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Integrating Autonomous Last-mile Deliveries with Public Transit

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Abstract

Lately, research has shown the potential of automation in freight transport by reducing energy consumption, emissions, noise, and operating costs—often focused exclusively on either freight (e.g., robots and drones) or passenger (e.g., automobiles and buses) transport. Hence, this research investigates the potential of technological advancements in self-driving and connected vehicles for better coordination between freight and passenger vehicles. To achieve the objective of integrating robotic last-mile deliveries with autonomous minibuses, Chalmers University in Sweden has been chosen as a case study. Pilot tests were conducted to measure the travel, handling, boarding and alighting times, and energy consumption for robots and the minibus. Freight and passenger demand were obtained from the historical daily demand data. Several scenarios for routing and bus stop locations were examined for the energy efficiency of freight deliveries via electric pickup trucks. The minibus required around 34 daily trips, operating two to three buses during peak times. The results demonstrated that robots exhibited superior energy efficiency at lower demand levels, while integrating with minibuses led to a further reduction in energy use by 20-50%. Two-way minibus movement maximised the overlapping of routes between the robot and the minibus, reducing passenger travel time; however, with an increase in the bus kilometres travelled. To reap maximum benefits of integration, it is vital to prepare an optimal plan considering the demand, vehicle size, routing, and bus stops to overlap with freight destinations.

Keywords: Last-mile deliveries; Automation; Integrated freight and public transit

1. Background and Introduction

One of the key aspects of urban mobility is the movement of goods. Efficient goods transportation supports local businesses and stimulates economic activity. With the rapid growth of e-commerce, last-mile delivery (LMD) has

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become increasingly important. It refers to the final step of the supply chain, in which goods are transported from a distribution centre to the end customer. LMDs are growing across the globe due to rapid urbanisation and an increase in demand for home deliveries, according to Boysen et al. (2021). As per a report published by Capgemini Research Institute (2019), LMD is not just the most expensive leg of the supply chain but also the most polluting. In urban logistics, LMD has various impacts, including noise pollution, traffic congestion, and traffic safety (Viu-Roig and Alvarez-Palau, 2020; Leite et al. 2022). Techniques that are now in place to improve LMD performance, such as transport management, routing, demand management, and improved vehicle emission requirements, are highlighted. Yuzhan Wu et al. (2021) focused on the shift towards inclusive sustainability, i.e., combining freight and passenger transportation during off-peak hours. In a simulation study, the Bruzzone et al. (2021) results showed that by combining freight and passenger transport in off-peak hours, resource utilisation can be optimised, congestion can be reduced, and transportation experiences can be enhanced. Pimentel and Alvelos (2018) introduced a mixed integer programming model for operational planning of an urban logistics distribution service that benefits from the existing passenger transport network. The model consists of assigning origin loads to inbound hubs, transferring the inbound hubs' loads to a bus service, and transferring the bus loads to bus stops, to be collected by micro-logistics operators operating environmentally friendly vehicle fleets. Mathematical models have also lately been developed for understanding the interaction between freight trams and cars at docking stations, according to Galkin et al. (2019). Li et al. (2014) showed that taxi networks could integrate people and parcels for urban mobility. From the perspective of a taxi company, the Share-a-Ride Problem and Freight Insertion Problem models are presented, and it is concluded that taxi-sharing systems perform best when requests are concentrated in urban centres. Hu et al. (2023) explored the use of an underground metro for the transportation of urban freight. Li et al. (2022) proposed a capacity matching model for integrating passenger and freight transportation. Performance evaluations suggested that the integration could result in reducing congestion and transport emissions. Simoni et al. (2020) presented a special version of the Weighted Interval Scheduling Problem to analyse the influence of different features on the robot's design and operation for last-mile deliveries. The study found that robot deliveries were quite efficient in highly congested areas. Autonomous public transport, however, has been relatively less explored. Pigeon et al. (2021) investigated factors affecting and usage of autonomous vehicles for public transport. The most important factors were found to be service (frequency and fares) and safety-related (road safety).

However, all the above-mentioned research focuses on human-driven freight and passenger transit, where the key challenges for integration, as presented by Rześny-Cieplińska (2023), are maintaining the same passenger service level post integration, consistent arrival times, and the presence of personnel on board to load and unload the goods, which could be overcome in the future through automation and connected vehicles. Hence, this research fills this gap by investigating potential integration of automated public transport and robot deliveries. Extensive literature on autonomous public transport is available. However, the same cannot be said for autonomous freight transportation, which is significantly underrepresented. Currently, freight transport and public transit systems operate independently, with separate vehicles, schedules, and infrastructure. The autonomous robots are primarily designed for short-range, on-demand delivery tasks within confined environments, such as transporting goods or documents across a campus or facility. In contrast, autonomous minibuses are intended for passenger transport over longer distances within the broader campus or urban area. The scope has been limited to focusing on integrating autonomous last-mile deliveries, replacing the pickup trucks with a driverless public transit system using the minibus. For robot deliveries, the results from the past research by Kalahasthi et al. (2022) have been incorporated. However, bus stops, scheduling, and routing were planned for an efficient matching with the robot deliveries. Combining the two could improve the overall transportation system by reducing the number of freight vehicles/vehicle kilometres travelled on our roads.

2. Study Area and Data Description

The study area is confined to the Chalmers University of Technology campus located at Johanneberg in Gothenburg, Sweden (Fig. 1a). Chalmers University is striving to create a 'five-star campus', with the goal to further reduce the environmental impact of the daily operations while fostering better transport facilities. At present, the transport on the campus comprises electric pickup vans for freight, and access via public transit is limited to the vicinity. The university has a central warehouse called Transport Central (TC), which handles all incoming and outgoing freight for more than twenty buildings on campus (see Fig. 1). Figure 1 also shows the road network for the minibus, the robot and the minibus used. Unlike shown in the picture, the robot is planned to be attached to the minibus on the outside using a magnetic locking system. This research combined several datasets about the robot operations, minibuses, and LMD at Chalmers University and various other secondary datasets, as discussed in the sub-sections. The primary data is the freight shipment data collected from March 16, 2019, to March 15, 2020, comprising information such as date, destination, package type, and sender information. The sample size was over thirty-two thousand packages for 248 days, with an average number of deliveries per day of about 132. In addition, about 70% of the days had between 100 and 170 deliveries.

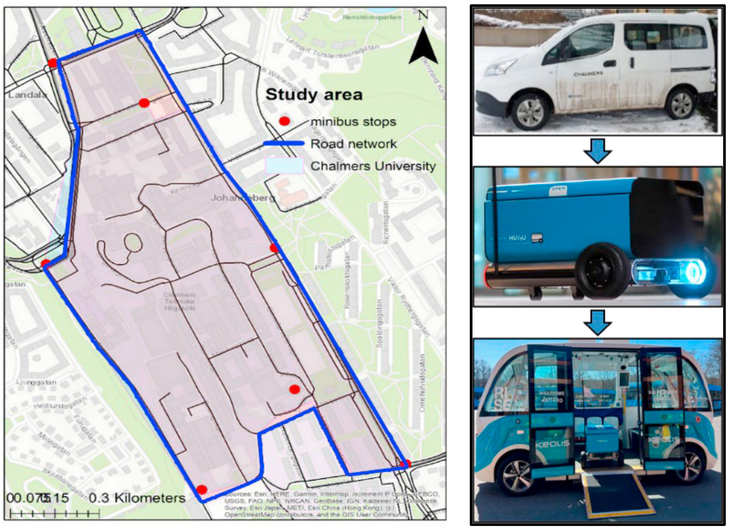

Fig. 1 (a) Study Area, road network, and minibus stops; (b) Minibus and delivery robot.

All freight goods coming inside the campus were divided into six types: pallets weighing over 25 kg (PALL), ordinary packages (PKG), personal letters and domestic registered mail (REK), cold packages requiring temperature-controlled storage (COLD), UPS, DHL, and FedEx express letters (EXP), and internal letters or packages (INT). Fig. 2 (a) shows the share of different types of packages, and Fig. 2 (b) shows the top five delivery destinations that attract about 85% of all deliveries. The PKG type of package is the most common type of package on campus. About 78% of the packages are ordinary packages (PKG). About 14% of the packages are of the EXP type. About 92% of the packages are of type PKG and EXP. The shipments' dimensions and weights were estimated using statistical inference techniques. For further details on robot deliveries, please refer to Kalahasthi et al. (2022).

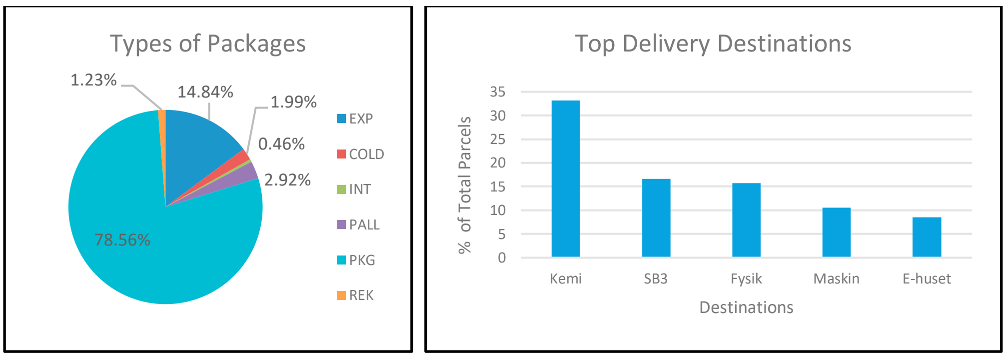

Fig. 2. (a) Share of different types of packages; (b) Top delivery destinations

Passenger demand data was unavailable for the self-driving minibus, as there was no existing service inside the campus. Two datasets were combined to deduce the passenger demand data for various scenarios of bus stops. Firstly, student enrollment data from seventeen departments was obtained for the academic term starting in January 2023.

Secondly, the passenger occupancy of the bus route line 55 was collected at four existing bus and tram stops via the four bus stops shown in Fig. 3. The figure shows the bus stops and the buildings near the bus stop. The four bus stops mentioned above were included in the minibus route. In contrast, additional stops were added, assuming passengers within a radius of 200 meters (by pedestrian walking route) would use these bus stops. The bus stops and nearby buildings (the bus stops serve the demand for) are marked in the same color. Data obtained from the bus route line 55 suggested that the morning and evening peak hours were 7 am-8 am and 4 pm-5 pm, respectively. Most people travel between 6 am and 9 am, and 3 pm to 6 pm. The GIS layers for the bus network were prepared, showing seven bus stops that can be adjusted based on passenger demand to maximise overlap.

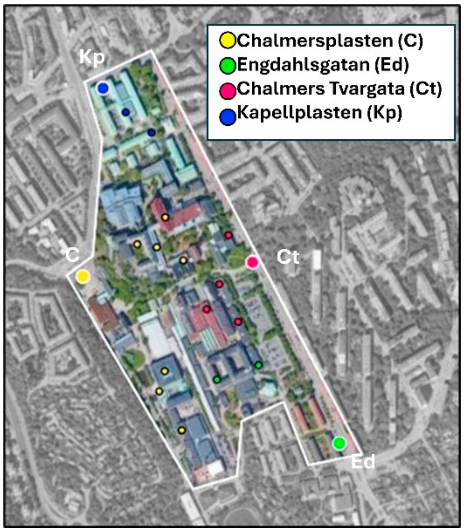

Fig. 3. Major existing bus stops and nearby departments

The robot network, with 21 destination buildings and the TC, operates on pedestrian paths and was manually built using open street maps in QGIS (version 3.40) developed by QGIS Development Team (2024). The bus routes differ from the robot routes, and the network includes existing bus stops and new ones. Minibuses and robots were deployed across the campus to gather data on location, travel times, speeds and energy consumption. The minibus was tested over 38 days: 7 days in January 2023 and 31 days from February to April 2023. Two identical minibuses, P94 and P95, each with a capacity of eight passengers, operated at an average speed of 4 to 5 kilometres per hour (km/h). The robot, with a cabin capacity of 60x60x60 cm, was tested for nine days between 2020 and 2022. The robot's energy consumption ranged from 12 to 16 watt-hours per kilometre (Wh/km), that varied based on cargo weight, cabin size, routing, and weather.

3. Methodology

The methodology comprises two parts. The first is focused on the effective transfer of parcels to robots, and the second is focused on preparing a public transport schedule.

3.1. Robot deliveries

The optimal plan for transferring freight parcels to robots is aimed at minimising total robot kilometres and energy consumption. This plan depends on daily package deliveries in terms of their size, weight and destinations. This involved solving a 3D bin packing problem (3DBPP) and a vehicle routing problem (VRP). The 3DBPP minimises the number of robots needed while the VRP finds the best delivery routes. The aim is to maximise the space utilisation within each robot to decrease the number of robots required. A heuristic-based approach, which packs first and routes simultaneously, was used to find the optimal path of the robot for each day. A wall-building heuristic was used for the 3DBPP and the VRP was formulated as an integer program using Dantzig-Fulkerson-Johnson formulation (Kalahasthi et al., 2022).

3.2. Scheduling procedure of minibus

Fig. 4 presents the flow chart of the steps for preparing the minibus schedule, developed by Vukan R. Vuchic (2005). First, bus stop locations were determined based on convenience for residents and workers.

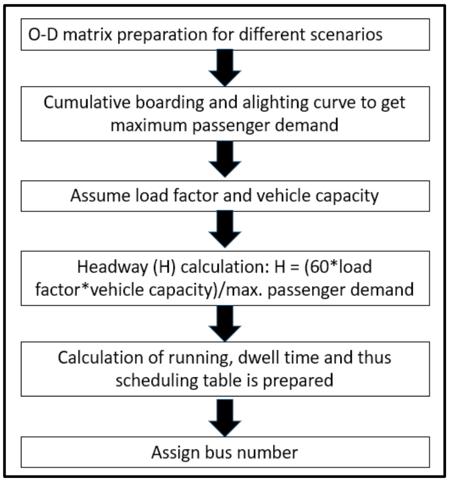

Fig. 4. Schematic of the minibus scheduling process.

Six different scenarios were built by varying the number of bus stops and their locations (Table 1). Throughout this paper, the names of bus stops have been abbreviated as follows: Chalmersplatsen (C), Sven Hultins plats (Sh), Engdahlsgatan (Ed), Chlamers Tvargata (Ct), Kapellplatsen (Kp), E-huset (E), and Kemi (K). Bus stop 'SB3' is the official building name and has not been abbreviated. One-way movement and two-way movement of the minibus were also considered. One-way movement refers to all buses traversing the clockwise route, i.e., C→Sh→Ed→Ct→Kp. While the two-way movement means the schedule involves buses traversing in both clockwise and anticlockwise directions.

Table 1. Bus Stops and Routes for Various Scenarios.

Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
C	C	C	C	C	C
Sh	Sh	Sh	SB3	SB3	SB3
Ed	E	E	Sh	E	Sh
Ct	Ed	Ed	Ed	Ed	E
Kp	Ct	Ct	Ct	Ct	Ed
	Kp	K	K	K	Ct
		Kp	Kp	Kp	K
					Kp

An Origin-Destination (O-D) matrix was prepared using the passenger demand estimates, mode choice (assuming 3-4% of students will use the minibus service), and mode split (60% of passengers use public transportation during peak hours, while 20% do so during off-peak hours). These estimates were established using results obtained from the minibus pilot test. O-D tables were built for different scenarios and different time periods. Cumulative boarding and alighting curves show the total number of passengers boarding and alighting a vehicle over time. This helps us estimate the maximum passenger demand. Fig. 5 shows the cumulative boarding and alighting curve for scenario 1 during off-peak hours.

The load factor, defined as the ratio of utilised capacity to total capacity, is taken as 0.8 since buses generally run at 80% capacity most of the time. A minibus with a capacity of 8 passengers was used for this analysis. Headways, defined as the time interval between two consecutive vehicles on the same section of the road, were calculated using the formula mentioned in Fig. 4.

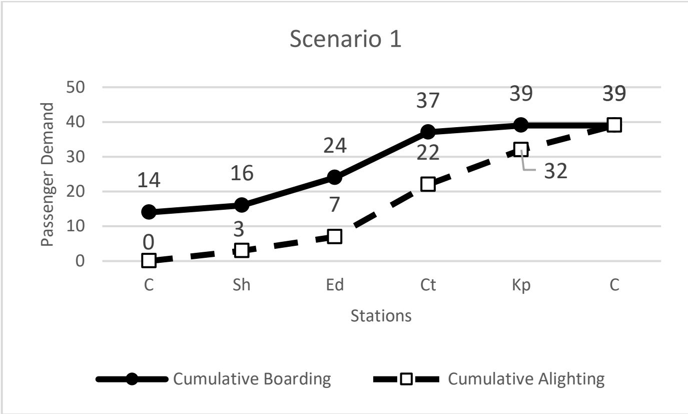

Fig. 5. Cumulative boarding and alighting curve for a trip in scenario 1.

The travel and dwell times were estimated based on the pilot test results. Schedules were created to ensure buses arrive frequently to minimise wait times. Next, buses are assigned to routes efficiently to avoid idle buses and meet passenger demand. Table 2 presents the schedule chart for Scenario 1. The table shows the distance between the stops, the time taken to reach the stop from the previous stop, and the dwell times.

Table 2. Schedule chart for scenario 1.

Bus No./ Station	**C**	**Sh**	**E**	**Ct**	**Kp**	**C**
1	06:00	06:08	06:15	06:23	06:35	06:41
2	06:20	06:28	06:35	06:43	06:55	07:01
3	06:40	06:48	06:55	07:03	07:15	07:21
1	07:00	07:08	07:15	07:23	07:35	07:41
2	07:07	07:15	07:22	07:30	07:42	07:48
4	07:14	07:22	07:29	07:37	07:49	07:55
3	07:21	07:29	07:36	07:44	07:56	08:02
5	07:28	07:36	07:43	07:51	08:03	08:09
6	07:35	07:43	07:50	07:58	08:10	08:16
1	07:42	07:50	07:57	08:05	08:17	08:23
2	07:49	07:57	08:04	08:12	08:24	08:30
4	07:56	08:04	08:11	08:19	08:31	08:37
3	08:03	08:11	08:18	08:26	08:38	08:44
1	08:23	08:31	08:38	08:46	08:58	09:04
2	08:43	08:51	08:58	09:06	09:18	09:24
			Summary			
Distance (*km*)	0	0.557	0.37	0.51	0.7	0.4
Running time	00:00:00	00:08:00	00:06:00	00:08:00	00:11:00	00:06:00
Dwell time	00:00:30	00:00:30	00:00:30	00:00:30	00:00:30	00:00:30

The robots undertake a circular tour while the minibus takes a predetermined route. The shortest path for the bus was found using Dijkstra's algorithm (Dijkstra, 1959). Each segment of the robot route was compared against the shortest path to identify overlaps. Hence, the segments where the robot can travel concurrently with the bus were identified. It should be noted that a robot could take two routes in visiting destinations, as the travelling salesman problem with constant costs (distances) has two optimal solutions. For example, a robot with an optimal route traversing TC, Kemi, SB3, TC, could also take the route TC, SB3, Kemi, TC. Both routes would lead to the same distances.

4. Results

The methodology presented above was followed for all the scenarios. The total energy consumption by the minibus and robot was calculated by multiplying the energy consumption rate (obtained during the pilot run) by the total distance travelled. The number of parcels to be delivered in a day obtained from the freight dataset was arranged in ascending order, and every 5th percentile was used to evaluate the energy savings. Energy savings were calculated for all scenarios when the buses were allowed to move only in a clockwise direction, only in an anticlockwise direction, and both. Results obtained from evaluating the different scenarios are presented in this section. It was found that allowing two-way movement of minibuses significantly increases energy savings. Table 3 presents descriptive analysis of energy savings for different scenarios with two-way movement of the minibus. Since we have considered every 5th percentile, twenty-one data points exist for each scenario. The table presents summary statistics, including the minimum, maximum, quartiles, mean, and standard deviation of percentage energy savings for each scenario. On average, automated deliveries reduced short-distance travel energy use by 27% to 84%. It was found that combining robots with minibuses could save even more energy, between 20 and 50%, with an average of around 40% compared to just using robots alone.

Table 3. Descriptive analysis of % of energy savings (two-way movement of minibus).

Statistic	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Count	21	21	21	21	21	21
Mean (%)	0.01	3.81	40.71	49.14	51.64	52.42
Std. (%)	0.01	4.56	13.61	15.27	14.68	14.74
Min (%)	0.00	0.86	19.00	21.95	21.95	21.95
Q1 (%)	0.00	1.41	31.09	37.27	44.16	46.70
Q2 (%)	0.01	1.76	40.83	50.88	54.23	54.38
Q3 (%)	0.01	3.43	49.11	57.88	59.12	60.49
Max (%)	0.02	16.63	73.94	77.03	77.83	77.83

Figure 6 (a) represents the energy savings for scenario 6 with one-way and two-way movement of the minibus. Energy savings are similar for clockwise and anticlockwise movement of the minibus, but an increase in energy savings can be seen when two-way movement of the bus is allowed. Figure 6 (b) shows the energy savings for all scenarios with two-way movement of the minibus. Scenario 6, involving 7 bus stops, was optimal and resulted in the highest energy savings. Scenarios 1 and 2, with 5 and 6 stops, respectively, had fewer overlapping legs with the robot's path.

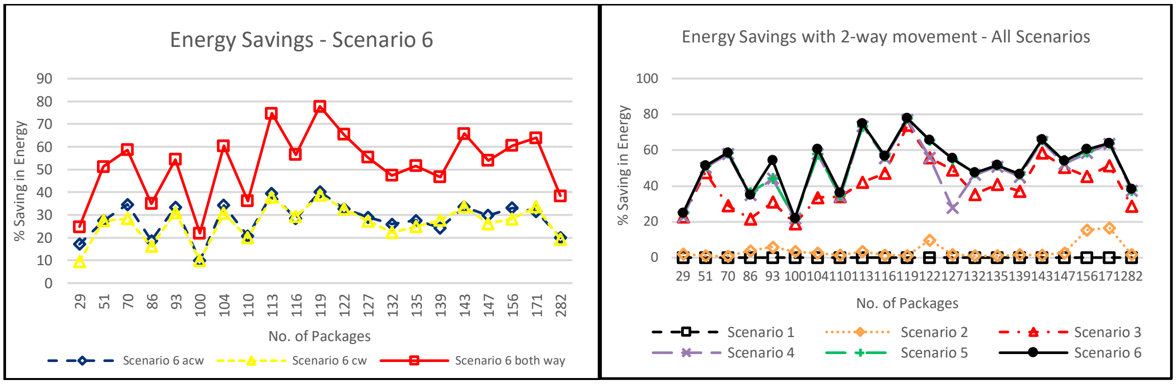

Fig. 6. (a) Energy savings for scenario 6; (b) Energy savings for all scenarios with both way movement.

5. Conclusions

Integrating public transport with last-mile deliveries through autonomous robots and self-driving minibuses offers a transformative approach to urban logistics. This model can significantly reduce traffic congestion by utilising existing public transit networks for freight movement, minimising the need for additional delivery vehicles. Energy consumption and emissions can be lowered as autonomous delivery robots coordinate with shared transport infrastructure, optimising routes and reducing idle time. Pilot programs in controlled environments like university campuses and shopping malls will help refine these systems, addressing technical, operational, and regulatory challenges before implementing them in larger urban areas. These trials can provide insights into vehicle coordination, scheduling, and interaction with pedestrians. Integrating autonomous freight with public transport could also turn transit hubs into efficient urban logistics centres, allowing for seamless transfers between delivery robots and minibuses. This innovation has the potential to enhance overall system efficiency, improve convenience for businesses and consumers, and reduce last-mile delivery costs. As cities continue to grow and demand for e-commerce rises, such solutions will play a crucial role in ensuring sustainable and efficient urban freight movement. Hence, the future of transportation revolutionised by automation and connected vehicles must include two key aspects. First is to optimally plan for combining both public transit and freight. Second is to have a real-time integration mechanism to minimise traffic congestion, emissions and energy consumption, as this research has shown there is considerable benefits associated with it.

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