak hours (Schröder and Liedtke 2017, Pimentel and Alvelos 2018, Bruzzone, Cavallaro et al. 2021, Cavallaro and Nocera 2021, Kiba-Janiak, Thompson et al. 2021). Hence, this study went a step further to investigate integrating autonomous vehicles in LMD (by robots) with the public transit (self-driving minibus) systems to reduce the externalities of the overall transport sector. The main challenges are finding an appropriate location for pilot tests, availability of demand (passenger and freight) data, infrastructure to support AV navigation and lack of methodologies for an efficient allocation of AVs and minibuses. This study overcame all the challenges mentioned above by testing the use of AVs for LMD (and passenger transit) in confined environments such as university campuses, collecting data on demand, typologies, shipment sizes, number of passenger boarding and alighting, network, performing pilot tests using robots and minibuses inside the Johanneberg campus and developing algorithms for optimal planning of robot deliveries, minibus stop locations and schedule.

The outcomes from this project directly come under the umbrella of Drive Sweden's vision of utilizing digital technologies to optimize vehicle usage, promote sustainable mobility, and improve people's health (Drive Sweden 2023). Automation could promote sustainable transportation by 1) Lowering the cost of transport compared to pickup trucks or vans (Ranieri, Digiesi et al. 2018); 2) Providing flexibility to customize the vehicle size, shape, and battery capacity for optimal usage of energy, and resources (Jaller, Otero-Palencia et al. 2020); 3) Reduction in pollution, congestion, and parking requirements (Jennings and Figliozzi 2019); 4) Improved safety as the robots operate at lower speeds, and equipped with collision avoidance sensors (Jennings and Figliozzi 2019).

4. Project set up

4.1 Purpose

Why is this project important and what was the purpose of the project?

To initiate constructive dialogue with diverse stakeholders operating within a prospective urban setting, encompassing entities such as property owners, public infrastructure providers, researchers, and developers.

One purpose is to develop a description of business models and policy alternatives that facilitate the scaling up and replication of autonomous deliveries from a business perspective.

There is a high and rising interest from the city development sector regarding how the implementation of self-driving vehicles will affect city planning, and vice versa. But there is little knowledge about what this implies in terms of key challenges and opportunities. Therefore, work package 3 gave important contributions with its three folded purpose: firstly, to contribute to solution proposals regarding implementation from an urban development perspective (project result objective 3), secondly to engage stakeholders in the real estate and urban development area and give them opportunities for learning and influence, and thirdly to bring together actors from different sectors to create new forms of cooperation opportunities.

The main purpose of this project is to investigate the potential of automation in improving energy efficiency and reducing the traffic congestion and noise of last-mile deliveries in confined environments. Also, this study aimed to explore the feasibility of integrating freight and passenger autonomous vehicles to enhance the overall performance of the transport sector. Smaller size automated robots that travel at lower speeds (~4 kmph) were deployed for cargo, while self-driving minibuses with a capacity of eight passengers were used for passenger transport. The key idea is to attach the robot externally to the minibus as much as possible to minimize the vehicle distance travelled, energy consumption, and traffic congestion.

To test interaction between freight robot and AV making the robot more endurant

The project was initiated to contribute towards a more sustainable, efficient, inclusive and safe urban goods- and passenger transport. The twofold purpose of the work package was to:

(i) Investigate what is needed from an automated logistic system concept that uses bots to support LMD at a campus to create a positive user experience and lessen users' workload?

and;

(ii) Further explore where and how a bot should interact within the public space to ensure a positive user experience and acceptance.

This, to be able to create concepts and prototypes to make the sending/delivery sequence as positive for the sender/receiver as possible whilst increasing their acceptance towards the solution.

4.2 Objectives

Describe the objectives of the project as it was described in the application. If the objectives have been changed explain why and how they have changed.

Work package 3 was responsible for result objective 3: Initial solution proposals linked to the implementation of automated last-mile goods and passenger transport from an urban development perspective. We have described proposed solutions so that they can contain recommendations and requirements regarding infrastructure, organization, and business models.

1. Estimation of freight and passenger transport demand:
   Freight deliveries to various buildings at Chalmers University occur from a central warehouse called Transport Central, from which the freight demand data for a year before the pandemic were collected and analyzed. Additional datasets were collected for the dimensions and weights of the shipments delivered, which play a crucial role in estimating the number of robots required, and the routing plan. The dimensions, and weights were then imputed in the freight data using statistical modeling approaches. The passenger demand was obtained from student enrollment and bus (line 55) occupancy datasets. The origin-destination (OD) flows between various bus stops were estimated based on the students visiting or leaving their respective department buildings. The OD flows were estimated per hour between 6-18, assuming the peak hours were 7-8 and 16-17.

2. Propose an Optimal Plan for Integrated Automation:
   The robot deliveries and the minibus schedule have conflicting objectives; the former aims to achieve the least possible total vehicle distance traveled while the latter tries to minimize the passengers' wait time. In addition, transferring packages from electric trucks to robots required solving two complex mathematical estimation problems. First, the 3-dimensional bin packing problem estimates the minimum number of robots needed to load the entire freight demand, which may not lead to the best possible solution for the least vehicle distance (energy consumed) traveled. Second is the vehicle routing problem, which provides the lowest vehicle distance traveled but cannot guarantee meeting the demand at each destination. Hence, this research built a heuristics-based algorithm to obtain the best possible plan to shift daily cargo to be delivered at each building at Chalmers University. The algorithm estimates the number of robots required, the packages to be loaded in each robot (placement of each package) and the routing plan to obtain the least energy consumption. The routing plan for the robots is merged with the transit schedule to facilitate the integration of the robot into the minibus.

3. Investigate the integration scenarios of robots to the self-driving minibuses:
   Integrating robots with self-driving minibus schedules depends on bus stops' number and location. Finding the right balance between the number of bus stops and the robot routes is vital for the combined system to work effectively. Because if the bus stop

locations do not coincide with most of the buildings the robot visits, the integration will lead to minimum savings. If the bus is made to stop at all the buildings the robot visits, the bus schedule will take longer and be unusable for the passengers. Hence, this project evaluated multiple scenarios before finding that the seven bus stops (Chalmerplasten, Sven Hultins plats, E-huset, Engdahlsgatan, Chalmers Tvargata, Kemi, Kapellplatsen) are the most feasible and effective in combined operations of robots and minibuses.

An interaction between self-driving vehicles and freight robots through carpooling has been shown to be possible. We have used the ramp of the self-driving vehicle to drive the robot on board. That system should be developed further in another project. A digital solution has been developed by Hugo AB where delivery robots and self-driving vehicles can be connected to be able to go to a delivery point. We have shown that the basics of combined deliveries will really work in a future smart city

One aim was to make LMD as complete and user-friendly as possible.

4.3 Project period

2022.01.01 - 2023.06.30

4.4 Partners

Hugo Delivery, Akademiska hus, Chalmers Tekniska Högskola, Chalmersfastigheter, Ericsson, Framtiden Byggutveckling, Handelshögskolan Göteborgs Universitet, Johanneberg Science Park, Keolis, Landvetter Södra Utveckling, MölnDala fastighets AB, PostNord, Riksbyggen, Skanska, Tele2, Trafikkontoret Göteborgs Stad, Västtrafik och Wallenstam.

5. Method and activities

- What methods have been used to carry out the project?

1. Data Collection Method: The focus of WP4 (Transportation efficiency) was to collect accurate data on the robot's consumption. To improve measurement accuracy, resources were allocated to develop software and create a detailed document for data collection. The data collection phase was condensed to one week, prioritizing measurement accuracy over the duration of data collection.
2. Establishing Communication with Keolis' Autonomous Bus: The project required the robot to coordinate pick-up and drop-off with Keolis' autonomous bus. However, keeping the robot loose inside the bus was deemed unsafe and inefficient. Determining

bus occupancy in advance without prioritizing the robot over people proved impractical. Therefore, this concept was explored in theory, and more details about pre-tests at the Keolis depot and a risk analysis document were available in the appendix folder.

3. Development of Separate Web Interfaces: To enable customer interaction with the robot Hugo for package handling, separate web interfaces were developed. The customer interface allowed account creation, tracking Hugo's location, and remotely controlling the box. The operator interface facilitated box monitoring, text messaging to customers, and lock/unlock control. These web interfaces were utilized during live testing in Stockholm in spring 2022, utilizing a flask-backend and JavaScript frontend technology stack.

In WP 2 (business models) workshops and multi-actor-multi-criteria-analysis were utilized together with interviews of key stakeholders.

Workshop with Ericsson and Hugo AB
Testing robot and autonomous vehicle at site for verification of boarding of robot in different situations

The data collection methods used were primarily based on semi-structured interviews and questionnaires. The analyses were based on thematic analysis and basic statistical methods.

- What activities have been performed?

* Driving at Linholmspiren to collect data to count on emission (Chalmers)
* Driving at Linholmspiren to collect data to see people's behaviors (Chalmers)
* Driving at ICA Maxi, Mölndalsvägen to collect data to see people's behaviors (Chalmers)
* Driving at Chalmers to test with fully automated delivery solution.
* Workshop at Handelshögskolan
* Workshop at Chalmers
* Workshop at Berge, Linholmspiren

In WP 2 (business models) workshops and multi-actor-multi-criteria-analysis were utilized together with interviews of key stakeholders.

The main activities of work package three have been six co-creative workshops:
1. One workshop dealing with user perspectives and associated design issues (2023, see AP6).
2. One workshop addressing business models that support scaling up in sustainable cities (2023, see AP2).
3. Two workshops dealing with implementation aspects in existing city districts (2022).
4. Two workshops dealing with implementation aspects in planned city district (2022).

To provide real conditions and objectives that strengthen the validity of the results, the analysis has taken urban development projects from participating parties' project portfolios as a point of departure. We looked at two planned districts (WS1 Forsåker and WS2 Landvetter södra) as well as a densification case in an existing district (WS3 Frölunda). In the fourth workshop, we focused more on collaborative aspects and citizen engagement. In the last three workshops, we had guest speakers who made important contributions to the work. Here we list the four workshops with the main issues addressed (for more details see the appendix):

- Forsåker, 5 April 2022
  - Where will self-driving vehicles drive? Coexistence? GCR tracks!
- Landvetter Södra, 2 June 2022
  - What infrastructure is required? Couplings to the physical planning process?
  - Guest: Sara Ranäng RISE "Future assurance of deliveries to new districts"
- Densification in Frölunda, 28 September 2022
  - 1) + 2) in the case of densification in an existing area? Coordination & sharing of P-hubs?
  - Guest: Anastazia Kronberg BRG "Cluster analysis micro mobility"
- Collaboration and citizen engagement, 24 November 2022
  - How to organize the collaborations between Robot + Bus? Which transport services can be made more efficient?
  - Guest: Vaike Fors University Halmstad "User perspective and citizen dialogue"

Regarding the layout, implementation, and results of workshops on user perspectives and business models, we refer to the corresponding other parts (WP2 and WP6) of this report.

The activities and respective approaches followed in each task are explained below.

1. <u>Data collection</u>
   1.1. Freight demand: A centralized warehouse known as “Transport Central” handles all the cargo deliveries at Chalmers University. The data on number of packages, typologies, and destinations were collected for a year right before the pandemic restrictions commenced. The dimensions, shipment sizes, and weights were unavailable, which played a crucial role in deciding the number of robots required. Hence, a sample of shipment sizes was collected for a week, which was then imputed to all the shipments in the year based on statistical and econometric estimation.
   1.2. Passenger demand: The bus schedule depends on the number of passengers boarding and alighting each stop per hour. Since the bus stops were non-existent before, the data were not available. An estimation of passenger demand is performed based on two datasets. Firstly, the student enrolment data from seventeen departments were collected. Second, the occupancy rates of the transit bus service (line 55) were processed to obtain the number of passengers boarding and alighting at the existing bus stops around the Chalmers campus.
   1.3. Network data: The GIS layers for the robot and bus network are different from the existing road network as these vehicles are smaller and can traverse routes that cannot be used by pickup truck or passenger buses. Hence, the GIS layer combining all possible links for robots and minibuses is prepared and processed to estimate the distances between the buildings and bus stops.
2. <u>Pilot tests</u>
   2.1. Robot: The autonomous delivery robot was driven across the campus, covering all the buildings to estimate the speeds, travel times, loading, unloading, and waiting times. In addition, the paths were geocoded to obtain the energy consumed by travelling in each network link. These tests were

performed for nine days, with varying weather conditions and setting the robot at different speeds.

2.2. Minibus: The self-driving minibus was driven for more than 30 days in January and February 2023 with an average speed of 4 to 5 kmph. The capacity of the bus is eight passengers. One of the key limitations was that the minibus pilot tests did not provide any data on actual passenger demand at the stops and energy consumption. Hence, this study used secondary datasets (student enrolment and public transit bus) for passenger demand. The energy consumption is estimated based on the findings from the literature as a function of battery capacity, occupancy, distance travelled, and speed.

3. Model development
   3.1. Heuristics-based algorithm for robot deliveries: Obtaining an optimal number of robots and respective delivery (routing) plan that minimizes the total energy consumption required an iterative process solving a 3D bin packing and vehicle routing problems. This study developed a heuristics-based algorithm to estimate the best possible solution for meeting the demand at each building using the least vehicle distance by the robots.
   3.2. Bus scheduling: The bus schedule was prepared based on the passenger demand during the peak (7-8 and 16-17) and non-peak hours, which minimizes the total wait time of the passengers.
4. Numerical analysis
   4.1. Scenarios for integrated deliveries: The bus scheduling and the heuristics algorithm were jointly used to estimate the robot delivery plans for different scenarios of bus stop locations.
   4.2. Estimation of energy savings: The total energy consumption was estimated and compared with that of pickup trucks for each scenario.

Mainly testing robot and autonomous vehicle at site for verification of boarding of robot in different situations. Digital solution for robot and AV to interact has been carried out separately by Hugo AB

The research design for the first part of the work package included:

(i) Focus group with recipients & senders,
(ii) ideation session with logistic service provider,
(iii) concept evaluation & ideation session with logistic personnel,
(iv) concept evaluation with logistic service provider,
(v) field trial with prototype,
(vi) concept evaluation with project actors, and;
(vii) workshop with project actors.

The research design for the second part of the work package included:

(i) a user study with bystanders i.e. pedestrians, cyclists and car drivers,
(ii) concept evaluation with traffic system expert, and;
(iii) workshop with project actors.

6. Results and Deliverables

- What are your findings?

1. WP4 focused on collecting accurate data on the robot's consumption. The data collection phase was condensed to one week to prioritize improving measurement accuracy.
2. Establishing communication with Keolis' autonomous bus was a challenge. It was unsafe to keep the robot loose inside the bus, and determining bus occupancy in advance without prioritizing the robot over people proved impractical.
3. Separate web interfaces were developed to enable customer interaction with the robot Hugo for package handling. The customer interface allowed account creation, tracking Hugo's location, and remotely controlling the box. The operator interface facilitated box monitoring, text messaging to customers, and lock/unlock control.
4. Live testing was conducted in Stockholm in spring 2022 using the web interfaces. The customer interface utilized a flask-backend and JavaScript frontend, while the operator interface used the same technology stack.
5. Tests were conducted in 2022 for Postnord to evaluate combined deliveries involving the local post service and a nearby grocery store. The aim was to assess customer response and benefits of merging two separate deliveries into one operation.
6. A new SMS-based communication system was developed for customers, similar to Instabox and Budbee. Customers received SMS notifications instead of using mobile apps, simplifying the process and enhancing customer interaction with the robot service.
7. The goal was to explore integrating the SMS-based communication system into Postnord's existing infrastructure, streamlining the customer experience, and reducing reliance on app-based interactions.

We have found it possible for the robot and AV to interact both by a digital system and physically by robot to board the AV via a ramp

The result of part one of the work package is a proposal for an overall concept based on a basic logistics principle that was identified as the most suitable for a university, company and/or hospital, namely: unmanned, predefined (set times when deliveries are made) and 'on-demand' deliveries where the person picking up the boxes with parcels and mail either does so on his/her own behalf (individual pick-up of mail and parcels) or on behalf of others (collective pick-up of mail and parcels).

However, this principle requires a number of features in order to work: an automatic and modular (thus scalable) logistics system based on delivery robots which includes at least two racks consisting of three rack-modules each. Both racks include spaces for two boxes each and one 'buffer' space. One rack is located at the local hub and the other rack is just outside the building where the sender/receiver works. The rack enables unmanned pick-up, transportation and delivery to the sender/receiver. This system is accompanied by a number of other features that need to be in place for this to work, such as the exchange of information between logistics personnel and the system, and between logistics personnel and sender/receivers; proposed layout changes at the local hub where the logistics personnel work, and one way for senders/receivers to interact with the rack via a phone application. The conclusion regarding this part of the work package was that the box size and the way to interact with the rack via the phone should be standardized, something that needs further investigation.

The result of part two of the work package is a proposal for a concept to increase the positive user experience of pedestrians, cyclists and motorists based on their needs and insights. The concept means that the delivery robots must act more predictively when they drive and deliver mail and parcels, but also when they interact with other road users, for example when they have to slow down for a pedestrian. The concept means that delivery robots primarily move together with people who are walking but must also be able to adapt their speed according to the surrounding traffic flow on occasions when they have to move with other types of traffic, such as cyclists. It was also identified that if and when delivery robots become a reality, there may be a high concentration of the same (which there was also a concern about). The proposal to minimize potential dissatisfaction and possible incidents with delivery robots when this happens is that when a threshold value is reached, which must be defined and calculated via further studies, for the number of robots, the delivery robots must have their own lane that is clearly defined and marked for all other road users. This is a step towards minimizing negative consequences such as poor user experience and that other road users may no longer accept the solution with delivery robots. In terms of when delivery robots should operate it was concluded that they can operate during all hours of the day but should if possible avoid rush hours. This to reduce possible incidents and/or bystander annoyance. Furthermore, it could also be observed that to minimize the risk of incidents and thus dissatisfaction the solution that is implemented must ensure that where the robot travels, it must be expected, be seen and show its intentions more clearly. Suggestions for this included a solution with lights on the robot that are at eye level of pedestrians and cyclists and that are visible when the delivery robot turns a corner.

- What has been delivered?

For WP4, our main objective was to collect accurate data on the robot's consumption. Originally planned for several weeks, we decided to prioritize improving measurement accuracy rather than extending the data collection period. Resources were allocated to develop software and create a detailed document for data collection. Consequently, the data collection phase was condensed to just one week. Additional information, including the Data Collecting Method and a route image, can be found in the appendix folder.
Another challenge we faced was establishing communication with Keolis' autonomous bus. The robot needed access to the bus and communication capabilities for pick-up and drop-off coordination. However, keeping the robot loose inside the bus was unsafe and had a low success rate for boarding. Determining bus occupancy in advance without prioritizing the robot over people proved impractical. Therefore, we only explored this concept in theory. More details about the pre-tests at the Keolis depot and the risk analysis document are available in the appendix folder.

To enable customer interaction with the robot Hugo for package handling, we developed separate web interfaces. The customer interface allowed account creation, tracking Hugo's location, and remotely controlling the box. The operator interface facilitated box monitoring, text messaging to customers, and lock/unlock control. These web interfaces were used during live testing in Stockholm in spring 2022. The customer interface utilized a flask-backend and JavaScript frontend, while the operator interface used the same technology stack.

In 2022, we conducted tests for Postnord to evaluate combined deliveries involving the local post service and a nearby grocery store. The goal was to assess customer response and benefits of merging two separate deliveries into one operation. Customers placed orders from XXL.se and Hemköp. A new SMS-based communication system, similar to Instabox and Budbee, was developed. Customers received SMS notifications instead of using mobile apps, simplifying the process and enhancing customer interaction with the robot service. The aim was to explore integrating this system into Postnord's existing infrastructure, streamlining the customer experience and reducing reliance on app-based interactions.

Tests that verified the interaction and a digital system als a DEMO- day for stakeholders was held on the 23rd of May.

Two concepts – One concept describing how an automated logistic system using bots should be designed to be implemented into a university, company and/or hospital, and another concept (included as a part in the aforementioned concept) suggesting how and where an automated delivery bot should operate to increase user experience and acceptance whilst 'en route'.

- State how the project is connected to Drive Sweden's vision and long-term + short-term stated goals

We believe this project supports the DS vision by leveraging digital technology to shape a more sustainable transportation system.

Since Drive Sweden's vision is *"...that Sweden takes a leading role in leveraging digital technology to shape a more sustainable transportation system."* The project supports that vision by doing foundational research on what is needed to create a more sustainable transportation system whilst at the same time developing synergies among many actors. Which was not only important for the current project but could in turn also support future collaborations between academia and private companies, increasing the possibilities for new innovations related to digital technology and sustainability.

- State how the project has contributed to Drive Sweden achieving our vision and set long-term + short-term goals

Digital solution are applied in this project for to optimize the use of different vehicles, also this project will enable the sustainable mobility for people and freight

The work package has contributed to Drive Sweden's vision by doing research on different users' needs. Needs that are fundamental to understand in order to create solutions that will be successfully implemented. By not understanding different user groups needs, efficient and sustainable solutions might not be accepted and thus not successful.

* For a zero emission future
* Sustainable delivery methods
* Development of an autonomous solution for public transportation and presenting it for public use.

In WP 2, workshops were conducted to explore three general business model setups for collaborative autonomous transportation. The setups aimed to evaluate different aspects related to stakeholder groups and their involvement. Key considerations included the role of the autonomous transportation system in the local area, the interaction between a mobility hub and the autonomous system, and the sharing of infrastructure costs. The three setups proposed were: 1) a local collaborative delivery system involving a combination of truck and delivery robot, coordinated through a mobility center; 2) a terminal-based autonomous delivery system utilizing a robot that coordinates with the transportation system and delivers to specific locations; and 3) a terminal-based local delivery system where the robot is transported by truck to an area near the destination. These setups were compared to the existing delivery practices, which involve trucks transporting goods between terminals, hubs, and delivery points.

Ten organizations took part in the assessment exercise to evaluate the impact of different scenarios on their respective goals and priorities. Multi-Actor Multi-Criteria Analysis (MAMCA) was employed for this purpose. The participants first described their organization's current situation and goals, then prioritized them by comparing each goal to others. They subsequently evaluated how the three scenarios would affect their ability to achieve their goals compared to the current situation.

A total of 48 goals were identified across the 10 organizations and categorized into five main categories: productivity, economy, environment, sustainability, and innovation. Participants recognized the overlap and significant interactions between these goals. Economic goals were considered the most important, followed by environmental, sustainability, productivity, and innovation goals.

The scenarios were ranked based on their aggregated scores. The local collaborative delivery system was ranked as the most attractive scenario due to its balance between social values and economic costs. It offered a high level of automation while facilitating local community-building functions. The terminal-based autonomous delivery system was the second most popular option, seen as futuristic and efficient but potentially challenging to implement due to a large number of robots moving through the city. The terminal-based local delivery system was considered the least attractive, combining unfavorable aspects of an autonomous system and a truck-dependent system. Participants discussed the use of hitching areas and combined spaces for pedestrians, bicycles, and robots, such as GCR lanes, which were seen as potential opportunities if properly utilized and adapted to traffic patterns. The current situation was generally regarded as the least favorable but also perceived as the least risky option.

The ranking of scenarios varied among different participant groups. Municipal actors and representatives of the transportation system highly favored the local collaborative scenario, while actors involved in technology and real estate development preferred the terminal-based autonomous delivery system. The differences in preferences stemmed from varying perspectives on the social value generated by a mobility hub and its significance to each group.

The establishment of a collaborative autonomous transport system is expected to be a complex process involving technological innovations, regulation, and behavioral changes. Collaboration and open innovation were identified as key factors for success, requiring the combination of technical expertise, production capacity, and market experience among various actors. Coordination and a unified information system were seen as necessary to minimize negative local impacts and enable cost-effective deliveries. Involving real estate developers early on and integrating transport solutions into urban design were considered important. Financial costs and risks associated with investments posed challenges, suggesting the need for risk-sharing and public ownership of key resources. Reshaping regulations and streamlining decision-making processes were requested to facilitate the adoption of autonomous technologies. Deregulation or re-regulation and policy instruments that incentivize resource efficiency were seen as ways to stimulate innovation while balancing risks and predictability.

Detailed results can be found in the appendix, but here are examples of some key observations and conclusions:

Challenges

- Cooperation and synergies require land, premises, streets, charging infrastructure, systems for loading and unloading, sensors and ICT systems that hold together throughout the value chain.
- The provision of such infrastructure is judged to be a challenge. And, how to ensure that it is used?
- Costs. How can different solutions be financially justified? Through direct profitability or that the area itself becomes more attractive?
- Stamp planning
- Agreements are concluded too early and are too inflexible so that they cannot be adapted to changing circumstances.

Possibilities

- Mobility houses/mobility hubs can improve efficiency and play a central role in achieving synergies between delivery robots and self-driving buses.
- Positive with early and ongoing dialogue with all stakeholders, "early discussions and late decisions"
- The municipal actors are central, and more governance/regulations may be needed.
- Sharing of infrastructure and mobility services within and between different detailed plans.
- The planning needs to include several detailed planning areas and consider aspects outside the area.

The work in AP3 addressed many different issues in addition to city planning, which was the focus of AP3: primarily challenges with new business models, the need for digital solutions and the importance of policy development. Contributions have thus been created for several Drive Sweden's thematic areas and effect logic.

The workshops in AP3 have also brought together a wide range of actors from business, academia, and public actors, but the mix of disciplines and industries is also large with representation from: property owners, researchers, municipal traffic planners, traffic strategists, private property developers, urban developers, vehicle developers, community planners, telecom business developers, civil servants, traffic operators, innovation leaders.

AP3 has thus given stakeholders in the real estate and urban development area opportunities for learning and influence and brought together actors from different sectors to create new cooperation opportunities. Overall, this creates good conditions for taking the next step in development towards real implementation, for example through larger demonstration projects in one of the addressed urban development projects.

This project found that if the robot deliveries were planned efficiently, they would reduce energy consumption by -23% to 84% compared to electric pickup trucks. The savings vary based on the demand profile, shipment sizes (dimensions and weight), and destinations. An average of 27% is possible if robots were used every day. However, some days, the electric pickup truck shows better energy efficiency. The robot's capacity (cabin size), weather, and speed are crucial to energy savings. The number of robots required varies from 2 to 18 depending on the demand, where 7 to 8 robots could fulfil the demand more than 50% of the days. Around 37 bus trips among seven bus stops were needed to meet the passenger demand. The Chalmers should own a maximum of six buses to fulfil the peak hour (7-8 and 16-17) demand. Attaching the robots to the minibuses has the possibility to reduce energy consumption by 16-35% compared to using robots alone. Since the robot currently shares the space with pedestrians, the size of the cabin is constrained to a cube of 60 centimetres. Bigger cabin sizes and higher robot speeds could result in more savings. All these results were based on the current freight conditions, passenger demands, minibus and robot features. The robot shares space with pedestrians, because of which a 60-centimetre cube limited the cabin capacity. The daily deliveries vary from 30 to 280, with the total vehicle distance travelled between 4.5 Km and 50 km. The estimated energy consumption of a loaded robot at an average speed of 4 kmph consumed 12.5 Watt-Hour per kilometre (Wh/Km) and 16 Wh/Km if the speed is 2.5 Kmph. The minibus, operated at four kmph, consumes around 390 Wh/Km.

This project directly assists Drive Sweden in achieving one of its prominent visions for sustainable transportation (Drive Sweden 2023), i.e., to use digital technologies, connected, and automated systems to support sustainable goods movements. This research developed a comprehensive plan and proved that the use of automation, and digital technologies, mainly connecting freight transport with passenger transit systems, could be potential future transport operations which are environmental-friendly, energy efficient, safer traffic conditions and occupies lesser road space. In addition, such projects could help make Swedish autonomous vehicles technology, startups, and industries globally competitive in solving real-world problems and expanding their businesses into the global markets.

7. Conclusions, Lessons Learnt and Next Steps

Areas for Further Investigation.
One area warranting further exploration is the wheel design on the Hugo robot. Specifically, the adoption of Ackermann steering or similar mechanisms should be investigated to address existing issues. Eliminating the use of caster wheels would not only enhance the ride quality and accuracy but also minimise vibrations during operation. Consequently, experiments involving a four-wheeled version of the Hugo robot are planned for the immediate future. Another important aspect to consider is the reduction of costs associated with various components, with the ultimate goal of achieving a more affordable price point for the robot. This entails investigating avenues for cost-cutting measures in components such as the computer system, cameras, and batteries. Furthermore, the development of a solution for multi unattended delivery poses a significant challenge.
The aim is to enable a robot to autonomously deliver multiple packages along its designated route. Designing an effective system to accomplish this task requires thorough

investigation and experimentation. Lastly, it is crucial to iterate on the robot and bus communication protocol, followed by the initial implementation on both the bus and robot platforms. Prior to physical deployment, conducting simulations to validate the effectiveness and reliability of the protocol would be a prudent approach.

In summary, the workshops and evaluations conducted in WP 2 provided valuable insights into the different business model setups for collaborative autonomous transportation. The local collaborative delivery system and the terminal-based autonomous delivery system emerged as the most attractive scenarios, while collaboration, coordination, and open innovation were identified as crucial for scaling up and creating a sustainable and well-functioning autonomous logistics solution that considers the needs of goods owners, riders and stakeholders. A split between public and private actors in their assessments of the scenarios indicated different views on value and scaling potential.

The findings emphasised the importance of cooperation between stakeholders to foster innovation and enable the successful implementation of a collaborative autonomous transport system. In conclusion, WP 2 indicates that further research is needed to support the successful implementation and scalability of collaborative autonomous transport systems. Efforts should be directed towards developing effective collaboration models, identifying regulatory opportunities, and exploring the benefits of autonomous systems for resilience and social sustainability. Addressing these research gaps will pave the way for a future where autonomous transportation contributes to a more efficient, equitable, and sustainable urban landscape.

Besides the large number of detailed results, the key findings of work package 3 are:

- Cooperation between delivery robots and self-driving shuttles can strengthen shared mobility and contribute to a more sustainable urban development.
- The systems for passenger travel and goods transport should be designed coherently – not as two separate solutions/services.
- Implementation of self-driving vehicles will affect planning/design of both new city districts and densification projects – and vice versa.
- The city development sector has a great interest, and the SAT participants are now judged to be better equipped for future real-world implementations.

The next step could be a more concrete feasibility study, maybe supplemented with key pilots, in close connection with some of the addressed city development projects.

The primary takeaway from this project is that automation in last-mile deliveries requires proper customised planning to be effective. Integrating freight deliveries and passenger transport is feasible. It has a huge potential for implementation in the real world due to its significant possibilities to eradicate the negative externalities of the transportation sector, especially last-mile deliveries. Automation leads to lower energy consumption (by 27%) and reduces traffic congestion and noise. The findings show that the implementation should start at a smaller scale, in confined environments such as university campuses, shopping centres, and residential colonies. The use of autonomous robots and self-driving buses (or their integration) at the urban or regional level needs further substantial research to evaluate practical challenges to user safety, energy efficiency, and feasibility.

Despite sincere efforts, a few limitations require future research. The main limitation is the need for primary datasets for shipment size (dimensions and weight) and passenger demand. These datasets should be collected at a larger scale to improve the accuracy of the estimations for energy savings. The robot and bus capacities were fixed to 60 centimeters cube and eight passengers, respectively. Further analysis is required to examine various scenarios for robot and bus capacities. Automation in the loading, unloading, entry and exit of buildings could be included in the project's next phase.

- Take-aways

We have seen that an integration of a freight robot and autonomous vehicle is possible from a digital and boarding/physical point of view

- What potential the results of the project have for future projects

That it is possible to combine different transports within a city environment, however further tests needs to be carried out

- Next steps

Physical integration platform needs further work to find a suitable solution. Ig do not physically mix goods and people

There is potential for a positive user experience and acceptance as well as for a successful introduction of automated logistic systems using bots.

An automated logistic system using bots to be used at a university, company and/or hospital should primarily be based on a combination of unattended (not logistic personnel present when a parcel is either received and/or sent), fixed (predefined times) and on-demand deliveries using both individual (the end-receiver receives his-or her own parcel) and collective delivery options (a representative for the end-receiver retrieving the parcel on behalf of him/her).

Bots should operate together with pedestrians until the concentration of bots (or other road users) becomes too high, then they need their own lane. However, where these bot lanes are most needed needs to be further investigated.

A bot 'segment and/or network congestion index' needs to be developed. This is to understand the threshold value when the number of bots in mixed traffic starts to become annoying and/or incidents start to occur and 'bot lanes' need to be introduced. To do so the factors relevant for such an index need to be determined.

Regardless of who the logistic service provider is, the way a sender/receiver uses a logistic service application on the phone and how the sender/receiver interacts with the rack used for unattended deliveries should be the same regardless of logistics service provider.

8. Dissemination and Publications

- How have the results been spread or will be spread?

* Through Chalmers social media
* Demo day at Johanneberg Science Park
* Video montage of Hugo and Keolis Autonomous working together
* Through Hugos Homepage
* Through Hugos Instagram

- State the publications published in combination with this project.

Demonstration movie.
www.youtube.com/watch?v=bILYiKjz5xA

Examples of communication and publications:

- Website: https://www.johannebergsciencepark.com/projekt/samverkande-autonoma-transporter-sat
- News: https://www.johannebergsciencepark.com/nyheter/trafikmote-mellan-sjalvkorande-fordon
- News https://www.johannebergsciencepark.com/nyheter/sjalvkorande-fordon-jobbar-ihop-pa-campus
- News WS1: https://www.johannebergsciencepark.com/nyheter/autonoma-last-mile-transporter-med-forsaker-i-molndal-som-testcase
- News WS2: https://www.johannebergsciencepark.com/nyheter/innovativ-mobilitet-testas-i-landvetter-sodra
- News WS3: https://www.johannebergsciencepark.com/nyheter/autonoma-fordons-paverkan-i-byggd-miljo

Media

- Article in Ny Teknik: https://www.nyteknik.se/sponsrad/goteborgsprojekt-far-autonoma-fordon-att-samverka-i-staden/2018774
- Article in BreakIT: https://www.breakit.se/artikel/36822/har-ar-svenska-omradet-som-redan-trafikeras-av-sjalvkorande-fordon
- Article in Transport & logistics: https://www.transportochlogistik.se/20220121/14073/chalmers-testar-sjalvkorande-fordon

- Article in Voister: https://www.voister.se/artikel/2022/01/sjalvkorande-fordon-i-trafik-testas-i-goteborg/
- Article in Transportnytt: https://transportnytt.se/nyheter/autonoma-fordon-i-par-test
- Article in Dagens PS: https://www.dagensps.se/teknik/chalmers-testar-sjalvkorande-fordon-tillsammans-i-stadsmiljo/
- Article in Bussmagasinet: https://www.bussmagasinet.se/2022/01/forarlosa-fordon-mots-i-goteborg/
- Article in Dagens Infrastruktur: https://www.dagensinfrastruktur.se/2022/01/21/mote-mellan-sjalvkorande-fordon/
- Article in Svensk Byggtidning: https://www.svenskbyggtidning.se/2022/01/14/johanneberg-science-park-drivkraft-i-regionalt-klimatinitiativ/
- Article in ETN: https://etn.se/index.php/nyheter/68639-testar-sjalvkorande-kombo.html

The results have been presented during a 'SAT Demo-day' the 23rd of May.

https://www.johannebergsciencepark.com/nyheter/samverkande-sjalvkorande-transporter-en-del-av-morgondagens-stadsbild

The project and results have been presented via an advertisement by Tele2 in NyTeknik (https://www.nyteknik.se/sponsrad/goteborgsprojekt-far-autonoma-fordon-att-samverka-i-staden/2018774).

The user-study conducted in the work package has been accepted for presentation at the 5th VREF Conference on Urban Freight in Gotheburg (18-20 Oct, 2023).

- State the publications published in combination with this project.

An article – '*Public Acceptance of Autonomous Delivery Robots inside Cities: A Case-Study conducted in Gothenburg, Sweden'* has been accepted for presentation at the 5th VREF Conference on Urban Freight in Gotheburg (18-20 Oct, 2023).

The below paper was presented at the Transpiration Research Board annual meeting in Washington DC in 2022.

- Kalahasthi, L., I. Sánchez-Díaz, C. Zhang, W. Bingcheng and S. K. Muthukrishnan. An Exploratory Study of Ground Autonomous Last Mile Deliveries: A Case of Chalmers University, Sweden.

<u>The below publications and conference papers under progress</u>:

- Kalahasthi, L., P. Sutar, L. Bishk, I. Sánchez-Díaz. Delivery Robots as a Sustainable Alternative for Last-Mile Deliveries: A Novel Algorithm for Packing and Routing. *Transportation Research Part C: Emerging Technologies.*
- Kalahasthi, L., K. Aditya, A. Abhishek, I. Sánchez-Díaz. Integrating Automated Last-Mile Deliveries with Self-Driving Bus Transit System. *Transportation Research Board Annual Meeting (Due on August 1, 2023).*

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Kalahasthi, L., I. Sánchez-Díaz, C. Zhang, W. Bingcheng and S. K. Muthukrishnan (2021). An Exploratory Study of Ground Autonomous Last Mile Deliveries: A Case of Chalmers University, Sweden (Submitted). Transportation Research Board Annual Meeting 2022, Washington D.C., USA.

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Wang, Y., D. Zhang, Q. Liu, F. Shen and L. H. Lee (2016). "Towards Enhancing the Last-Mile Delivery: An Effective Crowd-Tasking Model with Scalable Solutions." Transportation Research Part E: Logistics and Transportation Review **93**: 279-293.

Attachments

Attachment 1 WP2 Scientific Report.pdf

Attachment 2 SAT WP3_Report workshops.pdf

Attachment 3 SAT_Report_WP4.pdf

Attachment 4 SAT report WP 5 svensk.pdf

Attachment 5 Report AP6_MAK rev 6 - Final - User experience.pdf

Drive Sweden is one of the Swedish government's seventeen Strategic Innovation Programs (SIPs) and consist of partners from academia, industry and society. Together we address the challenges connected to the next generation mobility system for people and goods. The SIPs are funded by the Swedish Innovation Agency, Vinnova, the Swedish Research Council Formas and the Swedish Energy Agency. Drive Sweden is hosted by Lindholmen Science Park AB.

Published by - Sara Berge, Hugo Delivery AB

Drive Sweden is one of the Swedish government's 17 Strategic Innovation Programs (SIP). Drive Sweden gathers partners from academia, industry and public organizations and is working towards a vision for Sweden to take a leading role in leveraging digital technology to shape a more sustainable transportation system. The SIPs are funded by the Swedish Innovation Agency Vinnova, the Swedish Research Council Formas and the Swedish Energy Agency. Drive Sweden is hosted by Lindholmen Science Park AB.

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