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Ride Parcel Pooling – Sustainable Integration of Parcel Services into Mobility-on-Demand Systems

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Executive Summary

The transportation sector is currently facing four interrelated challenges: climate change, urbanization, the expansion of e-commerce, and changing urban mobility needs. Climate change, fueled by escalating greenhouse gas emissions, has triggered extreme weather events and rising sea levels, posing a global threat. At the same time, urbanization has skyrocketed as people migrate to cities in search of better economic prospects, leading to denser urban populations and increased traffic. The e-commerce boom is another notable development, with online shopping and home delivery contributing significantly to greenhouse gas emissions, particularly in the area of last-mile delivery. This surge in e-commerce inevitably translates into increased urban freight activity, exacerbating traffic congestion, road accidents, and adverse public health impacts. As urbanization and e-commerce continue their upward trajectory, the need for a paradigm shift in urban mobility becomes increasingly urgent. The current transportation system, dominated by private cars and trucks, is unsustainable and poses significant environmental, economic, and social challenges. Addressing these challenges requires a multifaceted approach that combines policy initiatives, technological advances, and behavioral changes. Emerging technologies, such as vehicle electrification and the digitalization of mobility services, hold great promise for promoting sustainability, especially in urban environments where people and transportation systems are closely intertwined. Meanwhile, behavioral changes, including increased reliance on public transit, carpooling, cycling, and walking, offer opportunities to reduce the prevalence of single-occupancy vehicles on the road. In summary, climate change, urbanization, the growth of e-commerce, and evolving urban mobility demands form a complex web of challenges that require a comprehensive strategy to address their significant environmental and societal impacts.

In recent years, a very interesting branch of research has developed in the field of passenger and freight transportation. This involves the combination of passenger and freight trips, especially in urban areas where space is a scarce commodity and transport externalities have a direct impact on residents. The most sustainable approaches aim to use existing passenger trips for additional freight transport within the city. This is a promising approach not only from an environmental but also from an economic point of view, as the last mile accounts for 30-40% of the cost of a parcel shipment.

First, this research analyzes the state of integrated transportation systems for passengers and freight in research and practice. This thesis extends the current state of research by introducing a novel urban mobility service, hereafter referred to as Ride Parcel Pooling. It then explores the possibilities and best practices for evaluating urban mobility vehicle fleets in a holistic manner, taking into account the entire life cycle of mobility services. Second, this thesis defines the envisioned Ride Parcel Pooling service by evaluating the state of the art and defining the most promising combination of passenger and freight transportation.

Third, the resulting on-demand ride-pooling service is modeled in a simulation case study for Munich, Germany, and evaluated by a custom-built fleet evaluation tool using a life-cycle sustainability assessment approach. Finally, the mobility service was tested under real-world conditions in a one-week field test in Munich.

The modeling approach incorporates real-world demand data, introduces different operational scenarios, assignment strategies for parcel-to-passenger assignment, parcel demand penetration rates, and three different vehicle types that make up the Mobility on Demand fleet. The results of the case study show that the Combined Decoupled Parcel Assignment (CDPA) strategy best reflects the goal of integrating freight transportation into a ride-pooling provider's system, resulting in the lowest number of miles traveled. The simulations show that the integration of logistics services into a ride-pooling service is possible and can utilize unused system capacity without degrading passenger service. Depending on the chosen assignment strategy and vehicle category, almost all parcels can be served up to a parcel to passenger demand ratio of 1:10, while the total fleet kilometers can be reduced compared to the status quo, i.e. two separate fleets for passenger and parcel transport. In order to assess the impact of Ride Parcel Pooling in a holistic way, the presented fleet evaluation tool aims at a new way of evaluating vehicle fleets in urban environments over their entire life cycle, taking into account environmental, economic and social impacts. The case study shows significant savings in global warming potential, fleet operating costs, and social impacts compared to the status quo. Electric vehicles have an advantage over internal combustion engine vehicles, especially in the environmental and economic dimensions, but also in the social dimension. The real-world test of Ride Parcel Pooling introduces a web application consisting of front-end, back-end, and fleet control, and serves as a digital platform for integrated transportation services for passengers and freight. Ride Parcel Pooling was shown to be ready for real-world applications and demonstrated the need for sufficient demand from both passengers and freight to produce pooled trips.

This dissertation addresses the pressing challenges of climate change, urbanization, e-commerce growth, and evolving urban mobility patterns, emphasizing the need for a comprehensive strategy to mitigate their environmental and societal impacts. It introduces Ride Parcel Pooling, an on-demand mobility service that integrates passenger ride-pooling and urban parcel transportation to deliver environmental, economic, and social benefits. Through thorough analysis, simulation, and real-world testing, the thesis demonstrates the feasibility and benefits of Ride Parcel Pooling, highlighting its potential to transform urban mobility into a more sustainable system.

Acknowledgment

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Writing a Ph.D. thesis not only affects one's professional career, but also one's personal life. Therefore, I would like to thank my parents Brigitte and Michael from the bottom of my heart for accompanying me through this time and for always supporting me in my life so far. A special thank you also goes to my stepfather Harald, who was not only a great role model for my PhD path, but also always challenged and supported me. Last but not least, I would like to thank my wife Annika and my son Jonas for always being at my side, but most of all for always showing me that there is another very important side to life apart from professional achievement.

Contents

Chapter 1

Introduction

Chapter Essentials

- Today's transportation systems face the challenges of climate change, urbanization, the growth of e-commerce, and changing urban mobility patterns.
- The transportation sector accounts for 27% of the world's climate relevant emissions (global warming potential), of which 60% is caused by passenger transport and 40% by freight transport.
- Three different forms of passenger transport, i.e. public transport, individual transport and mobility on demand, as well as three different forms of urban freight transport, i.e. courier, (express) parcel and cargo logistics are identified.
- Technological and societal trends affecting urban passenger and freight transport and their integration are digitalization, automation, electrification, and the expansion of new mobility services.
- The overall research objective of the thesis is to investigate and explore if and how the integration of urban passenger and freight transport flows can lead to a more sustainable urban transport system.

Climate change, urbanization, the growth of e-commerce, and changing urban mobility patterns are four interrelated issues that have received significant attention in scientific research and public discourse in recent years [IPCC, 2022; Rotem-Mindali & Weltevreden, 2013; Zhangyuan et al., 2022]. Climate change, caused by the increase in Green House Gas (GHG) emissions, does already today lead to extreme weather events and rising sea levels, threatening humanity worldwide [Pörtner et al., 2022]. Urbanization, on the other hand, has increased rapidly as more people move to cities in search of better economic opportunities, leading to the growth of urban areas and an increase in urban population density and traffic [Zhangyuan et al., 2022]. Urban transportation plays a critical role in shaping the functionality, livability, and sustainability of cities. Efficient and sustainable transportation systems are essential to support economic growth, improve access to goods and services, and minimize GHG emissions and air pollution. The development of e-commerce is another phenomenon having seen rapid growth in recent years. With the rise of online shopping and home deliveries, e-commerce has been identified as a significant contributor to the increase in GHG emissions, especially caused by last-mile deliveries [Laghaei et al., 2016]. The growing demand for e-commerce also creates an increase in urban freight traffic, leading to congestion, traffic accidents, and adverse effects on human health [Krzyzanowski et al., 2005; Retallack & Ostendorf, 2019]. As urbanization and e-commerce continue to grow, while transportation infrastructure is hard to change, there is an urgent need for change in urban mobility behavior and strategies. Especially, the current road-based transportation system, dominated by private cars and trucks, is unsustainable and leads to significant environmental, economic, and social challenges. A shift in urban mobility is needed to reduce the negative impacts of transport, to improve air quality, to reduce congestion, and to provide equitable access to transport. The transition to more sustainable road-based urban mobility or rail-based systems requires a combination of policies, technologies and behavioral changes [Vergragt & Brown, 2007]. New technologies such as vehicle electrification, digitization of mobility services, or completely new mobility services could enable sustainable change, especially in the urban context where citizens and transport are in close proximity. Behavioral changes such as increased use of Public Transportation (PuT), car-pooling, cycling, and walking could help to reduce the number vehicles on the road. All in all, climate change, urbanization, the growth of e-commerce, and changing demands for urban mobility are interrelated issues that require a holistic approach to address the significant environmental and social challenges they pose.

Figure 1.1 shows a customized visualization of the results obtained by the Crippa et al. [2020], European Commission [2013], and Oranisation for Economic Co-Operation and Development [2023], showing the shares of transport-related CO_2e emissions from passenger (60%) and freight (40%) transport in the European Union, combined with the total share (27%) of the transportation sector in the total European Global Warming Potential (GWP). It shows that an essential part of the transport-related CO_2e emissions is generated by urban transport for passenger (17%) and freight (6%) transport respectively. Furthermore, local air pollutants, land use, and congestion effects are particularly relevant in the urban context. These facts imply that innovative and environmentally friendly solutions for urban transport are urgently needed. This is especially true when existing solutions, such as expanding public transport networks, are expensive and difficult to implement (e.g. due to land use conflicts). The need for innovative, road-based, and high occupancy mobility solutions is further supported when considering the economic consequences of high traffic volumes and land use, which are also particularly relevant in an urban context [Bull & Thomson, 2002; Krzyzanowski et al., 2005; Schröder et al., 2023]. To achieve the highest possible utilization of existing transport modes, especially within urban areas where multiple forms of mobility and solutions are available, the question is whether the traditionally separate flows of passenger and freight transport could be combined and integrated.

The idea of transporting freight along with passengers is not a new one. As early as in the year 1610, the first recorded stagecoach traveled between Edinburgh and Leith, carrying passengers as well as small parcels [Maxwell G., 1992]. Nowadays, it is also not

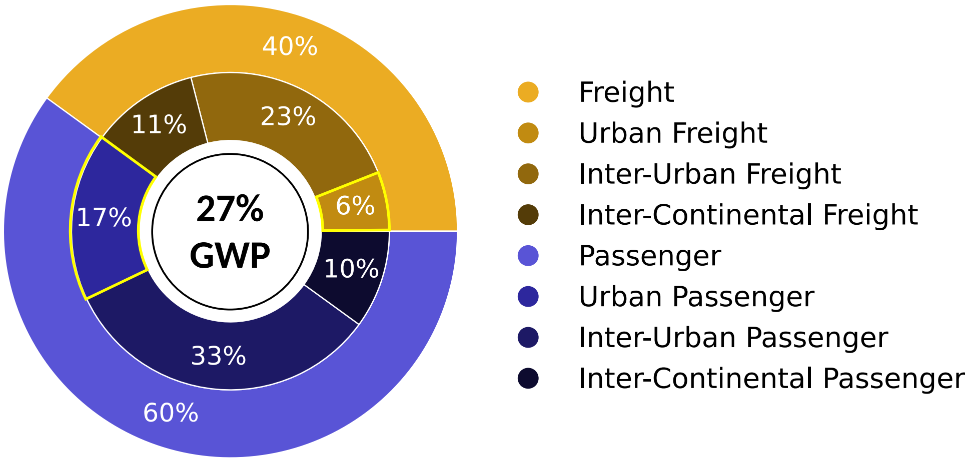


Figure 1.1: Share of CO_2e emissions related to transport in the European Union (PRIMES and TREMOVE Transport Models) European Commission [2013], European Environment Agency [2022], and Joint Research Center European Commission [2023].

uncommon for passengers and freight to be transported together. Passenger planes typically carry cargo as well. Combined transportation of people and goods is also common in ocean shipping and ferry services. However, there are far fewer combined transportation services in an urban context. However, this is where intelligent solutions are needed, as urban phenomena such as increased travel times, scarcity of space, noise emissions and poor air quality have worsened considerably in recent years, according to the German Ministry of the Environment [Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection, 2022; Pishue, 2021]. This leads to the need for efficient and combined passenger and freight transportation in urban areas to make better use of existing transportation resources. The aim of this dissertation is to examine the current concepts of integrated passenger and freight transport and to evaluate existing simulation studies.

Rodrigue [2020] classifies urban transport into three different categories, namely PuT, Individual Transportation (InT) and Freight Transportation (FrT). As a form of collective transportation, PuT provides mobility to people in specific areas of a city and is accessible to anyone who pays the fare. PuT systems are particularly successful where a large number of passengers need to be transported and their trips have similar Origin-Destination (OD) relationships. PuT includes modes such as trams, buses, trains, subways, and ferries. By contrast, InT is the result of a personal route choice and includes modes such as automobile, walking, bicycling, or motorcycling. In addition to the main categories of passenger transport, FrT plays an important role in urban transport. Traditionally, FrT movements are carried out by large delivery vehicles that transport freight to and from distribution centers and major terminals such as ports, railroad stations, and airports. However, with the growth of e-commerce, new delivery solutions are emerging and beginning to replace traditional delivery vehicles. In the urban context, freight mobility belongs to the emerging field of urban logistics. This doctoral thesis applies the categories of Rodrigue [2020] to structure the assessment of the state of the art in urban passenger and freight transportation, and provides a deeper understanding of the categories in the following sections.

1.1 Forms of Urban Transportation

The definition of Rodrigue [2020] is further differentiated in the following. The existing urban passenger transportation infrastructure includes a variety of transportation modes, including PuT (road and rail), motorized and micro-mobility InT, Mobility On Demand (MoD) (station-based and free-floating), and urban freight transportation FrT, including letter, courier, express, parcel, and cargo logistics. In the following, this research examines different forms of urban passenger and freight transport, investigates their characteristics, and finally groups them according to scientific definitions and passenger and freight transport markets.

Urban Passenger Transportation

This dissertation introduces urban passenger transport referring to two main categories. InT, such as private cars and bicycles, serves the mobility needs of a single or a small group of passengers with the same origin and destination, while PuT provide services to many passengers with different origins and destinations. In recent years, both InT and PuT have been subject to a variety of service concepts, which will be analyzed in more detail in the next parts of this section. To do so, this work focuses on the urban transport modes identified by Schröder and Gotzler [2021].

Public Transportation

Traditional PuT consists of road-based bus and boat services, as well as rail-based metro, train, and tram services. Rail-based services rely heavily on their underlying infrastructure, which allows them to operate only on fixed schedules and itineraries. Buses and boats can operate more flexible and can adapt routing in between of stations, however they also follow a defined schedule. Traditionally, all PuT services operate on fixed routes with fixed schedules [Ceder, 2002]. To paint a complete picture, there are several variations of road-based PuT that loosen either the ties to timetables or the ties to routes and stops to match demand, however they are not of high relevance in the further course of this thesis and therefore not introduced in detail.

Individual Transportation

A mode of transportation must meet two criteria to be called InT. First, it must satisfy the mobility demand of a single or small group of passengers with the same origin and destination. Second, the mobility demand is satisfied by one and the same vehicle and the trip is not shared among members of different passenger groups. In this context, this research introduces two main subcategories of InT, namely micro mobility and motorized InT [Brunner et al., 2018]. Here, micro mobility refers to all modes of transportation with relatively low speeds, operating over short distances. This includes walking, bicycles, scooters, and pedelecs [Yanocha & Allan, 2019]. Motorized InT includes powered two-wheelers such as mopeds and motorcycles, as well as private cars. In recent years, vehicle sharing concepts such as scooters, bicycles and car sharing have been introduced in urban areas. In this research, these concepts are included in the individual transport domain, as the vehicles and modes of use are very similar. In general, sharing concepts are either free-floating or station-based [Eren & Uz, 2020; Hardt & Bogenberger, 2020; Zardini et al., 2022; F. Zhou & Zhang, 2020], meaning that vehicles can be rented and left in a particular service area or at particular stations.

Mobility-on-Demand Transportation

In addition to the PuT and InT mentioned above, this research considers a third category of urban transportation services. These are called MoD services and are characterized by users requesting rides on-demand, either through a smartphone app, a phone call, or by hailing them on the street [Conway et al., 2018]. This includes traditional taxi operations, but also ride-sourcing services, matching riders with drivers of private vehicles, or fleet operators that centrally match incoming requests with drivers [Shaheen et al., 2016]. MoD provides a convenient service, due to short pick-up times and (nearly) door-to-door transportation. As a result, MoD providers such as Uber, Lyft, and Didi have experienced strong growth in recent years. For example, in 2016, 15% of all intra-city car trips within San Francisco (USA) were made with MoD [Feigon & Murphy, 2016]. Centrally managed ride-pooling services, where multiple users are dynamically pooled into the same vehicle to share the ride, have not yet achieved the same market penetration as taxi, i.e. ride-hailing, services. However, the number of services [Foljanty, 2022] as well as the number of research studies [Zwick, Kuehnel, & Axhausen, 2022] is increasing steadily.

The left part of Figure 1.2 shows the different forms of urban passenger transport considered in this work. This research distinguishes between *individual*, *public*, and *on-demand* transport forms, and their respective *dynamic* and *static* characteristics. In the case of passenger transport, the term *dynamic* refers to a flexible availability of the transport service, both in temporal and spatial dimensions. For this reason, station-based and scheduled PuT services are referred to as *static*, and individual forms of transport, as well as MoD services are referred to as *dynamic*.

Urban Freight Transportation

This research categorizes freight transportation through an analysis of spatial, temporal, weight, and size dimensions. Specifically, the spatial focus of this work is on the urban context and therefore includes the concepts of urban logistics, urban freight distribution, and last-mile logistics. City logistics refers to the movement and delivery of goods and materials within cities and other urban areas. It encompasses a wide range of activities, including transportation, warehousing, inventory management, and supply chain coordination. Savelsbergh and Van Woensel [2016] discuss a variety of current and anticipated challenges and opportunities of urban logistics, including alternative modes of transportation, such as electric vehicles and cargo bikes, and the implementation of urban consolidation centers, as well as congestion, air pollution, noise, and safety. There are several different forms of urban logistics, each of which plays a critical role in ensuring the efficient and timely delivery of goods and services to businesses and consumers in urban areas. Rose et al. [2017] identify three distinct stakeholder groups in urban logistics: community citizens, business and industry, and government officials. In their literature review, the authors distinguish between intra-regional flows and inbound and outbound logistics flows. In addition, the freight flows can be classified according to size, weight and priority. In Germany, one can differentiate between *mail logistics* [Bundesverband Briefdienste, 2023], *Courier, Express, and Parcel (CEP)* services [Bundesverband Paket und Expresslogistik e. V., 2023] and *cargo* logistics [Bundesverband Spedition und Logistik, 2023], represented by the respective national logistics associations. This thesis categorizes the temporal dimensions of urban logistics according to the time constraints for pickup and delivery, i.e. the urgency of the service. In this work, *dynamic* logistics includes any service booked less than a day in advance, while *static* logistics is booked in advance or takes several days to fulfill. In this case, the logistics trips are known to the logistics services at the beginning of each day. In the *dynamic* case, the trip requests come spontaneously during the day and can be classified as on-demand *courier* or *express parcel* deliveries. The weight and size dimensions of urban freight range from classic postal *parcels* to heavy and over-sized *cargo* deliveries. Looking at the specifics of urban logistics, one can additionally identify shipments that need to be kept warm or cold (e.g. food and grocery delivery) and shipments that rely on special vehicles or containers (e.g. waste disposal), however this research does not focus on these due to the high complexity of the entire supply chain.

In the following, further insights into three derived forms of urban logistics, namely courier, parcel, and cargo services are provided. To this end, this research focuses on the organization of logistics prevailing in Central Europe and therefore divides the forms of logistics on the basis of German logistics interest groups [Bundesverband Paket und Expresslogistik e. V., 2023; Bundesverband Spedition und Logistik, 2023]. The right part of Figure 1.2 shows the different attributes of urban logistics services considered in this work.

Courier Logistics

Courier shipments are delivered the same day (*dynamic*) or according to special arrangements (*static*) and picked-up and delivered by the same parcel carrier. They have binding delivery times, guarantee fast delivery [Bundesverband Paket und Expresslogistik e. V., 2023] and include the concepts of crowd-sourced (i.e. platforms connecting logistics providers and individuals who act as couriers [Tu et al., 2020]) and same-day (i.e. customer order is fulfilled the same day it is issued [M. Ulmer, 2017]) delivery. The concept of crowd-sourced delivery comprises food delivery (e.g. Just Eat Takeaway, Uber Eats), as well as classical courier or grocery delivery services (e.g. Flink, MAX, DoorDash). This work assumes courier and express shipments being delivered directly and without any intermediate stops in logistics hubs. It considers food and grocery deliveries to be express logistics services, due to the similar time and space requirements.

(Express) Parcel Logistics

Parcel shipments do not have fixed delivery times, however, the pickup or delivery times are specified day-accurate [Bundesverband Paket und Expresslogistik e. V., 2023]. The time, size and weight constraints of parcel logistics reach from classic parcels, with a process time of several days to same-day (express) delivery, typical dimensions between 35x25x10 cm to 120x60x60 cm, and weight between 2 kg and 31.5 kg [Deutsche Post AG, 2023]. Parcels usually refer to inter-city deliveries and therefore are trip chains. Since this work focuses on urban logistics, only the first- and last-mile legs are of special interest. Here, the last-mile leg is a *static* logistic service, as the delivery of the parcel is known ahead due to preceding transport steps. In Germany, 87% of online shoppers prefer home delivery as their privileged delivery place [DPDgroup, 2017]. Even though, a delivery to a consolidated pickup point would be possible as well. The first-mile leg is also considered a *static* logistic service similar to the last-mile leg. However, in Germany, most private senders bring their shipments to a central collection point (e.g. parcel shop, post office, retailer store, parcel locker station) [DPDgroup, 2017].

Cargo Logistics

Cargo logistics refers to all kinds of large, bulky, and heavy weight deliveries, including euro-pallets, furniture, large electronic devices, construction materials or waste [Bundesverband Spedition und Logistik, 2023]. Waste logistics includes all kinds of household and commercial waste, container waste or bulky waste [Abfallwirtschaftsbetrieb München, 2023]. Cargo logistics often requires specialized providers which use special vehicles, e.g., waste trucks or vehicles with large loading area and lifting platforms, to transport goods. Due to its size, cargo is usually planned many days ahead to delivery and thus is considered as a *static* logistic service.

1.2 Technological and Social Trends

In recent years, urban passenger and freight transportation has undergone a transformative evolution, driven by social and technological trends. Increasing urbanization leads to enhanced demands on transportation systems, requiring innovative solutions to reduce congestion, environmental impact, and improve overall efficiency. At the same time, technological advances, including the rise of autonomous vehicles, the integration of smart technologies (e.g. artificial intelligence), and the emergence of sustainable energy sources, are reshaping the landscape of urban mobility. This intersection of societal imperatives and technological advances is fostering a dynamic environment where the future of urban transportation promises to be more connected, accessible, and environmentally sustainable.

Trends in Urban Passenger Transport

As elaborated earlier, PuT critically contributes to urban mobility by offering affordable and accessible transportation to a vast number of passengers. Many cities commonly utilize

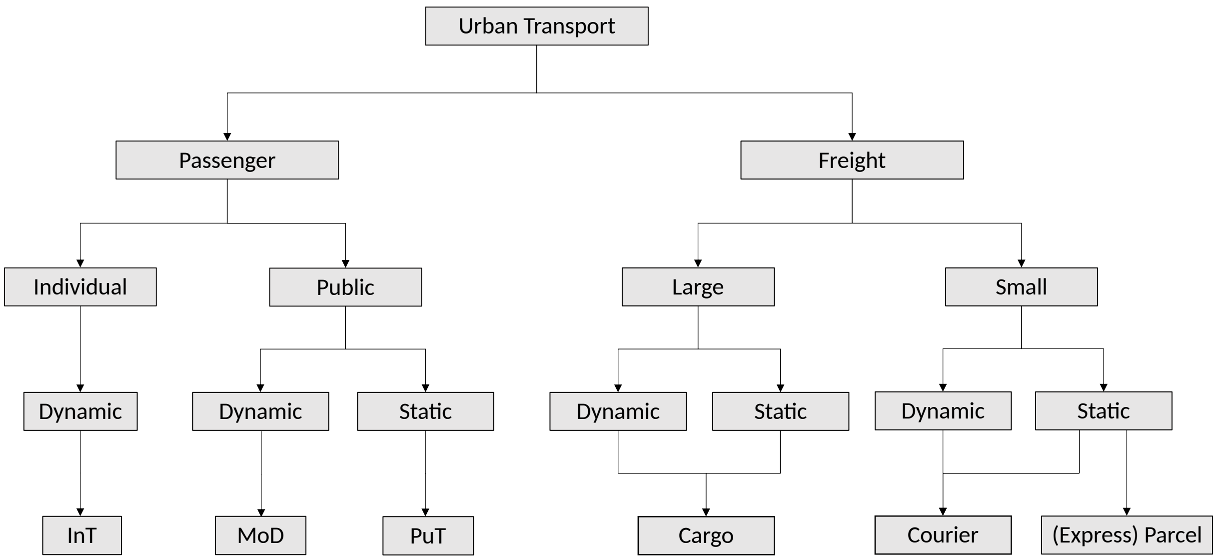


Figure 1.2: Different forms of urban passenger and freight mobility services considered in this work.

road-based PuT, such as buses and minibuses, while larger cities additionally feature rail based PuT, including subways, trams, and light rail systems. Motorized individual transport, such as cars and motorcycles, is prevalent in urban areas, with private cars being the most commonly used mode of transport. Despite providing convenience, motorized individual transport is a significant contributor to GHG emissions [Joint Research Center European Commission, 2023], air pollution [Krzyzanowski et al., 2005; Laumbach & Kipen, 2012], and congestion [Retallack & Ostendorf, 2019]. Micro-mobility options, such as bicycles, motorcycles, and e-scooters, have emerged as alternatives to individual motorized transportation, providing last-mile mobility in urban areas. On-demand mobility options, including station-based and free-floating sharing services (e.g. bikes, scooters, cars) provide convenient and flexible transportation options for (often irregular) short trips in urban areas. van Audenhove et al. [2018] assume that the demand for urban passenger transport will increase by more than a third by 2030 and double by 2050 They base their findings on data from the United Nations Department of Economic and Social Affairs, the International Transport Forum of the Organization for Economic Cooperation and Development, and their own data. The above-mentioned negative impacts of increasing transport volumes and the expected developments lead to an urgent need for action, especially in the urban context. More sustainable vehicles, new mobility solutions and improvements in the efficiency of existing transport modes could help to improve the situation and offset the expected increase in demand for passenger and freight transport.

Automation of transportation systems is rapidly transforming urban transport, with autonomous vehicles and drones offering the potential for safer, more resilient, and more efficient transportation systems [Ha et al., 2020]. Many experts expect autonomous vehicles to be safer [Fagnant & Kockelman, 2015], cheaper [Bösch et al., 2018], and to increase accessibility [Meyer et al., 2017] in cities. PuT services will most probably profit from autonomous driving because it eliminates their largest cost factor, the driver [Negro et al., 2021; Othman, 2020]. In this context, especially automated MoD services gain a lot of attention [Pavone, 2015; Salazar et al., 2018; Zardini et al., 2022]. Large scale applications of these automated MoD services show huge benefits for transportation systems, and are currently tested under real-world conditions with back-up drivers [mobileye tm, 2023]. The fleet size within a city decreases by a factor of up to nine if private vehicle trips are replaced by higher vehicle utilization [Alonso-Mora et al., 2017; Fagnant & Kockelman, 2015]) and traffic flow improves even further, if passengers share trips [Engelhardt et al., 2019; Fiedler et al., 2018]. Electrification is also gaining momentum, with electric vehicles becoming increasingly popular and many cities setting targets for the electrification of their transportation systems to reduce GHG and improve air quality [Requia et al., 2018]. Ride-pooling services such as "Uber Pool" and "Lyft" have the potential to disrupt traditional taxi services, offering on-demand, app-based transportation services that are often cheaper and more convenient than traditional options [Rayle et al., 2016]. Sharing concepts, such as car-sharing and bike-sharing schemes, have become popular in many urban areas and offer a more sustainable and cost-effective alternative to owning a private vehicle. Micro-mobility options, including bicycles and electric scooters, have also emerged as a popular option for short trips in urban areas. However, there are challenges to overcome, including safety concerns, regulatory frameworks, public acceptance, and infrastructure requirements. Overcoming these challenges will require collaboration between policy makers, technology providers and transport operators to ensure that urban transportation systems are sustainable, efficient and accessible to all.

Trends in Urban Freight Transport

Urban logistics is a critical component of the economy and transportation system, delivering goods to businesses and consumers in urban areas. van Audenhove et al. [2018] estimate that urban logistics volume will increase even more than passenger transportation. They predict growth of about 80% by 2030 and triple by 2050 of urban freight transport. Internal combustion engine and electric trucks and vans are the most common forms of urban delivery vehicles, providing the ability to efficiently deliver large volumes of goods [Melo & Baptista, 2017]. However, the use of diesel vehicles is becoming increasingly critical due to their negative impact on air quality and CO_2e emissions. As a result, many logistics providers are exploring the use of electric vehicles, which offer a more environmental friendly alternative [Juan et al., 2016]. Urban logistics hubs, located outside city centers, allow for the consolidation of goods and the use of larger delivery vehicles, reducing the number of vehicles on the road and minimizing traffic congestion [Jacyna, 2013]. Consolidation hubs, which allow multiple logistics providers to share a single hub, offer additional benefits in terms of reducing delivery costs and improving efficiency [Cheong et al., 2007]. Small zero-emission vehicles, such as cargo bikes, have emerged as a promising solution for last-mile delivery in urban areas, particularly for smaller deliveries [Juan et al., 2016]. These vehicles are nimble, environmentally friendly, and can easily navigate narrow streets and congested areas.

In 2021, more than 4.5 billion shipments have been delivered in Germany, more than ever before [Bundesverband Paket und Expresslogistik e.V., 2022]. This is due to the growth of e-commerce, which has been amplified by the COVID-19 pandemic, but can be seen to still increasing after the pandemic. This enormous growth in logistics volume poses challenges not only for logistics companies, but also for the transportation sector and cities. According to an international study with 23,450 participants, 87% of German customers expect their parcels to be delivered directly to their door within a few days [DPDGROUP, 2017]. In other countries, alternative delivery points such as parcel lockers or shops are more common delivery destinations. As urban logistics grows in importance, it is critical that logistics providers and policymakers work together to develop sustainable transportation solutions that balance the need for efficient freight delivery with the need to reduce environmental impact and reduce urban traffic.

Urban logistics is a rapidly evolving industry facing social challenges such as increasing consumer demand for fast and reliable delivery, the growth of e-commerce, and the impact of delivery vehicles on urban congestion phenomena and air quality [JUAN et al., 2016; REQUIA et al., 2018]. Same- or next-day delivery have become an expectation for many European consumers, leading to increased pressure on logistics providers to offer faster and more efficient delivery services [M. W. ULMER, 2020]. Crowd logistics, which uses the unused capacity of private vehicles to deliver goods, has emerged as a potential solution to the challenges of last-mile delivery [S. LI et al., 2019; TU et al., 2020; UPADHYAY et al., 2022]. The growth of e-commerce has led to increased demand for logistics services in urban areas, and many logistics companies are developing new strategies to meet this demand. However, downtown retailers are facing challenges as consumers shift to online shopping, resulting in reduced foot traffic and lower sales [WORZALA et al., 2002]. To address these challenges, many retailers are exploring new strategies such as click-and-collect services and pop-up stores. The growing volume of e-commerce shipments some times leads to multiple delivery vehicles servicing on one street at the same time, leading to confusion and annoyance among consumers [BUNDESVERBAND PAKET UND EXPRESSLOGISTIK E. V., 2017]. For this reason, the installation of parcel boxes is increasingly required in German development plans for residential areas. Overall, the existing urban transport infrastructure consists of a mix of different transport modes, each with its own advantages and challenges. As cities face increasing environmental and social challenges, the need for a shift towards sustainable urban mobility is becoming more urgent. The integration of new technologies, the promotion of active mobility options, and the adoption of innovative business models are necessary to create a sustainable, integrated, and efficient urban transportation system.

Trends towards Integrated Transport Solutions

In summary, today's urban passenger and freight transport often leads to congestion, increased local and global emissions, and large land consumption [GÖSSLING, 2016]. Local emissions such as carbon oxides, particulate matter, nitrogen oxides, sulfur dioxide and noise pollute the environment and have a direct impact on the health of citizens [KRZYZANOWSKI et al., 2005; LAUMBACH & KIPEN, 2012], and on a global scale, passenger and freight transport related CO_2e emissions accelerate climate change and occur in urban, interurban and intercontinental settings (see Figure 1.1). In addition, urban space is reserved for vehicles instead of being used for housing or open space, and congestion not only affects the quality of life but also causes economic problems [Thomson, 1998]. Therefore, public awareness and acceptance of integrating passenger and freight transportation is likely to be higher in cities than in rural areas where these problems are less pronounced.

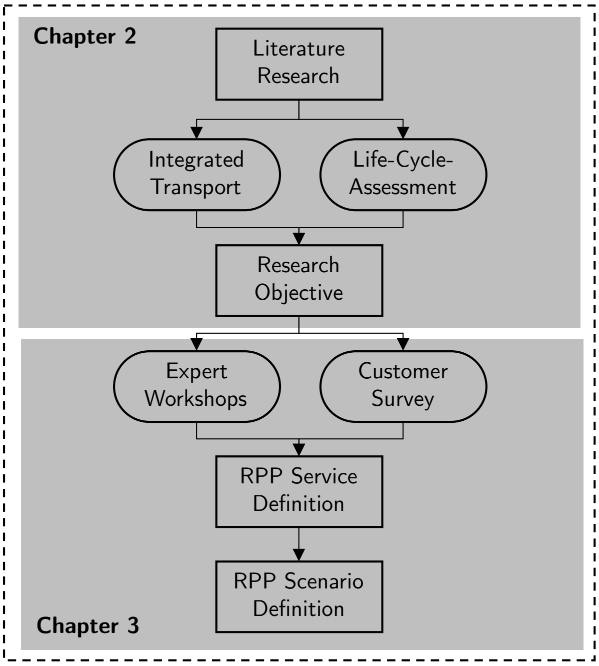
In recent years, digitalization has disrupted the transportation landscape. In the mobility sector, dynamic bookings via smartphone apps have enabled the rise of the sharing economy [Mouratidis et al., 2021]. But the logistics sector is also undergoing transformation: digitalization has enabled fast paced food and grocery delivery services, and parcels can be tracked in real time [Petrovic et al., 2013]. The resulting data availability enables the organization and planning of integrated services for both mobility and logistics: Free capacities in mobility services can be detected, matching logistics flows can be identified and, if necessary, routes can be dynamically adopted to serve both passenger trips and logistics deliveries [Dohrmann et al., 2022]. This leads to an increasing amount of research attempting to develop models, test new services in field trials, and quantify the benefits of such integrated services [Cavallaro & Nocera, 2022]. Integrated transportation solutions can offer many benefits, including reduced driven distances, emissions, and space consumption, as well as higher utilization rates and greater accessibility [Cavallaro & Nocera, 2022; Nocera et al., 2021]. These solutions can often offer lower prices [He, 2023], greater flexibility, and more customer-focused service. However, the complexity of these solutions can be a challenge and they may require convertible and flexible vehicle concepts or lead to monopolistic structures [Kucharski & Cats, 2022; Le et al., 2019].

In conclusion, the integration of passenger and freight transportation could be a solution to many of the presented problems, especially in an urban context. Furthermore, the introduced technological trends (i.e. autonomous driving, digitalization, electrification), hand in hand with the social trends (i.e. mobility sharing, growing e-commerce, environmental awareness), foster the possibilities and chances of reintegrating passenger and freight transport. The history of integrated transport is long and storied, dating back to the days when stagecoaches and ferries were the primary means of transportation. A few hundred years ago, transportation was limited primarily by the number of vehicles available. At that time, it was common for passengers and freight to be transported in the same vehicle. Over time, the transportation industry has evolved with the introduction of aircraft and rail networks. With technological and social progress and the expansion of road infrastructure, more and more people could afford their own vehicle. Gradually, the limiting factor was no longer the number of vehicles, but the availability of infrastructure such as roads and parking spaces. Today, this development can be seen especially in large cities, which are increasingly suffering from lack of space and increased traffic.

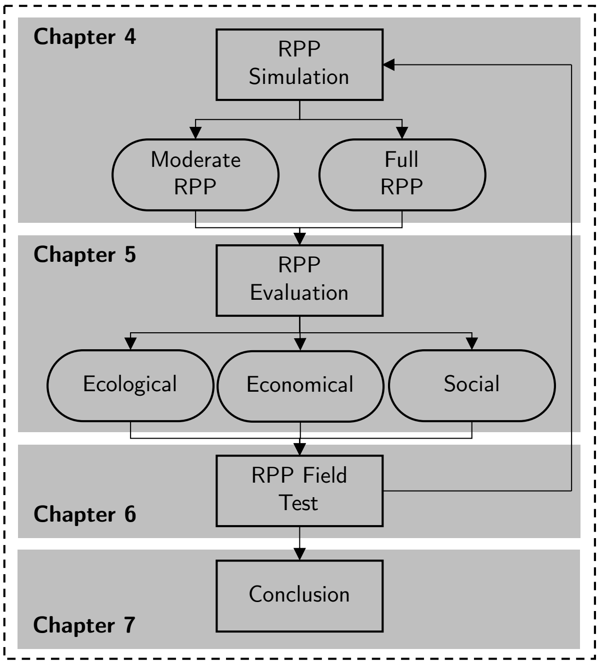
1.3 Thesis Objective and Outline

The overall research objective of this doctoral thesis is to explore and investigate whether the integration of urban passenger and freight transportation streams can lead to more sustainable urban transportation systems and will be specified further in Chapter 2 by providing detailed research questions.

The remainder of this doctoral thesis is divided into two main parts, i.e. service conceptualization and service modeling and testing, see Figure 1.3. First, this thesis proposes and conceptualizes a promising integrated transportation service, including a detailed literature review on integrated urban passenger and freight transportation solutions (Chapter 2), the Ride Parcel Pooling (RPP) service definition and specification of the RPP idea through expert workshops, a survey of potential customers (Chapter 3), and the definition of possible RPP operation scenarios. In the further course of this dissertation, the selected scenarios are modeled and quantified in an agent-based simulation environment (Chapter 4) before evaluating them in terms of the environmental, economic, and social components of sustainability using a novel Life Cycle Sustainability Assessment (LCSA) evaluation approach for urban vehicle fleets (Chapter 5). Subsequently, the RPP service is tested in the real world by a field trial (Chapter 6). This trial is additionally used to calibrate the simulation environment. Finally, all elements of this research are brought together in a conclusion (Chapter 7) (Figure 1.3b).



(a) Service conceptualization



(b) Modeling and testing

Figure 1.3: High-level structure of the dissertation.

Chapter 2

State of the Art in Integrated Urban Transportation

Chapter Essentials

- The scope of the literature review is defined on the introduced passenger (public, individual, and mobility-on-demand) and freight (courier, parcel, and cargo) transport forms and consists of the combination of all forms.
- The examined research reveals different models and methodologies for integrating passenger and freight transport, including case studies, mathematical modeling, and simulation.
- Practical applications of integrated passenger and freight transport exist mainly in mobility-on demand systems or individual transport (crowd-sourced logistics), however the focus is rarely on minimizing driven distances, but rather on maximizing profits.
- Of the assessment methods examined, only life cycle assessment offers the possibility to examine a transport service over its entire life cycle and to include upstream processes, which is of particular interest when vehicles are no longer needed due to the integration of transport flows.
- Life cycle assessment is a well suited and valid methodology for evaluating urban vehicle fleets, but existing research rarely focuses on vehicle fleets and innovative and integrated mobility concepts, but rather on comparative vehicle evaluations.
- The research questions open the field for an innovative transport service that combines urban passenger and freight transportation with the aim of minimizing adverse effects on humanity.

2.1 Integrated Urban Mobility Services in Research and Practice

This chapter explores existing solution approaches for integrating passenger and freight transportation with a focus on urban environments in research and practice. Thereby, the state of the art is analyzed according to the previously introduced transportation services in passenger and freight mobility, resulting in the possible combinations displayed in Table 2.4.

2.1.1 Modeling of Integrated Transport Services in Research

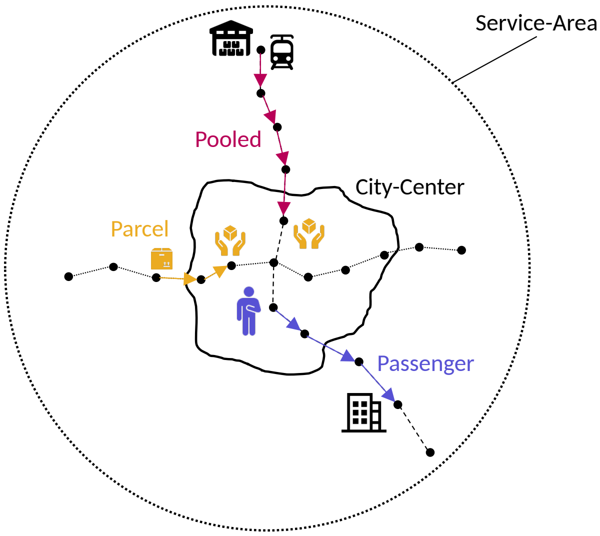
Scientific research on the integration of passenger and freight flows in the city can be found mainly in the field of Operations Research (OR), a multidisciplinary field that uses mathematical modeling, statistical analysis, and optimization techniques to analyze and improve complex systems and decision-making processes [Brown & Easterfield, 1951]. In addition to that, literature reviews, like Alnaggar et al. [2021], Cavallaro and Nocera [2022], Nocera et al. [2021], and Zhangyuan et al. [2022] aim to present the current state of research and to derive current trends in operations and strategic planning. In general, many strategic planning models have been developed to support decision making in urban passenger and freight transport. To this end, this literature research distinguishes between line-based (Figure 2.1a) and road-network-based (Figure 2.1b) integration of passenger and freight flows. In line-based systems (i.e. bus, tram, subway, cable car), freight can travel along the lines and be loaded or unloaded at the stations. From there, a subsystem has to take over the last mile delivery or the recipients must collect their shipments at a local delivery point. This also works the other way around, where parcels are collected for the shipping to their destinations. In road-based systems (i.e. InT, MoD), the freight can be collected at or delivered to any point located on the road network.

The following review examines the literature in particular with regard to the used mode of transportation, the specific characteristics of the freight service (i.e. courier, parcel, and cargo), the integration approach (i.e. existing or new infrastructure/resources), and the testing of the proposed solution in a case study with synthetic or real-world data.

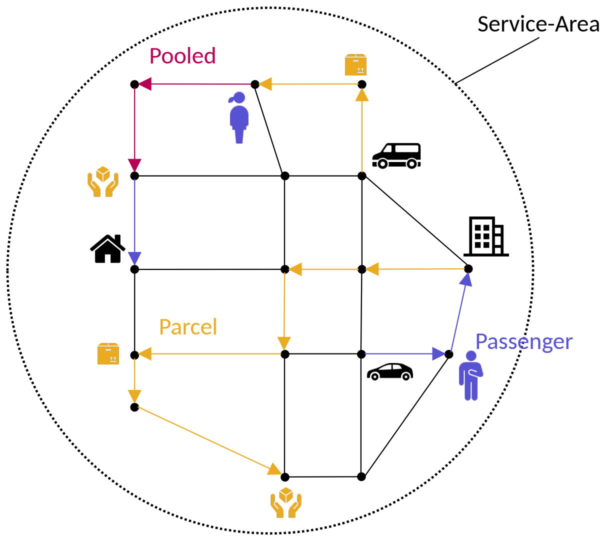
Public Transportation

This section provides an overview of recent OR advancements on the integrated transportation of passengers and freight on PuT systems, and provides insight into several international case studies illustrating different approaches to integrated forms of transportation. Review papers investigate recent advances in the theory and practice of collaborative forms of urban transportation involving the cooperation of multiple stakeholders in urban areas [Cleophas et al., 2019; Cochrane et al., 2016; van Duin et al., 2019]. The papers also present practical examples of collaborative transportation initiatives, such as urban consolidation centers, crowd-sourced solutions, and shared mobility services emphasizing the importance of a supportive policy and regulatory environment to foster its development.

The following paragraph analyzes studies from the OR field and categorizes them in Table 2.1. The review structures existing research by the mode of transportation considered,



(a) Line-based integration.



(b) Road-network-based integration.

Figure 2.1: Forms for integration of logistics into existing passenger transport modes.

the specific characteristics of the integrated freight service, the integration approach, and the existence of a case study.

Integrated transportation of passengers and freight in rail based PuT systems (Figure 2.1a) can use trains, metros, trams, buses, and boats, all of which run on predetermined routes and mostly on a (fixed) schedule. The approaches to integrate freight transport into existing passenger transport schemes can be distinguished by the fact that the integration of freight transport takes place on *existing* vehicles that would be used for passenger transport anyway, or including *additional* vehicles, which are sharing only the same infrastructure (i.e. rail network or stations) [Alessandrini et al., 2012; Dampier & Marinov, 2015; Fatnassi et al., 2015]. Thirdly, there exist approaches incorporating both, *existing* and *additional* vehicles [De Langhe et al., 2019; Z. Li et al., 2021; F. Zhou & Zhang, 2020]. All of the PuT modes studied have in common that they can, at least theoretically, carry large freight in addition to passengers, as their doors and vehicles tend to be large. Unless specified in the studies, this literature review assumes that trains, metros and trams can carry large freight and buses can carry at least medium freight. The temporal flexibility of the integrated freight service is rather limited, since the schedule of the lines must be respected. Therefore, only *static* freight demand, i.e. transport requests revealed before the day, can be integrated into PuT. The spatial constraints of the integrated transport approaches are very similar for this group of transport modes and rely either on a subsystem for collection and distribution starting and ending at the stations or on a logistics hub located at them. In terms of modeling approaches for integrating the freight transport into the exiting schemes of passenger transport, a couple of different solutions exist with most of them relying on macroscopic modeling [Dampier & Marinov, 2015; Fatnassi et al., 2015]. One can distinguish between mathematical models [Behiri et al., 2018; Galkin et al., 2019; Z. Li et al., 2021] and solution heuristics [Ghilas et al., 2016; Larrodé & Muerza, 2020; Ozturk & Patrick, 2018; Ye et al., 2022], whereby mathematical models aim for optimal and exact solutions based on precise mathematical representations and computations, while heuristics provide good approximate solutions to complex problems efficiently, often sacrificing precision for speed. In their case studies, the investigated research assess economic aspects of the integration of passenger and freight flows [Dampier & Marinov, 2015; De Langhe et al., 2019; Z. Li et al., 2021; Ye et al., 2022], as well as the environmental implications [Alessandrini et al., 2012; Behiri et al., 2018; Kikuta et al., 2012; Larrodé & Muerza, 2020; F. Zhou & Zhang, 2020] besides the operational conditions.

The road-bound integration of PuT and FrT, i.e. bus and boat, (Figure 2.1a) is very similar to rail based PuT literature, as these services also travel predetermined routes and stop at fixed stations. In bus and boat systems, only existing resources (vehicle capacities) are used, i.e. no additional vehicles are used for freight integration. The temporal and spatial service constraints are consistent with rail based PuT systems. Similar to rail based PuT, there are mathematical [Ghilas et al., 2018; T. Wang et al., 2023; Zeng & Qu, 2022] and heuristic [Masson et al., 2017; Trentini et al., 2012] modeling approaches, and the case studies examine operational [Bruzzone et al., 2021; Ghilas et al., 2018; Jansen, 2014; Zeng & Qu, 2022], economic [Bruzzone et al., 2021; Machado et al., 2023; Tiannuo et al., 2023; Zhangyuan et al., 2022] and environmental [Bruzzone et al., 2021; Machado et al., 2023; Masson et al., 2017; Pimentel & Alvelos, 2018] viability of the integration.

Reference	Transportation Mode	Integration Approach		Freight Service	Case Study
		existing resources	additional resources		
Alessandrini et al. [2012]	Train	-	✓	Cargo, Parcel	✓
Kikuta et al. [2012]	Metro	✓	-	Cargo, Parcel	✓
Trentini et al. [2012]	Bus	✓	-	Parcel	✓
Jansen [2014]	Bus	✓	-	Parcel	✓
Dampier and Marinov [2015]	Metro	-	✓	Cargo, Parcel	✓
Fatnassi et al. [2015]	Train	-	✓	Cargo, Parcel	✓
Ghilas et al. [2016]	Metro	✓	-	Cargo, Parcel	✓
Masson et al. [2017]	Bus	✓	-	Parcel	✓
Behiri et al. [2018]	Metro	✓	-	Cargo, Parcel	✓
Galkin et al. [2019]	Tram	✓	-	Cargo, Parcel	✓
Ghilas et al. [2018]	Bus	✓	-	Parcel	✓
Ozturk and Patrick [2018]	Train	-	✓	Cargo, Parcel	-
Pimentel and Alvelos [2018]	Bus	✓	-	Parcel	-
De Langhe et al. [2019]	Tram	✓	✓	Cargo, Parcel	✓
Larrodé and Muerza [2020]	Train	✓	-	Parcel	✓
Bruzzone et al. [2021]	Bus, Boat	✓	-	Parcel	✓
Z. Li et al. [2021]	Train	✓	✓	Cargo, Parcel	✓
Ye et al. [2022]	Metro	✓	-	Cargo, Parcel	✓
F. Zhou and Zhang [2020]	Metro	✓	✓	Cargo, Parcel	✓
Zeng and Qu [2022]	Bus	✓	-	Parcel	✓
Machado et al. [2023]	Bus	✓	-	Parcel	✓
He [2023]	Bus	✓	-	Parcel	✓
T. Wang et al. [2023]	Bus	✓	-	Cargo, Parcel	✓
Tiannuo et al. [2023]	Bus	✓	-	Cargo, Parcel	✓

Table 2.1: Existing Models in PuT literature and assorted research characteristics (i.e. transportation mode, integration approach, freight service, and case study). The existing and additional attributes of the integration approach refer to whether the integration of freight takes place on vehicles that would be used for passenger transport anyway, or induced additional trips/vehicles). The freight service (i.e. Courier, Parcel, and Cargo) refers to item size, temporal (schedule: static, dynamic), and spatial delivery constraints of the freight service.

Overall, this literature review on integrated transport of passengers and freight on PuT systems reveals that the comparably large PuT vehicles have the potential to integrate even cargo logistics services and can improve the efficiency and sustainability of urban transportation. However, the PuT service constraints limit the possibilities for logistics operation. For example, door-to-door delivery is not possible due to the fixed lines and stops, and time flexibility is also very limited to the lines' schedules. The integration approach of FrT can rely on *existing* or *additional* infrastructure or vehicles, meaning that *existing* capacity is utilized and by that occupancy is increased or additional vehicles are employed. The review reveals that most approaches set their focus on *existing* infrastructure and vehicles [Bruzzone et al., 2021; Ghilas et al., 2018; He, 2023], however some also deploy *additional* vehicles (e.g. additional train on the same rail system) [Alessandrini et al., 2012; Dampier & Marinov, 2015; Ozturk & Patrick, 2018]. The studies employ various methodologies such as case studies, mathematical modeling, and simulation to evaluate the potential benefits of multi modal transportation systems in terms of environmental, energy, and economic savings. The proposed systems involve the use of different transportation modes such as metro, buses, trams, and railways for transporting freight from distribution centers to final destinations in urban areas. The studies collectively demonstrate the substantial potential for integrating passenger and freight transportation systems in urban areas to achieve a range of benefits. These include significant environmental advantages, such as reduced CO_2 emissions [Tiannuo et al., 2023], lower energy consumption [Bruzzone et al., 2021; T. Wang et al., 2023], and fewer traffic accidents [Ye et al., 2022]. Operational benefits encompass improved efficiency [Ghilas et al., 2018; He, 2023], reduced congestion [Larrodé & Muerza, 2020], and minimized delivery delays [Kikuta et al., 2012], particularly in challenging weather conditions [Ye et al., 2022]. Additionally, integrated systems have been shown to be economically viable [De Langhe et al., 2019], offering cost savings and enhanced resource utilization [Behiri et al., 2018]. The studies underscore that by combining existing passenger transit networks with innovative logistics solutions, cities can create sustainable and efficient urban transportation systems that simultaneously address environmental concerns, alleviate traffic congestion, and enhance overall urban mobility and logistics. However, the studies also reveal some challenges, such as the need for effective planning and control of passenger and goods flows [Trentini & Malhene, 2012], appropriate sizing of delivery volumes, and dealing with time constraints for parcel delivery [Trentini et al., 2012] that can increase vehicle kilometers traveled. The literature review suggests that the integration of PuT with urban logistics can be a promising approach to address the challenges of urban freight transportation. However, further research is needed to address the challenges associated with integrating these two types of transport, i.e. mainly the spatio and temporal flexibility, and to develop effective solutions that can be implemented in the real world and in a variety of urban contexts.

Individual Transportation

This section presents a review of recent research on the integrated transport of passengers and freight in InT, i.e. private vehicle trips, and gives an overview on several case studies, illustrating different approaches. Similar to the procedure in the last section, this research investigates the OR literature in the field and takes literature reviews into account. Considering the combination of InT and FrT the term *crowd-sourced* transportation services is very prominent. These services rely on the participation of individuals or groups of people, often facilitated by digital platforms, to provide transportation services [Alnaggar et al., 2021; Misra et al., 2014]. Although crowd-sourced transportation services are not exclusively limited to InT systems, they can also occur in PuT services, i.e. passengers carry shipments, crowd-sourced delivery is mostly found in InT, e.g. "New Dada", "Instacart", "Deliveroo", "DoorDash", "Deliv", "Fetchr", and "Postmates".

Doan et al. [2011] and Sampaio et al. [2019] define *crowd sourcing* as a distributed problem solving process that involves the combination of a large number of people via the internet and discuss several forms. The authors state that crowd sourcing can be applied to a wide variety of problems and expect that it will be applied more and more in the future. Buldeo Rai et al. [2017] discuss the challenges associated with the implementation of crowd-sourced logistics, such as the need for appropriate regulations and policies, the management of the multiple stakeholders, and the need for effective online platforms to facilitate coordination and tracking. Upadhyay et al. [2022] find that trust and reliability are key components to achieve successful and sustainable last mile delivery in crowd-sourced delivery.

The literature review of this section is again structured by the mode of transportation considered, the type of integration, the integration approach and the freight service constraints considered, as well as the (non-)existence of a case study, see Table 2.2. In their literature review on crowd shipping, Sina Mohri et al. [2023] classify research from the field of OR and present promising areas of applications, operations, and management. The considered modes of transportation of crowd shippers range from classical passenger car, over bicycle transport and walking. For this part of the literature review, the integration approach into anyways existing passenger trips plays a very important role, as InT crowd-sourced solutions tend to induce transport trips and by that increase driven distance [Tapia et al., 2023; Upadhyay et al., 2022]. In this regard, *existing* integration refers to trips that would have taken place anyway, whereas *additional* integration refers to induced trips. Mostly, crowd-sourced approaches combine both, existing and additional trips to guarantee a certain level of service [Archetti et al., 2016; Dayarian & Savelsbergh, 2020; Voigt & Kuhn, 2022]. The temporal constraints of freight transport are very interesting in InT crowd-sourced approaches, as *dynamic* service constraints [B. Li et al., 2014] allow for real time transport requests, whereas *static* [Mousavi et al., 2022; Tapia et al., 2023; Voigt & Kuhn, 2022; F. Wang et al., 2018; Z. Zhou et al., 2021] refers to parcel requests revealed on the previous day. Most InT solutions can transport freight door-to-door, however one investigated study relied on logistics hubs instead [Ghaderi et al., 2022]. The OR modeling approaches can again be divided in mathematical [Yildiz & Savelsbergh, 2019] and heuristic approaches [Arslan et al., 2016; Gdowska et al., 2018; Macrina et al., 2017; Mousavi et al., 2022; Silva et al., 2022]. The case studies investigate operational [Dayarian & Savelsbergh, 2020; Ghaderi et al., 2022; Guo et al., 2019; S. Li et al., 2019; Mousavi et al., 2022; Tao et al., 2023; F. Wang et al., 2018], economical [Archetti et al., 2016; Cebeci et al., 2023; Devari et al., 2017; Ermagun & Stathopoulos, 2018; S. Li et al., 2019; F. Wang et al., 2018; Zou & Kafle, 2022], and environmental [Devari et al., 2017; Tapia et al., 2023] aspects of integrating freight transport into InT by applying crowd-sourced solution approaches.

Reference	Transportation Mode	Integration Approach existing resources	Integration Approach additional resources	Freight Service	Case Study
L. Li et al. [2014]	Any	✓	✓	Courier	-
Archetti et al. [2016]	Car	✓	✓	Courier	✓
Arslan et al. [2016]	Car	-	✓	Courier	✓
Devari et al. [2017]	Any	✓	✓	Courier	✓
Macrina et al. [2017]	Any	-	✓	Courier	✓
Kafle et al. [2017]	Walk, Bike	✓	✓	Courier	✓
Ermagun and Stathopoulos [2018]	Any	✓	✓	Courier	✓
Gdowska et al. [2018]	Car	-	✓	Courier	✓
F. Wang et al. [2018]	Car	✓	✓	Courier	✓
Guo et al. [2019]	Car	✓	✓	Courier, Parcel	✓
S. Li et al. [2019]	Any	✓	✓	Courier	✓
Yildiz and Savelsbergh [2019]	Any	✓	✓	Courier	✓
van Duin et al. [2019]	Any	✓	✓	Courier	✓
Dayarian and Savelsbergh [2020]	Car	✓	✓	Courier	✓
Ghaderi et al. [2022]	Car	✓	✓	Courier	✓
Mousavi et al. [2022]	Any	✓	✓	Parcel	✓
Voigt and Kuhn [2022]	Any	✓	✓	Parcel	✓
Zou and Kafle [2022]	Any	✓	✓	Parcel	✓
Silva et al. [2022]	Any	✓	✓	Courier	✓
Tapia et al. [2023]	Car, Walk, Bike	✓	✓	Parcel	✓
Cebeci et al. [2023]	Any	-	✓	Courier	✓
Tao et al. [2023]	Car	✓	✓	Courier	✓

Table 2.2: Existing Models in InT (crowd-sourced delivery) literature and assorted research characteristics (i.e. transportation mode, integration approach, freight service, and case study). The existing and additional attributes of the integration approach refer to whether the integration of freight takes place on vehicles that would be used for passenger transport anyway, or induced additional trips/vehicles). The freight service (i.e. Courier, Parcel, and Cargo) refers to item size, temporal (schedule: static, dynamic), and spatial delivery constraints of the freight service.

The investigated literature on the integration of InT and FrT discusses different approaches to solving last-mile delivery problems using crowd sourcing and stand by drivers. The studies cover a variety of topics, such as cooperative intermodal freight transportation planning, dynamic pick-up and delivery with ad-hoc drivers, leveraging social networks for last-mile delivery, vehicle routing with stand by drivers, and using cyclists and pedestrians as crowd sources. The studies also explore the benefits of using stand by drivers, such as reducing delivery costs and overall emissions while ensuring fast and reliable delivery.

The research demonstrates that integrating stand by drivers can significantly reduce delivery costs [Guo et al., 2019; Zou & Kafle, 2022] and enhance efficiency in last-mile logistics [Kafle et al., 2017], with various models and mechanisms proposed to achieve cost advantages [Gdowska et al., 2018; Macrina et al., 2017]. Additionally, the studies highlight the importance of leveraging social networks [Devari et al., 2017] and the willingness of individuals to participate in crowd based delivery, which ensures fast (courier) delivery [Devari et al., 2017; Tao et al., 2023]. Furthermore, computational studies and optimization models showcased the ability to produce near-optimal solutions [Arslan et al., 2016]. Overall, the literature review suggests that crowd-sourced logistics has the potential to improve operations in the last-mile delivery process [Kafle et al., 2017]. However, implementing crowd sourcing presents various challenges, such as the need for appropriate policies and regulations [Tapia et al., 2023], effective coordination and online platforms, and management of multiple stakeholders. Furthermore, the literature review reveals that crowd-sourced delivery solutions are seen critically when it comes to trust in the crowd shippers and system reliability from a user and an operator point of view [Upadhyay et al., 2022]. In some cases crowd-sourced delivery was even found to increase congestion and GHG transport related emissions [Tapia et al., 2023]. On top of that, a big difficulty with crowd-sourced delivery options is the dynamic component in the system. With stand by drivers, a decision must always be made for each time step, introducing a high degree of decision-making complexity [Macrina et al., 2017; Upadhyay et al., 2022]. The above literature review of last-mile, crowd-sourced delivery shows that, in all cases, a backup fleet is needed to ensure reliable transport of the parcels (i.e. punctual and safe transport of all considered shipments) [Archetti et al., 2016; Gdowska et al., 2018; Silva et al., 2022]. It therefore seems like that it is not possible to build a functioning logistics system with a pure crowd-sourcing solution, since the stand by drivers are not purely committed to the logistics service.

Mobility-on-Demand Transportation

This section comprises a literature review on research aiming to integrate MoD solutions and FrT. Table 2.3 gives an overview of the analyzed research and categorizes it according to the tables before, in terms of integration approach and freight service characteristics. Mourad et al. [2019] provide a comprehensive review of the literature on models and algorithms for optimizing shared mobility and review various solution methods, including heuristic algorithms, mathematical programming, simulation-based methods, and machine learning techniques. The author finds that the optimization of shared mobility systems can improve utilization of vehicles, reduce travel time and cost for users, and increase the availability of transportation options.

In order to provide a comparison of the different OR approaches and to compare the results of different case studies, this paragraph provides an overview of the existing research papers in the field of integration of MoD and freight logistics. Accordingly to the literature review of PuT and InT integration with FrT, this paragraph investigates the integration approaches, distinguishing between *existing* [Beirigo et al., 2018; L. Li et al., 2014; Romano Alho et al., 2021; Soto Setzke et al., 2017; Staritz et al., 2023] and *additional* [Bosse et al., 2023; Y. Chen et al., 2020; Liu & Li, 2023; Manchella et al., 2020; Schlenther et al., 2020; van der Tholen et al., 2021] resource utilization. As all reviewed MoD integration approaches relied on passenger cars or vans, the size constraints for freight transport was assumed to be at least medium, if not further specified in the studies. The temporal constraints were defined in line with Tables 2.1 and 2.2 and refer to *dynamic* [B. Li et al., 2014; Ronald et al., 2016; Schlenther et al., 2020; Z. Zhou et al., 2021] or *static* (i.e. revealed pre-day) [Bosse et al., 2023; Fehn et al., 2021; Liu & Li, 2023; Romano Alho et al., 2021; Soto Setzke et al., 2017] transport requests for freight. Similar to InT crowd-sourced solutions, MoD services can offer door-to-door delivery of freight and do not necessarily rely on logistics hubs. The modeling approaches in MoD services also reach from exact mathematical solutions [Zhang et al., 2022] to heuristics, trying to approach optimal solutions as close as possible [L. Li et al., 2014; Mourad, 2019; Nguyen et al., 2015]. The findings of the case studies can again be grouped into *operational* [C. Chen & Pan, 2016; C. Chen et al., 2017; Y. Chen et al., 2020; Ronald et al., 2016; Schlenther et al., 2020; Soto Setzke et al., 2017; Staritz et al., 2023; van der Tholen et al., 2021; Z. Zhou et al., 2021], *economic* [Beirigo et al., 2018; Bosse et al., 2023; Meinhardt et al., 2022; Nguyen et al., 2015], and *environmental* [Fehn et al., 2021; Manchella et al., 2020; Najaf Abadi, 2019] considerations.

Reference	Transportation Mode	Integration Approach		Freight Service	Case Study
		existing resources	additional resources		
B. Li et al. [2014]	pooling	✓	-	Courier	✓
Nguyen et al. [2015]	pooling	✓	-	Courier	✓
C. Chen and Pan [2016]	hailing	✓	-	Courier	-
Ronald et al. [2016]	hailing	✓	-	Courier	✓
Soto Setzke et al. [2017]	hailing	✓	-	Parcel	✓
C. Chen et al. [2017]	pooling	✓	-	Courier	✓
Beirigo et al. [2018]	pooling	✓	-	Courier	-
Mourad [2019]	pooling	✓	-	Courier	-
Najaf Abadi [2019]	hailing	✓	-	Courier	✓
Y. Chen et al. [2020]	pooling	✓	✓	Courier	✓
Manchella et al. [2020]	pooling	✓	✓	Courier	✓
Schlenther et al. [2020]	hailing	✓	✓	Courier	✓
van der Tholen et al. [2021]	pooling	✓	✓	Courier	-
Romano Alho et al. [2021]	hailing/ pooling	✓	-	Parcel	✓
Fehn et al. [2021]	pooling	✓	-	Parcel	✓
Meinhardt et al. [2022]	pooling	✓	-	Courier	✓
Zhang et al. [2022]	pooling	✓	-	Courier	✓
Z. Zhou et al. [2021]	hailing	✓	-	Courier	✓
Bosse et al. [2023]	pooling	✓	✓	Courier	✓
Liu and Li [2023]	hailing	-	✓	Parcel	✓
Staritz et al. [2023]	pooling	✓	-	Courier	✓

Table 2.3: Existing Models MoD literature and assorted research characteristics (i.e. transportation mode, integration approach, freight service, and case study). The existing and additional attributes of the integration approach refer to whether the integration of freight takes place on vehicles that would be used for passenger transport anyway, or induced additional trips/vehicles). The freight service (i.e. Courier, Parcel, and Cargo) refers to item size, temporal (schedule: static, dynamic), and spatial delivery constraints of the freight service.

The above literature review reveals that several studies have investigated the integration of MoD and FrT. The studies have proposed different models and algorithms to handle the transportation of both passengers and parcels using taxis, shared mobility, and connected vehicles. Many studies have used real-world data from major cities, and simulations to evaluate their models' feasibility and efficacy.

They demonstrate that leveraging taxis and ride-sharing services for parcel delivery can significantly enhance the efficiency of last-mile logistics [Manchella et al., 2020; Mourad, 2019; Z. Zhou et al., 2021], achieving high successful delivery rates and substantial fleet distance savings [Fehn et al., 2021; Meinhardt et al., 2022]. Moreover, the research highlights the feasibility and benefits of combining passenger and freight transport, with models showing improved experiences for both operators and customers [Ronald et al., 2016]. Deep reinforcement learning algorithms, optimization approaches, and simulation tools have been applied to better understand the complex dynamics of integrated transportation systems. The studies reveal that such integration has the potential to reduce traffic congestion [Najaf Abadi, 2019; Nguyen et al., 2015; Romano Alho et al., 2021], environmental impact [Fehn et al., 2021], and overall transportation costs [Beirigo et al., 2018; C. Chen & Pan, 2016] while providing a robust solution for the modern demands of e-commerce and urban mobility. However, they also highlight the importance of careful planning and anticipatory policies [Schlenther et al., 2020] to maximize the advantages of integration and avoid sub-optimal utilization of vehicle fleets. Most studies suggest that co-modality approaches, which allow passengers and parcels to share vehicles, provide improved experiences for both operators and customers, are more resilient to uneven or unexpected demands, and provide more options for travel compared to single-purpose fleets [Liu & Li, 2023; Schlenther et al., 2020; Z. Zhou et al., 2021]. However, some studies found that shared mobility is not as scalable as conventional truck based logistics systems in terms of operating costs [Bosse et al., 2023; Nguyen et al., 2015]. Results show that this form of integration has the potential to save vehicle kilometers compared to traditional delivery systems [Fehn et al., 2021; Meinhardt et al., 2022; Najaf Abadi, 2019].

2.1.2 Existing Services in Practice

Analogous to the previous chapter, which looked at the different integration forms of passenger transport and freight transport in research, this chapter gives insight into existing concepts and field tests in practice. To analyze existing real-world applications in parallel to the research activities of the previous section, this review investigates existing integration approaches of FrT into PuT, InT, and MoD.

Public Transport

This subsection provides an overview of real-world examples of integrating the transport of passengers and freight on existing PuT infrastructure. Several cities around the world have implemented various concepts to combine the transport of passengers and freight. Examples include the Amsterdam "City Cargo Tram" [Mobilität der Zukunft, 2007], a freight tram in Brussels [Strale, 2014], the "cargo- and e-tram" in Zurich [City of Zurich, 2022], the "amazon prime now" service on New York metro [Crow, 2023], the "CarGoTram" in Dresden [Oelmann, 2022], the "LastMileTram" in Frankfurt [Schocke et al., 2020], the "Logiktram" in Karlsruhe [Karlsruhe Institut für Technologie - Forschungszentrum Informatik, 2022] (Figure 2.2b), the automated TaBuLaShuttle project in Lauenburg [Kucharski & Cats, 2022], the "Cargo Tram" in Brussels [Strale, 2014], the "TramFret" project in Saint Étienne [Ozturk & Patrick, 2018], and the "Freight*Bus" concept in London [Frost, 2008]. In Vienna, the "Öffi-Packerl" [Hayek, 2022; Wiener Linien, 2022], and the "KEP-Train" [Fraunhofer Austria, 2022], are examples of running initiatives, while the "GüterBim" [Fochler, 2022] in Vienna has been discontinued. Maes and Vanelslander [2011] investigate new logistics concepts involving rail transport as part of the supply chain in an urban context. They focus on two research subjects, namely the economic and ecological viability and capacity utilization of urban rail transport and refer mainly to the *Monoprix* (France) and *Proctor and Gamble* (Belgium) field tests [Maes & Vanelslander, 2011]. Maes and Vanelslander [2011] show that, especially the delivery tram in Paris shows great potential, replacing 12,000 trucks in the city center, saving 70,000 liters of fuel, resulting in a decline of 340,000 tonnes of CO_2 and 25 tonnes of NO_X. They conclude that that the use of rail transport for city distribution purposes should be possible and shows a clear profit for society, as noise emissions, air pollution and congestion are pushed back. However, the integration is limited to the rail infrastructure and not an integration of passenger and freight inside the vehicles. Furthermore, the authors state that current supply chains, now dominated by road transport, will have to be rethought and reorganized. Strale [2014] state that for the discontinued project in Brussels, there is only poor knowledge about urban freight flows and high competition with passenger services on light rail networks and that only small-scale or private initiatives can survive. The New York City test comprised two delivery workers pushing large trolleys of Amazon parcels on the subway. The project was using regular underground trains for Prime Now deliveries because traffic on Manhattan's gridlocked streets made it impossible to fulfill a 60-minute delivery guarantee. The Amsterdam solution was one of the largest freight tram projects in Europe. The goal was to shift the traffic load from trucks to streetcars to distribute goods between stores and restaurants in the city. During a test phase in March 2007, the streetcars transported beer loads for the city's pubs, clothing for a fashion store, and waste paper. The operation was limited to the hours of 07:00 to 23:00 to avoid noise pollution. According to calculations, the tram would have had the potential to avoid 2.500 truck movements within the city per year and reduce the city's pollution by 15% [Mobilität der Zukunft, 2007]. However, after the successful pilot test, the company was unable to raise sufficient funds. By November 2008, the company was declared insolvent. The integrated tram systems in Zurich are still existing and use the existing rail infrastructure to deploy special trains for collecting old appliances and e-waste in dedicated trailers. The tram solution in Dresden also makes use of the existing tram rail network, delivering parts to a "Volkswagen" production site with dedicated trams. The timetable for the delivery trams used to "swim" in the traffic of passenger trams, however the integrated operation has been discontinued. The Saint Étienne service uses old trams to transport cargo in the city's network, moving supermarket goods from a warehouse on the outskirts of the city to the busy downtown area [Ozturk & Patrick, 2018]. The examples from Frankfurt and Karlsruhe are similar in their logistic concepts and aim for an environmentally friendly transport system making use of overshoot capacities in times of low passenger demand. However, Schocke et al. [2020] state that the simultaneous transport of passengers and freight in the same vehicle is not legally solid at the moment and needs further policy making. A historically grown idea is the "Dabbawala" system in Mumbai, India (Figure 2.2a) [Roncaglia, 2013]. The couriers, i.e. Dabbawalas, deliver lunch boxes by public transit and a sub-system with bicycles all over the city of Mumbai. Onomotion GmbH [2022] and Riemann [2022] released concept studies for the combination of tram and cargo bikes. Their solutions builds on standardized containers, which can easily be mounted on bikes and trains. The bus concept of Frost [2008] was never implemented, but aims for carrying passengers and parcels simultaneously and was planned to operate within the London PuT system. The Vienna KEP-Train system aims for bringing the concept of crowd sourcing to rail. The project team estimates that around 20% of the GHG emissions currently generated by parcel transport could be saved if the deliveries were made by PuT rather than by delivery truck. For the future, the project shall be extended to other, more rural regions in Austria. In the sub-urban area Deutsche Post AG [2020] and Sylvester [2019] started two demonstrator projects within the initiative "LandLogistik", a bus system in "Uckemark", and a train system in "Hessen", both combining the transport of passengers and freight on already existing passenger transportation systems, which are not used to capacity. The projects include digital mapping of the supply chain with the overall aim to reduce transport related emissions.

(a) Dabbawallas [Parkin & Rodrigues, 2020].   (b) LogIKTram [Häs, 2023].

Figure 2.2: Service visualizations of PuT and FrT integration.

It can be concluded that the current supply chains, nowadays dominated by road transport, will have to be rethought and reorganized in many cities around the globe. This offers various solution opportunities for the integration of passenger and freight transport on already existing PuT infrastructure. The success of these initiatives, however, depends on various factors, including existing infrastructure, regulation, and public acceptance.

Individual Transport

Quite in contrast to the multitude of practical tests for the integration of PuT and FrT, there are very few practical examples in the field of InT which rely on an integration of the two traffic flows. Hitch Delivery Limited [2023] is a so called “on-the-way” delivery service in Ireland that allows shippers to get in touch with drivers sharing the same or a similar route with their parcel’s route (Figure 2.3a). The service promises that one can send, receive, or even transport parcels in a fast, flexible, and cost-efficient way and consider themselves to be the largest local same-day delivery service in the country. Another well established service is the Nigerian MAX.ng [2022]. The service comprises a platform for crowd-sourced delivery and aims for transporting passengers and goods with all kinds of vehicles (Figure 2.3b). However, it is not clear from the service definition whether the goal of the service is to actively pool trips between passengers and logistics goods in order to create an efficient and sustainable service, or simply to offer all types of transportation.

(a) Hitch Delivery [Hitch Delivery Limited, 2023].

(b) MAX [Burn Media, 2019].

Figure 2.3: Service visualizations of InT and FrT integration.

Mobility-on-Demand

In the area of integrated transport of MoD and FrT, the situation is similar to the previous section. Again, the number of use cases is severely limited compared to PuT integration. Real-world applications and concept studies comprise the Turkish "Dolmus" services [Brosnahan, 2022], which offer on-demand rides on more or less fixed routes (Figure 2.4a). The service transports mainly passengers, but also freight can be loaded into the vehicles. The world famous "TukTuk" services in Philippines, Indonesia and India can be seen similar. The focus lies on the transport of passengers, however from time to time also integrated transport happens, but more by chance than by organized planning. "Bussgods" [Bussgods i Norr AB, 2022] is a logistics company from Sweden. The company transports goods for both private individuals and companies. Many of the tours go by regular on-demand bus, which means that passengers and parcels are driven in the same vehicle (Figure 2.4b). The company claims to offer an environmentally friendly and punctual service. In Munich, a local taxi provider recently extended its offer and aims for combining the classical taxi service for passengers with a dedicated premium courier service [IsarFunk Kurier, 2022]. However, similar to the example of "MAX" in Nigeria, it is not fully clear from the service definition whether the trips are actually intended to be pooled, or whether it is an additional demand that will be served separately during periods of low passenger demand.

(a) Dolmus [Roving, 2013].

(b) Bussgods [Salomonsson, 2016].

Figure 2.4: Service visualizations of MoD and FrT integration.

2.1.3 Interim Conclusion and Implications

In conclusion, the comprehensive literature review on passenger and freight integration provides a nuanced understanding of the potential and challenges associated with this approach in both research and practice. The review highlights the ability of large PuT vehicles to seamlessly integrate freight logistics services, contributing to improved efficiency and sustainability in urban transport. However, the inherent constraints of PuT services, such as fixed routes and limited time flexibility, pose challenges for logistics operations and limit capabilities such as door-to-door delivery. The integration strategies for FrT can utilize existing or additional infrastructure and vehicles, with a predominant focus on leveraging existing resources. The methodologies employed in the reviewed studies, including case studies, mathematical modeling, and simulation, demonstrate the multiple benefits of integrating passenger and freight transportation. These benefits include positive environmental advances, energy savings, congestion reduction, operational efficiency, and economic viability. However, challenges such as effective planning, appropriate sizing of delivery volumes, and time constraints on parcel delivery must be addressed for successful integration. Crowd-sourced logistics in last-mile delivery processes offer potential cost benefits and efficiency improvements. However, these often add additional miles to the system, and standby drivers are typically required to make the system reliable. In addition, challenges related to policy implementation, coordination, and trust issues require careful consideration. The integration of MoD and FrT presents promising models and algorithms using taxis, ride-sharing services, and connected vehicles, demonstrating potential efficiencies in last-mile logistics. The studies reviewed advocate a rethinking and reorganization of existing road-dominated supply chains, suggesting a shift towards integrated passenger and freight transportation. Practical examples of real-world applications highlight the potential of combined passenger and freight transport. However, challenges in public acceptance, regulation, and infrastructure compatibility highlight the need for further research and implementation efforts to fully realize the benefits of integrated urban transport systems. Collectively, the literature reviewed highlights the transformative potential of integrating passenger and freight systems and provides a blueprint for cities to create sustainable, efficient, and resilient urban mobility solutions that meet the evolving needs of modern society.

The following Table 2.4 aims to provide an overview of the found existing approaches in the research area of integrated urban mobility services for passengers and freight in an urban and suburban context. Table 2.4 covers both the current state of research and practice. It provides a overview of existing solutions by creating a matrix of the urban forms of passenger and freight transport identified previously.

		PuT	**InT**	**MoD**
Courier	Research	X	✓	✓
	Practice	X	?	✓
Parcel	Research	✓	✓	✓
	Practice	?	?	✓
Cargo	Research	✓	X	X
	Practice	?	?	?

Table 2.4: Existing solutions integrating freight transport (rows) into urban passenger transportation (columns) in research and practice.
Legend: ✓: existent, ?: unknown or not fully compliant, and X: non existent

The focus of the subsequent work is on the urban context, as there are usually a variety of passenger transport modes available for possible integration [Schröder & Gotzler, 2021], as well as comparably higher demand, which fosters the possibilities of integrating freight transport in anyway existing passenger trips, by creating pooled trips. Furthermore, the logistics chain loses its high efficiency on the last mile, which is usually achieved by bundling similar logistics flows, which are becoming more disperse on the first and last mile [Blösl, 2022]. Therefore, a higher integration potential can be expected in the urban and suburban context, not only on the passenger side, but also on the logistics side. ***Note that this research considers integration only in one direction, i.e. the integration of urban logistics into existing passenger transportation systems, and not the other way around. This means that this dissertation assumes that passenger transport has priority over freight transport. For this reason, time critical shipments, are later on excluded from consideration in this research.*** Existing passenger transport solutions, on the one hand, offer a high integration potential due to their design for peak loads (services of general interest), which leads to free capacities in off-peak times. On the other hand, the dimensioning of logistics transport is usually planned for the entire operating period and region, which reduces free capacities for passenger transport. In addition, in most cases, freight vehicle concepts would have to be significantly modified to allow passenger transport. For these reasons, the integration of passengers into existing logistic transport is less common and mostly limited to applications in very remote areas and special vehicles (e.g. ferries, airplanes, helicopters, or snowmobiles).

Overall, this work investigates the basic forms of integration of *courier*, *parcel*, and *cargo* logistics in PuT, InT, and MoD, resulting in nine possible integration scenarios: (1) PuT + Courier, (2) PuT+ Parcel, (3) PuT + Cargo, (4) MoD + Courier, (5) MoD + Parcel, (6) MoD +

Cargo, (7) InT + Courier, (8) InT + Parcel, and (9) InT + Cargo. The resulting Table 2.4 will be addressed again in Chapter 3 for the definition of the envisioned RPP service.

2.2 Evaluation of Urban Transportation Systems

With the pressing challenges of climate change, urbanization, the growth of e-commerce, and the need for sustainable mobility solutions, the evaluation of urban transportation systems is becoming increasingly important in urban planning and development. Comprehensive evaluation methods are needed to assess new transportation systems in terms of economic viability, environmental impact, safety, and user satisfaction. In their literature review, Karjalainen and Juhola [2021] identify Multi-Criteria Analysis as the most commonly used assessment method when it comes to evaluating transportation systems. Jeon et al. [2013] emphasize that all three dimensions of sustainability, i.e. economic, environmental and social dimensions, need to be considered in addition to performance measures of system effectiveness. Overall, three main evaluation methods for the transport sector can be derived from the literature: Cost-Benefit Analysis, Multi-Criteria Analysis, and Balancing, Ranking and Discussion Methods [Karjalainen & Juhola, 2021; Lee Jr, 2000; Sun et al., 2020]. Cost-benefit analysis is a quantitative method that belongs to the category of economic evaluation. It involves comparing the costs and benefits associated with transportation projects to determine their overall economic viability. Multi-criteria analysis in European transportation involves assessing the availability, accessibility, information, time, customer satisfaction, comfort, safety, and environmental consequences of transportation systems [EN 13816:2002, 2002]. Balancing, ranking and discussion methods often build on the first two assessment methods and enrich them with input from expert panels or public opinion for weighting against a specific project context. In the German context, the evaluation of transportation systems is build upon guidelines and standardized assessment procedures (e.g. Standardized evaluation of transport infrastructure investments in public transport [Arbeitsgemeinschaft Intraplan Consult GmbH / Verkehrswissenschaftliches Institut Stuttgart GmbH, 2023]), which often consider the above mentioned methods. When awarding contracts for new transportation systems, public tenders with predefined quality criteria are defined and used to evaluate the bids.

In the case of the integration of passenger and freight transport in an urban context, the elimination of delivery vehicles means that not only the distance saved during the use phase, but also the upstream processes based on the reduction of vehicle prices play a decisive role. For this reason, it is advisable at this point to take a closer look at the concept of Life Cycle Assessment (LCA) as an evaluation method.

All integrated transportation solutions have in common that capacity is to be allocated more efficiently, i.e. utilization increases, compared to the status quo, which is not considering integration of passenger and freight flows. As a result, a smaller number of vehicles is needed in the first place, but also have to be replaced earlier due to the increased utilization. To investigate integrated transportation systems properly, conventional macroscopic evaluation approaches, i.e. pure kilometers driven, are not sufficient, but a life cycle approach, taking into account vehicle production, becomes necessary. This assessment extends the scope of investigation beyond the use phase of transportation services. It is required to investigate integrated transportation solutions with a LCA approach because it provides a comprehensive analysis of the environmental impacts associated with the entire life cycle of the transportation service. LCA is a widely accepted methodology that evaluates the environmental impacts of a product or service from cradle to grave, including all stages of Raw Material Extraction (RME), Production (PRO), Use (USE), and End of Life (EOL). By conducting a LCSA, one can even identify the environmental, economical, and social effects of the above reviewed integrated transportation solutions. In the case of RPP, a LCA approach can help to assess the potential reduction in GHG emissions, energy consumption, and other environmental impacts compared to traditional parcel delivery services.

The literature relevant for creating a LCA model comprises on the one hand technical reports, like the ISO 1040 [ISO Norm 14040.2006, 2016] and 14044 [ISO Norm 14044.2006, 2016] or handbooks, like the "Life cycle assessment handbook: a guide for environmentally sustainable products" of Curran [2012], offering guidance and policies for conducting proper and comparable LCA studies. On the other hand, there are research papers that apply these guidelines to case studies, collect data for life cycle inventories and open up new fields of application. In addition, there is a number of software and databases that can assist in the creation of a comprehensive LCA and the modeling of complex product systems. All of the above areas will be considered in the course of this literature review and the aspects relevant to the evaluation chapter of this dissertation will be addressed in detail.

2.2.1 Theory and Components of Life Cycle Assessment Studies

A LCA study provides a systematic approach to evaluating the environmental impact of a product, process or service throughout its life cycle. The Life Cycle Cost Assessment (LCCA) and Social Life Cycle Assessment (SLCA) methods were invented to quantify the economic and social impact of a product or process over its life cycle. All three approaches together form a so-called LCSA and cover all dimensions of a sustainability assessment. A LCSA is a powerful tool for identifying areas for improvement and making informed decisions that minimize adverse environmental, economic and social impacts. Potential applications include product development and improvement, strategic planning, public policy making, marketing, and many others.

A LCA is a comprehensive method to evaluate the environmental impact of a product, process, or service throughout its entire life cycle, from the extraction of raw materials to the disposal or recycling of waste materials [Hauschild et al., 2018; Rebitzer et al., 2004]. According to ISO Norm 14040.2006 [2016], the four main components (see Figure 2.5) of a LCA study are:

1. Goal and Scope Definition
2. Life Cycle Inventory (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation of Results

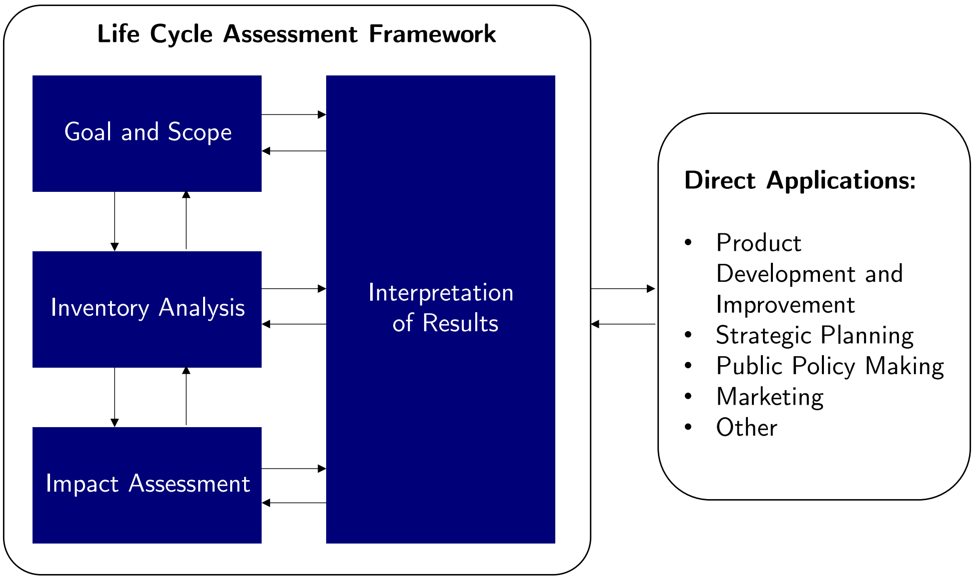


Figure 2.5: Stages and applications of an LCA according to ISO Norm 14040.2006 [2016].

In addition to the identified main components of a LCA, the data base, LCA methodologies, and modeling software play a critical role in obtaining reliable and comparable results. For this reason, this study first discusses the components *target and scope definition*, *LCI*, *LCIA*, and *interpretation of results* of a LCA in detail. Subsequently, the existing databases, the LCA methods, and the software relevant for the modeling of mobility services in Germany is presented.

Goal and Scope Definition

The goal and scope definition is the first and most important step of a LCA study, as it defines the basis of the analysis. It involves specifying the goal and scope of the analysis, which means determining the purpose of the research, the product system to be evaluated, and the impact categories to be considered. Defining the goal and scope also includes setting system boundaries, identifying data sources, determining the functional unit, and selecting the appropriate LCA methodology.

According to ISO Norm 14040.2006 [2016], the goal and scope definition includes the *application* of the study, the *reason* for initiating the investigation, and the intended *audience* of the study. The *product system*, i.e. all the activities required to produce, use, and dispose the product, must be defined. Therefore, it's the *functional unit*, i.e. the quantified performance of a product system, or the unit to which each flow is referred and its respective *reference flow*, typically expressed in terms of mass, volume, units, or energy. The next step is to clarify the study's *allocation procedures*, defined as "the allocation of input and/or output flows of a process to the product system under study" [ISO Norm 14040.2006, 2016], and relate them to the *impact types*, i.e. environmental, economic, or social impact categories (e.g. climate change, resource depletion or human health impacts). The *system boundary* for a LCA study is usually drawn around the core components of the product or service, encompassing all life cycle phases from raw material extraction, through production and use, to end-of-life treatment. However, it may also exclude certain phases or components, e.g. road infrastructure, when evaluating the life cycle processes of a passenger car. Finally, the term *cut-off criteria* is used to describe criteria that lead to the (dis)consideration of certain inputs or outputs. These are usually applied as a relative proportion to the categories of mass, energy and environmental, economic or social significance.

The goal and scope of a LCSA consider a broader set of sustainability objectives compared to a conventional LCA and must also consider the temporal and geographical system boundaries of the assessment and identify the stakeholders and their needs [Alejandrino et al., 2021; Zamagni, 2012]. It is also possible to assume different goal and scope definitions for the LCCA, SLCA and LCA. However, the comparability of the LCA, LCCA, and SLCA could suffer from this because the adopted system boundaries differ and thus may no longer be directly comparable.

Life Cycle Inventory Assessment

The LCI involves the collection and quantification of data on energy and material inputs and outputs of the product or process under evaluation and is specified in ISO Norm 14044.2006 [2016]. This includes all activities involved in the life cycle of the product system, such as extraction and transportation of raw materials, manufacturing, distribution, use and end-of-life treatment. The data are collected using primary data (i.e. direct measurements) or secondary data (i.e. published data from various sources). The LCI data are then used to calculate the environmental impact indicators for the product or process being evaluated. The relevant inputs and outputs include first hand or generic material lists for the different products and all associated processes, i.e. all inputs and outputs of each process within the value chain of the product. The data quality should be monitored by the publishers and checked for consistency (i.e. temporal, geographical and technological coverage, precision, completeness, representativeness and reproducibility) by the authors of the study. In addition, the comparability between all the systems studied, e.g. the different product types, should be checked for equivalent assumptions; this should also be ensured by the scope definition of the study. The data classification includes energy inputs, raw material inputs, auxiliary inputs and other physical inputs, as well as products, co-products and wastes, releases to air, water and soil and other environmental aspects. The allocation of all relevant flows and releases involving by-products and recycling systems are related to the reference flow of the study and should be included in the calculation where appropriate. In addition to the environmental aspects, social and economic aspects shall be considered in a LCSA. This includes the quantification of social and economic indicators (e.g. human health and safety, as well as service costs and revenues).

Life Cycle Impact Assessment

LCIA is the phase in which the environmental impact of a product system or process is assessed. The data collected in the LCI stage is translated into impact indicators using LCIA methods. There are many LCIA methods that represent different scientific perspectives, value judgments, and stakeholder preferences. They focus on different environmental impact categories, such as climate change, human toxicity, and ecosystem quality, and use different indicators, models, and assumptions to quantify potential impacts [Hauschild et al., 2018]. The choice of LCIA method depends on the purpose and scope of the LCA study, and the availability and quality of LCI data [Curran, 2012]. Generally, LCIA methods can be distinguished in *midpoint* and *endpoint* indicators. Midpoint indicators represent a more intermediate stage in the cause-effect chain of environmental impacts. They are generally closer to the actual emissions associated with a product or process (e.g. GWP, eutrophication potential, or human toxicity potential). Endpoint indicators provide a more comprehensive view of the ultimate or final environmental impacts. They are typically more user-oriented and are often used to communicate results to non-specialists and policymakers (e.g. ecosystem quality impact or resource depletion impact). The most common LCIA methods are presented in Table 2.5.

The LCIA in a LCSA integrates the social, economic and environmental indicators to assess the overall sustainability of the product or process being assessed [Alejandrino et al., 2021; Zamagni, 2012]. The LCIA methods used in a LCSA must be able to capture the interrelationships between the different dimensions of sustainability. LCCA describes its impact in monetary terms, whereas SLCA relies usually on impact categories related to human well-being.

Interpretation of Results

The interpretation of results in a LCA involves analysis and communication of the study results to stakeholders and decision makers. This last step includes a consistency check of the data analysis and assessment, taking into account data quality and uncertainty. It should also examine the key issues, i.e. impacts and hot spots, include a sensitivity analysis (i.e. varying assumptions and parameters on the results and identifying critical areas for improvement), and include a comparative analysis of similar studies. Finally, this last step must communicate the results using appropriate and transparent methods and include recommendations for system and process improvements. [ISO Norm 14040.2006, 2016].

The interpretation of the results in a LCSA considers environmental, social and economic aspects and identifies potential trade-offs and synergies between the different dimensions of sustainability [Alejandrino et al., 2021; Zamagni, 2012].

Life Cycle Assessment Data, Modeling Approaches, and Software

The data, modeling approaches, and software used in LCA studies are critical to ensuring the accuracy and reliability of the results. Modeling approaches help translate this data into meaningful insights that can inform decision making and policy development. LCA software simplifies data management, enables the use of different LCA methodologies, provides impact assessment tools, supports scenario analysis, and generates reports and visualizations. Table 2.6 summarizes LCA databases of particular interest for transportation modeling.

The data requirements for LCA studies include the material list of the products and their respective life cycle emissions. This usually requires a number of assumptions to be made,

Method	Description
IPCC GWP	The IPCC (Intergovernmental Panel on Climate Change) GWP methodology serves as a widely accepted LCA midpoint approach recognized for providing a comprehensive examination of environmental consequences. It is widely recognized as the standard LCIA method for assessing GWP.
ReCiPe	The ReCiPe (Recourse Environmental and Impact Assessment) methodology is a widely used LCA that provides a comprehensive analysis of environmental impacts. It covers a wide range of impact categories, including climate change, human toxicity, and ecosystem damage, and uses a midpoint approach to impact assessment.
CML	The Centre of Environmental Science, Leiden University (CML) method is another widely used LCA method that focuses on impact categories related to energy and resource use, such as climate change, acidification and eutrophication. It uses a midpoint approach to impact assessment.
TRACI	The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) is a LCA methodology developed by the U.S. Environmental Protection Agency. It focuses on a wide range of environmental impact categories, including human health, ecosystem quality, and resource depletion.
Eco-Indicator 99	The Eco-Indicator 99 methodology is a LCA developed by the Dutch research institute PRé Consultants. It focuses on environmental impact categories related to human health, ecosystem quality and resource depletion, and uses a midpoint approach to impact assessment.
IMPACT 2002+	The IMPACT 2002+ methodology is a LCA methodology developed by the U.S. National Institute of Standards and Technology (NIST). It covers a wide range of environmental impact categories and uses a midpoint approach to impact assessment.
EPS 2000	The EPS 2000 (Environmental Priority Strategies in Product Design) methodology is a LCA developed by the Swedish Environmental Protection Agency. It uses an intermediate approach to impact assessment and focuses on endpoint environmental impact categories related to human health, ecosystem quality and resource depletion.
ILCD	The International Life Cycle Data System (ILCD) is a LCA methodology developed by the European Commission. It is designed to be a standardized framework for LCA studies and covers a wide range of environmental impact categories, including mid- and endpoint indicators.

Table 2.5: Most relevant LCIA methodologies for transportation models.

Database	Description
ecoinvent	The world's most widely used LCA database, containing international industrial life cycle inventory data on energy supply, resource extraction, materials supply, chemicals, metals, agriculture, waste management services, and transportation services, with more than 18,000 reliable records.
GREET	The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model is developed and maintained by the U.S. Argonne National Laboratory. It includes more than 100 fuel production pathways and more than 70 vehicle/fuel systems.
IDEA	Hybrid inventory database that contains both statistical and process-based data. It comprehensively covers almost all economic activities in Japan and contains about 3,800 processes.
IDEMAT	Compilation of LCI data designed to meet the needs of designers, engineers and architects in the manufacturing and construction industries. The data is based on peer-reviewed scientific papers and additional LCI produced by Delft University of Technology and Plastics Europe.
LCA Commons	Free database of 9,200 LCA data sets collected and developed by various U.S. government agencies.
NEEDS	Database created by "New Energy Externalities Developments for Sustainability" project, which includes industrial life cycle inventory data on future transport services, electricity and materials supply.
ProBas	Data set library originally provided by the German Federal Environmental Agency and freely available for academic use. It includes unit and aggregated processes for the following topics: Energy, materials and products, transportation services, and waste.

Table 2.6: Databases for LCA relevant for transportation models, adapted from GreenDelta GmbH [2023].

such as the location and energy mix for production, the associated transport processes, the exact material composition and characteristics of the product system and process categories under consideration, or the disposal processes. The limitations of a LCA study are mainly related to the mentioned assumptions, but also comprise uncertainties in the use and operation pattern of the product systems.

Regarding modeling software for LCA, there are many different commercial solutions, such as "SimaPro", "GaBi", "Umberto", or "Altermaker". However, "OpenLCA" is the only open source solution that offers a professional environment for ecological, economic, and social LCA that guarantees the reproducibility of the results obtained [GreenDelta GmbH, 2023]. In general, all software offers similar features, including data management components for managing, as well as organizing data on materials, processes, emissions, and energy consumption, LCA methodologies that allow users to evaluate the environmental impact of products and processes. These methodologies can range from simple to complex and the choice depends on the level of detail required for the LCA study. For impact assessment, all of the software mentioned above provide tools for quantifying the impact of a product system or process. This includes the ability to assess the impact of emissions on various environmental categories such as climate change, water use and loss of biodiversity. Most software also provides tools for scenario analysis, which involves assessing the impact of different options for a product system or process. Finally, most software solutions also include tools for generating reports, graphs, and other visualizations of LCA results.

In terms of data, modeling approaches, and software, a LCSA requires additional information beyond what is typically required for a LCA. In particular, a LCSA requires data on social and economic indicators as well as environmental indicators. In addition, the modeling approach for a LCSA must take into account the interrelationships and trade-offs between social, economic, and environmental indicators [Alejandrino et al., 2021]. Finally, software for LCSA must be able to handle the additional data and complexity of the modeling approach, which may require more advanced functionality and user interface design.

2.2.2 Existing Research in Life Cycle Assessment of Mobility Services

LCA is an important tool for decision making in the context of evaluating new forms of transportation in comparison to the status quo [Zamagni, 2012]. With the increasing demand for sustainable transportation solutions, LCA can provide valuable insights into the environmental performance of different transportation options, including their energy use, GHG emissions, and resource consumption. By assessing the LCIA results of new transportation options and comparing them to the impacts of existing modes, LCA can help to identify opportunities for improvement and to inform decision makers about the environmental implications of their choices [Alejandrino et al., 2021; ISO Norm 14040.2006, 2016]. Overall, LCA provides a comprehensive approach to evaluating the sustainability of transportation options and can help guide the transition to more sustainable and efficient transportation systems. The LCA methodology can be applied to shared mobility fleets by considering the life cycle impacts of vehicles. This analysis can help to identify opportunities to reduce the environmental impact of shared mobility services, such as the use of electric or hybrid vehicles, optimizing vehicle routing and utilization, and to compare them to the status quo of the transportation system. In addition, the use of shared mobility fleets can also have an impact on the GHG emissions of a transportation service. For example, a shared mobility service that replaces private vehicle ownership can reduce the total number of vehicles on the road [Bösch et al., 2018; Engelhardt et al., 2019], leading to a reduction in GHG emissions and other environmental impacts. In addition, a well-designed shared mobility service can encourage the use of sustainable modes of transportation, such as walking, cycling, or public transit, which can further reduce the environmental impact of the transportation system [Schröder et al., 2023].

In the following, this literature review presents case studies that apply LCA approaches to the evaluation of vehicle fleets, mostly in an urban context. The studies investigate environmental sustainability in the transportation sector, with a particular focus on the life cycle assessment of different vehicle types and mobility strategies. A recurring theme across several studies is the critical importance of considering the entire life cycle of vehicles and transport systems to gain a holistic understanding of their environmental impacts [Bartolozzi et al., 2013; Gawron et al., 2019; González Palencia et al., 2012; Severengiz et al., 2020]. In particular, Hawkins et al. [2012] emphasizes that the emissions of electric vehicles are highly dependent on factors such as battery production and the source of electricity used for charging, revealing that coal-powered electric vehicles can have emissions comparable to those of conventional internal combustion engine vehicles. Meanwhile, other studies highlight the importance of fleet penetration rates, electricity sources, and vehicle weight reduction in electrification pathways [Burchart-Korol et al., 2018; Garcia & Freire, 2017; González Palencia et al., 2012]. Gawron et al. [2019] provide a framework for evaluating autonomous taxis, revealing the potential for significant GHG emissions reductions in electric autonomous fleets and highlighting pathways for further improvement. Their case study of the Austin, Texas, fleet shows that strategic deployment of an electrified taxi fleet can reduce cumulative energy and GHG emissions by 60%. In addition to urban passenger fleets, there are also LCA studies on urban freight transport [Lemardelé et al., 2023; Marmiroli et al., 2020], showing that electric vehicles combined with smart delivery strategies can significantly reduce CO_2 emissions. Taken together, the studies reviewed underscore the complexity of assessing the environmental impacts of transportation and urge consideration of multiple variables, including energy sources, vehicle types, and logistics approaches, to navigate the path toward reducing GHG emissions and promoting sustainability in urban passenger mobility and goods transportation.

Overall, LCA provides a valuable tool for evaluating the environmental performance of transportation services, including emerging shared mobility services. However, to the best of the author's knowledge, there is no LCA framework for evaluating the integration of passenger and freight transportation into one common vehicle fleet. By considering the LCIA results of integrated transportation options and promoting sustainable modes, LCA can help guide the transition to a more sustainable and efficient transportation system for both urban passenger and freight transportation. On the one hand, there is no simple, modular approach to calculating the life cycle emissions of a vehicle fleet that is also open to the introduction of new vehicle models and concepts for comparative LCA. On the other hand, the approach of using existing passenger trips for the transport of parcels has not yet been investigated with a LCA approach. This creates a very interesting research gap, because the integration of an entire vehicle fleet into another and thus its replacement can only be analyzed holistically with a LCA approach.

2.3 Methodological Research Approach and Research Questions

As the present literature review on applications of integrated transport solutions for passenger and freight in research and practice shows, the range of possible combinations of passenger and freight transportation is very wide. It includes different modes of transportation, such as rail- and road-based PuT services, individual crowd-sourced approaches, or the idea of centralized assignment of passengers and parcels to a fleet of vehicles, as in the case of MoD services.

Existing studies in the area of MoD have mostly focused on the integration of passenger and freight on the same means of transportation at different times, i.e. passengers and freight do not share the ride. In addition, studies often assume time windows for parcel pick-up and drop-off, which simplifies allocation but does not fully exploit the integration potential of existing passenger trips. This thesis will focus on the integration of freight transportation into the operation of a MoD ride-pooling service, i.e. passengers and freight share rides. Thereby, special emphasis is placed on the simultaneous transportation of passengers and freight (i.e. passengers and parcels can be on board the same vehicle at the same time). This approach aligns with the growing need for innovative and sustainable urban transportation solutions. As the literature review revealed, the traditional separation of passenger and freight transport has led to inefficiencies, increased congestion, and environmental concerns. By integrating both modes, the thesis aims to explore a more holistic and resource-efficient approach that maximizes the use of existing transportation infrastructure. ***The focus of this thesis on the integration of freight transportation into the operation of a MoD ride-pooling service is driven by the high degree of spatial flexibility that ride-pooling services offer, making it even possible to display doorstep deliveries. Furthermore, the temporal flexibility allows for an approach which incorporates parcels into the existing schemes of a ride-pooling provider by addressing the core idea of RPP, minimizing adverse effects on humanity, like increased traffic volumes, environmental effects, or air pollution. A detailed service definition of the envisioned RPP service follows in Chapter 3 of this doctoral thesis.***

The existing literature on the evaluation of urban transport systems has shown that there is a wide variety of assessment methods for the evaluation of transport systems, but only LCA and especially LCSA take into account the long-term effects that transport systems create and include upstream effects, which become particularly interesting when vehicles can be saved by integrating passenger and freight flows. By reducing both the number of trips and the number of vehicles needed, integrated transportation solutions have the potential to significantly reduce the negative impacts of transportation systems, but this requires looking not only at the use phase of transportation systems, but at their entire life cycle. Chapter 5 of this dissertation aims to provide an assessment methodology for evaluating urban transportation fleets over their entire life cycle, including all three dimensions of sustainability, i.e. the economic, environmental, and social dimensions.

The methodological research approach and the research questions of this doctoral thesis are derived from the state of the art findings presented here. Both, the methodology and the research questions follow the basic scheme presented in Figure 1.3. First, the envisioned RPP is conceptualized in Chapter 3, by conducting a market analysis based on expert workshops and a potential customer survey, resulting in potential RPP use-cases and finally simulation scenarios. In Chapter 4, this thesis proposes a simulation environment, where decisions to serve passengers and parcels must be made online to allow for online decisions on how the demand (passengers and parcels) can be served in a realistic environment. When introducing parcels into the ride-pooling service, special attention is given to making the best use of existing passenger trips. To do this, it is necessary to not offer an immediate service, or to guarantee time windows, but to "wait" for a passenger trip that is as "suitable" as possible. ***While recent studies focused on exploiting the idle time of MoD fleets explicitly for logistics services and modeled the logistics service as an "as soon as possible" delivery service (i.e. using strict time constraints on parcel pickup and delivery), the goal of this work is to actively integrate parcel pickup and delivery into vehicle routes. No explicit time constraints on parcel pickup and delivery are enforced, but the goal is to integrate parcel pickup and delivery into the scheduled vehicle routes resulting from the underlying ride-pooling service in order to minimize the additional vehicle kilometers driven.*** The efficiency of this integration and the developed assignment approaches are evaluated in terms of their impact on operator, customer, and traffic effects based on real logistics demand within a case study for Munich, Germany. Furthermore, recent studies did not quantify the benefits that occur over the complete life cycle of such an integration. To achieve this, Chapter 5 of this dissertation evaluates the results obtained from the case study in a LCSA tool, which is customized for shared mobility fleets and incorporates all three dimension of sustainability assessment by including ecological, cost and social analysis. Finally, this research tests the concept of RPP in Chapter 5, which describes a real-world field test in the city of Munich, Germany.

The research questions of this doctoral thesis are oriented on the dissertation outline and are accordingly related to the main Chapters 3 "Service and Scenario Definition" (i.e. Conceptualization), Chapter 4 "Modeling and Simulation" (i.e. Modeling), and Chapter 5 "Life Cycle Evaluation" (i.e. Evaluation). In order to define the RPP service, this dissertation will answer the following research questions:

Conceptualization:

- Which service characteristics and use cases contribute to a sustainable change of the existing transportation system by integrating urban passenger and freight transport?

Modeling:

- How could an on-demand Ride Parcel Pooling service look like and what are suitable control strategies?

- How could a holistic life cycle assessment for urban vehicle fleets look like and which parameters should be included?

Evaluation:

- Is a Ride Parcel Pooling service economically competitive compared to the status quo (separate state of the art ride-pooling and last mile freight transport)?
- Can Ride Parcel Pooling cause a sustainable change of urban mobility-on-demand vehicle fleets?

Chapter 3

Service and Scenario Definition

Chapter Essentials

- Definition of the Ride Parcel Pooling scope by analyzing existing passenger (public, individual, and mobility-on-demand) and freight (courier, parcel, cargo) transportation systems and applying physical, temporal, and spatial service requirements for evaluating feasible integration combinations.
- The resulting solution space reveals that only the combination of parcel logistics and mobility-on-demand passenger transport fulfills all requirements.
- Expert workshops applying the scenario technique found four promising Ride Parcel Pooling use cases, namely "Prioritized Ride Parcel Pooling", "Parcel Hopping", "Mobile Parcel Lockers", and "In-Vehicle Delivery".
- The customer survey for potential market analysis revealed that idea of Ride Parcel Pooling is perceived very positive and provided insight into accepted service parameters, such as waiting times, delays, detours, and pricing policies, which are later on implemented in the simulation.
- The "Prioritized Ride Parcel Pooling" use case was chosen for further in-depth analysis in the agent-based simulation due to the positive feedback in the expert workshops and the potential customer survey.

As the research methodology and research questions formulated at the end of Chapter 2 indicate, this work focuses on the integration of freight flows into existing MoD passenger transport structures in order to utilize free capacity without significantly degrading passenger traffic. In this context, the MoD solutions seem very promising due to their high flexibility in terms of spatio-temporal network coverage and relatively low capacity utilization. Although there is much to be learned from the crowd-sourced approaches and their integration into dynamic systems with reliable central decision making, the proposed solutions are mostly not in line with the idea of using existing passenger trips for additional freight transport, but rather induce trips or require a backup fleet to guarantee a reliable service. In the following this dissertation will develop the idea of Ride Parcel Pooling into a real world applicable mobility service, including different use cases and scenario definitions.

3.1 Ride Parcel Pooling Scope

Up to this point, the literature review has shown that the integration of existing means of passenger transport with urban logistics is very promising. However, it also highlighted some obstacles and the need for further research. In order to find the most promising combination for the integration of PuT, InT, MoD and FrT and to define the RPP niche for further research, this thesis proposes evaluation criteria to define the solution space for the following chapters of this dissertation. The goal of the Ride Parcel Pooling idea is to use existing passenger trips to integrate freight flows. Thereby, the overarching aim is to increase vehicle occupancy, reduce travel distance, and conserve resources.

3.1.1 Analysis of Existing Integration Solutions

In order to determine whether integrating a freight logistics service into a passenger transport service appears feasible, this research introduces three *evaluation criteria*. Each of these criteria covers a different aspect of the transport service that is deemed necessary for the successful integration of a logistics service into the respective passenger transportation system. In the following, this thesis describes each of the three evaluation criteria.

Physical:
Each unit of the passenger transportation system needs to have the physical capacity to at least theoretically transport passengers and freight at the same time. Depending on the logistics requirements (size, weight, count) of the freight, passenger transportation systems will be chosen as suitable or not suitable for integration.

Temporal:
For the temporal evaluation, the passenger transportation service needs to be able to perform the logistic service in the required time frame while still maintaining its role as a passenger transportation service. The temporal requirements for each logistic service were defined in Chapter 2.

Spatial:
The passenger transportation services need to be able to fulfill any spatial dependencies of the logistic service. The spatial requirements for each logistic service are defined in Chapter 2.

To evaluate the feasibility of integrated transportation systems, this work first presents the integrated systems in a systematic approach. To do this, it combines all high-level urban passenger transportation systems with all logistics systems presented in Chapter 1 and 2, respectively. This creates Table 2.4 and opens a solution space for integrated systems combining urban passenger transportation and urban logistics services. Each logistic service is further divided into three rows corresponding to the evaluation criteria introduced in the previous paragraphs forming Table 3.1. For each combination, the resulting assessment of the criteria is then given one of the following symbols: a green check mark, a yellow question mark, or a red cross. A green checkmark indicates no restrictions on the criteria, a yellow question mark indicates some restrictions on the criteria but possible niche cases, and a red cross indicates that the criteria are unlikely to be met. If any of the criteria for an integrated system are deemed not to be met, the system is not considered for further evaluation. In the following, the evaluation of the criteria for each form of urban passenger transport is detailed.

Public Transportation

PuT commonly uses large vehicles to transport a great amount of passengers, which makes them suitable to carry any form of freight. Therefore, the physical criterion is fulfilled in all combination cases. Temporal and spatial spread of PuT services are both regulated by a schedule. Accordingly, door-to-door or time sensitive services (courier and express logistics) are not compatible with PuT services. For cargo and standard parcels this gives some constraints but functional service is still possible if a solution for the final transport leg from a PuT station can be found. Furthermore, if performed well, the integration of freight transport into the system is not an inconvenience for passengers. Ultimately, they might benefit from it by getting reduced transportation fees. For safety and insurance reasons, the required space to store the parcels should not be accessible for other passengers. Altogether, integration in PuT is, according to these criteria, possible in combination with a cargo and parcel service, although with some restriction in temporal and spatial aspects.

Individual Transportation

For InT services, temporal and spatial restrictions depend on the private drivers, however as the literature review (Chapter 2) revealed, the acceptance of larger detours and travel time increases is very limited. Furthermore, the crowd-sourced solutions cannot guarantee a smooth logistics operation without a fall back logistics fleet in the background. Therefore, the temporal and spatial criteria in InT are marked as compliant with restrictions. The physical constraint depends on the respective vehicle, however the transport of large and heavy cargo will, for most private vehicles, cause problems. Therefore, the physical criterion is marked as unfulfilled. In addition, integrating logistic services into InT would cause greater inconveniences than in any of the previous transportation services as the passenger would be directly responsible for any freight that needs to be collected over the course of their trip. Moreover, the financial incentive to perform this logistic service might in many cases not outweigh the costs. Only at larger scales the financial incentive could outweigh the additional effort.

Mobility-on-Demand Transportation

MoD services are flexible in terms of the temporal and spatial criteria. This allows for door-to-door services and time sensitive services. Separation of customer and freight is possible as current, non-specialized vehicles already provide this option. However, this holds only true for small and medium sized freight as there is limited physical capacity in the individual vehicles. Accordingly, the physical criterion in cargo is not fulfilled. The integration of a logistics service into MoD affects passengers more than the previous two forms of transportation. This is especially true for the combination of courier services and MoD. Courier services have been defined as trips from origin to destination without any consolidation, vehicle change, or storage in between, and may have strict time windows for pickup and delivery. This accounts for the two orange question marks in the table 3.1 for the temporal and spatial criteria. Still, the only inconveniences faced by the passenger are small detours and a few additional stops [Fehn et al., 2023]. However, these can be compensated by a reduced transportation fee. Concluding, MoD services allow for an integration of all logistic services but cargo due to constraints in the physical capacity.

3.1.2 Solution Space

From an organizational point of view and taking into account the defined evaluation criteria *physical*, *temporal*, and *spatial*, the combinations with a red cross in Table 3.1 can be excluded, because the combinations PuT + courier, InT + Cargo, and MoD + Cargo do not comply with at least one of the three evaluation criteria. In addition, the evaluation matrix contains many question marks indicating evaluation criteria that are only partially satisfied. The combinations with InT are questionable in terms of temporal and spatial constraints, because especially in the case of InT the literature suggests that a systematic, fair, and reliable integration is difficult to achieve on crowd-sourced service based approaches. Furthermore, the literature review showed that crowd-sourced solutions can only act as a supplement to proper logistics networks, as their reliability is very limited. The remaining PuT combinations may not be compatible in time and space constraints, as loading and unloading must be done at the stations during a limited dwell time. Additionally, until now there is no clear legislative basis for integrated transport of passengers and freight on PuT in Germany [Bammerlin, 2021]. Only the combination MoD + Parcel is fully compliant for *physical*, *temporal* and *spatial* constraints. Therefore, this is the combination that will be investigated in the remainder of the service definition.

In the further course of this dissertation, PuT and InT solutions are discarded from the analysis. PuT cannot cope with the temporal and spatial complexity of doorstep delivery, which 87% of all Germans prefer as a delivery option [DPDgroup, 2017], and crowd-based delivery solutions do not yet offer a robust solution in terms of legal, reliable and safe handling of additional freight transport [Bammerlin, 2021; Upadhyay et al., 2022]. Furthermore, many solutions are not in line with the idea of RPP, which is to use mostly already existing passenger trips for additional freight transport and to induce as few trips as possible for additional freight transport.

	Criteria	PuT	InT	MoD
Courier	Physical	✓	✓	✓
	Temporal	X	?	?
	Spatial	X	?	?
Parcel	Physical	✓	✓	✓
	Temporal	?	?	✓
	Spatial	?	?	✓
Cargo	Physical	✓	X	X
	Temporal	?	?	✓
	Spatial	?	?	✓

Table 3.1: Solution space of the integration of freight transport (rows) into urban passenger transportation (columns).
Legend: ✓: fully compliant, ?: compliant with some restrictions and X: not compliant.

3.2 Idea of Ride Parcel Pooling

Based on the defined solution space for integrated passenger and freight transport in an urban context in Germany, this thesis elaborates the idea of RPP using the tools of expert workshops and survey of potential customers to analyze the potential RPP market. In the course of the expert workshops, problems, requirements, trends, solution approaches, and stakeholders in urban passenger and freight transport are defined with the help of the scenario technique and an impact analysis is elaborated. ***The survey of potential customers of RPP explores the opinions of the respondents with regard to basic attitudes towards pooled services, certain characteristics of RPP, and acceptable waiting and detour times, which are later used in the agent-based simulation setup. Overall, the expert workshops and the potential customer survey aim at investigating and defining a potential market for the RPP idea.***

3.2.1 Expert Workshops

The scientific expert workshops on the topic of integrated urban passenger and freight transport aimed to bring together researchers, practitioners, and policymakers to discuss the latest advances and challenges in this area. RPP is a novel concept that involves the sharing of MoD services with parcel delivery, in order to increase transport efficiency and reduce the number of vehicles on the road. The workshop formats covered various topics, such as a structured investigation for the identification of problems in urban traffic, the development of innovative solution approaches, and the discussion of potential impacts of RPP on traffic congestion, the environmental benefits of this approach, and the potential social and economic impacts. Participants had the opportunity to exchange ideas, share their experiences, and collaborate on future research and development initiatives in this field. The workshop provided a platform for the scientific community to discuss the latest research findings and explore innovative solutions for sustainable urban mobility.

The expert workshops brought together practitioners from the automotive sector, PuT operators, representatives of urban institutions, technical transport infrastructure providers, experts from the logistics sector, transportation engineers, and researchers. In order to analyze the realities that will drive the RPP service and to define the service fundamentally, a variation of methods, including Delphi Study, Nominal Group Technique, Scenario Technique, and brainstorming and group discussion approaches, are available.

This thesis makes use of the scenario technique, which is one of the most popular forecasting methods and an important element of futurology [Albers & Broux, 1999]. It was especially suitable for the definition of a RPP service, as it includes a consecutive five step approach taking into consideration:

1. Problem Analysis
2. Impact Analysis
3. Descriptor Analysis
4. Scenario Development
5. Strategies and Measures

These five steps were used for an initial in detail analysis of problems, impacts, and descriptors influencing the integrated transport of passengers and freight (see Figure 3.1 and Figure 3.2). In the next step, the scenario technique was used to develop scenarios of the future, derive potential use cases and challenge these use cases based on their contribution to solve the initially identified problems of current transportation systems. Overall, the scenario technique was chosen as it allows for integrating various aspects and perspectives influencing the idea of RPP and is very suitable to be applied in expert workshop formats.

The first step of the scenario technique includes the problem analysis and description of the current situation. The focus was on questions such as what is "last mile" mobility (passengers and freight), are there problems associated with it, how exactly does the problem manifest, how can it be recognized, what causes the problem, what makes it worse, what are the social, economic, or environmental consequences if the problem persists, and what could be solutions? The goal was to achieve the broadest possible understanding of the subject matter and a detailed description of the current situation from multiple perspectives. The result was clusters of problem areas, possible solutions, requirements, trends and stakeholders involved. Subsequently, a vote was taken among the experts to determine the main influencing factors from the clusters, which will be taken into the next step of the scenario technique process. In the following step, the participants analyzed influencing factors and developed a basic impact analysis before trends and key parameters were worked out in the descriptor analysis. The aim was to create a model of the system with effects and interrelationships and to consider their possible development over a period of time. The result of this is captured in Figure 3.1 and Figure 3.1 and provides a basic understanding of the cosmos in which a potential RPP service would operate and how it might relate to other relevant influencing variables. It shows that the defined main influencing factors include *Livability*, *Transportation Offers*, *Accessibility*, *Traffic Volumes*, *Flexibility*, *Effectiveness*, *Quality of Service*, and *Sustainability*. RPP was perceived to have a positive impact on all of them. These factors were later on used to define the investigated indicators in the agent-based simulation in Chapter 4 and found application in the development of the LCSA Fleet Evaluation Tool of Chapter 5.

The further one looks into the future, the greater the number of possible future states. Figure 3.3 illustrates the so called scenario funnel, describing potential solution spaces in the future, including future scenarios.

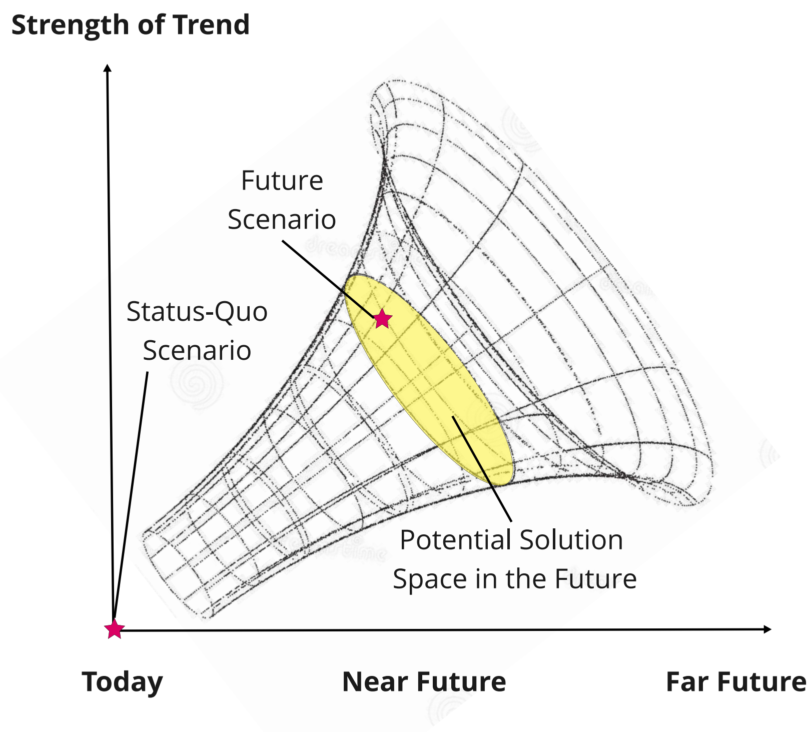


Figure 3.3: Scenario funnel, visualizing potential solutions space in the future and one specific future scenario.

The theory behind the funnel illustration is that the further one looks into the future, the less accurate the prediction will be, i.e. the funnel of possible solution spaces opens towards later stages of the future [Kosow & Gassner, 2008]. This means that we can accurately describe the here and now and thus are able to predict the near future with relative precision. However, the further in the future the prediction lies, the larger the potential solution space becomes and the number of possible scenarios increases with it. Therefore, it was decided, that the expert committee should focus on a potential solution space in the near future and develop respective future use cases for the general RPP idea. In the next step, the scenario technique provides an overview of the problem and the multiple interactions, extrapolating the identified trends into the future assuming one trend scenario and two extreme scenarios, resulting in the scenario funnel and a potential solution space in the future. The scenarios should be free of contradictions, comprehensible and comprehensive, and it should be determined in advance how far one wants to look into the future [Albers & Broux,

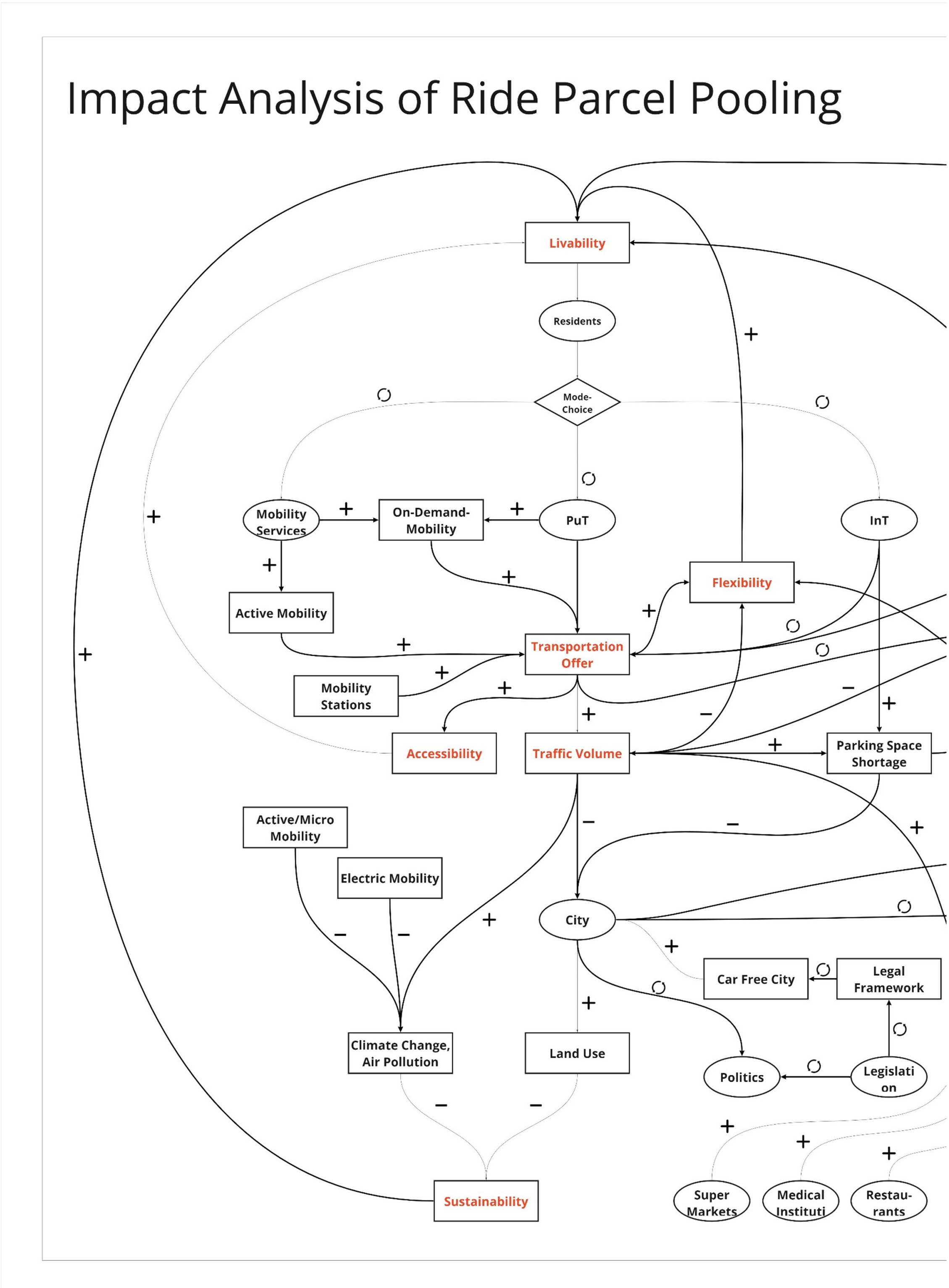


Figure 3.1: Impact analysis of a potential RPP service derived from expert workshops (left).

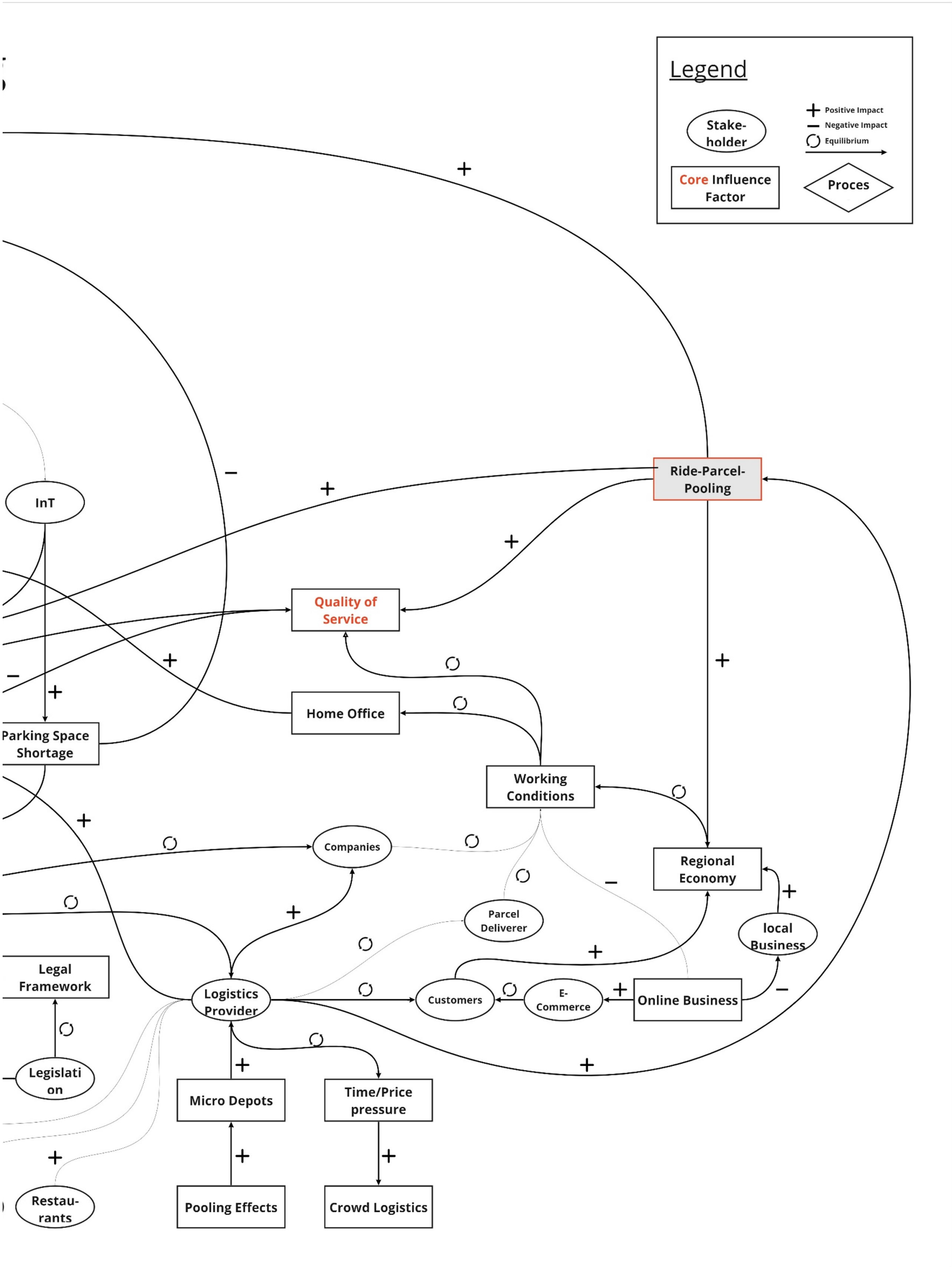


Figure 3.2: Impact analysis of a potential RPP service derived from expert workshops (right).

1999]. The goal of the workshop was to find four fully formulated near future use cases, additionally to the status quo. The status quo describes the unaffiliated delivery of parcels by a logistics provider and the independent transport of passengers by a MoD provider. The two services operate completely independently of each other and optimize the respective fleets independently and according to purely economic aspects.

The use cases defined in the expert workshops are presented in the following list:

1. **Prioritized Ride Parcel Pooling:** This scenario describes the combined transport of passengers and parcels according to defined prioritization rules, i.e. passengers have priority, in a RPP service. The routes for passenger and parcel transport are combined in the best possible way, under certain optimization conditions.

2. **Parcel Hopping:** This scenario also describes the combined transport of passengers and parcels according to defined prioritization rules in a RPP service. However, in contrast to the previous prioritized RPP scenario, the parcels can "transfer" to other (more suitable) vehicles at certain nodes in the network.

3. **Mobile Parcel Lockers:** This scenario describes a RPP service that collects parcels during the day and provides a mobile parcel locker service during off-peak hours. This means that the parcels are driven to the vicinity of the delivery addresses and can be picked up there by the recipients in the car trunks. In addition, parcels could also be deposited to the mobile parcel lockers.

4. **In-Vehicle Delivery:** This scenario describes a RPP service that delivers parcels (e.g. groceries, e-commerce parcels) to the passengers of a ride-pooling provider during the ride. Parcels are "pooled" in pre-reserved MoD rides and handed over to the recipients during the ride. As it is common in ride-pooling operations, additional passengers and parcels can be picked up at any time during the ride. Subsequently, the vehicle serves the next passengers and parcels. This scenario has the potential to even reduce total passenger trips, this concept could make shopping trips obsolete.

Subsequently, the scenario technique aims at interpreting the derived scenarios, including a transparency and coherence check. Therefore, the use cases were discussed in the expert group with the aim to derive tailored recommendations, aims, and strategies for the respective stakeholders. Lastly, the findings were concluded and feedback was incorporated into the obtained results. The Prioritized Ride Parcel Pooling use case forms the basis for most of the other use cases and reflects the idea of integrating freight trips into already existing passenger trips by minimizing distance traveled and vehicle usage. Therefore, the expert group voted to prioritize the study and implementation of this use case. ***In conclusion, the prioritized RPP scenario was found to offer the most benefits and therefore will be implemented in the following agent-based simulation.***

3.2.2 Empirical Survey of Potential Users

This section focuses on an empirical survey of potential users of the RPP service to investigate what requirements and preferences customers might have. It consists in substantial parts of the publication "Ride-Parcel-Pooling: Insights to Integrated Passenger and Freight Transportation through a Customer Survey" published at the 10th hEART Symposium of the European Association for Research in Transportation [Fehn et al., 2022] and reflects the results in the overall context for this dissertation.

The survey was divided into four main categories: participant socio-demographics and socio-economics, attitudes toward ride-pooling services, parameters for ride-pooling simulations, and acceptance of RPP scenarios. The detailed research topics and question categories are shown in Figure 3.4.

The survey was conducted online via a web browser and participants were approached with an information flyer in the city of Munich from September to October 2021. The survey took approximately 10 to 15 minutes to complete and a total of 102 respondents were recruited. The relatively small sample size and the strong bias towards young, highly educated, high earners do not allow for a detailed regression analysis, so the statements are limited to purely descriptive statistics, which, however, allow for some interesting statements about the potential market and input variables for the simulation of RPP.

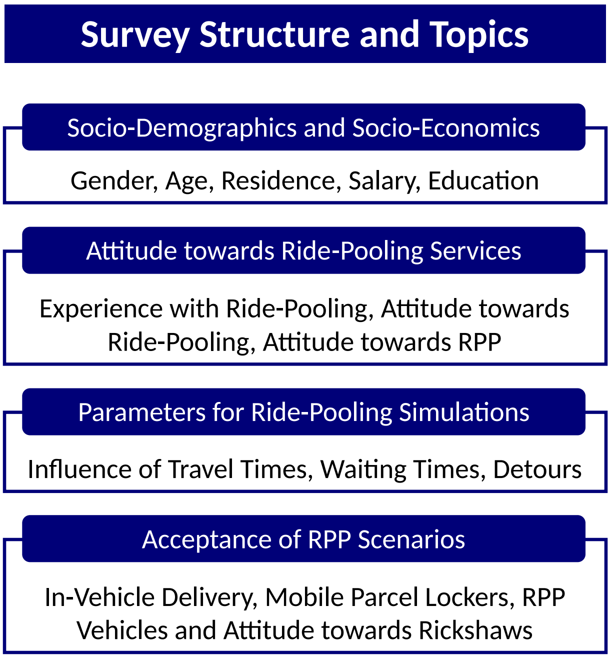


Figure 3.4: Research topics and categories of survey questions.

For a first market analysis of the envisioned RPP service, this section presents results from the survey, addressing the research topics and question categories stated in Figure 3.4. The socio-demographic and socio-economic analysis of the respondents shows that 51% of the participants are male and 49% are female. Most of them live in or near the city center. The sample is highly educated: 6% have a Ph.D. or equivalent as their highest degree, and 54% have a university degree. In terms of economic status, most respondents (30%) receive a net salary between 2,000 € and 3,000 €. Figure 3.5 shows the average net salary of the respondents [1] compared to the Munich average salaries [Average Salary

[1] Survey salaries do not add up to 100%, as some respondents did not disclose salary information.

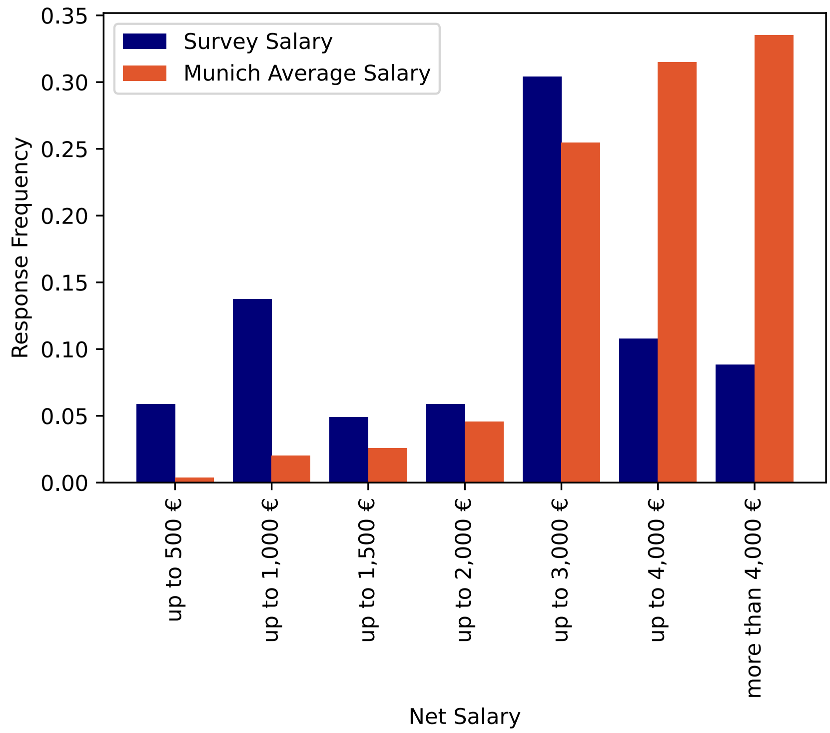
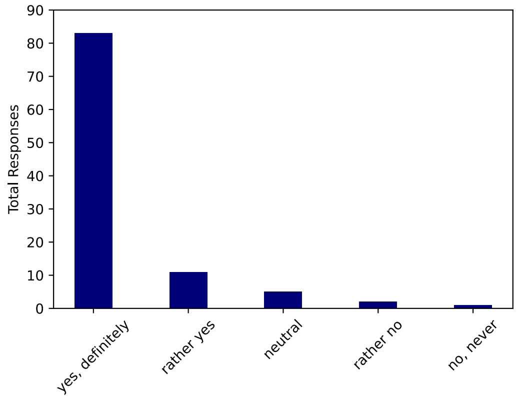


Figure 3.5: Survey net salaries compared to the Munich average net salaries for the year 2022 [Average Salary Survey, 2023].

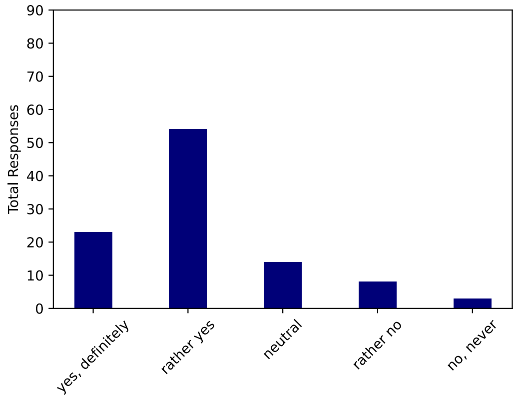
Survey, 2023]. Income classes between 1,000 and 2,000 € are over represented. At this point, it is already clear that the sample shows a bias towards high levels of education and relatively low (student and young professional) incomes. However, this could be in line with the characteristics of early adopters of new mobility services [Kawgan-Kagan, 2015].

The respondents' attitudes towards ride-pooling services were sought by first asking them about their personal experience with ride-pooling services. Approximately 36% of the sample reported having used ride-pooling services, and approximately 82% have a positive attitude toward ride-pooling. There is no significant difference in positive attitudes between people who had used ride-pooling and people who had not. In the next step, the survey asked about the attitude towards the idea of RPP. Again, the majority (87%) expresses a positive attitude and there is no significant difference between respondents with ride-pooling experience and the others. It was found that the idea of RPP is evaluated even more positively than the pure passenger ride-pooling idea.

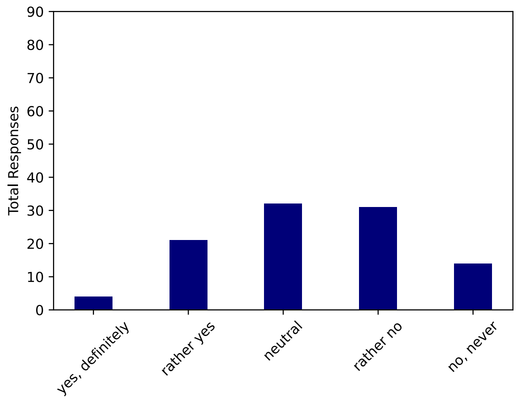
The next part of the survey was aimed at defining service parameters as input parameters for simulations. The goal was to determine the influence of travel time, waiting time, and detours options on customer satisfaction. The impact of travel time increase due to additional parcel transportation in RPP is estimated by asking respondents about their willingness to share a ride if the parcel added 0%, 10%, 25%, or 50% travel time to their respective trip. Figure 3.6 shows the evolution of customer satisfaction on a scale from "yes, definitely" to "no, never" regarding willingness to share a ride.



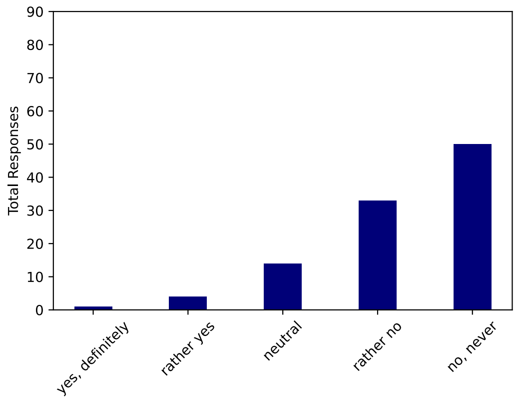
(a) 0% additional travel time



(b) 10% additional travel time



(c) 25% additional travel time

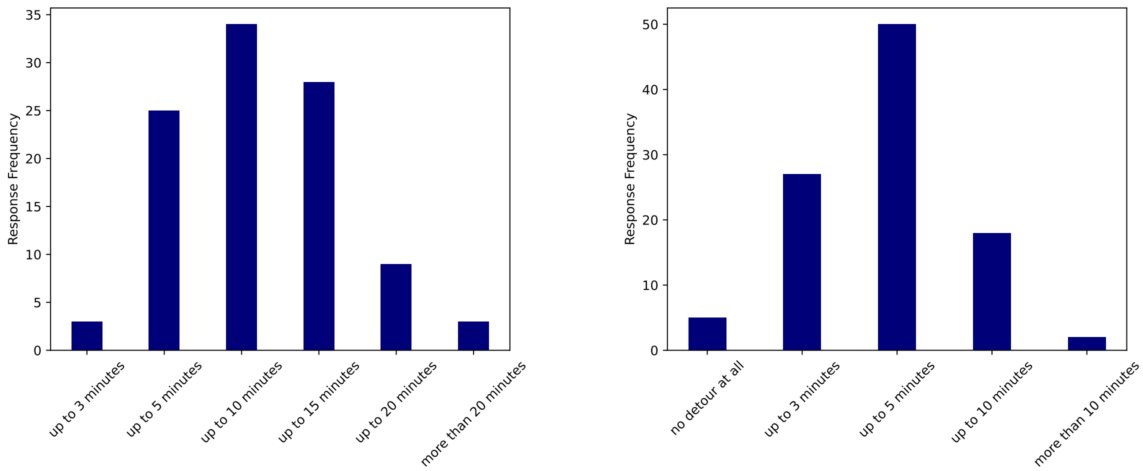


(d) 50% additional travel time

Figure 3.6: Willingness to share a trip in RPP under the assumption that parcels increase travel time.

It is noticeable that as the travel time increases, the willingness of customers to share a ride with parcels decreases. The high number of negative responses to a 50% increase in travel time also indicates that customers are unlikely to be willing to accept a higher increase in travel time. In general, it can be said that an increase in travel time has a direct impact on the acceptance of RPP among potential customers; however, survey questions using percentages can be confusing and need to be evaluated carefully as respondents may interpret them differently.

The influence of waiting and detour times of a RPP service was also considered in this survey. Respondents indicate the acceptable waiting time before the driver arrives after the request and the maximum detour time for a pooled trip as shown in Figure 3.7a and 3.7b, respectively. Most respondents indicate an acceptable waiting time of up to ten minutes and a detour time of up to five minutes for a representative trip of seven km length and fifteen minutes travel time. The obtained results were used in the parameterization of the simulation of the RPP service in Chapter 4.



(a) Acceptable waiting time (b) Acceptable detour time

Figure 3.7: Acceptable maximum waiting and detour time for a pooled trip with 15 minutes of direct travel time.

In the process of designing a RPP service in Chapter 3, this research came up with several use cases that a provider could offer. To test the acceptance of the use cases among potential RPP users, this survey presented them to the participants and asked for their opinions and preferences.

The first scenario is called "in-vehicle delivery" and describes the combination of a pre-booked trip with an integrated in-vehicle parcel delivery for a specific customer. The parcel (e.g. groceries, e-commerce parcel) has been pre-ordered and is now delivered en route rather than to the customer's home. The survey results show that 83% of the respondents like the idea, 12% are not sure and 5% do not like the idea.

In the second scenario, the RPP vehicle acts as a "mobile parcel locker," where customers can pick up or drop off parcels near their homes during specific time windows. The survey found that three out of four people liked the idea of mobile parcel lockers and could see themselves using such a service, 19% answered "don't know" and only 6% of respondents did not like the idea. Regarding the maximum acceptable distance of the mobile parcel locker, the most chosen answer was 0.25 to 0.5 kilometers.

Finally, the survey investigated the participants' attitudes towards their preferred vehicle for RPP services. This question is particularly interesting in view of the fact that a possible prototype for a RPP vehicle was to be developed and used in field trials of Chapter 6. Respondents could choose from four vehicle categories, namely city bus, minivan, passenger car, and rickshaw. About 40% of the participants liked the classic bus as an RPP vehicle, 65% chose a minivan, 58% chose the passenger car, and 37% voted for the rickshaw. Please note that multiple choices were possible. A rickshaw is a very sustainable, space-saving, and affordable mode of transportation and for these reasons was used in the RPP field test in Chapter 6. Therefore, this survey aimed at gaining a deeper understanding of the respondents' attitudes towards this type of vehicle. The survey asked the potential users how they felt about a rickshaw as a mode of transport for RPP services (Figure 3.8).

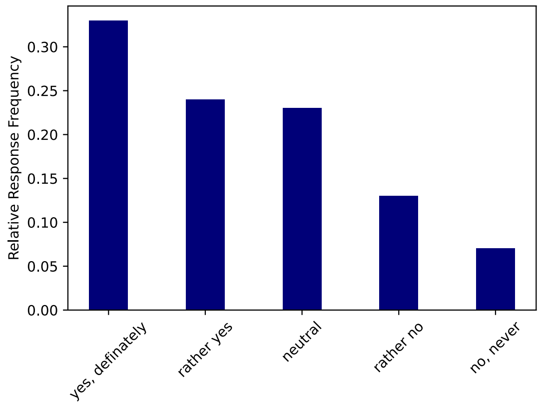


Figure 3.8: Attitude towards ("would you like") a rickshaw as a RPP vehicle.

The answers reveal that the rickshaw as a means of transportation is not universally viewed positively. However, some people have a purely positive attitude towards rickshaws. In addition, the survey asked the participants to justify their choice. From the answers, the following positive and negative statement categories stood out:

Positive

- Environmentally friendly (lower CO_2-footprint, local emissions, noise).
- Solves space problems in cities and is more flexible during rush hours.
- Great means of transportation for short distances, little luggage, crowded streets.
- Fresh air/ see more riding experience in urban space.
- Attractive appearance.

Negative

- The effort of the driver (smell, discomfort, pity, etc.).
- Confined space (especially when pooling), limited pooling capacity.
- Insufficient weather protection.
- Unfamiliar, one feels observed, safety concerns (accidents, luggage, parcels).
- Unattractive appearance.

The results suggest that a rickshaw is perceived as a very sustainable, space-saving, and environmentally friendly means of transportation. Some see it as a great opportunity for short trips, offering a nice riding experience. However, many participants may feel uncomfortable, because of the exertion of the driver, the confined space, and the lack of weather protection. Some respondents also mentioned the feeling of being watched and general safety concerns.

Based on the positive feedback from the survey of potential users and the associated sustainable appearance of the rickshaw in conjunction with a reasonable price and the possibility of easy conversions, the choice fell on an electrified bicycle rickshaw as the vehicle for the field test. A more detailed description of the modifications and design for the prototype is given in Chapter 6.

Since user acceptance of ride-pooling has been well studied in the scientific literature, this study focused on perceptions of RPP in particular. The positive and negative aspects associated with RPP, show a similar structure to those found for ride-pooling [Kostorz et al., 2021]. However, many respondents mention the "green" image of RPP in terms of emissions, space savings, and less road traffic. Some also state that it could be cheaper than other modes of transportation. On the negative side, many respondents could imagine problems associated with the additional transportation of parcels, such as lack of space, damage to the parcels and unknown contents, and inconvenient delays or detours.

Although the survey has a rather small sample size and a strong bias, some interesting correlations could be established. The following dependencies stood out:

- Older respondents appear to be less supportive of ride-pooling and RPP than younger respondents.
- Respondents who live in or near the city center are more likely to have used ride-pooling.
- Younger respondents and respondents with higher incomes are more likely to accept less detour and wait time.
- Younger respondents are more open to RPP scenarios (in-vehicle delivery, parcel station) than older respondents.
- People who live further away from the city center are willing to accept longer distances to a parcel station.
- Female respondents would like the mobile parcel stations to be closer than male respondents.

The dependencies found are in line with expectations, especially regarding the value of time for busy people, and the phenomenon that young people in particular could be early adopters of a future RPP service.

In conclusion, the idea of RPP is perceived as very positive and the service scenarios presented are well received. The survey provides insight into service parameters such as waiting times, delays, and detours, which are incorporated into the setup of the agent-based simulation in Chapter 4.

3.3 Concept Definition and Scenarios

The overarching concept of RPP is to integrate parcel transportation into the existing schemes of an on-demand ride-pooling operator without significantly degrading passenger transportation by integrating parcels traveling in the same general direction. ***This approach aims to reduce the number of individual vehicles on the road and optimize the use of existing transportation resources [Fehn et al., 2023]. The passenger requests are received dynamically in the sense of an on-demand mobility service, whereas the parcel demand is available for the entire day, i.e. static, as it is usually the case for parcel delivery. This makes it possible to check for each time step whether one or more parcels fit onto an existing passenger trip with minimal detours. A detailed description of the design and the assignment strategies can be found in Chapter 4 of this dissertation.*** As ride-pooling exists mainly in urban environments, this is because of the offers to function meaningfully a high density of demand and supply is required [MOIA, 2023], the research of this thesis will also focus on an urban setting. RPP could address the problems of congestion and the environmental, economic, and social impacts of transportation. It could reduce transportation costs for individuals and businesses, increase the efficiency of delivery operations, and improve the overall accessibility and convenience of transportation services [Fehn et al., 2023]. At this point, it should be mentioned that MoD services, if used on a large scale, will require dedicated infrastructure for boarding and disembarking passengers and loading parcels, in order to avoid negative impacts on traffic flow and the safety of all road users.

Based on the solution space derived from literature and real-world applications of integrated transportation solutions, the expert workshops, and the survey of potential customers, the RPP service in this thesis develops a concept that incorporates the premise that freight transportation is integrated with existing passenger transportation and that passengers have priority over parcels, i.e. the additional transportation of parcels must not significantly degrade passenger transportation. The concept of RPP is based on combining the efficiency of ride-sharing services with parcel delivery to utilize unused capacity on existing trips, creating a more efficient and sustainable transportation system. The goal is to create a symbiotic ecosystem where passengers and freight can coexist and thrive while using the same fleet of vehicles and combining trips. The concept of RPP offers significant opportunities for various stakeholders. For ride-sourcing providers, expanding their services to include parcel delivery opens up new revenue streams and improves the utilization of their existing infrastructure. For parcel delivery companies, RPP offers an alternative and potentially more (cost-)efficient means of last-mile delivery, creating savings potential on the costly last-mile leg, which accounts for approximately 30% of total delivery costs [Blösl, 2022]. The four resulting simulation scenarios for Chapter 4 are presented below and visualized with generic drawings in Figure 3.9.

3.3.1 Status Quo Scenario Definition

The *Status Quo* scenario shows two completely separate transportation services, one used for parcel delivery and the other for MoD passenger transportation. This scenario represents the typical delivery scheme in Germany, where a CEP provider's fleet of vehicles collects parcels at a depot, from where the various vehicles deliver the parcels to the doorsteps of the recipients, here characterized by the truck l_1 transporting the parcels p_i from their origin o_i^p (the depot) to their destinations d_i^p. The parcels are distributed as efficiently as possible to as few carriers as possible and delivered over the course of a day. For the passenger transportation service, this scenario involves a ride-pooling service that aims to combine incoming transportation requests as efficiently as possible, while also trying to guarantee certain customer requirements. In this illustration, vehicle v_1 picks up customer c_1 at origin o_1^c and transports it to destination d_1^c before picking up the next customer and transport it to its destination (Figure 3.9a). In a ride-pooling scheme, the two passenger requests could potentially be combined and the customers would be transported simultaneously in the same vehicle, if appropriate (i.e. waiting and travel time, as well as distance constraints are fulfilled). The blue lines symbolize passenger only routes, whereas the yellow lines represent parcel only trips. The red lines indicate that passengers and parcels are on board of the vehicle simultaneously [2].

3.3.2 Light Ride Parcel Pooling Integration

The *Light RPP Integration* scenario incorporates the parcel delivery service into the MoD passenger transportation operations. The rule set applied for the integration is that the vehicles v_i are assigned to nearby parcel OD pairs and use exclusively their idle times for the additional logistics services. In the example illustrated in Figure 3.9b vehicle v_1 is assigned to the three parcels, after dropping customer c_1 at its destination d_1^c and before picking up the next customer at its origin o_2^c. With *Light RPP Integration*, as with the status quo, customers and parcels are not transported simultaneously at any time but have the vehicle exclusively. The *Light RPP Integration* was implemented and tested in Fehn et al. [2021]. Results showed no substantial differences towards the *Moderate RPP Integration*, neither in the investigated passenger, nor in parcel transportation indicators. ***The Light RPP Integration scenario is therefore not considered further in the simulations of this dissertation***.

3.3.3 Moderate Ride Parcel Pooling Integration

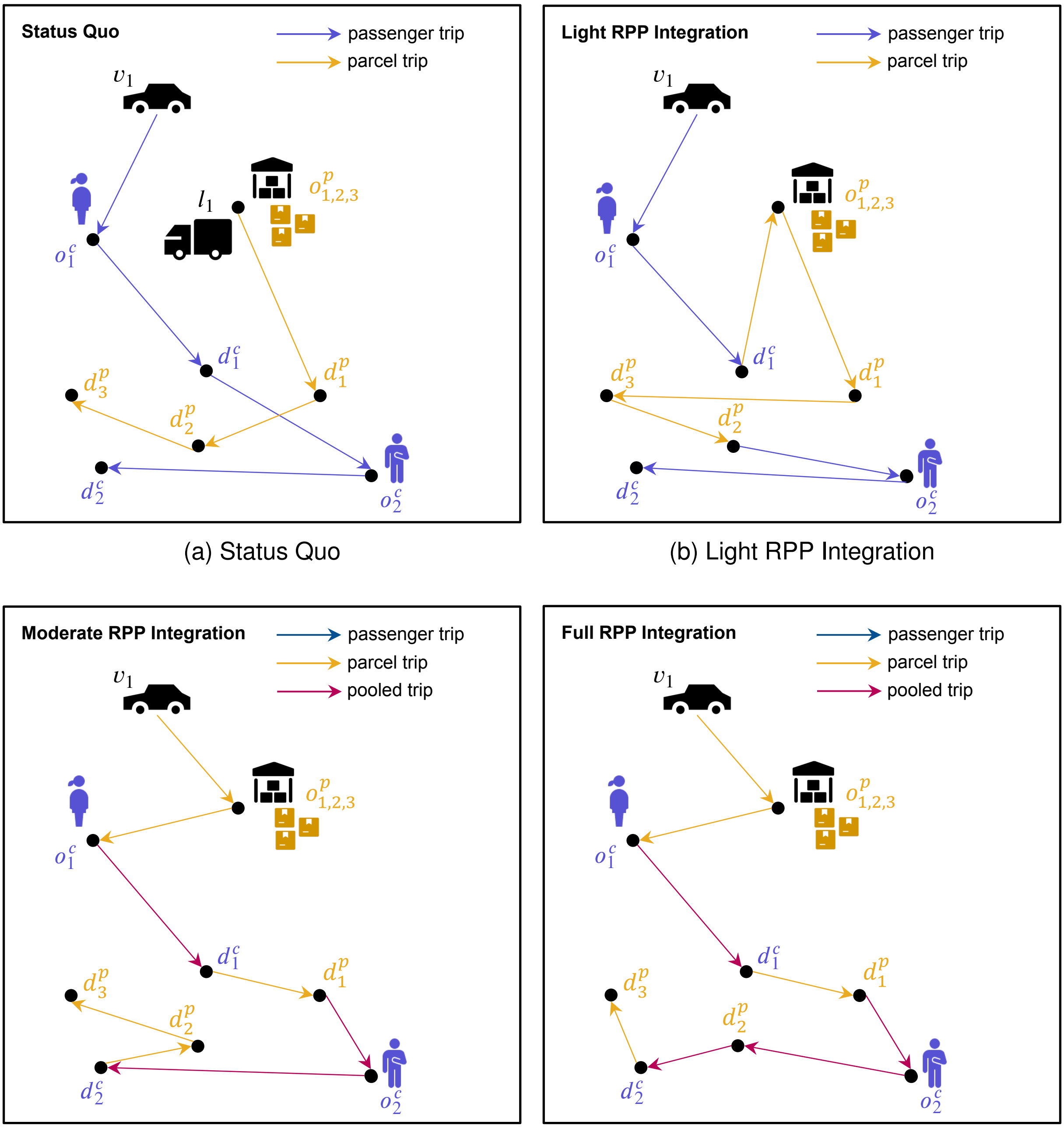
The *Moderate RPP Integration* scenario removes the paradigm that customers and parcels are never simultaneously in the same vehicle. However, it retains the restriction that the passenger must not notice the integration of parcel services. Therefore, parcels can only be integrated in passenger trips during the approach, the departure or idle times of the MoD vehicle. In the illustration, presented in Figure 3.9c the vehicle v_1 first collects the three parcels at the depot, before picking up the first customer c_1. On the approach to the next customer's origin o_2^c the one parcel is delivered to its destinations d_1^p. However, there is never any pickup or delivery of parcels as long as there are still customers on board. Finally, the customer c_2 gets picked up and is driven to its destination d_2^c. After that, the

[2] A table of color codes used in this work can be found in the Appendix in Table 1.

remaining two parcels are transported to their destinations d_2^p, and d_3^p. The three red arrows symbolize a pooled trip of one or multiple passenger(s) and one or multiple parcel(s), which are simultaneously in the same vehicle.

3.3.4 Full Ride Parcel Pooling Integration

The scenario *Full RPP Integration* describes a service, which transports customers and parcels and both can take notice of each other. It represents the most integrated of the presented scenarios and allows the collection or delivery of parcels while passengers are on board. However, certain maximum detour times and travel time increases must always be observed in order to avoid a lasting deterioration in passenger transport. In the example represented in Figure 3.9d the vehicle v_1 first collects the three parcels at the depot, then picks up customer c_1 at o_1^c and drives her to d_1^c. Subsequently, it delivers the first parcel at d_1^c on the approach to the origin of the second customer at o_2^p. On the way form o_2^p to d_2^c, the RPP service integrates a parcel delivery at d_2^p, before dropping the second customer at d_2^p. In the end the third parcel is delivered at d_3^p. Further explanations of the chosen constraints will be given in the modeling Chapter 4.



(a) Status Quo

(b) Light RPP Integration

(c) Moderate RPP Integration

(d) Full RPP Integration

Figure 3.9: Integration Scenarios for urban passenger and freight transportation.

Chapter 4

Modeling and Simulation of Ride Parcel Pooling

Chapter Essentials

- The agent-based simulation framework "FleetPy" is adapted for simulating a Ride Parcel Pooling service and integrates three heuristic parcel assignment strategies into a ride-pooling fleet control algorithm.
- Two integration scenarios (Moderate and Full RPP Integration) together with three parcel assignment strategies (CDPA, SDPA, SCPA) are compared to the Status Quo scenario.
- The findings suggest that the "Combined Decoupled Parcel Assignment (CDPA)" strategy reflects best the aim of integrating freight transportation into the schemes of a ride-pooling provider, as it leads to lowest traveled distances.
- Three different vehicle categories (rickshaw, car, and van) with different fleet sizes, capacities and driving constraints are introduced and compared to the status quo consisting of separate fleets for passenger and parcel transportation.
- The results indicate that the integration of logistics services into a ride-pooling service is possible and can exploit unused system capacities without deteriorating passenger transportation.
- Depending on the chosen assignment strategies and vehicle categories, nearly all parcels can be served until a parcel to passenger demand ratio of 1:10 while the overall fleet kilometers can be decreased compared to the status quo.

To simulate the RPP service defined in Chapter 3, one needs the functionalities of an agent-based simulation framework to represent the decision-making processes that take place on the operator and customer sides. In transportation engineering, there are several agent-based simulation tools that provide these functionalities, like "SUMO and JADE" [Soares et al., 2014], "Simmobility" [Adnan et al., 2016], "POLARIS" [Auld et al., 2016], "MATSim" [Horni et al., 2016], and "MaaSSim" [Kucharski & Cats, 2022], however the extension of existing frameworks from pure ride-pooling to the additional transport of parcels exploiting unused capacity was best possible in the "FleetPy" simulator [Chair of Traffic Engineering and Control, 2023; Engelhardt et al., 2022]. This is due to its modular structure, which enables transferability of existing fleet control strategies, used for ride-pooling simulations, to the shared use of a MoD vehicle fleet for the transportation of passengers and freight. While FleetPy can be used for a variety of mobility simulations, it offers several features that make it particularly suitable for RPP simulations.

4.1 FleetPy Simulator

The FleetPy simulation environment is an open source simulation tool for mobility on demand services developed by the Chair of Traffic Engineering and Control at the Technical University of Munich. The published source code can be accessed via the research group's GitHub page [Chair of Traffic Engineering and Control, 2023]. The remainder of this subchapter gives an overview of the existing use cases and modules and a short description of the software, including the main modeling components and the simulation flow. For a more detailed description of the simulation framework, the interested reader is referred to the FleetPy launch paper of Engelhardt et al. [2022] and for the latest software developments to the GitHub repository [Chair of Traffic Engineering and Control, 2023].

4.1.1 Introduction to the Simulation Framework

FleetPy was developed as a research-oriented simulation framework to answer research questions related to MoD from an operational viewpoint. The focus was mostly on how a future MoD system could best complement the existing transportation system or make parts of it more efficient. Compared to the other reviewed simulation frameworks, FleetPy is able to display real-world interactions between customers and the MoD operator. This means that on the one hand, customers send requests via a mobile-phone application and receive real-time information from the MoD operator. The MoD operator on the other hand, receives the customer requests and makes decisions based on all information revealed for the respective time-step. In addition, FleetPy is able to facilitate broker-based systems, i.e. scenarios with multiple operators, integration of public transit and MoD systems or, which is of special importance for this work, the integration of secondary demands like freight transport into realistic MoD operator schemes. The transferability of existing models for new application areas and the possibility to select an appropriate level of detail are additional features of FleetPy that make it the best choice for modeling the integration of freight transportation into a MoD system.

4.1.2 Software Description

The structure of simulating scenarios in FleetPy is depicted in Figure 4.1. The required input data can be categorized into two types: input parameters and data files. Input parameters describe the modules and configuration used in the FleetPy simulation and are handled by scenario definition files. Since FleetPy relies on multiple parameters, with only a few typically varying across simulations, two input files are used. The first file contains constant parameters, while the second file includes the parameters that vary among simulations, making it easier for analysts to compare and understand the differences between different scenarios. Together with specific modules, those are loaded into the simulation environment, initialize the fleet simulation class, and return the simulation class. Necessary input data for the initialization of a FleetPy simulation are network information (graph of nodes and edges), traveler demand (request with start and end location and request time), vehicle types (e.g. capacity, range, costs). Optionally, vehicle infrastructure, like depots, parking, or charging stations. Output data comprise user statistics (i.e. acceptance/rejection, pick-up/drop-off time and location, offer parameters and operator, service vehicle), operator statistics (i.e. time, vehicle ID, location, and order), time-dependent statistics, and log-files. [Engelhardt et al., 2022] The input parameters control the execution of specific modules and parts of the code, while the data files provide structured inputs. These data files are essential for describing networks, zones, customer demand, vehicles, and infrastructure. During the simulation initialization, the data files are loaded along with the modules. The selected simulation modules specified in the input parameters determine the code that is executed during the simulation flow, as shown in Figure 4.1. The simulation generates disaggregated records for vehicles, users, and, if applicable, infrastructure [Engelhardt et al., 2022]. However, since analysts are usually interested in the bigger picture, automatic evaluation functions are used to generate aggregated outputs from these records.

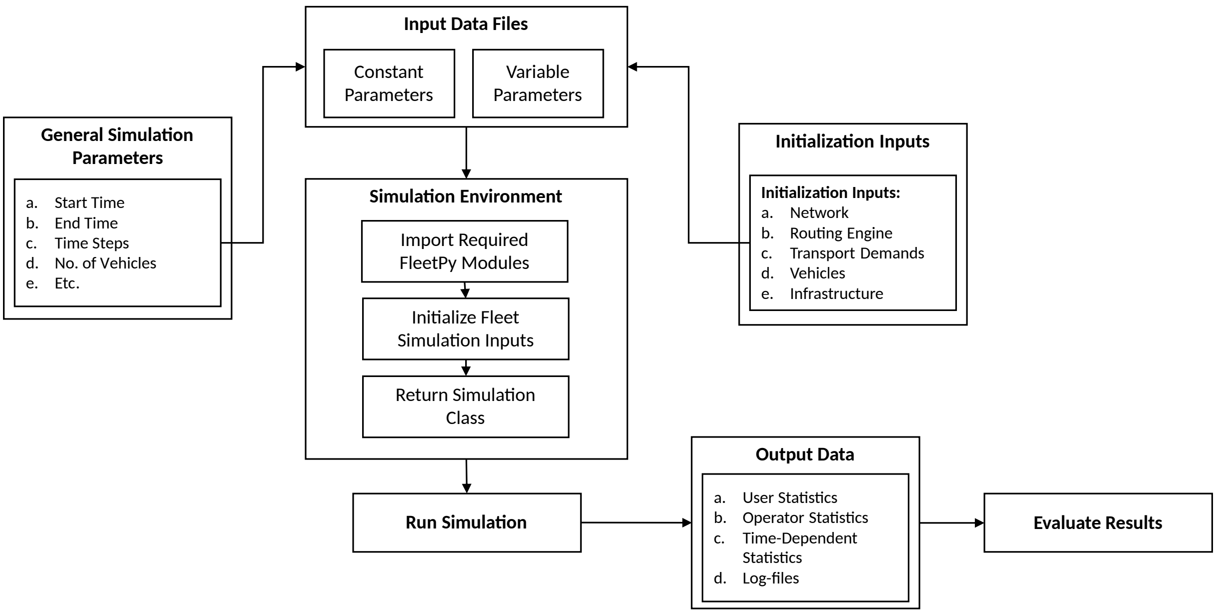


Figure 4.1: Flowchart of the main components of a FleetPy simulation scenario.

4.1.3 General Definitions of the Simulation Environment

The FleetPy simulation environment comprises a street network represented as a directed graph $G = (N, E)$, consisting of nodes N and edges E connecting these nodes [1]. Each edge is associated with a travel time and a distance. A customer request $r_i^c = (o_i^c, d_i^c, t_i^c)$ is represented by its origin location $o_i^c \in N$, the destination location $d_i^c \in N$ and the respective request time t_i^c. [ENGELHARDT et al., 2022]

The goal of the fleet operator is to assign schedules to its vehicles $v \in V$ to serve customer (and parcel) requests. A schedule ψ describes the sequence of pick-up and drop-off stops assigned to a vehicle. Stops are connected via the fastest network route, i.e. an ordered list of connected nodes minimizing the overall travel time. A schedule is considered feasible, if:

- the drop-off succeeds the pick-up for each request.
- at no point during the schedule the maximum passenger capacity c_v^c exceeded by on board passengers.
- for each customer request r_i^c, the waiting time (time between request time t_i^c and expected pick-up) does not exceed t_{max}^{wait}.
- the in-vehicle time of each customer r_i^c does not exceed $t_{max}^{travel} = (1 + \Delta)tt_i^{direct}$, with the direct travel time from its origin to destination tt_i^{direct} and a detour factor Δ.

A feasible vehicle schedule $\psi_k(v; R_\psi)$ is defined as the k-th feasible permutation of stops of vehicle v to serve the set of customer requests R_ψ within the schedule. Stops are associated with the location, boarding and alighting customers (or parcels) and the time needed for boarding or alighting t_b. In between stops, vehicles travel along the fastest route in the network G. [ENGELHARDT et al., 2022]

Schedules are rated by an objective function $\phi(\psi_k(v; R_\psi))$. The goal of the fleet operator is to assign schedules minimizing the aggregated objective function for all of its vehicles.

4.1.4 Framework Adaptions from Ride Pooling to Ride Parcel Pooling

Compared to the core functionalities of FleetPy, displaying a passenger ride-pooling service, the RPP service needs the introduction of a secondary demand, i.e. parcel transport demand and its corresponding attributes, like parcel sizes. It is assumed that the parcel delivery request was submitted at least the day before and is therefore known in advance for the whole simulation period. Thus, a parcel request $r_i^p = (o_i^p, d_i^p, s_i^p)$ is represented only by the corresponding origin (pick-up) location o_i^p, destination (drop-off) location d_i^p, and parcel size s_i^p without a specific pick-up or delivery time during the day. Secondly, the RPP service requires vehicles with a parcel capacity attribute (e.g. space in the trunk). Therefore, it has to be guaranteed that for feasible schedules the current load of parcels never exceeds the vehicles' parcel capacity c_v. Thirdly, the objective ϕ of the operator needs to be adapted to the additional transport of parcels within the schemes of ride-pooling operations. Lastly,

[1] A list of symbols used in this chapter can be found in the Appendix in Table 2.

new assignment algorithms for the parcels, which are revealed day-ahead, need to be developed. Thereby, it is important to incorporate the new parcel time constraints and vehicle capacity constraints into the assignment strategies. ***FleetPy is particularly suitable for RPP integration, due to its modular structure, which was designed explicitly to allow the integration of novel mobility services. Detailed descriptions of the FleetPy framework adaptions are presented in the following sections.***

4.2 Modeling of Ride Parcel Pooling

The following section contains all adaptions to the existing FleetPy infrastructure and consists in substantial parts of the publication "Integrating parcel deliveries into a ride-pooling service — An agent-based simulation study" [Fehn et al., 2023] published in Transportation Research Part A: Policy and Practice in 2023 and reflects the introduced principles and results in the overall context for this dissertation.

The service consists of a MoD ride-pooling vehicle fleet and a central operator taking decisions, i.e. vehicle assignment and routing. In the envisioned RPP service, passenger transport has priority over parcel transport requests, as the service to passengers should not be degraded. The service assumes that parcels are transported from urban logistics hubs to customers. It is further assumed that it is possible to pick up or drop off the parcels at the customer's premises at any time, which in reality could be realized by small parcel lockers. Therefore, no explicit business hours are modeled for the logistics service. However, parcel pick-ups and deliveries are integrated with passenger trips, so most parcel pick-ups and deliveries will occur during the day, when passenger demand is highest. The size and weight characteristics of the parcels are assumed to be boxes that can be carried by one person and fit into the trunk of a conventional passenger car. Passenger comfort is not compromised while the parcels are on board the vehicle, as it is assumed that the parcels are transported spatially separated in the trunks of the vehicles, leaving enough space for passengers' luggage. In addition, the service provides a typical parcel logistics service and does not guarantee a specific delivery time during the day. The operator's goal is to provide an additional service without compromising too much on the additional vehicle kilometers traveled by the fleet and customer satisfaction, i.e. waiting times, travel times, and detours. It also allows the fleet operator to achieve higher utilization and occupancy rates for the fleet and to maintain the service even during periods of low passenger demand, which in turn could lead to higher customer satisfaction through more extensive operation. In addition, the RPP service aims at contributing to the goal of a "livable city", since two vehicle fleets (i.e. the logistics fleet and the MoD fleet) become one, and occupation urban space and emissions can be reduced by pooling passengers and parcels. The main assumptions influencing the functioning of the combination of passenger and parcel trips are shown in Table 4.1.

In addition to the assumptions from Table 4.1, other simulation inputs also play a decisive role in determining whether and if so how many trips can be pooled. These include in particular the underlying road network, the demand pattern for passengers and parcels

Assumption	Parameter
(De-)Boarding Time Passenger	30s
(De-)Boarding Time Parcel	60s
Detour Factor for Pooling Passengers	40%
Detour Factor for Pooling Parcels	10%

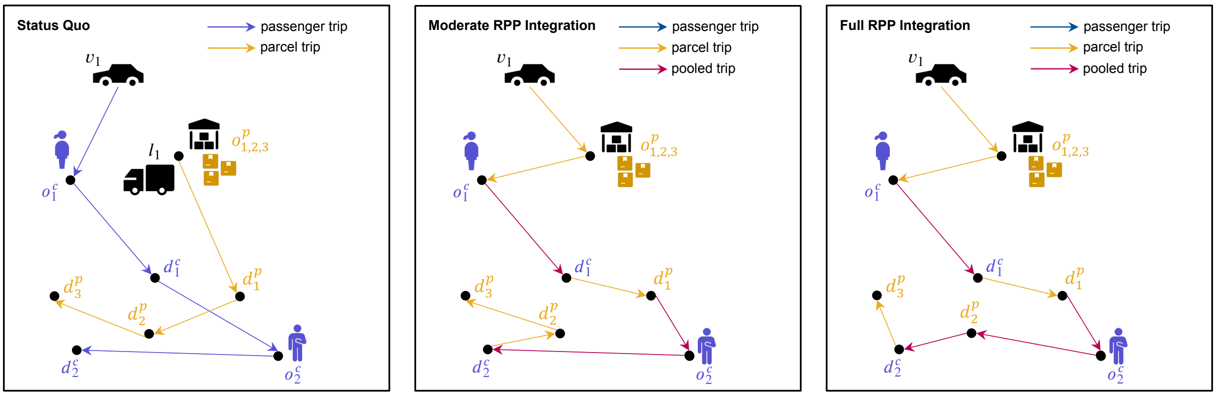
Table 4.1: Constant simulation parameters influencing the pooling of passenger and parcel, as well as boarding and deboarding times.

and the varying travel times in the network over the course of the day. These factors are therefore of course very important when it comes to projecting the simulation results from the case study to other cities or related use cases.

4.2.1 Simulation Scenarios and Methodology

All four scenarios developed in Chapter 3 were tested in day-ahead simulations, i.e. all information and inputs are revealed, of Fehn et al. [2021]. ***The Light RPP did not show any advantages compared to the Moderate RPP approach, neither in customer, nor in operator Key Performance Indicators (KPI). Therefore, it was excluded for further consideration in the online simulation cases.*** The first scenario represented in online simulations depicts the current *Status Quo*, where passenger and parcel requests are served by two independent vehicle fleets, one specialized in a ride-pooling MoD service and the other in a typical urban pick-up and delivery parcel logistics use case applying respective specialized vehicle fleets. In the second scenario, denoted by *Moderate RPP* integration, the logistics service is integrated with the MoD service, and both passenger and parcel requests are served by the same MoD fleet. However, there is a requirement that no parcels are picked up or delivered during a passenger trip, so that passengers do not experience parcel pick up and drop off or detours due to additional parcel transportation. The third scenario, *Full RPP* integration, relaxes this requirement, allowing a parcel to be picked up or dropped off during a passenger trip. In this scenario, a passenger's trip may be extended or a detour may be required to accommodate the additional parcel transport. Figures 4.2a, 4.2b, and 4.2c illustrate the respective simulation scenarios and give a schematic overview of the possible assignments of requests to vehicles and the resulting routes. It is important to note that a passenger request always consists of a OD pair and a parcel request always starts at a parcel depot and ends at the consignee. It would also be possible to operate the service from sender to depot, i.e. the first mile. This would only slightly change the modeling of the RPP service. However, as stated in Chapter 2, parcels sent in Germany are primarily delivered to postal shops, while recipients prefer doorstep delivery [DPDgroup, 2017].

To model the integration of logistics in a MoD ride-pooling service, the agent-based sim-



(a) Status Quo (b) Moderate RPP integration (c) Full RPP integration

Figure 4.2: Simulation Scenarios implemented in the simulation environment FleetPy.

ulation framework 'FleetPy' [Engelhardt et al., 2022] is extended for this use case. The framework consists of four main agents:

1. Customers requesting trips from the fleet operator.
2. Parcels that need to be transported by the service.
3. A fleet operator offering the service and assigning schedules for its fleet of vehicles to pick-up and drop-off customers and parcels.
4. Vehicles traveling along these assigned schedules within a street network and fulfilling the corresponding pick-up and drop-off tasks.

The overall methodology behind the RPP simulation study includes a demand data set for passengers and parcels, the already introduced constant simulation parameters from Table 4.1, as well as the variation of parcel penetration rates, the detour factor for integrating parcels into the existing MoD ride-pooling service, and the influence of different fleet sizes, parcel capacities, and different vehicle types. The main changes compared to a pure passenger ride-pooling simulation comprise of new vehicle types and assignment principles for integrating the parcel transport service into the existing passenger transport schemes. The overall system is first evaluated on the basis of customer (i.e. waiting time, travel time, and detour) and operator (distance traveled, number of passengers and parcels served, and revenue) KPIs in Chapter 4. In the following Chapter 5 the RPP service is investigated using a life cycle assessment approach with respect to all dimensions of sustainability, i.e. economic, environmental and social aspects. A more detailed description of the input parameters and the simulation methodology, and the evaluation of the results follows in the next chapters.

4.2.2 Simulation Environment and Fleet Control Strategies

Let now $\psi_k(v; R_\psi, P_\psi)$ be the vehicle schedule that additionally to the set of passenger requests R_ψ, serves the set of parcel requests P_ψ. Then for this study the objective function was defined as:

$$\phi(\psi_k(v; R_\psi, P_\psi)) = d(\psi_k(v; R_\psi, P_\psi)) - P(|R_\psi| + |P_\psi|). \tag{4.1}$$

$d(\psi_k(v; R_\psi, P_\psi))$ refers to the distance to drive to complete the schedule. $|R_\psi|$ and $|P_\psi|$ are the number of customers and parcels to be served with the schedule, respectively. P is a large assignment reward of 100,000 meters to prioritize serving customers and parcels over minimizing the driven distance. Based on the tight time constraints on passenger pick-up and drop-off it is assumed, that passengers always accept the service if those constraints are fulfilled. Therefore, minimizing passenger waiting and travel time is not incorporated in Equation 4.1. Additionally, Equation 4.1 does not control the prioritization of passengers over parcels. This prioritization is incorporated in the heuristic algorithms described in the following. The actual optimization is handled by assigning the smallest possible value for the objective function of the to be assigned vehicle schedule $\phi(\psi_{\tilde{k}})$, see Equation 4.2.

The high-level simulation flow is shown in Figure 4.3. The demand for the simulation is divided into a set of passenger requests and a set of parcel requests. It is assumed that the operator has access to all parcel requests for the entire simulation period and is free to decide when to serve which parcel. Passenger requests, on the other hand, are dynamically revealed to the fleet operator during the course of the simulation. Within each time step, the operator first tries to accommodate new customer requests by inserting them into the current vehicle schedules. In a next step, rebalancing trips are computed to distribute idle vehicles according to expected demand. Based on the new vehicle assignments, decisions are made to serve specific parcels. Finally, vehicle movements and boarding operations are performed. Details on customer insertion, rebalancing, and the parcel delivery decision process are provided in the following subsections. Since the applied control strategy of ride-pooling fleets is studied in several other research papers, the focus of this chapter is to describe the methodology for integrating parcel pick-up and delivery into the existing ride-pooling control strategy.

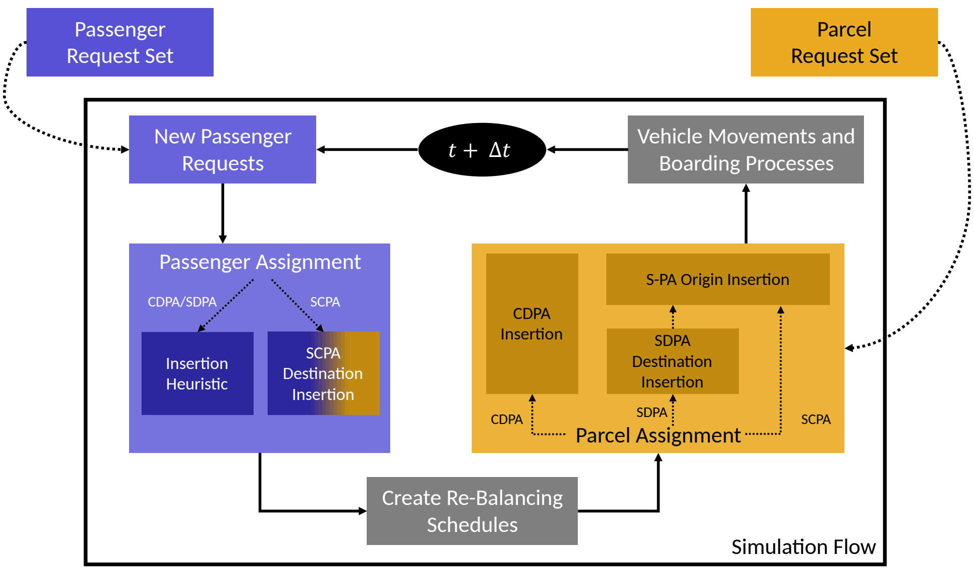


Figure 4.3: Flowchart of the simulation framework with different proposed parcel assignment strategies.

Passenger Assignment and Rebalancing

The passenger assignment and rebalancing strategies applied in this work are standard modules from the FleetPy repository [Chair of Traffic Engineering and Control, 2023; Engelhardt et al., 2022] and display the state of the art in ride-pooling operation schemes. To assign new customer requests to vehicles and corresponding schedules, an insertion heuristic is used to solve the customer assignment problem. Given the currently assigned schedule $\psi_k(v; R_\psi, P_\psi)$ of vehicle v, the pick-up and drop-off operations for a new customer request r_i^c are inserted at all possible positions within the currently existing sequence of stops (the drop-off must follow the pick-up stop). The new set of feasible schedules can be enumerated again and results in schedules $\psi_{\tilde{k}}(v; R_\psi \cup \{r_i^c\}, P_\psi)$ if a feasible insertion can be found. The selected vehicle v_a and schedule ψ_l for serving the customer request is then determined:

$$v_a, \psi_l = \underset{v, \psi_{\tilde{k}}}{\operatorname{argmin}} \, \phi(\psi_{\tilde{k}}(v; R_\psi \cup \{r_i^c\}, P_\psi)) - \phi(\psi_k(v; R_\psi, P_\psi)) \quad \forall v, \psi_{\tilde{k}} \,, \tag{4.2}$$

i.e., the vehicle schedule is assigned, which reduces the change in objective value the most when the new request is served. Each time a new customer requests a trip, the schedules are updated iteratively. If no solution is found by the insertion heuristic, i.e. no vehicle can serve the customer within the given time constraints, the customer leaves the system unserved. Figure 4.4 and Algorithm 1 outline the described algorithm. The method *insert*($\psi_k(v; R_\psi, P_\psi), r_i^c$) returns the best possible insertion of r_i^c into $\psi_k(v; R_\psi, P_\psi)$ with respect to the objective function ϕ.

While more sophisticated algorithms for solving the ride-pooling assignment can be found in the literature (e.g., [Alonso-Mora et al., 2017; Engelhardt et al., 2020]), using this simple insertion heuristic has the advantage that the assignment of customer and parcel requests can be decoupled into different decision processes, reducing overall complexity and thus computation time.

To dynamically distribute idle vehicles according to the expected demand in the network, the reactive rebalancing algorithm proposed by Alonso-Mora et al. [2017], which is available in the FleetPy repository [Chair of Traffic Engineering and Control, 2023], is applied in this dissertation. Each time a customer remains unserved, the origin location of the requested trip is marked as a rebalancing target. After each simulation time step, an idle vehicle is assigned to each rebalancing target by solving an assignment problem that minimizes the total distance traveled. If there are fewer idle vehicles than rebalancing targets, each idle vehicle must travel to one rebalancing target.

Parcel Assignment

Since there are no explicit time constraints on parcel pick-up and delivery in this work, different assignment strategies (compared to the presented passenger assignment) were developed to assign parcels to vehicle schedules. While parcels could be served during periods of low customer demand to increase the temporal utilization of the vehicles, the goal of this study is to evaluate whether parcel pick-up and delivery can be performed

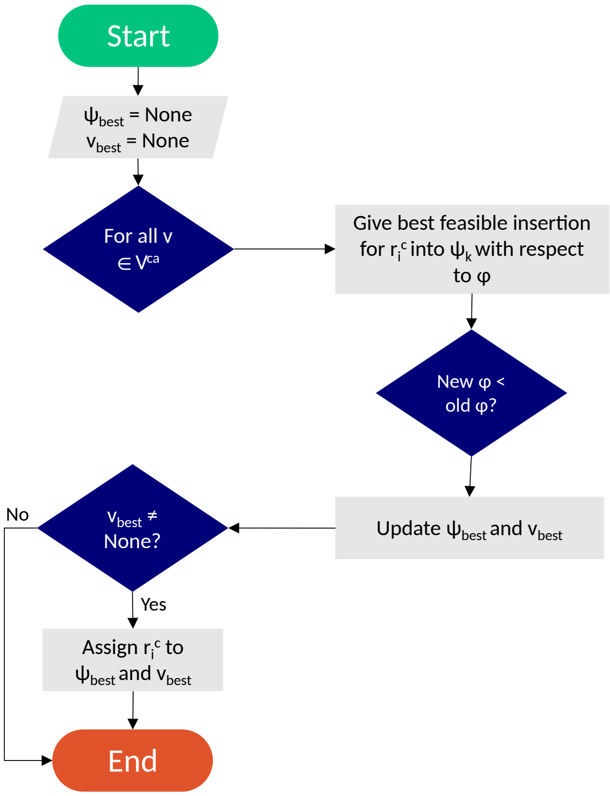


Figure 4.4: Functional flowchart of the customer assignment algorithm in FleetPy.

when vehicles pass by occasionally to minimize the need for additional vehicle kilometers traveled. Three different parcel assignment strategies are developed and described below.

To achieve this in a dynamic setting with online decision making about whether or not to assign a parcel to a requested passenger trip, different assignment strategies and a detour parameter τ_{th} were introduced:

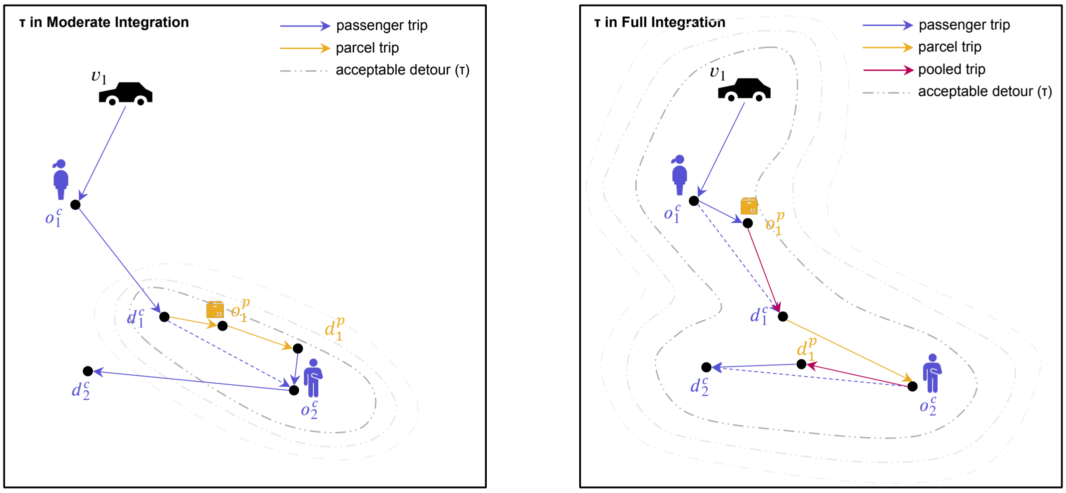
$$\tau_{th} = \frac{d(\psi_k)}{d(\psi_k \cup \{r_i^p\})} \tag{4.3}$$

If τ_{th} approaches 1 less detour is accepted to serve the parcel, for both, *Moderate* (Figure 4.5a) and *Full RPP* integration (Figure 4.5b).

Combined Decoupled Parcel Assignment (CDPA) In the first assignment strategy, both the origin as well as the destination of a parcel are assigned at once. An assignment of a parcel request r_i^p to vehicle v is only made if the detour to add the pick-up and the drop-off into the currently assigned schedule $\psi_k(v; R_\psi, P_\psi)$ is small compared to the distance of the direct parcel route $d(o_i^p, d_i^p)$. The detour is measured by comparing the distance that has to be driven to complete the schedule, including the new parcel request $\psi_l(v; R_\psi, P_\psi \cup \{r_i^p\})$, with the distance not considering the parcel, i.e. $\psi_k(v; R_\psi, P_\psi))$. A possible assignment is identified if:

$$d(\psi_l(v; R_\psi, P_\psi \cup \{r_i^p\})) - d((\psi_k(v; R_\psi, P_\psi))) < (1 - \tau_{th}) d(o_i^p, d_i^p), \tag{4.4}$$

with a threshold parameter $\tau_{th} \in \{0, 1\}$ indicating the amount of detour relative to a direct route to be accepted to serve the parcel r_i^p. If τ_{th} approaches 1 no detour is accepted to serve the parcel, for both, *Moderate* (Figure 4.5a) and *Full RPP* integration (Figure 4.5b).



(a) τ_{th} in Moderate RPP integration

(b) τ_{th} in Full RPP integration

Figure 4.5: Visualization of the threshold parameter τ_{th} for detour(s), which is accepted for the integration of parcel transport in *Moderate* and *Full RPP*.

Figure 4.6 and Algorithm 2 sketch the procedure of assigning parcels with the CDPA strategy. Let P_u be the set of currently unassigned parcels and V^{ca} the set of vehicles with schedules, that have been updated in the current simulation time step. The method *insert*$(\psi_k(v; R_\psi, P_\psi), r_i^p)$ returns the best feasible insertion of r_i^p in $\psi_k(v; R_\psi, P_\psi)$ with respect to the objective function ϕ. For each unassigned parcel, an insertion is checked for each vehicle with an updated schedule (an insertion in other vehicles would have already been checked in previous time steps). If a new schedule fulfills the constraint of Equation 4.4, a candidate insertion is found. In the end, the candidate schedule with the minimum objective value is picked to be assigned. If no candidate is found, the parcel is tried to be assigned again at a later time step. [2]

Subsequent Decoupled Parcel Assignment (SDPA) The idea of the second assignment strategy is that, because no time constraints are imposed on the parcel drop-off, the decision on when to drop-off the parcel does not have to be made when the decision of the parcel pick-up is made. This assumption can be made under the condition that the loaded parcels do not significantly affect the energy consumption of the vehicles. Therefore, the decision to pick-up a parcel is separated from the decision to drop-off a parcel. The decision to pick-up a parcel is taken similar to the CDPA strategy and summarized in Algorithm 3. The differences to Algorithm 2 can be summarized as follows: first, only the insertion of the origin o_i^p is tested for parcel request r_i^p by the method *insertOrigin*, second, the possible assignment is identified if:

[2] All algorithms are presented in concise pseudo-code in Appendix 2.2.

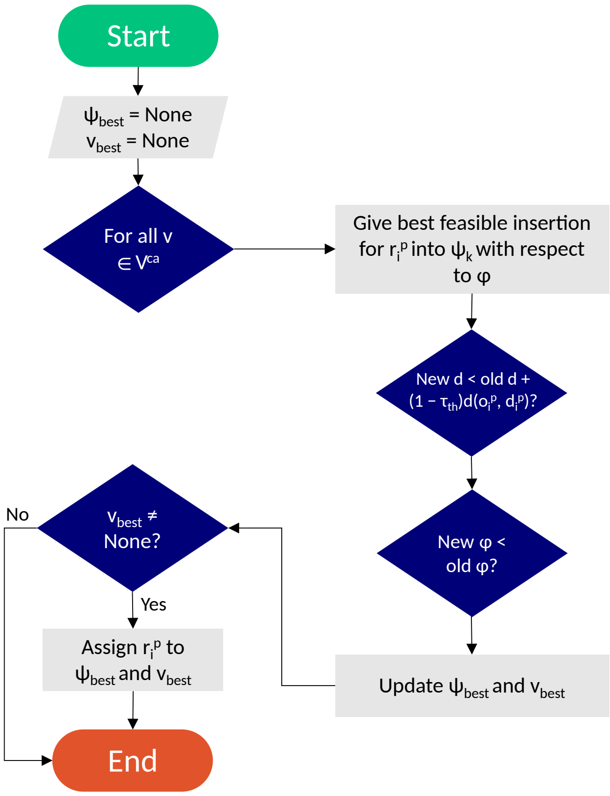


Figure 4.6: Functional flowchart of the CDPA algorithm.

$$d(\psi_l(v; R_\psi, P_\psi \cup \{o_i^p\})) - d((\psi_k(v; R_\psi, P_\psi))) < (1 - \tau_{th})d(o_i^p, d_i^p)/2. \tag{4.5}$$

Note that the threshold is divided by 2 (compared to CDPA) to account for an even split of the overall detour for parcel pick-up and drop-off. The time horizon in which passenger requests are revealed does not allow for a more elaborate distribution of detours than splitting the detour factor for parcels, τ_{th}, evenly between origin and destination. An attempt could be made to predict future passenger requests and thus achieve a more sophisticated distribution of the parcel detours, however this is beyond the scope of this work. If a feasible insertion of the origin of r_i^p is assigned to vehicle v, r_i^p is added to the set P_v^a to keep track of assigned parcel pick-ups for each vehicle.
A similar approach is chosen to assign the parcel drop-off in any later simulation time step and is sketched in Algorithm 4. For all vehicles with scheduled pick-ups or on-board parcels, the insertions of drop-offs for all parcels $r_i^p \in P_v^a$ is checked. A possible assignment is considered if:

$$d(\psi_l(v; R_\psi, P_\psi \cup \{r_i^p\})) - d((\psi_k(v; R_\psi, P_\psi \cup \{o_i^p\}))) < (1 - \tau_{th})d(o_i^p, d_i^p)/2. \tag{4.6}$$

Thereby, $\psi_l(v; R_\psi, P_\psi \cup \{r_i^p\})$ refers to the schedule including origin o_i^p and destination d_i^p of parcel r_i^p.

The simulation first tests possible drop-off locations for vehicles with an updated schedule, and then creates possible pick-up locations for parcel pick-ups, similar to the comprehensive parcel assignment strategy. The disadvantage of this strategy is that there is no guarantee that a drop-off will be found for every parcel by the end of the simulation. However, parcels should not remain on the vehicles until the end. Therefore, when a certain simulation time T_p^{max} is exceeded, all remaining parcels on board are scheduled to be dropped off by iteratively inserting them into the current vehicle schedule.

Subsequent Coupled Parcel Assignment (SCPA) In the last assignment strategy, the decision to assign the drop-off of a parcel is again made independently of the decision to assign the pick-up. While the pick-up assignment decision remains the same compared to the following independent parcel assignment strategy (algorithm 3), the drop-off assignment decision is linked to the passenger assignment. The idea is to assign passengers, and thus new vehicle schedules, that pass by the drop-off location of on-board parcels. This increases the possible solution space for parcel drop-off assignments. For this purpose, the formulation of the passenger assignment is revised.

Let R_t^{new} be the set of new customer requests in time step t. In the first step, the best possible solution for just serving a new customer request $r_i^c \in R_t^{new}$ is calculated using the same insertion heuristic as for the passenger assignment. The resulting schedule $\psi_l(v_a) = \psi_l(v; R_\psi \cup \{r_i^c\}, P_\psi)$ is used as a benchmark for the decision to assign a parcel drop-off. In a second step, instead of inserting a parcel drop-off into the overall best solution $\psi_l(v_a)$, an insertion of each on-board parcel requests r_i^p is tried for feasible schedules in combination with the new request r_i^c, resulting in the schedules $\psi_{\tilde{l}}(v; R_\psi \cup \{r_i^c\}, P_\psi \cup \{r_i^p\}) \forall v \in V_{r_i^c}$. A possible assignment of the parcel is found if:

$$d(\psi_{\tilde{l}}(v; R_\psi \cup \{r_i^c\}, P_\psi \cup \{r_i^p\})) - d(\psi_l(v_a; R_\psi \cup \{r_i^c\}, P_\psi)) < (1 - \tau_{th}) d(o_i^p, d_i^p)/2, \quad (4.7)$$

i.e. the driven distance of the best possible solution without parcel delivery is only increased by at most a threshold factor compared to the direct distance of the inserted parcels. If multiple of these options exist, the vehicle schedule minimizing the objective ϕ is assigned. If none of these options exist, only the best schedule for serving the customer is assigned. The corresponding logic is sketched in Algorithm 5. For reasons of clarity and comprehensibility, not the computationally most efficient version of the algorithm is depicted in Algorithm 5. For example, all solutions from the first customer insertion can be stored in a list, which makes the re-computation of the insertion in the second loop over vehicles redundant.

4.2.3 Simulation Case Study for Munich, Germany

The proposed framework is applied and evaluated for a case study in Munich, Germany. The considered service area of the MoD operator extends almost to the freeway ring, which surrounds the city center. The research design of the case study is based on a street network $G = (N, E)$ with edge travel times for each hour of a usual working day, as well as passenger demand is extracted from a calibrated microscopic traffic simulation described in [Dandl et al., 2017]. The street network and operating area are shown in Figure 4.7. Parcel demand is based on a real-world data set of a worldwide leading logistics company. The impact of additional parcel transportation within the running ride-pooling service is evaluated using customer (waiting and travel times) and operator (served customers, parcels, fleet kilometers, and revenue) KPIs. The simulation was carried out with different detour factors for the integration of parcels (τ_{th}), parcel penetration rates and vehicle types. The simulation parameters influencing the pooling of passengers and parcels, as well as boarding and deboarding times from Table 4.1 were kept constant. These parameters were set to proven and accepted values, fostered by the potential customer survey of Chapter 3. The variation of these are subject of investigation in a couple of ride-pooling simulations [Engelhardt & Bogenberger, 2021; Zwick, Kuehnel, & Hörl, 2022] and considered to be out of scope and of minor insight for this study.

Input Data, Simulation Settings and Preprocessing

Since, to the best of the authors' knowledge, no real-world data exists regarding the operation and usage of a RPP service, an artificial passenger demand is created for this

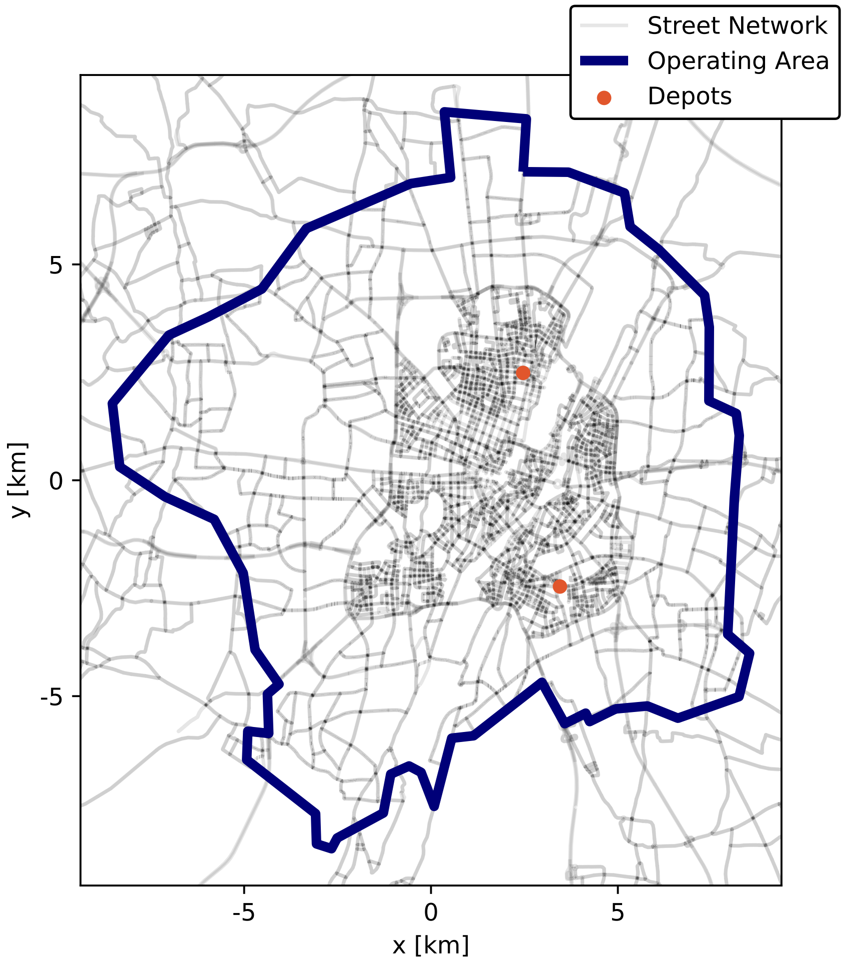


Figure 4.7: Street network, operating area and depots for the modeled RPP service in the case study of Munich, Germany.

research. Customers for the MoD service are created by sampling from private vehicle trip OD matrices extracted from the same microscopic traffic simulation from which the network is extracted. There are 24 matrices, one for each hour of the day, containing approximately one million trips originating and terminating within the service area. *Poisson* processes are used to sample requests for the MoD service, with *Poisson* rates defined by the corresponding OD entries times a penetration factor. In this study, a penetration factor of 5% is used, which can be interpreted as the MoD service displacing 5% of the private vehicle trips within the service area, resulting in approximately 50,000 trips per day. The origin and destination nodes for the sampled requests are randomly matched to intersection nodes within the associated zones defined by the OD matrices. Using different random seeds for the sampling process, three different sets of requests are generated and used for the simulations to account for stochastic variations while maintaining an acceptable overall computational time to run all scenarios.

One month of real-world parcel delivery data from a leading logistics provider was available to create parcel demand for the RPP service. The data includes the delivery date, the local depot from which the parcel was delivered, and a destination address. In the first step, the destination address is converted to coordinates using the open source geocoding API 'Nominatim', which relies on publicly available OpenStreetMap data. All deliveries outside the MoD service coverage area are removed, resulting in 56,000 parcels within the coverage area. Using the coordinates, parcel delivery destinations are matched to the nearest intersection node in the network. A maximum of c_v^p parcels with the same origin-destination relationship are aggregated into the same parcel request. Since there is no information about the size of the parcels in the data, the size of a parcel request s_i^p is determined by the number of aggregated parcels. The parcels in the real-world data set were shipped from two depots, both located outside the MoD operating area (north and east of Munich). It is assumed that if a RPP service such as the one presented in this study is implemented, corresponding depots will need to be established within the service area. Therefore, two new depots in the northern and eastern part of the city are defined and shown in Figure 4.7. Parcels shipped from the original northern (eastern) depot will be assigned to the newly implemented northern (eastern) downtown depot. A goal of the study is to observe the system limits, i.e. how much parcel demand can be served with a given passenger demand. Therefore, the parcel demand data for the whole month is used as input for the simulations. To vary the ratio of passenger to parcel demand, the total parcel demand is sub-sampled into proportions ranging from 1% to 50%. In the base scenario, a 10% sub-sample of parcel demand is used, resulting in a ratio of approximately 1 parcel to 10 passenger requests, to represent a service that prioritizes serving passenger demand. Analogous to the passenger demand, three different sets of parcel requests are created using different random seeds within the sub-sampling process.

In contrast to the simulations modeling the RPP service, the *Status Quo* is modeled with two independent vehicle fleets that serve as a baseline to evaluate the efficiency of integrating parcel delivery into the MoD service. The first fleet corresponds to the MoD service without parcel delivery. The simulations described here are performed without any parcel demand. The second fleet corresponds to the pure logistics service. Here, vehicles are initially placed at each of the two depots. Parcels for the corresponding demand scenario are iteratively inserted into their schedules, minimizing the driven distance including the return to the depot at the end of the route. The aggregated driven distance within these schedules is used by the logistics service to approximate the fleet vehicle kilometers.

Within the simulation, the service parameters describing the maximum customer wait time t_{max}^{wait} are set to 10 min, while the maximum detour factor Δ is set to 40%. These assumptions represent a behavior where customers will always accept a service as long as these maximum wait time and detour time constraints are met, otherwise the service will not be used. Similar assumptions are made in other studies with MoD services and in the absence of data to calibrate more detailed mode choice models (e.g. [Alonso-Mora et al., 2017; Engelhardt et al., 2019; Santi et al., 2014; Simonetto et al., 2019]). The MoD car fleet is operated with a capacity of $c_v^c = 4$ passengers and $c_v^p = 8$ parcels. In the *Status Quo* scenario, it is assumed that the logistics provider operates delivery vehicles with a capacity of 100 parcels [DHL Global, 2019]. The fleet size of the RPP operator for the following simulations is determined by first running several simulations with no parcel demand and varying the fleet size. Finally, a fleet size of 600 vehicles is chosen, which allows a service rate of approximately 90% of customers served. It is assumed that vehicles take 30 seconds to complete the passenger boarding process. If a parcel is to be delivered, this boarding time increases to 60 seconds. However, parcel lockers and a high degree of automation may be required to achieve this delivery time, which is relatively low compared to a conventional average delivery speed of 12 parcels per hour [Bundesverband Paket und Expresslogistik e.V., 2021]. This includes the assumption that at every node within the graph network, the pick-up and drop-off of passengers and parcels is possible, either by stopping second row or using dedicated infrastructure.

Parcels that have been picked up but have not reached their destination by $T_p^{max} = 10$pm are actively assigned for delivery. In some cases, parcels will not be picked up at all if the parcel assignment strategies do not find suitable insertions. These parcels are left undelivered in the simulations to explore the limits of the RPP system. It is assumed that the undeliverable parcels are either returned to the system the next day or delivered by a conventional logistics service. In the life cycle assessment evaluation of the RPP service in Chapter 5, the remaining parcels are delivered by a fleet of logistics vehicles that is comparatively smaller than that required in the *Status Quo* scenario in order to have fully comparable scenarios.

To estimate the fare an operator has to take for transporting a parcel, the following calculations to quantify the profit P_{RPP} of a RPP operator are made:

$$P_{RPP} = \sum_{i \in R_{served}} d_i^{direct} f_r + \sum_{j \in P_{served}} f_p - d_{fleet} c_v \tag{4.8}$$

The first term sums to revenue of all served MoD customer R_{served} based on their direct travel distance d_i^{direct} and a distance dependent fare f_r. The second term calculates the revenue from served parcels P_{served}. Similarly to incumbent logistics pricing schemes a constant fare f_p is assumed for shipping a parcel, thereby d_{fleet} is the overall driven distance of the fleet and c_v a distance-based operating cost. Negro et al. [Negro et al., 2021] calculated c_v that comprises acquisition, vehicle ownership, driver, staff, office and facilities, cleaning, vehicle maintenance and wear, and energy/fuel costs for MoD operators. The value $c_v = 1.06$ €/km is used for driver-operated fleet vehicles and $c_v = 0.45$ €/km for automated vehicles. To estimate fares, this study assumes the following break-even calculation. The break-even fare for customers f_r^{be} is calculated for the *Status Quo* (no parcel delivery, i.e. $P_{served} = \emptyset$) setting:

$$P_{RPP}^{StatusQuo} = \sum_{i \in R_{served}} d_i^{direct} f_r^{be} - d_{fleet} c_v = 0 \; . \tag{4.9}$$

When also parcels are transported by the service, fewer customers are going to be served with the same number of fleet vehicles. The loss in revenue from fewer served customers has to be compensated by parcel fares which determines the break-even of parcel fares f_p^{be}:

$$P_{RPP} = \sum_{i \in R_{served}} d_i^{direct} f_r^{be} + \sum_{j \in P_{served}} f_p^{be} - d_{fleet} c_v = 0 \tag{4.10}$$

Investigation of Different Assignment Strategies

First, simulations are performed for all parcel assignment strategies (CDPA, SCPA, SDPA), as well as for *Status Quo* and *Moderate* and *Full RPP)* integration. Within these simulations, the influence of the assignment threshold parameter τ_{th} on different KPIs is evaluated. In a second step, simulations are performed with varying parcel demand penetration ranging from 0% to 50% of the total parcel demand data-set, while keeping τ_{th} constant, to evaluate the number of parcels that can be accommodated by the RPP service, holding passenger demand constant.

Investigation of Different Vehicle Types

The RPP vehicle types implemented include a passenger rickshaw, a passenger car, and a passenger van. In addition, a delivery vehicle has been implemented to represent the current status quo, where two independent fleets serve passenger and parcel demand. The vehicle types differ in terms of passenger capacity, parcel capacity, and speed (Table 4.2). In addition, there are different propulsion technologies for all of the above vehicle types, which will play an important role in the LCA part of this thesis in Section 5.

4.3 Simulation Results

In the following, the results of the simulation of the presented case study for Munich, Germany are presented. All calculations are implemented in Python and run on an Intel Xeon Silver processor with 2.10GHz and up to 192GB RAM. The simulation times for one scenario range from 10.2 to 13.8 hours. Therefore, the algorithms presented would be applicable to real-world applications. For additional speed-up, the parcel insertion test could also be run in parallel.

In the next three subsections, first, the impact on customer and operator KPI is evaluated based on the different proposed RPP service integration and parcel assignment strategies with a varying threshold parameter τ_{th}. Second, the effects of different parcel demand levels are evaluated and compared to the *status quo*. Third, different RPP vehicle types with different characteristics are introduced and the effects on the proposed RPP service are studied. Subsequently, the obtained results are evaluated holistically by applying a LCA approach for the different vehicle fleets in Chapter 5.

4.3.1 Customer and Operator Key Performance Indicators

A crucial question for the success of the proposed RPP service will be whether the ride-pooling fleet can still ensure sufficient service quality for passengers despite the additional transport of parcels. In this research, it is assumed that logistics services are subordinate to passenger needs. In this context, for the scenario *Moderate RPP* integration, the collection or delivery of parcels is only allowed when there are no passengers on board, while this restriction is lifted for the scenario *Full RPP* integration. However, in both scenarios, the time constraints on passenger pick-up and maximum detour described at the beginning of this chapter must be met to ensure a good quality of service.

The quality of the mobility service from the customer's perspective is evaluated by the average customer waiting and travel times. The simulation results show that customer waiting and travel times are hardly affected by the integration of freight transport into the MoD service. The customer waiting times for all simulation scenarios and the different assignment thresholds (τ_{th}) are maximally increased by less than 0.5%. The customer's travel times are also only marginally affected by the additional transport of freight in the MoD system. For the CDPA strategy, the increase in travel time is constantly between 0.1% and 0.5% for the examined assignment thresholds (τ_{th}). Overall, the change in travel time is limited to 1.5%, which is only about 12 seconds and not statistically significant.

Figure 4.8a and Figure 4.8b show the absolute waiting and travel time distribution of customers for the different RPP scenarios and the assignment strategies with fixed τ_{th}. The waiting time distribution shows that the customer assignment tends to add new passengers with waiting times close to the maximum allowed waiting time of 10 minutes. In general, it is clear that the difference in waiting and travel times between the *Status Quo* and RPP scenarios is relatively small, and their distribution is rarely affected. This means that RPP has little negative impact on the service quality of the represented MoD provider.

Taking a closer look at the difference between the *Full RPP* integration and *Moderate RPP* integration scenarios, we can see that from the customer's point of view, i.e. waiting and travel time, there is no big advantage in limiting parcel pick-up and drop-off to times when no customer is on board. The detours for parcel pick-up and drop-off, which passengers have to accept, seem to be compensated by the additional freedom in vehicle scheduling. In addition, the maximum waiting time and detours are still limited by the constraints t_{max}^{wait} and t_{max}^{travel}, also for parcel pick-ups and deliveries.

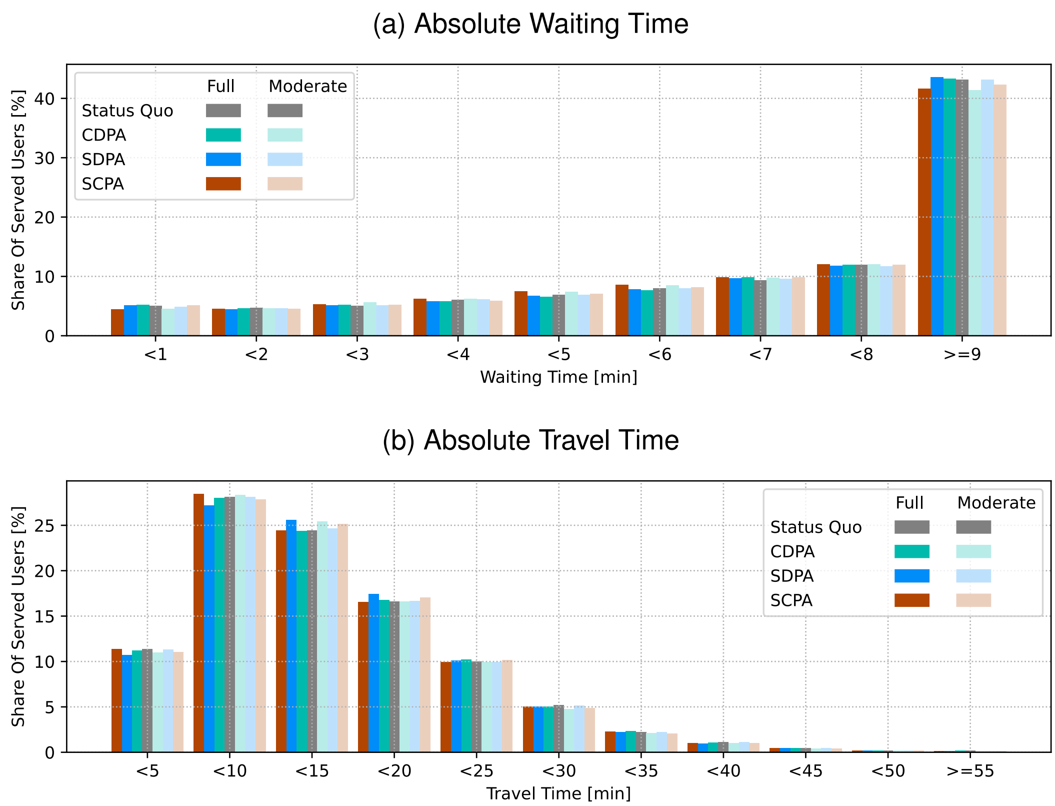


Figure 4.8: Waiting and travel time distribution of served customers within different RPP assignment strategies. $\tau_{th} = 0.80$ is considered in all scenarios shown (fleet size = 600).

In addition to the attractiveness of a mobility service for the customer, the operator's perspective plays a crucial role in its success. For the provider of a MoD ride-pooling service, it is important that the vehicle fleet can be operated efficiently even after the logistics service has been integrated. Each value presented in the results section refers to the average of the three simulations with different random seeds. Since the stochastic variations between the results computed with different seeds are small, error bars are only visible in some figures. Figure 4.9a shows the number of parcels served for assignment thresholds (τ_{th}) between 0.6 and 1.0. It can be seen that the number of parcels served generally decreases as the assignment threshold increases, due to stricter pick-up or drop-off constraints for a parcel in a given schedule. However, the CDPA strategy is more sensitive to higher thresholds than the SDPA and SCPA strategies, both of which are able to serve 100% of all parcels for all τ_{th} examined for the *Full RPP* integration. Looking at Figure 4.9b, one can see the number of customers served for different assignment thresholds. It shows that there is no significant decrease in the number of persons served for any of the strategies. Figure 4.9c shows the total fleet kilometers traveled throughout the day. It can be seen that the comprehensive (CDPA) strategy even produces a lower traveled distance than the *Status Quo* without integrated parcel delivery. Compared to the fleet kilometers to deliver only the parcels in the *Status Quo* $(2,614$ km on average), this corresponds to a 48% reduction in traveled distance for $\tau_{th} = 0.8$. This means that only $1,252$ additional kilometers were needed in the integrated transport approach compared to the ride-pooling fleet in the *Status Quo*. However, the slightly lower number of customers and parcels served compared to the *Status Quo* must be taken into account. However, the SCPA strategy and especially the SDPA approach lead to significantly higher driven distances compared to the *Status Quo*. Another interesting aspect in Figure 4.9a is that the following strategies (SDPA and SCPA) can serve almost all parcels with all thresholds for the *Full RPP* integration. This means that all parcels will be picked up, because even with a high threshold, the depots are very often on the route of the fleet. However, at the end of the day, those parcels that have been picked up but not yet dropped off are delivered, which also contributes to the significant increase in vehicle kilometers traveled by the fleet using these strategies. Both SDPA and SCPA do not take into account the destination of the parcels when picking them up, which can be a big disadvantage when it comes to final delivery, as the destinations of the parcels can be spread all over the network. For the *Moderate RPP* integration, the SDPA and SCPA approaches produce less fleet distance with higher τ_{th} values, corresponding to the decreasing number of customers served and parcels. [3]

Figure 4.9d shows the break-even fare f_p^{be} that the operator must charge to compensate for the loss of revenue from unserved customers. Based on Equation 4.9, the fare for customers is set to 0.90 €/km for driver-operated and 0.38 €/km automated vehicles. The minimum break-even fare, about 0.70 €/parcel, can be achieved with the CDPA strategy in the *Full RPP* integration scenario. This is mainly due to the low additional distance for parcel transport compared to the other two strategies. Assuming a rate of 7 € [Deutsche Post AG, 2023] for a parcel shipped in Germany and applying the assumption that the last mile accounts for 30% of the total rate [Blösl, 2022], a traditional parcel in the *Status Quo* would incur last mile delivery costs of approximately 2 €. However, this ignores the fact that parcels sometimes require multiple delivery attempts, which increases the cost and is already included in the 30% assumption but does not happen in the simulation. It can be seen that the minimum fares for the *Full RPP* integration scenarios do not change much when varying τ_{th}, but the fares for the *Moderate RPP* integration increase with increasing τ_{th}. As noted on the ordinate of Figure 4.9d, the break-even rate for an automated RPP service would decrease further (by a factor of 2.36 according to the assumed costs described in the case study section).

The evaluations have shown that the *Moderate RPP* integration consistently performs worse than the *Full RPP* integration: Significantly fewer parcels can be served, while the passenger experience is not much worse when using the *Full RPP* integration. ***Therefore, from here on only Full RPP integration is considered for further analysis. Additionally, the threshold parameter is set to*** $\tau_{th} = 0.8$***, the value at which the CDPA strategy begins to show a noticeable decrease in the number of parcels served.***

Figure 4.10 shows the temporal distribution of pick-ups and drop-offs for passengers and parcels and the different assignment strategies. Most of the passenger demand starts in the morning around 6 am and lasts until late in the evening around 8pm. It can be observed that only parcel deliveries take place while there is passenger demand to use the existing passenger trips for parcel deliveries. Strategies using off-peak deliveries from other studies

[3] A table of color codes used in this work can be found in the Appendix in Table 1

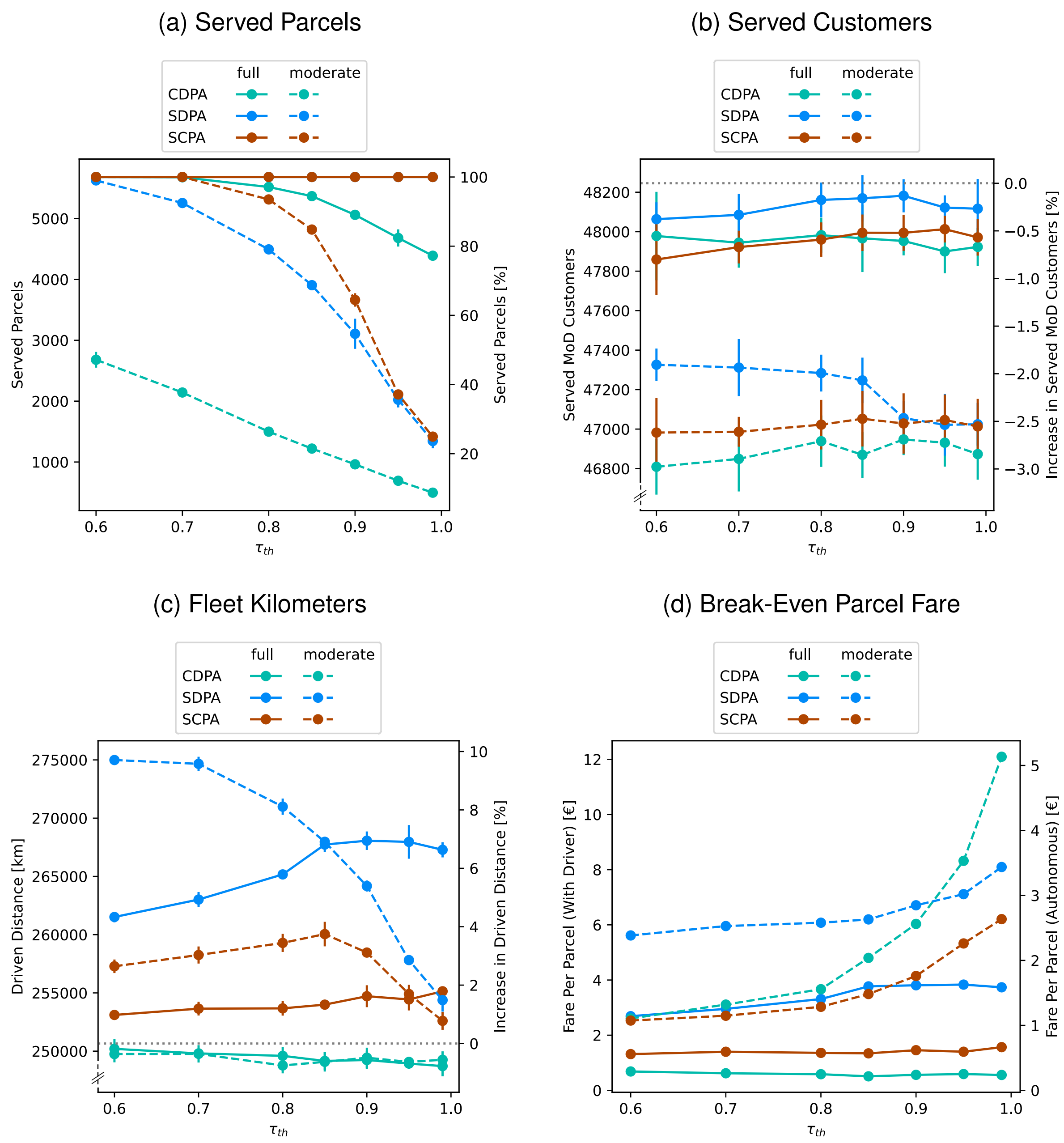


Figure 4.9: Impact of threshold parameter on the number of served parcels, served persons, fleet kilometers traveled and break-even parcel fares f_p^{be}.

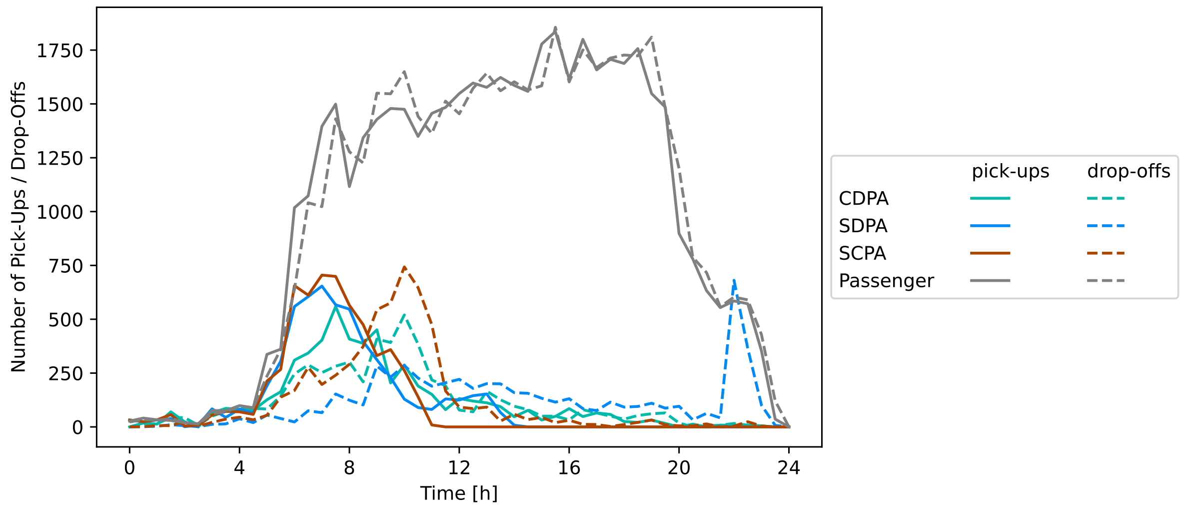


Figure 4.10: Time-dependent pick-ups and drop-offs of parcels for different parcel assignment strategies and threshold parameters $\tau_{th} = 0.8$. Full integration is considered in all scenarios shown.

could easily be added, which would further increase the capacity for parcel delivery. For the comprehensive (CDPA) strategy, the time distribution for parcel pick-ups (solid line) and drop-offs (dashed line) is similar, and the dashed line is slightly shifted to the right, indicating a rather fast delivery after pick-up, resulting from the simultaneous assignment of pick-up and drop-off. Therefore, the vehicle is actively guided to the drop-off locations. The following strategies (SDPA and SCPA) tend to pick up parcels at the very beginning of the day, around 7am. The morning peak indicates that it seems to be easy to find the routes, including the logistics depots. The SCPA strategy shows a higher success rate in delivering parcels during the day compared to the SDPA strategy, as almost all parcels could be served and the number of drop-offs decreases sharply after a peak around 11am. The SDPA strategy, on the other hand, shows a strong peak in the number of drop-offs at 10pm., when the parcels still on board the vehicles that could not be delivered earlier are driven to their destinations.

Figure 4.11 gives a detailed view of the temporal parcel occupancy states of the vehicles throughout the day. When no parcels or passengers are on board, vehicles are represented by black color. White color is used for idle vehicles. It can be observed that for the CDPA strategy a maximum of 150 of the available 600 vehicles have parcels on board during the day, indicating a rather fast delivery once a parcel is picked up, as stated previously. For the SDPA and SCPA strategies, most of the vehicles are filled with parcels in the morning, when they pass by the logistics depots and carry them around during the day. In the case of SCPA most of the parcels can be delivered during the day (Figure 4.10), resulting in low occupancy states at the end of the day. Looking at the SDPA strategy, the occupancy states at the end of the day are still high, which results in a delivery peak at around 10pm to drop-off the remaining parcels. In general, one can observe that the SCPA and SDPA strategies result in higher overall vehicle utilization, indicated by the area below the gray shape, compared to the CDPA strategy. This reflects the fact of higher fleet kilometers and the higher number of served passengers and parcels shown in Figure 4.9.

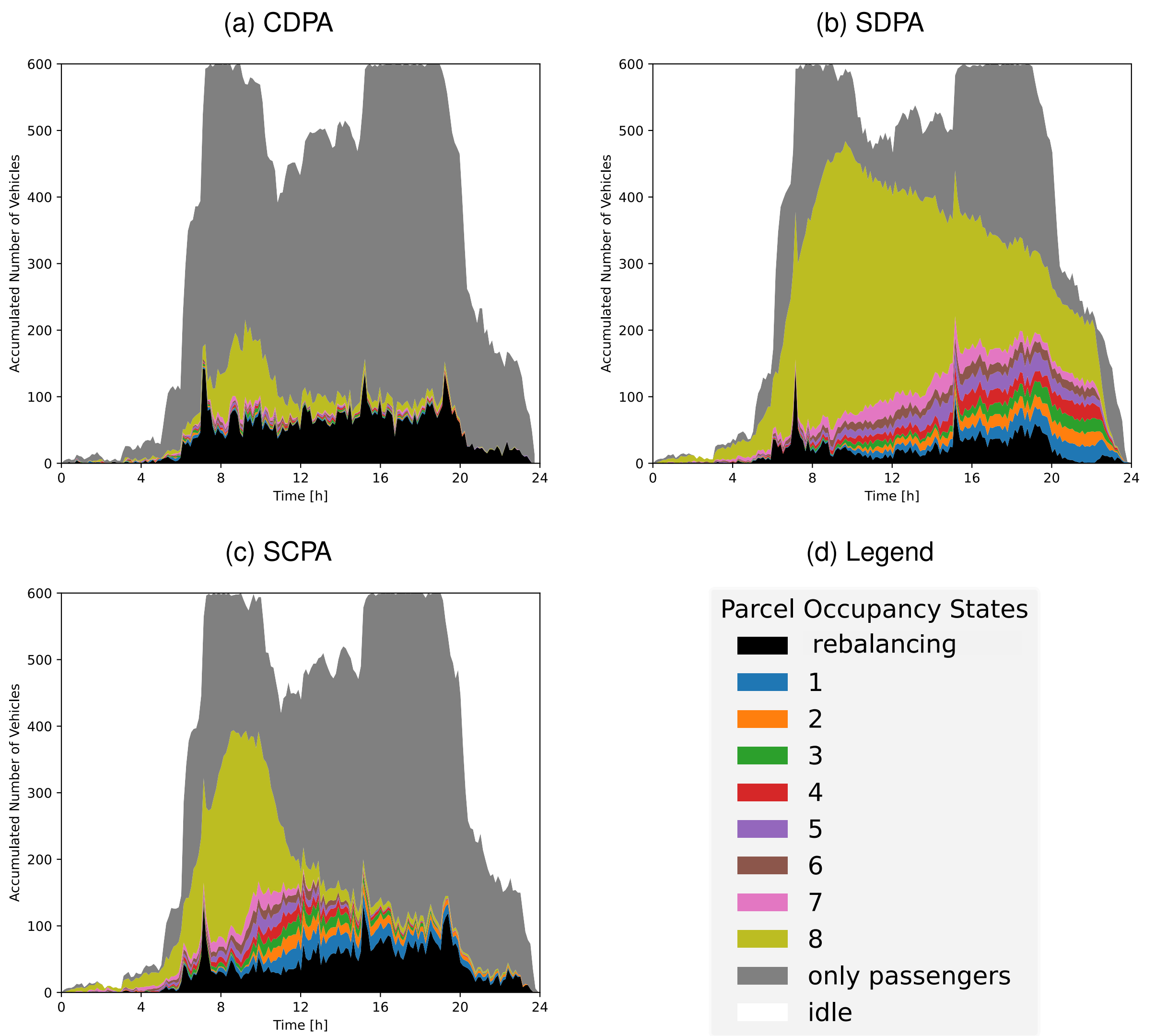


Figure 4.11: Parcel occupancy states of moving vehicles for different parcel assignment strategies. $\tau_{th} = 0.80$ and full integration is considered in all scenarios shown. (fleet size = 600)

4.3.2 Variation of Logistics Demand, Fleet Size and Vehicle Capacity

In order to investigate the system limits of the introduced RPP service, the logistics demand imposed on the MoD fleet, the fleet size, and the parcel capacity of the vehicles were varied. The total data-set of 56,000 parcel shipments is thus sub-sampled into proportions ranging from 1% to 50%, the fleet size is varied between 500 and 800 vehicles, and the vehicle capacity ranges from 4 to 16 parcels. As stochastic variation was very little, error bars are excluded in the further analysis and only average values are presented to increase clarity in the plots.

Figure 4.12a shows the total number of parcels served as a function of the share of parcel demand applied. It can be seen that all strategies reach a certain limit of parcel transport. The CDPA and SDPA strategies match the *Status Quo* up to a parcel demand of about 10%. The SCPA strategy is even able to meet a parcel demand of up to 20% (11,200 parcels per day). As already observed, the SDPA and SCPA approaches tend to pick up as many parcels as possible in the morning. However, unlike the SCPA strategy, the SDPA strategy is not able to deliver the majority of parcels throughout the day, resulting in a fleet state close to full load, indicated by a horizontal plateau in Figure 4.12a. CDPA and SCPA, on the other hand, can also deliver the majority of parcels during the service, freeing up additional capacity to serve more parcels. Figure 4.12b shows the absolute number of customers served. For all allocation strategies, the number of customers served decreases with increasing parcel demand as a trade-off for accommodating these parcels. However, overall there is only a small decrease of at most 1.5% $(790$ customers) compared to the number of parcels that can be delivered. The driven distance of the fleet is shown in Figure 4.12c and compared to the *Status Quo*. Note that the *Status Quo* not only consists of the driven distance of the MoD service but also includes the fleet kilometers of a separated logistic fleet as described in the case study section. For all strategies the driven distance stabilizes when the number of served parcel stabilizes at around 20% penetration (Figure 4.12a). The SCPA and SDPA tend to increase fleet kilometers heavily and produce around 15,000 km and 30,000 km more total distance when considering high parcel demand penetration rates. Only for the CDPA strategy the driven distance of the fleet is even decreased compared to the *Status Quo*. On the one hand this strategy seems to efficiently integrate logistic deliveries into the MoD service, on the other hand one has to keep in mind that little fewer customers and parcels are delivered compared to the *Status Quo*. Looking at Figure 4.12d one can observe the fleet kilometers per served customer and parcel in relation to the parcel demand penetration. This quantity also takes the number of served customers and parcels into account when comparing fleet kilometers. All strategies show lower traveled distance per served request with rising parcel demand, indicating a better integration. However, with high parcel penetration efficient routes for parcel delivery can be found while all parcels are served in the *Status Quo* (i.e. sum of driven distance for serving parcels in logistics fleet and passengers in ride-pooling fleet), leading to the lowest values for fleet kilometers per served customer and parcel in this scenario. ***These results indicate that the modeled integration of parcel delivery into the MoD service is only reasonable for parcel penetration rates of around 10%, as the Status Quo, with high-capacity logistics vehicles, outperforms the RPP service at the higher parcel penetration rates (i.e. >10%).***

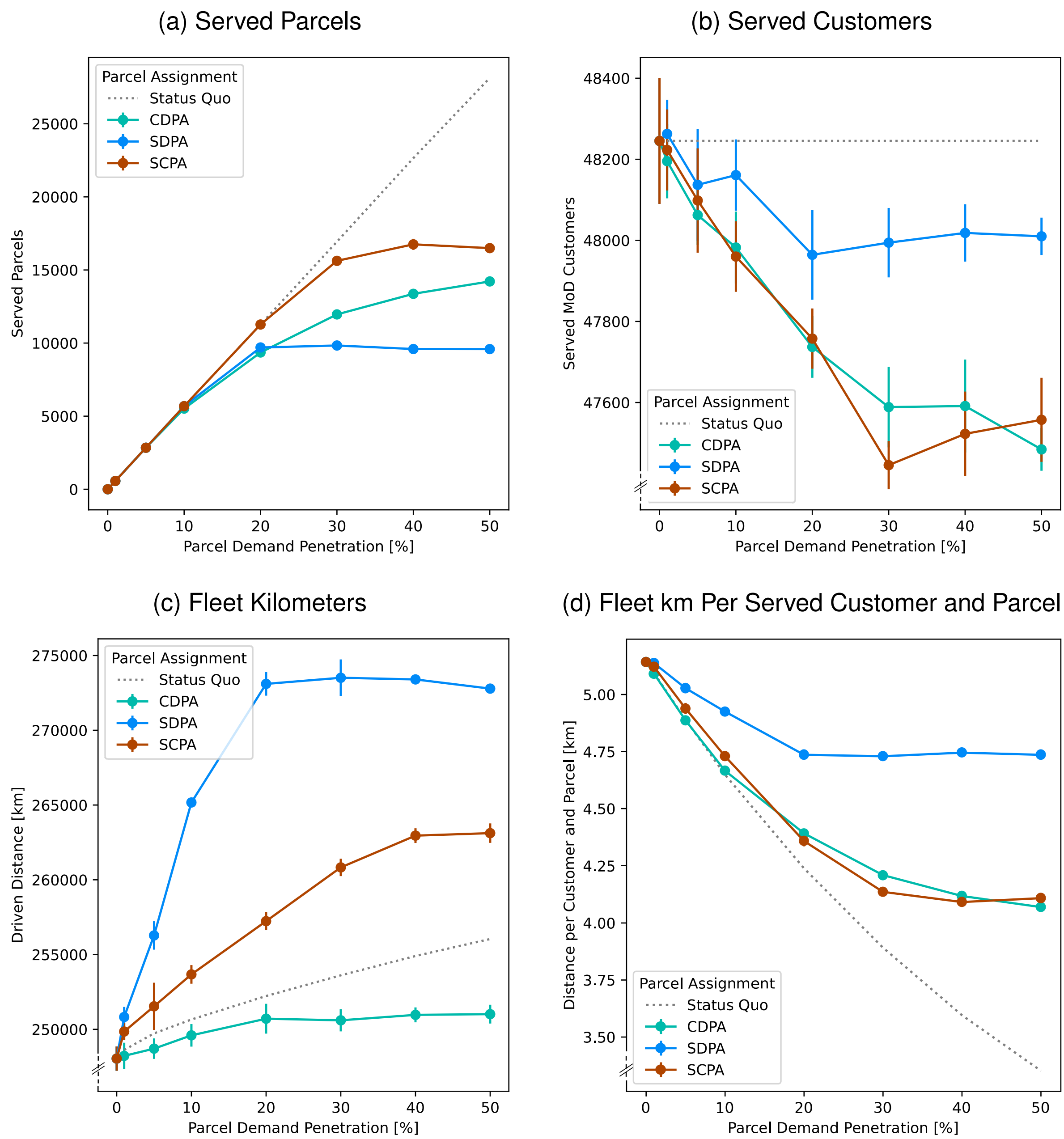


Figure 4.12: Impact of varying parcel demand on the number of served parcels, served persons and fleet kilometers traveled. In all simulations $\tau_{th} = 0.8$ and full integration is considered.

Figure 4.13a displays the number of served parcels depending on fleet size and vehicle capacity (c_v^p). It becomes obvious that the capacity has a higher influence on the share of served parcels, than the fleet size. Except for the SCPA and CDPA strategies with a vehicle capacity of 4, nearly all parcels can be transported in all remaining strategy and capacity combinations. The absolute (left y-axis) and relative (right y-axis) numbers of served customers are displayed in Figure 4.13b. The trend shows that for all strategy and parcel capacity combinations, the number of served customers grows with increasing fleet size. Last but not least, Figure 4.13c gives an overview on the driven distances for the respective strategy and capacity combinations depending on the chosen fleet size. It can be observed that with increasing fleet sizes, the driven distance also rises.

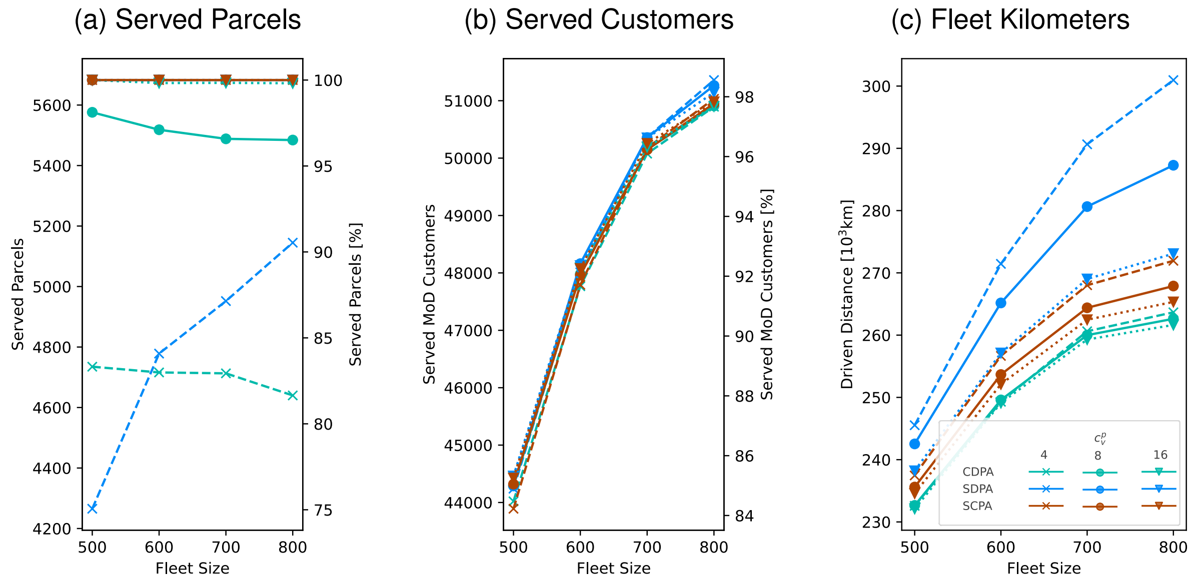


Figure 4.13: Impact of different fleet sizes and parcel capacity c_v^p. In all simulations $\tau_{th} = 0.8$ and full integration is considered.

4.3.3 Introduction of Different Ride Parcel Pooling Vehicle Types

The RPP simulations show that with a classic MoD vehicle, the integration of parcels into a running ride-pooling service works very well. Varying parcel demand, fleet size, and vehicle capacity were also tested. As mentioned earlier in this chapter, the simulation of a RPP service is now extended to include different types of vehicles, which are summarized in Table 4.2. These vehicle types differ mainly in their average travel speed and the available capacities for passengers and parcels. However, they also have different vehicle dimensions, materials, propulsion technologies, and emissions, which will be of particular interest in the following LCA evaluation chapter. In terms of agent-based simulation, only the different speeds and capacities are relevant.

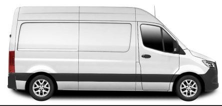
	Passenger Rickshaw	Passenger Car	Passenger Van	Delivery Vehicle
Vehicle Visualization				
Passenger Capacity	2	4	6	0
Parcel Capacity	4	8	15	100
Fleet Size	1,100	600	550	From 34 (10%) to 166 (50%)
Travel Times	free-flow (15km/h)	time-dependent (avg. 34km/h)	time-dependent (avg. 34km/h)	time-dependent (avg. 34km/h)

Table 4.2: Vehicle types implemented in FleetPy for RPP simulations.

The respective fleet sizes for the different RPP vehicle types have been calibrated assuming a passenger request acceptance rate of approximately 90% by first running several simulations with no parcel demand and varying the fleet size. This procedure results in the fleet sizes shown in Table 4.2. For the delivery vehicles serving parcels in the *Status Quo*, the fleet size varies between 34 and 166 vehicles, depending on the assumed penetration rates of parcel demand. ***Since the CDPA strategy represents the best compromise between the beneficial customer and operator KPI, only this allocation strategy is used to examine the different vehicle types. Likewise, the threshold parameter τ_{th} for detour(s) is set to a value of 0.8, as before for all simulations. The variable remains the parcel penetration rate.***

Similar to Figure 4.12, Figure 4.14 shows the total number of parcels served, MoD customers served, total distance traveled, and distance per customer and parcel as a function of the share of parcel demand applied. Figure 4.14a shows that all vehicle types reach a certain limit of parcel delivery and match the *Status Quo* up to a parcel demand penetration of about 10%. The van fleet can even challenge the *Status Quo* up to a parcel demand penetration of about 20%. After that, not all parcels can be integrated into the ride-pooling system. The total number of customers served can be seen in Figure 4.14b for the different vehicle types. It is clear that there are slight differences even for the respective *Status Quo*. This is mainly due to the different fleet sizes, but the differences are relatively small (max. 2.5%). As parcel demand increases, the number of customers served decreases, but the rickshaw fleet is the most resilient to increasing parcel demand penetration. Figure 4.14c shows the total distance traveled for each fleet. It can be seen that the rickshaw fleet travels the least distance and the car fleet travels the most, but one has to keep in mind the slight differences in the customers served MoD. All types of vehicles produce fewer fleet kilometers compared to the *Status Quo*, although one must take into account the decreasing number of customers served as the parcel penetration rate increases. Last but not least, Figure 4.14d shows the distance covered per passenger and parcel for each vehicle type, assuming different parcel penetration rates. It can be seen that the angel between the *Full RPP Integration* scenario and the *Status Quo* opens wider for the rickshaw fleet than for the car and especially for the van fleet. This is due to the higher capacity and travel speed offered by these vehicle categories, which limits the distance traveled per unit even at higher parcel penetration rates. However, the rickshaw fleet produces lower distances per unit for smaller parcel demands.

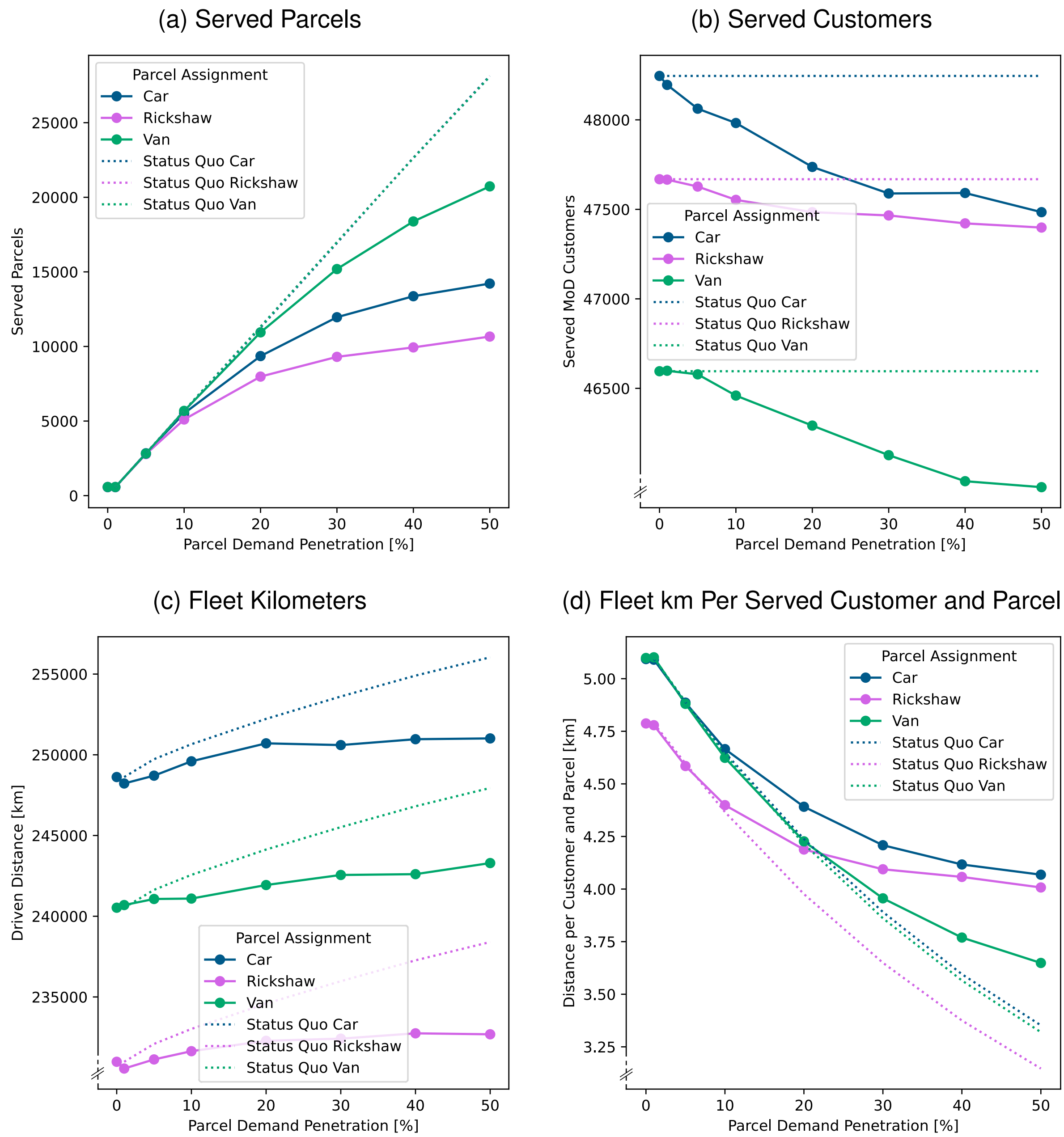


Figure 4.14: Impact of varying parcel demand on the number of served parcels, served persons and fleet kilometers traveled. In all simulations $\tau_{th} = 0.8$ and full integration is considered.

The occupancy plots for the different vehicle types show the vehicle occupancy over the simulation period of 24 hours. The white areas represent idle vehicles, the black areas represent rebalancing vehicles, and the gray areas represent passenger transport tasks. The different colors indicate how many parcels are on board a vehicle and differ for each vehicle type due to their different maximum parcel capacities of 4 (rickshaw), 8 (car), and 15 (van). It is interesting to note that the rickshaw fleet operates longer at the maximum parcel capacity than the car or van fleet, which transport most parcels before noon. Again, the idea of RPP is not to use the idle time of the vehicle fleet for parcel transport and thus create higher traffic volume, but to integrate the logistics service into already existing passenger trips.

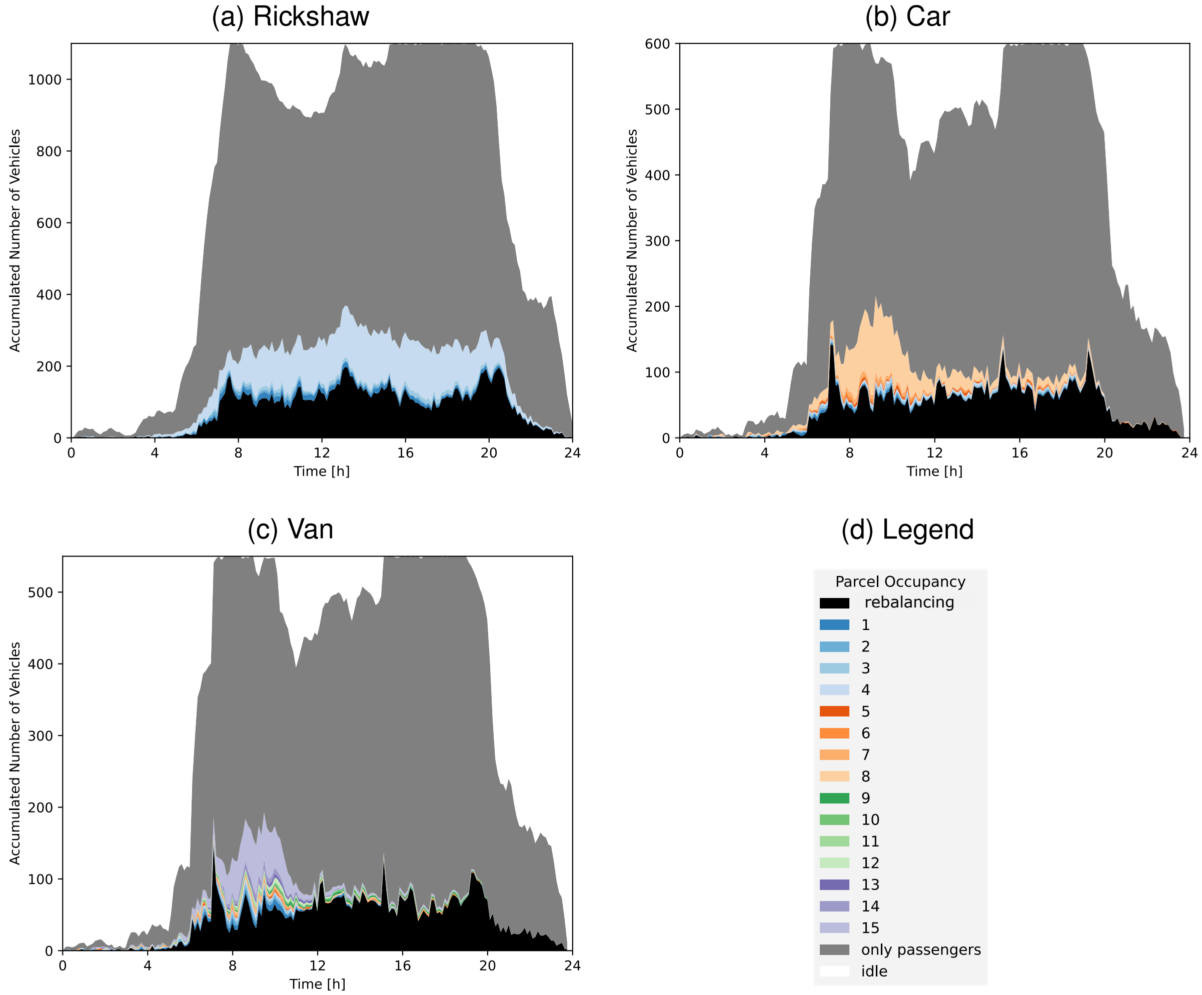
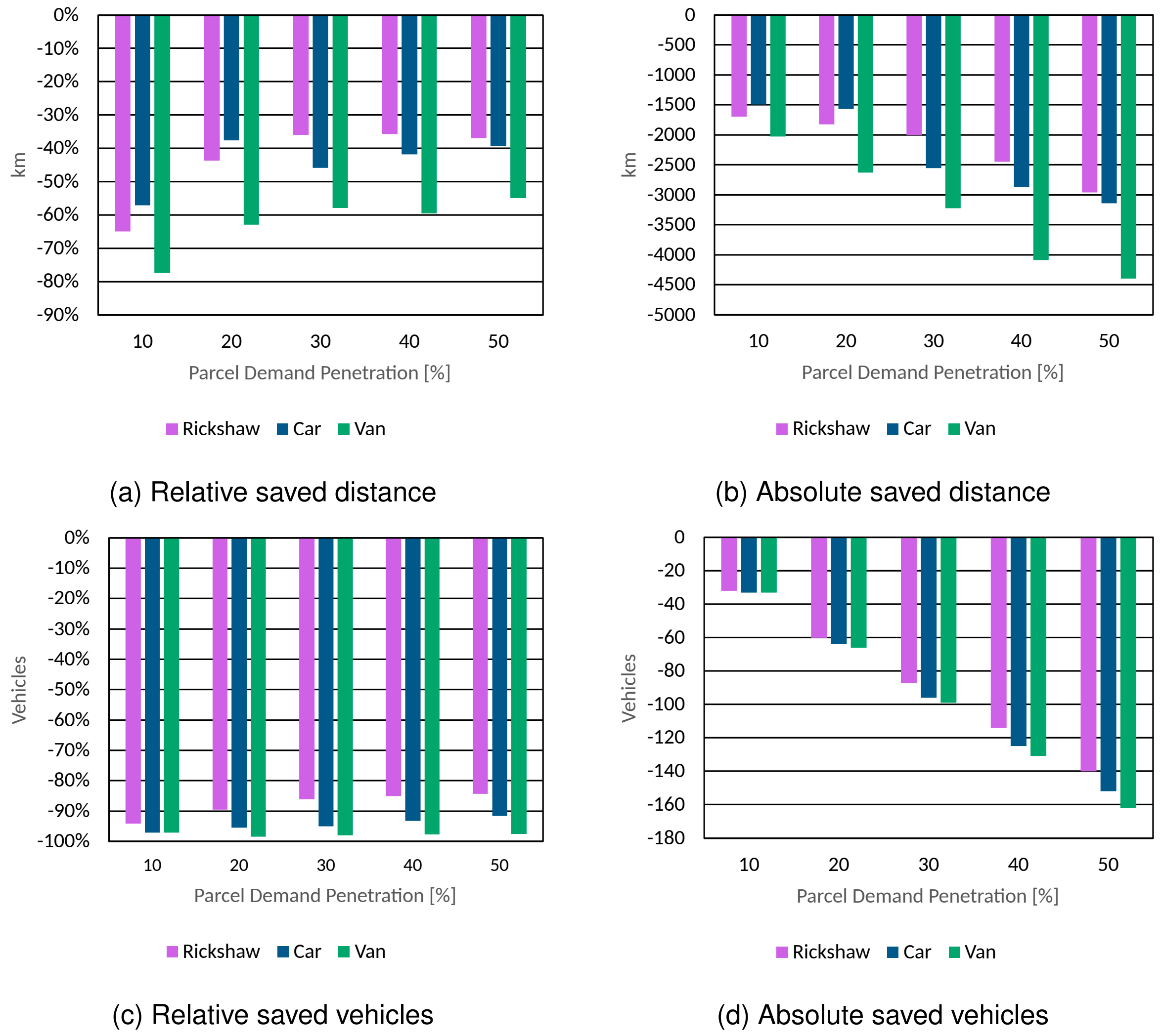


Figure 4.15: Parcel occupancy states of moving vehicles for different vehicle types. $\tau_{th} = 0.80$, CDPA assignment, and full integration is considered in all scenarios shown. (fleet sizes: rickshaw = 1,100, car = 600, van = 550)

Looking at the total reduction of driven distance within the system, the remaining parcels, which could not be incorporated into the vehicle schedules of the RPP service (see Figure 4.14a), must be delivered at the end of the day using either the RPP vehicle fleet or a separate fleet of delivery vehicles. ***To accommodate for that and create compara-***

ble scenarios, the simulation was extended by a heuristic module solving a pick-up and delivery problem for delivery vehicles transporting the remaining parcels, which were not served by the RPP fleet at the end of the day. Looking at the savings in total distance traveled on the road network and number of vehicles resulting from the implementation of a *Full RPP* service compared to the *Status Quo* scenario, it can be seen that during a complete day of *Full RPP* integration between 1,500 km (10% parcel penetration rate, car) and 4,400 km (50% parcel penetration rate, van) can be saved, which corresponds to a savings range of 35% to 77% in terms of relative distance comparing *Full RPP Integration* to the *Status Quo* logistics service. Looking at the total number of delivery vehicles required, the savings range from 32 vehicles (10% parcel penetration rate, rickshaw) to 162 vehicles (50%, parcel penetration rate, van), which corresponds to relative savings between 84% and 99% comparing *Full RPP Integration* to the *Status Quo*.



(a) Relative saved distance

(b) Absolute saved distance

(c) Relative saved vehicles

(d) Absolute saved vehicles

Figure 4.16: Relative and absolute savings in driven distance and needed delivery vehicles for *Full RPP* compared to *Status Quo*.

Chapter 5

Life Cycle Evaluation of Ride Parcel Pooling

Chapter Essentials

- Life cycle sustainability assessment is needed to holistically assess the implications of Ride Parcel Pooling as it takes into account all, i.e. economical, ecological, and social, dimensions of potential effects of mobility services.
- The introduction of the Life Cycle Sustainability Assessment Fleet Evaluation Tool aims at a new form of evaluating vehicle fleets in urban environments over their entire life cycle, taking into account environmental, economic, and social implications.
- The case study of the *Full RPP* scenario reveals considerable savings in global warming potential, fleet operating costs, and social implications compared to the *Status Quo*.
- For larger parcel volumes, the vehicle types with higher capacities (i.e. car and van) are at an advantage, whereas the rickshaw fleet attains good results for its relatively short traveled distances.
- Electric vehicles have an advantage over the internal combustion engine vehicles especially in the dimensions of environment and economy, but also in the social sphere.
- The interpretation of results and comparison to other studies proves the validity of the tool, model assumptions, and results.

The simulation results of Chapter 4 show that a holistic evaluation of the RPP idea is multifaceted and non-trivial, since integrating logistics services into a ride-pooling fleet can not only save driven distance, but also delivery vehicles. Furthermore, the different types of vehicles (rickshaws, cars, vans, and delivery vehicles) introduced in the simulation have considerably different production and operating costs in terms of economic and environmental aspects. For these reasons, it is worthwhile to examine the simulation results in more detail using a life cycle approach and to evaluate the results over the entire lifetime of the vehicles. RPP is an emerging mobility service that has the potential to significantly reduce the environmental impact of passenger and freight transportation by improving the efficiency of vehicle use and reducing the number of vehicles on the road. Therefore, it is important to understand the environmental impacts of this new service. Furthermore, LCA provides a comprehensive approach to evaluating the environmental, economical, and social impacts of transportation services. By considering the life cycle impacts of RPP, from Raw Material Extraction (RME) to Production (PRO) and Use (USE) to End of Life (EOL), LCA can provide a holistic picture of the environmental performance of the mobility service [1]. Overall, this study aims to include economic and social aspects in addition to environmental impacts. This makes it necessary to introduce the methods LCCA and SLCA, which describe an examination of the life cycle cost components of a product system and the social implications of the introduction of a RPP service, respectively. Together, LCA, LCCA and SLCA form a LCSA that examines all three dimensions of sustainability. The economic and social assessment is aggregated only to the USE phase, since the impact of a RPP service on the status quo in the USE phase is the core of this work, and reliable data on the other phases do not exist. Overall, the evaluation of RPP using the LCSA approach can provide valuable insights into the environmental, economic and social performance of this emerging mobility service, including Energy and Transport Processes (TRP), see Figure 5.1. By identifying opportunities for improvement and informing decision making, LCSA can help guide the transition to a more sustainable and efficient transportation system. The remainder of this chapter is structured as follows: First, this thesis will introduce the LCSA Fleet Evaluation Tool, which is an evaluation tool for assessing the life cycle sustainability of vehicle fleets in urban environments. Second, the simulation results of Chapter 4 are evaluated by the LCSA Fleet Evaluation Tool for a case study in Munich, Germany. Lastly, the results are presented and interpreted in terms of uncertainty and sensitivity.

5.1 Life Cycle Sustainability Assessment Fleet Evaluation Tool

The following section contains the description of the LCSA Fleet Evaluation Tool and consists in substantial parts of the publication "Life Cycle Sustainability Assessment Fleet Evaluation Tool" submitted to Transportation Research Part D: Transport and the Environment in 2024 and reflects the introduced principles and results in the overall context for this dissertation.

The LCSA Fleet Evaluation Tool for (on-demand) vehicle fleets in urban environments is based on the LCA data provided by the recognized LCA data provider "ecoinvent". It is available for academic use, which increases the reproducibility of the results and the adapt-

[1] A table of color codes used in this work can be found in the Appendix in Table 1

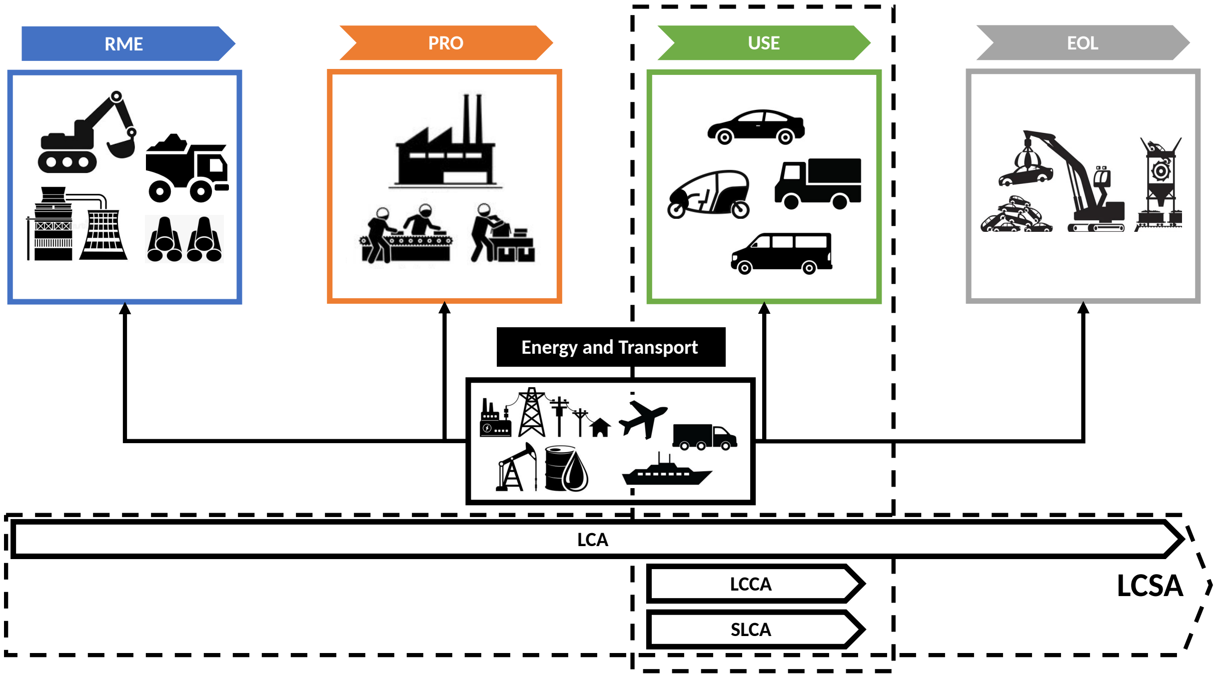


Figure 5.1: Representation or the investigated LCA phases with associated processes.

ability to potential future use cases. In addition, the LCSA Fleet Evaluation Tool integrates data from Handbook Emission Factors for Road Transport (HBEFA) for a more detailed evaluation of the emissions produced in the USE phase of a mobility service based on a fleet of vehicles. All data sources provide specific and comprehensive data for the European and German market, where the case study of this thesis is located. In addition to the theory and best practices of LCA provided in Chapter 2, the following sections present in more detail the model objective, evaluation metrics, necessary input parameters, and software and data sources required for the development and potential adaptation of the LCA fleet evaluation tool.

5.1.1 Model Objective

The LCSA Fleet Evaluation Tool consists of three main pillars representing the three dimensions of sustainability: an environmental LCA, an economic LCCA and a social SLCA. Figure 5.1 shows the included LCA phases: RME, PRO, USE and EOL, as well as the examined life cycle goals: LCA, LCCA and SLCA including the respective dimensions across the life cycle phases. The overall objective of this tool is to investigate the impact of introducing a novel mobility service into the existing urban mobility infrastructure. Therefore, the LCCA and SLCA focus exclusively on the service USE phase to quantify the resulting impacts. The LCA, on the other hand, examines all phases of the service's life cycle, since the choice of the vehicles used has a significant impact on the GWP during the RME and PRO phases. In order to evaluate and compare new mobility services, it is necessary to present a status quo scenario before assessing the impacts according to the evaluation metrics.

The scope of the tool can be categorized into temporal, spatial, and physical dimensions.

Since RPP is a near-future service, the temporal dimension is from the year 2023 onward. Spatial dimensions are generally worldwide, but the LCA case study is located in Munich, Germany. The physical dimensions include all processes related to the RPP vehicles, but road and technology infrastructure are out of scope, as well as material recovery and disposal, since the information on these processes is very poor. A generic visualization of the chosen scope for the LCA fleet evaluation tool, including the system boundaries for LCA, LCCA and SLCA, is shown in Figure 5.1.

5.1.2 Evaluation Metrics

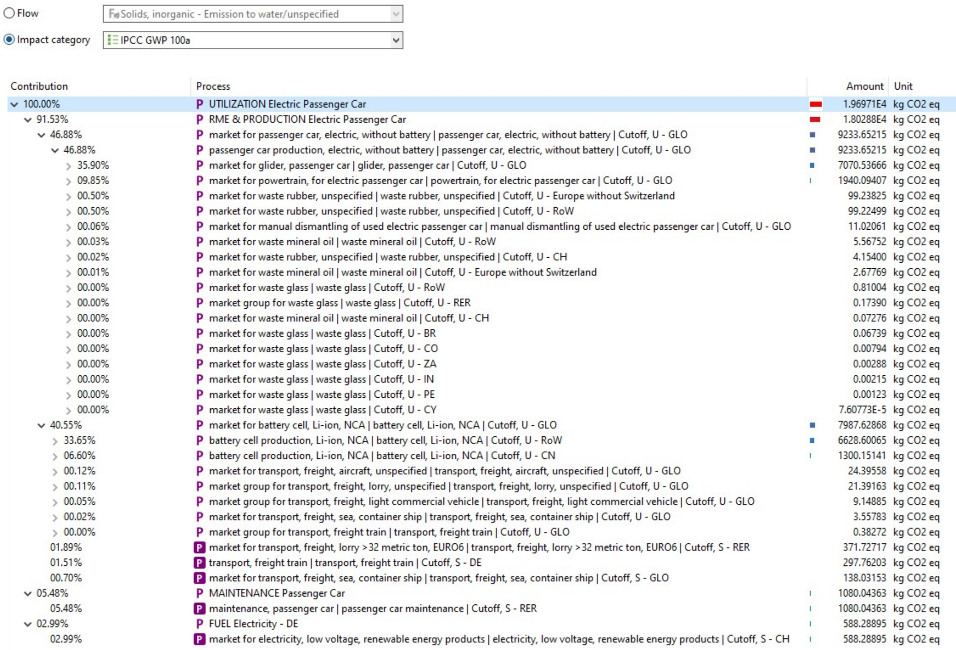
The evaluation metrics of the LCSA Fleet Evaluation Tool are grouped into the three aspects of sustainability assessment within the LCSA, i.e. environmental, economic and social impacts. They all compare the performance of the new mobility service to a predetermined status quo and present the results in comparison to it. So far, the LCSA Fleet Evaluation Tool includes data for the vehicle categories passenger rickshaw (electric), passenger car (petrol, diesel, electric), passenger van (petrol, diesel, electric), and delivery vehicle (petrol, diesel, electric), which were implemented in the course of the RPP case study. In general, however, the LCSA Fleet Evaluation Tool has a modular structure so that new vehicle categories can be easily integrated by providing primary data for all life cycle phases.

Environmental Metrics

The environmental metrics of the LCSA Fleet Evaluation Tool applied in the following case study builds upon the "IPCC 2013 GWP 100a" methodology, which focuses purely on GWP. However also alternative methods, covering other impact categories, like abiotic depletion potential, water consumption, eutrophication potential, ozone layer depletion potential and many more are within the scope of the LCSA Fleet Evaluation Tool. Climate change is quantified in GWP, measured by the integrated infrared radiative forcing increase of a GHG, expressed in kilograms of CO_2e [IPCC, 2022]. The LCSA Fleet Evaluation Tool builds its analysis on the data sets of ecoinvent 3.8 and models the product systems and processes in the software environment of OpenLCA. Figure 5.2 shows a typical output of an electric vehicle, modeled in OpenLCA applying ecoinvent data sets.

In addition, the tool integrates a very detailed macroscopic USE phase analysis, based on fleet operational data and macroscopic emission factors of Handbook of Emission Factors for Road Transport (HBEFA) [2023], considering the following air pollutants PM_{10}, NH_3, SO_2, NO_X, $NMVOC$ and CO. The specific emissions of the vehicle under investigation are determined on the basis of the vehicle type, driving conditions, its specific energy and fuel consumption as well as its total weight. Vehicles which do not have a distinct vehicle category in HBEFA can be scaled based on their specific fuel consumption (exhaust emissions) or weight ratio (non-exhaust emissions) compared to the closest existing vehicle category. Table 5.1 states a typical passenger car (petrol, diesel, and electric) built in the year 2023, driving in mixed urban traffic conditions, which was exported from HBEFA 4.1.

The climate related costs of the remaining life cycle phases, i.e. RME, PRO, and EOL, are accounted for by the LCA approach and are later on incorporated into the previously



Contribution	Process	Amount	Unit
100.00%	P UTILIZATION Electric Passenger Car	1.96971E4	kg CO2 eq
91.53%	P RME & PRODUCTION Electric Passenger Car	1.80288E4	kg CO2 eq
46.88%	P market for passenger car, electric, without battery | passenger car, electric, without battery | Cutoff, U - GLO	9233.65215	kg CO2 eq
46.88%	P passenger car production, electric, without battery | passenger car, electric, without battery | Cutoff, U - GLO	9233.65215	kg CO2 eq
35.90%	P market for glider, passenger car | glider, passenger car | Cutoff, U - GLO	7070.53666	kg CO2 eq
09.85%	P market for powertrain, for electric passenger car | powertrain, for electric passenger car | Cutoff, U - GLO	1940.09407	kg CO2 eq
00.50%	P market for waste rubber, unspecified | waste rubber, unspecified | Cutoff, U - Europe without Switzerland	99.23825	kg CO2 eq
00.50%	P market for waste rubber, unspecified | waste rubber, unspecified | Cutoff, U - RoW	99.22499	kg CO2 eq
00.06%	P market for manual dismantling of used electric passenger car | manual dismantling of used electric passenger car | Cutoff, U - GLO	11.02061	kg CO2 eq
00.03%	P market for waste mineral oil | waste mineral oil | Cutoff, U - RoW	5.56752	kg CO2 eq
00.02%	P market for waste rubber, unspecified | waste rubber, unspecified | Cutoff, U - CH	4.15400	kg CO2 eq
00.01%	P market for waste mineral oil | waste mineral oil | Cutoff, U - Europe without Switzerland	2.67769	kg CO2 eq
00.00%	P market for waste glass | waste glass | Cutoff, U - RoW	0.81004	kg CO2 eq
00.00%	P market group for waste glass | waste glass | Cutoff, U - RER	0.17390	kg CO2 eq
00.00%	P market for waste mineral oil | waste mineral oil | Cutoff, U - CH	0.07276	kg CO2 eq
00.00%	P market for waste glass | waste glass | Cutoff, U - BR	0.06739	kg CO2 eq
00.00%	P market for waste glass | waste glass | Cutoff, U - CO	0.00794	kg CO2 eq
00.00%	P market for waste glass | waste glass | Cutoff, U - ZA	0.00288	kg CO2 eq
00.00%	P market for waste glass | waste glass | Cutoff, U - IN	0.00215	kg CO2 eq
00.00%	P market for waste glass | waste glass | Cutoff, U - PE	0.00123	kg CO2 eq
00.00%	P market for waste glass | waste glass | Cutoff, U - CY	7.60773E-5	kg CO2 eq
40.55%	P market for battery cell, Li-ion, NCA | battery cell, Li-ion, NCA | Cutoff, U - GLO	7987.62868	kg CO2 eq
33.65%	P battery cell production, Li-ion, NCA | battery cell, Li-ion, NCA | Cutoff, U - RoW	6628.60065	kg CO2 eq
06.60%	P battery cell production, Li-ion, NCA | battery cell, Li-ion, NCA | Cutoff, U - CN	1300.15141	kg CO2 eq
00.12%	P market for transport, freight, aircraft, unspecified | transport, freight, aircraft, unspecified | Cutoff, U - GLO	24.39558	kg CO2 eq
00.11%	P market group for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - GLO	21.39163	kg CO2 eq
00.05%	P market group for transport, freight, light commercial vehicle | transport, freight, light commercial vehicle | Cutoff, U - GLO	9.14885	kg CO2 eq
00.02%	P market for transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, U - GLO	3.55783	kg CO2 eq
00.00%	P market group for transport, freight train | transport, freight train | Cutoff, U - GLO	0.38272	kg CO2 eq
01.89%	P market for transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, S - RER	371.72717	kg CO2 eq
01.51%	P transport, freight train | transport, freight train | Cutoff, S - DE	297.76203	kg CO2 eq
00.70%	P market for transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, S - GLO	138.03153	kg CO2 eq
05.48%	P MAINTENANCE Passenger Car	1080.04363	kg CO2 eq
05.48%	P maintenance, passenger car | passenger car maintenance | Cutoff, S - RER	1080.04363	kg CO2 eq
02.99%	P FUEL Electricity - DE	588.28895	kg CO2 eq
02.99%	P market for electricity, low voltage, renewable energy products | electricity, low voltage, renewable energy products | Cutoff, S - CH	588.28895	kg CO2 eq

Figure 5.2: Typical "contribution tree" output of OpenLCA for a generic electric passenger car modeled with ecoinvent 3.8 data.

described overall climate costs.

Economic Metrics

The economic evaluation includes the assessment of the financial viability of the investigated vehicle fleet. In the use case of MoD, the LCSA Fleet Evaluation Tool distinguishes between the stakeholders fleet operator and platform provider. Often both are united in one company, but there are also examples where the fleet consists of private and independent drivers who receive rides via a central (online) platform operator (e.g. Uber, Lyft, DiDi). In the course of this, according to Negro et al. [2021], the following cost groups are relevant for the fleet operator: "vehicle acquisition and ownership", "drivers", "staff, office and facilities", "cleaning, maintenance and wear", and "fuel/energy". Furthermore, it is assumed that a MoD service would operate two shifts of 8 hours duration. The following equations are used to calculate each cost component in accordance to the data displayed in Annex 3.2 and the procedure provided by Negro et al. [2021]:

$$c_{mn}^{VAO} = \frac{c_{mn}^{VPP} + c^{SMD} + c^{VO}}{\lambda_m} \tag{5.1}$$

According to Equation 5.1, the vehicle acquisition and ownership costs c_{mn}^{VAO} of vehicle type m with drive technology n are calculated by summing the vehicle purchase price costs c_{mn}^{VPP}, the monthly smartphone and mobile data contract costs c^{SMD}, and the monthly vehicle operating costs c^{VO}. This is then divided by the respective vehicle lifetime in years or months λ_m.

Emission Factor ϵ [g/km]	Petrol	Diesel	Electric
SO_2	0.000805764	0.000857653	0.000000000
CO	0.496793454	0.065856212	0.000000000
NO_X	0.072481718	0.499300145	0.000000000
PM_{10} (non-exhaust)	0.029250000	0.029249999	0.029250000
PM_{10} (exhaust)	0.001019089	0.004025472	0.000000000
$NMVOC$	0.004633903	0.004338227	0.012807975
NH_3	0.019604303	0.003850224	0.000000000
CO_2e	160.0997988	160.5935529	0.000000000
$Fuel$	55.70393944	53.60332521	0.000000000

Table 5.1: Exemplary output of HBEFA version 4.1 for a generic passenger car in urban driving conditions.

$$c^D = \frac{c^{DS} \cdot \gamma_m \cdot 2 \cdot 8}{\kappa_m} \tag{5.2}$$

Equation 5.2 calculates the driver costs c^D of the fleet operator by taking into account driver salary costs c^{DS} (Annex 3.2) and the respective fleet size γ_m of vehicle type m. This equation assumes two shifts of eight hours per day. In the end, the term is divided by the respective total daily fleet distance κ_m, to generate costs per driven distance.

$$c^{OSF} = \frac{c^S + c^{OFC}}{\kappa_m \cdot 365} \tag{5.3}$$

The office, staff, and facilities costs c^{OSF} are calculated in Equation 5.3 and consist of the sum of the yearly staff costs c^S (Annex 3.2) and the yearly office and facilities costs c^{OF} (Annex 3.2). This term is then divided by the total daily fleet distance κ_m of vehicle type m and multiplied by the total number of days in a year.

$$c^{CMW} = \frac{c^{IC} + c^{EC} + c^{MS}}{\kappa_m \cdot 365} \tag{5.4}$$

Equation 5.4 calculates the cleaning, maintenance, and wear costs c^{CMW}, by summing up the yearly indoor cleaning costs c^{IC} (Annex 3.2), the yearly exterior cleaning costs c^{EC} (Annex 3.2), and the yearly maintenance and servicing costs c^{MS} (Annex 3.2). In the end, this sum is divided by the total daily fleet distance κ_m of vehicle type m, multiplied by the total number of days in a year.

$$c^F = \frac{c^{FP}_{mn} \cdot c^{FC}_m}{\kappa_m} \tag{5.5}$$

The daily fuel costs c^F are calculated in Equation 5.5. The fuel price c^{FP}_n of drive technology costs n and the fuel consumption c^{FC}_m of vehicle type m are multiplied. The term is then divided by the respective total daily fleet distance κ_{mn}.

The total cost for the fleet operator is the sum of the individual cost components, see Table 5.8.

For the platform provider, the cost groups: "staff, office, platform", "vehicle branding and advertisement", "customer and driver acquisition", and "payment" are of interest. The LCSA Fleet Evaluation Tool uses the data and procedure introduced by Negro et al. [2021] to estimate the costs of the platform provider. However, this work groups the cost components of Negro et al. [2021] for better clarity in three cost component groups, namely "staff, office, and platform", "acquisition, branding, and advertisement", and "payment and fare", in accordance to the following equations:

$$c_m^{SOP} = \frac{c^{ES} + c^{OUE} + c^P}{\kappa_m \cdot 365} \tag{5.6}$$

Equation 5.6 displays the calculation procedure for the staff, office and platform costs c_m^{SOP} of vehicle type m for a mobility platform operator. The yearly employees' salaries costs c^{ES} (Annex 3.2) are summed with the yearly office rent, utilities, and equipment cost c^{OUE} (Annex 3.2), and the yearly platform costs c^P (Annex 3.2). The term is then divided by the total daily fleet distance κ_m of vehicle type m, to receive costs per driven distance.

$$c^{ABA}m = \frac{c^{ADC} + c^{VB} + c^{AD}}{\kappa_m \cdot 365} \tag{5.7}$$

The acquisition, branding, and advertisement costs c_m^{ABA} of vehicle type m are calculated in Equation 5.7 and consist of the sum of the yearly acquisition of drivers and customers costs c^{VB} (Annex 3.2), the yearly vehicle branding costs c^{VB} (Annex 3.2), and the yearly advertisement costs c^{AD} (Annex 3.2). This sum is then divided by the total daily fleet distance κ_m of vehicle type m to generate costs per driven distance.

$$c_m^P = \frac{c^{TF} + c^{PF} + c^{RF}}{\kappa_m \cdot 365} \tag{5.8}$$

The cost component for payment costs c_m^P of vehicle type m of the mobility platform provider are calculated according to Equation 5.8. The formula consists of the sum of the yearly transaction fare costs c^{TF} (Annex 3.2), the yearly pick-up fare costs c^{PF} (Annex 3.2), and the yearly ride fare costs c^{RF} (Annex 3.2), which is then divided by the total daily fleet distance κ_m of vehicle type m, to receive costs per driven distance.

The total cost for the mobility platform provider is the sum of the individual cost components, see Table 5.7.

Social Metrics

The social metrics of the LCSA Fleet Evaluation Tool focus on the internalization of external costs and include the monetization of: GWP, air pollutants, noise, land use and barrier effects, accidents, and congestion.

There are two distinct methodologies for the economic valuation of climate-related costs: the *damage cost approach* and the *abatement cost approach*. The *damage cost approach* involves the complex task of estimating and assigning monetary values to the comprehensive range of damages resulting from current and future climate change, all of which are subject to inherent uncertainties [Sommer et al., 2014]. The *abatement cost approach* requires the specification of a clear abatement target and the subsequent assessment of the costs associated with implementing the measures required to achieve that target, which are subject to considerable uncertainty [Saighani, 2020; Sommer et al., 2014]. In particular, the German Federal Environment Ministry advocates the use of the *damage cost approach*, which is based on the latest scientific findings on the costs of climate change damages and leads to more robust estimates of these costs [Matthey & Bünger, 2020]. In the following, the formulas and inputs for calculating social costs, i.e. climate, noise, land use and barrier effects, accidents, and congestion costs, in accordance with the *damage cost approach* are presented:

$$c_{mn}^{C} = \epsilon_{mn} \cdot c^{CP} \tag{5.9}$$

Equation 5.9 calculates the climate costs c_{mn}^{C} of vehicle type m and drive technology n, by multiplying the respective emission factor ϵ_{mn} (Table 5.1) of vehicle type m and drive technology n with the respective climate pollution cost [2] c^{CP} (Table 5.2).

Weighting of impacts	2020	2030	2050
Time preference rate of 1%	680	700	765
Time preference rate of 0%	195	215	250

Table 5.2: Climate damage costs in $€_{2020}/tCO_2e$ for the years 2020, 2030 and 2050 [Matthey & Bünger, 2020].

Assessing the costs of air pollution includes multiple dimensions, such as material degradation, crop failure, biodiversity loss, and adverse health effects. Given the unique emission dynamics in the transport sector, where emissions are released very close to the ground, the German Federal Ministry for the Environment provides adjusted cost values for transport emissions that vary with population density in 2016 and are expressed in Euros in the year 2020 Matthey and Bünger [2020]. In the context of transport, non-health impacts (such as crop loss, material degradation, and biodiversity loss) are usually grouped into a single category. The category of health impacts includes both tangible and intangible damages and usually exceeds the non-health aspects in terms of economic damages. The cost rates for emissions of air pollutants (PM_{10}, NO_X, SO_2, $NMVOC$, NH_3) result from a combination of emission factors for the respective vehicle type derived from Handbook of Emission Factors for Road Transport (HBEFA) [2023] and cost rates of the German Federal Ministry for the Environment, Table 5.3 using the following equation:

$$c_{mn}^{AP} = \sum_{k} \epsilon_{mnk} \cdot c_{k}^{AP} \tag{5.10}$$

[2]Using a time preference rate of 0% means that present and future losses are equally weighted. If a pure time preference rate of 1% is used, only 74% of the losses incurred by the next generation (in 30 years) are taken into account, and only 55% of the losses incurred by the generation after next (in 60 years).

The air pollution costs c_{mn}^{AP} of vehicle type m and drive technology n are calculated according to Equation 5.10 and consist of the sum of the respective emission factor ϵ_{mnk} of air polluter k (Table 5.1) and the respective air pollution costs c_k^{AP} (Table 5.3).

	Urban Driving Conditions	
Polluter	health-related	non health-related
PM_{10}	30,000	0
NO_X	15,800	3,700
SO_2	14,900	1,500
$NMVOC$	1,200	1,000
NH_3	24,200	10,900

Table 5.3: Cost rates for the emission of air pollutants in transport (€$_{2020}/t$ of emission factor) Matthey and Bünger [2020].

CO emissions are usually not monetized [Matthey & Bünger, 2020; Preiss et al., 2012] due to the short residence time in the atmosphere [Weinstock, 1969] and the significant decrease since the introduction of catalytic converters [Mott et al., 2002]. Nevertheless, this research includes them in the GWP considerations as a GHG according to [Genius, 2016].

The other external effects, i.e. noise emissions, space and barrier effects, accidents and congestion, are calculated accordingly by applying different cost ratios to all vehicle types and drive technologies according to the following equation:

$$c_{mn}^{EF} = \sum_{l} \epsilon_{mnl} \cdot c_l^E \tag{5.11}$$

Equation 5.11 calculates the additional externality costs c^{EF} of vehicle type m and drive technology n by summing up all the respective emission factors ϵ_{mnl} of externality l and the respective externality cost c_l^E.

The additional externality factors comprise noise emissions, space consumption and barrier effects, accidents, and congestion. The emission factor (EF) of externality l are calculated according to Schröder et al. [2023] applying the following equations:

$$c_{mn}^{N} = \zeta_{mn} \cdot \frac{\kappa_{mn}}{\kappa_{total}} \cdot \sum_{k} \Omega_k \cdot c_k^{NR} \tag{5.12}$$

The noise related costs c_{mn}^{N} of vehicle type m and drive technology n are calculated in Equation 5.12 and consist of the factors total daily respective fleet distance κ_{mn}, total daily distance of all road vehicles κ_{total}, and the sum of all the number of residents Ω_k affected by noise level k (Table 5.4) and the respective noise cost c_k^{RN} (Table 5.4).

$$c_m^L = c^{INV} + c_m^{PA} + c_m^{O} + c_m^{BE}, \tag{5.13}$$

Equation 5.13 displays the land use costs c_m^L of vehicle type m, summing up the annual investment costs of municipality for infrastructure c^{INV} in the research area, the total respective annual parking costs c_m^{PA} in the research area, the respective opportunity costs of parking c_m^O in the research area, and the respective barrier effect costs c_m^{BE} (Table 5.5).

L_{DEN} in dB(A)	Ω_k	c_k^{NR}
55–59	95,000	116.38
60-64	69,400	196.34
65-69	66,400	306.27
70-74	21,900	454.91
$\geq$ 75	1,500	650.74

Table 5.4: Affected person statistics for road traffic noise in Munich [Schröder et al., 2023] and respective cost rates for road related noise by sound level in €$_{2020}$ per affected person per year [Matthey & Bünger, 2020].

Transport mode	Costs in €-ct$_{2020}$/vkm
Car	2.27
Bus	3.75
Motorcycle	2.27
Bicycle	0.16

Table 5.5: External barrier effect costs per mode and Vehicle Kilometers (vkm) [Victoria Transport Policy Institute, 2022].

The barrier effect, as discussed by Victoria Transport Policy Institute [2022], refers to the time delay that motorized transportation introduces to active mobility modes. This can take the form of major roads that pedestrians must navigate or detour around to reach their intended destinations. Improving infrastructure for pedestrians and cyclists, or reducing motorized traffic overall, can provide benefits to active mobility modes.

$$c_m^A = \frac{1}{\kappa_m \cdot 365} \cdot \sum_h \frac{\xi_m}{\sum_m \xi_m} \cdot c_m^{Ah} \tag{5.14}$$

The accident costs c_m^A by vehicle type m are calculated according to Equation 5.14 and take into consideration the respective daily fleet distance κ_m, the respective accident costs where vehicle is harmed c_m^{Ah}, and the respective kinetic energy ξ_m.

The damage potential approach is a method used in modeling accident costs to assess the potential severity of accidents and their associated economic impact. This approach involves estimating the potential damage that could result from an accident, considering factors such as the extent of physical damage, injuries, fatalities, and environmental impact.

$$c_m^{CON} = c_{total}^{CON} \cdot \frac{\theta_m \cdot \kappa_m}{\sum_k \theta_k \cdot \kappa_k} \tag{5.15}$$

Equation 5.15 calculates the congestion cost c_m^{CON} caused by vehicle type m. The total congestion cost c_{total}^{CON} of road traffic of all road vehicles k is multiplied by the factors respective vehicle's space consumption on the road θ_m and space consumption of all vehicles on the road θ_k and divided by the sum of the total daily respective fleet distance κ_m and the total daily fleet distance of all vehicles κ_{total}.

The evaluation criteria introduced above were created for the case study in the following section, however, the LCSA Fleet Evaluation Tool can easily be extended or limited for further studies and is not bound to the scope of the RPP case study in Munich.

5.1.3 Input Parameters

The LCSA evaluation (i.e. LCA, LCCA and SLCA) of the RPP service requires inputs for all life cycle phases (i.e. RME, PRO, USE, and EOL phases), see Figure 5.1 on page 95. In addition, information on energy consumption in the respective phases, transport processes between different locations and economic and social parameters for the USE phase are necessary inputs.

LCSA Fleet Evaluation Tool inputs include data on RME, such as the types of materials used and their origins, the machinery and energy used, any transportation processes and transmission losses involved, etc. For the PRO phase, the vehicle types of the studied fleet, the production and manufacturing locations, and the transportation processes play a decisive role. For the detailed modeling of the USE phase, data of the fleet operator and the platform provider are of interest, as well as emission factors of the vehicles, economic input parameters (e.g. investment and depreciation costs) and social aspects (e.g. internalization of external costs). For the EOL phase, information on the dismantling location, the recycling processes involved and the associated transport processes are required.

5.1.4 Software and Data Sources

The LCSA Fleet Evaluation Tool uses the software "OpenLCA" for modeling all LCA related tasks. OpenLCA is a powerful open source software tool that is widely used to assess the environmental impact of products and processes. The software provides a number of features and functionalities to help users model and analyze life cycle data, including inventory data, impact assessment methodologies, and visualization tools for results. The software supports a wide range of data formats and includes an extensive library of data sets and impact assessment methodologies, including the widely used IPCC, ReCiPe, and IMPACT methodologies, see Table 2.5 on page 35. Furthermore, it incorporates the ecoinvent database, which is one of the most comprehensive and widely used LCA databases in the world, making it easy for users to compare their results with others in the field, see Table 2.6 on page 36. Another important feature of OpenLCA is its ability to perform sensitivity and uncertainty analyses, which allow the sensitivity of key parameters to be identified and tested, and the impact of uncertainties to be assessed. OpenLCA organizes itself into projects, which represent a collection of product systems, processes, and workflows related to a particular project or study. Product systems are a key component of LCA analysis because they represent the entire life cycle of a product, from raw material extraction to disposal or recycling. To understand the system models, the terms *Allocation* and *Substitution* are of great importance. *Allocation*, describes a transformation of multi-product activities into single-product activities by allocating the share of each input and emission to the reference product and by-products based on their economic value, and *Substitution*, refers to a transformation of multi-product activities into single-product activities by assigning all by-products to the input side with a negative sign, while by-products that can substitute other productions provide credits to the activity that produced them [ECOINVENT ASSOCIATION, 2023]. Processes represent individual steps in a product system, such as material extraction, manufacturing, transportation, and disposal. Flows represent the inputs and outputs of processes, including materials, energy, emissions, and waste. Users can specify the properties of each flow, such as mass, volume, and energy content, as well as the sources and destinations of each flow within the product system. In addition, OpenLCA supports multi-system models:

- **Allocation, cut-off by classification:** The system model is described as a recycling model. Here waste, i.e. emissions on primary production, are the responsibility of the polluter. No emissions are attributed to secondary materials. [ECOINVENT ASSOCIATION, 2023]
- **Allocation, cut-off, EN15804:** For producers of environmental product declarations, the system model "Allocation, cut-off, EN15804" is available. The requirements of EN15804, ISO21930 and ISO14025 are fulfilled. The individual effects are divided among the primary and secondary materials. [ECOINVENT ASSOCIATION, 2023]
- **Allocation at the point of substitution:** In the Allocation at the point of substitution (APOS) system model, an allocation is used to assign a burden of emissions to secondary materials. The APOS and the allocation, cutoff, EN15804 system model differ in requirements. It is the original model of ecoinvent. [ECOINVENT ASSOCIATION, 2023]
- **Substitution, consequential, long-term:** The system model is aligned according to the level of consequences of impacts. Thus processes are considered where impacts are avoided through substitution of, for example, impacts from supply chains. [ECOINVENT ASSOCIATION, 2023]

For consistency and to keep the modeling approach as simple and reproducible as possible, this study uses the well-established *allocation, cut-off by classification* approach, visualized in Figure 5.3.

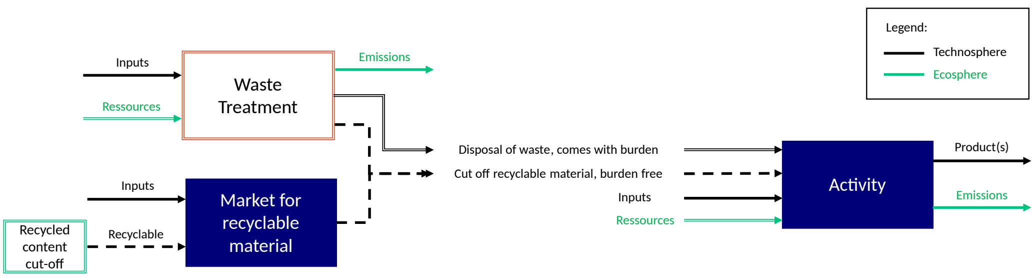


Figure 5.3: Representation of allocation, cut-off by classification system approach.

The approach distinguishes between three intermediate exchanges: allocatable, recyclable or waste. Allocatable products are ordinary (by-)products having economic value, e.g. heat, electricity, or materials. Recyclables have little or no economic value, but can still serve as an input or resource, such as scrap metal or waste paper. Waste products, on the other hand, are materials with no economic value and no interest in their collection without compensation, e.g. wastewater, chemically contaminated soil or radioactive waste [ECOINVENT ASSOCIATION, 2023]. Ecoinvent provides data for "allocation, cut-off by classification" system models and also includes primary data for the selected market of the case study. In addition, this dissertation includes primary data from HBEFA providing emission factors for the USE phase of different vehicle categories and a variety of traffic situations. This includes emission factors for all regulated and non-regulated pollutants as well as fuel/energy consumption and CO_2e emissions [HANDBOOK OF EMISSION FACTORS FOR ROAD TRANSPORT (HBEFA), 2023]. This makes in particular the modeling of the service USE phase and the evaluation of the RPP service much more detailed and realistic.

5.2 Case Study for Munich

This LCSA case study examines a RPP service in Munich, which was simulated in Chapter 4, and seeks to shed light on the environmental, economic, and social implications of this new mobility paradigm. In the quest for sustainable urban mobility, Munich has become an ideal testing ground for new mobility services, as it faces problems of traffic congestion, air pollution, and limited space that require a comprehensive evaluation of the environmental, ecological, and social impacts of such innovative transportation systems. RPP seeks to address these issues by optimizing vehicle sharing between passengers and parcel as a potential means to reduce the number of single-purpose, low occupancy vehicles on the road. Additionally, the city of Munich has a high spirit of innovation and a strong economic position that foster the establishment of test beds for new mobility innovations.

5.2.1 Goal and Scope

The overarching goal of the LCSA for a RPP service is to quantify the environmental, economical, and social impacts such an integrated transportation service would have in an urban environment. Furthermore, it is in the interest of this case study to show the influence of different vehicle concepts on the life cycle impacts of a RPP service for all three dimensions of sustainability. The intended audience of this case study is experts from the field and political decision makers in the field of transportation.

The scope of this case study includes all life cycle phases of the RPP service. However, it excludes road, business, and information technology infrastructure, as well as material recovery and disposal after EOL phase. In the case of MoD services this includes dedicated infrastructure for pick-up and drop-off of passengers. This is due to the poor information situation on vehicle recovery in Germany and incomplete data concerning the organization of a potential RPP provider. A visualization of the chosen technical system boundaries can be found in Figure 5.4. The geographical system boundaries for the LCA can be seen in Figure 5.5, however the LCCA and SLCA focus purely on the USE phase and therefore on the city of Munich. The temporal system boundary is set to the present, meaning that all input data is as up to date as possible and the vehicles considered are latest models.

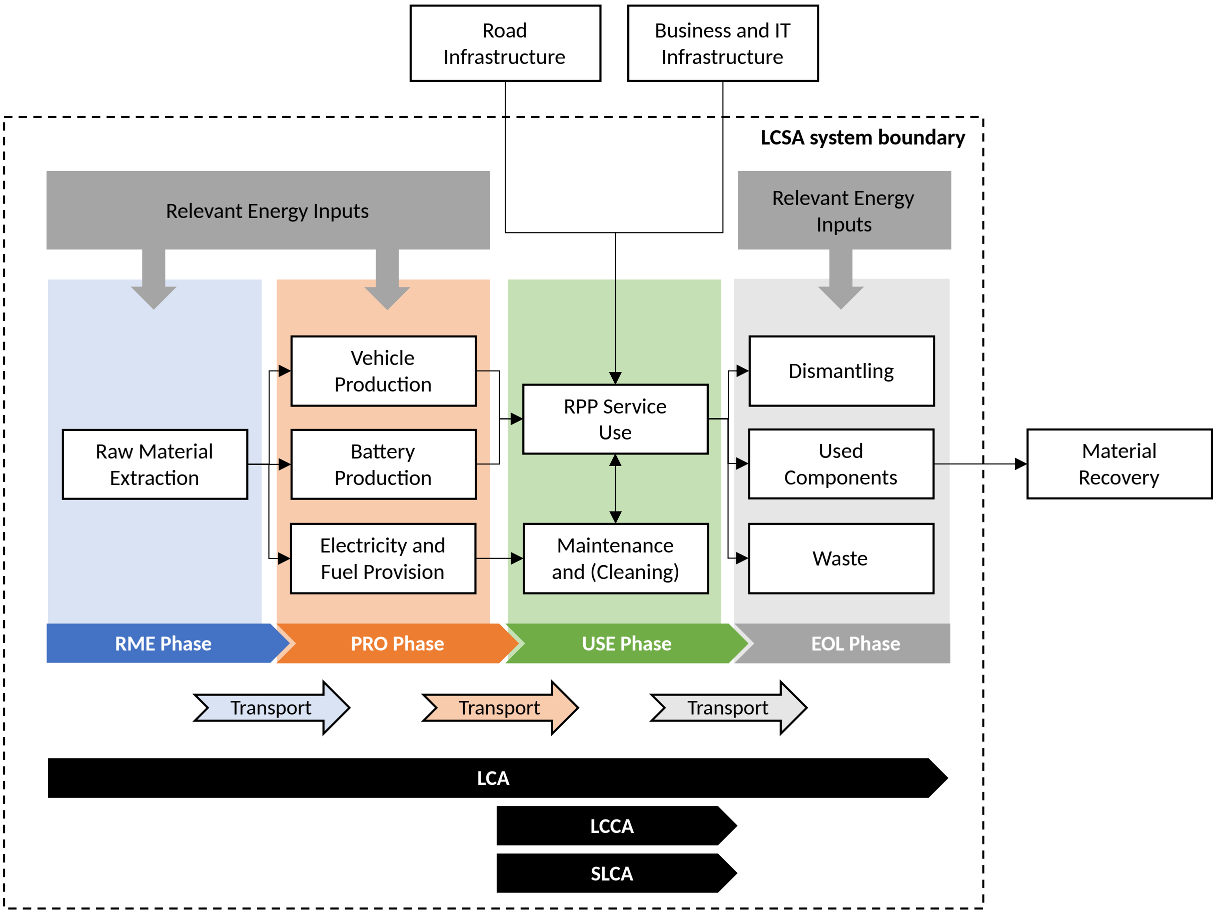


Figure 5.4: System boundaries for the LCSA Fleet Evaluation Tool case study.

Environmental Evaluation (LCA)

The primary goal of the LCA case study for a RPP service is to identify and assess the environmental impacts associated with the service's operations, infrastructure, and related activities. By conducting a LCA, the company or stakeholders can gain insight into which stages of the RPP process have the most significant environmental impacts. This knowledge can be used to develop strategies to reduce the environmental footprint and make more sustainable decisions.

The scope of the LCA case study ranges from RME through PRO and USE to the EOL phase of the RPP vehicle fleet. This includes transportation and operation, as well as ancillary activities (e.g. maintenance and cleaning), which results in the LCA arrow reaching across all investigated phases of Figure 5.4. By analyzing the entire life cycle of the RPP service, the LCA can provide a comprehensive view of its environmental impact (i.e. CO_2e for all life phases and local air pollutants for the USE phase). This information can guide decision-making processes to optimize the sustainability of the service, identify areas for improvement, and compare the environmental performance of different RPP systems and operational approaches. Ultimately, the goal is to promote greener practices and contribute to a more sustainable transportation sector.

Economical Evaluation (LCCA)

The primary objective of the LCCA for a RPP fleet is to assess and compare the costs of the operator associated with different vehicle options and parcel penetration rates. By conducting this LCCA, the economic viability of a potential RPP service will be assessed and potential threats, opportunities and system limitations will be identified.

The scope of the LCCA evaluation focuses on the USE phase of the RPP service and includes vehicle acquisition and operating costs over the vehicle's lifetime, applying typical ride-pooling usage patterns and additional parcel transport. The economic efficiency of the different scenarios and vehicle fleets is determined using a break-even analysis and quantified in terms of Euros per kilometer traveled.

Social Evaluation (SLCA)

The goal of the SLCA for RPP fleet is to assess and understand the social consequences of implementing and operating such a service. By conducting a SLCA, service providers, policy makers and other relevant stakeholders can gain insight into the potential impacts on individuals, communities and society as a whole.

The scope of the SLCA includes several aspects that relate only to the USE phase of a RPP service. These include, but are not limited to, monetization of GWP, air pollutants, noise, land use and barrier effects, accidents, and congestion. In addition, one could think of fare compensation for economically marginalized people, as social funding, due to integrated parcel transportation. Finally, these factors could be included in the LCCA by internalizing these external negative effects of transport services. This is achieved by applying cost factors to the adverse negative effects and evaluating them by internalizing the external costs and allocating them to vkm.

5.2.2 Inventory Analysis

The main basis for the evaluation of a vehicle fleet is data on the composition and use of the fleet. This includes the number and types of vehicles, as well as data on the operations of the mobility service. For this case study the data comes from the simulation study of the RPP service in Chapter 4. Table 4 in Annex 3.3 shows aggregated simulation results, which are input to the LCIA of the LCSA of this chapter.

Additionally, to material and process assessment, transport processes are important for all life cycle phases of a LCA as they can have a significant impact on the overall environmental footprint. In each of the life cycle phases, transport processes play a crucial role for a comprehensive assessment. Figure 5.5 displays a simplified and generalized visualization of the transport processes and life cycle phases involved in the modeling of the case study. It shows how interconnected the life cycle of a vehicle is in a globally networked world and how supply chains around the world influence the results of this LCA.

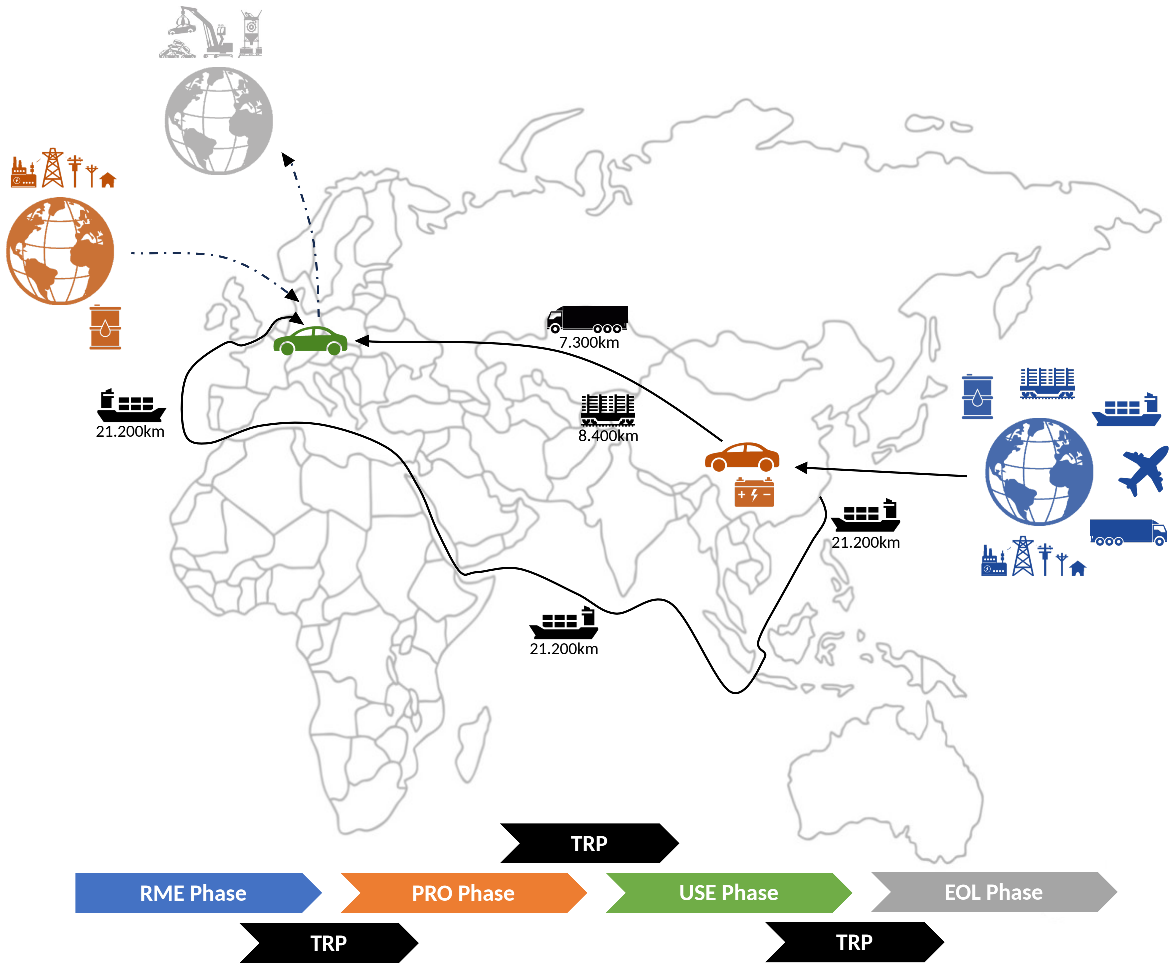


Figure 5.5: Simplified and generalized visualization of transport processes modeled for the LCSA Fleet Evaluation Tool.

Environmental Evaluation (LCA)

The environmental assessment includes GHG emissions (i.e. GHG) and local air pollutant emissions for the USE phase. Vehicle modules (electric scooter, passenger car (petrol, diesel, electric), and light commercial vehicle) from ecoinvent 3.8 (Annex 3.1) are adapted for the RME and PRO phases of the passenger rickshaw, car, van, and delivery vehicle. The data sets have been scaled on the basis of the vehicle weights (Table 5.6) and, where relevant, certain components have been expanded (e.g. rickshaw chassis, battery components for electric vehicles, and transport processes) to represent the selected vehicle types as closely as possible to reality and the scope of the case study. The USE phase is modeled assuming the average energy consumption for each vehicle type and drive technology combined with the respective emission factors of the Handbook of Emission Factors for Road Transport (HBEFA) [2023] shown in Table 5 in Annex 3.4. The EOL phase is again modeled based on the standard dismantling processes of ecoinvent 3.8 (Annex 3.1) and realistic transport processes, see Figure 5.4.

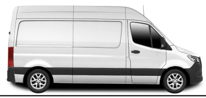
	Passenger Rickshaw	Passenger Car	Passenger Van	Delivery Vehicle
Vehicle Visualization				
Weight	170 kg (EV)	1,500|2,170 kg (ICEV|EV)	2,180|2,470 kg (ICEV|EV)	2,250|2,550 kg (ICEV|EV)
Land Use	3.3 m^2	8.2 m^2	9.4 m^2	15.5 m^2
Avg. Energy Consumption	5 kWh / 100 km	6.3|7.4 l / 100 km (d|p) 18 kWh / 100 km	7.6|8.9 l / 10 km (d|p) 21 kWh / 100 km	9.4|11.0 l / 100 km (d|p) 24 kWh / 100 km
Battery Size and Weight	12 kWh 75 kg	82 kWh 516 kg	82 kWh 516 kg	55 kWh 346 kg
Price	12,378 € (EV)	41,260 € (ICEV) 52,184 € (EV)	61,890 € (ICEV) 78,276 € (EV)	49,512 € (ICEV) 62,621 € (EV)
Lifetime	150,000 km	200,000 km	230,000 km	230,000 km

Table 5.6: Vehicle types and specifications implemented in LCSA Fleet Evaluation Tool for RPP evaluation. Weight, size, average energy consumption, battery size, and price are based on generic real-world vehicles [Allgemeiner Deutscher Automobil-Club e.V., 2023; EV Database v4.4, 2023], vehicle lifetime is modeled in accordance to [Blösl, 2022; Weymar & Finkbeiner, 2016].

Economical Evaluation (LCCA)

The inventory analysis for the economic evaluation is closely related to the previously presented evaluation metrics of LCSA Fleet Evaluation Tool. The results of the RPP simulation (Table 4 in Annex 3.3) and the input parameters of the Negro et al. [2021] (see Annex 3.2) are applied to the previously presented equations for both the fleet operator and the platform provider of the simulated MoD ride-pooling provider presented in Section 5.1.2. Table 5.7 and Table 5.8 summarize the results for the MoD platform provider and the ride-pooling fleet operator, respectively.

Vehicle Types	Staff, Office, and Platform	Acquisition, Branding, and Advertisement	Payment and Fare	Total
Rickshaw	0.148	0.226	0.146	0.520
Car	0.138	0.210	0.136	0.483
Van	0.142	0.217	0.140	0.499

Table 5.7: Costs [€/km] of the platform provider within LCSA Fleet Evaluation Tool for MoD ride-pooling fleets assuming different vehicle types (drive technologies do not lead to any differences, as only fleet size, number of trips, and fleet distance are of interest). The Equations 5.1, 5.2, 5.3, 5.4, and 5.5 state the calculation of the individual cost components.

Vehicle Types	Acquisition and Vehicle Ownership	Driver	Office, Staff, Facilities	Cleaning, Maintenance, Wear	Fuel/ Energy	Total
Rickshaw (EV)	0.172	0.914	0.025	0.064	0.015	1.190
Car (ICEV)	0.253	0.463	0.020	0.128	0.120	0.985
Car (EV)	0.308	0.463	0.020	0.128	0.052	0.972
Van (ICEV)	0.313	0.439	0.020	0.128	0.144	1.045
Van (EV)	0.385	0.439	0.020	0.128	0.061	1.033

Table 5.8: Costs [€/km] of the fleet operator within LCSA Fleet Evaluation Tool for MoD ride-pooling fleets assuming different vehicle types and drive technologies (Internal Combustion Engine Vehicle (ICEV). Electric Vehicle (EV). The Equations 5.6, 5.7, and 5.8 state the calculation of the individual cost components.

Taking both the fleet operator and the platform provider together, the operation costs are 1.71 €/vkm for the EV rickshaw, 1.47 €/vkm for the ICEV car, 1.45 €/vkm for the EV car, 1.54 €/vkm for the ICEV van, and 1.53 €/vkm for the EV van. For the cost calculations, the fleet sizes (Rickshaw: 1,100; Car: 600; Van: 550) play a decisive role, as the driver and vehicle acquisition costs are the two main cost components of the fleet operator. In an automated future, these prices could be reduced by the cost component "driver", which would lead to a significant cost reduction for the fleet operator, especially for the rickshaw fleet.

Social Evaluation (SLCA)

The SLCA inventory analysis for social evaluation goes hand in hand with the economical evaluation and enriches it by monetizing adverse external effects, i.e. GWP, air pollutants, noise, space consumption and barrier effects, accidents, and congestion. To do so, the equations presented in the previous evaluation metrics in Section 5.1.2 are applied to the fleet data of a MoD ride-pooling service (Table 5.6). For estimating the CO_2e and air pollution emissions of the respective vehicle fleets, Table 5 of Annex 3.4 and Table 5.3 of Section 5.1.2 were applied to Equation 5.10, resulting in Table 5.9 displaying monetized emission factors per vkm for each vehicle fleet.

For the other external effects, i.e. noise emissions, space consumption and barrier effects, accidents, and congestion, Equations 5.11, 5.12, 5.13, 5.14, and 5.15 were applied to the data provided in Table 5.6. Wherever appropriate the vehicles' monetization factors were scaled based on the vehicle's weight, speed, and space dimensions. For noise estimation the vehicle's weight and speed relations were considered, for land use and barrier effects, the vehicle's space dimensions were compared, for accident costs, the vehicle's weight and speed was considered, and for congestion costs, all vehicles using the road were considered the same, resulting in the monetization factors per vkm displayed in Table 5.9.

Vehicle Type	Passenger Rickshaw	Passenger Car			Passenger Van			Delivery Vehicle		
Drive Technology	EV	P	D	EV	P	D	EV	P	D	EV
	Cost Factors [ct/km]									
GWP 1 ($195€_{2020}/tCO_2 - eq.$)	0.00	3.12	3.13	0.00	3.75	3.76	0.00	4.65	4.67	0.00
GWP 2 ($680€_{2020}/tCO_2 - eq.$)		10.89	10.92		13.06	13.10		16.22	16.27	
PM_{10}	0.0322	0.0908	0.0998	0.0878	0.1090	0.1198	0.1035	0.1353	0.1487	0.1237
NO_X	0.0000	0.1413	0.9736	0.0000	0.1696	1.1684	0.0000	0.2106	1.4507	0.0000
SO_2	0.0000	0.0013	0.0014	0.0000	0.0016	0.0017	0.0000	0.0020	0.0021	0.0000
$NMVOC$	0.0000	0.0010	0.0010	0.0000	0.0012	0.0011	0.0000	0.0015	0.0014	0.0000
NH_3	0.0000	0.0688	0.0135	0.0000	0.0826	0.0162	0.0000	0.1025	0.0201	0.0000
Sum Air Polluters	0.0322	0.3033	1.0893	0.0878	0.3640	1.3072	0.1035	0.4519	1.6231	0.1237
Noise	0.2424	0.7183	0.8620	0.6465	0.8157	0.9788	0.7244	0.8166	0.9800	0.7252
Land Use & Barrier Effects	2.4724	5.6170	5.6170	5.6170	6.4706	6.4706	6.4706	10.6971	10.6971	10.6971
Accidents	4.7200	3.8200	3.8200	3.8200	3.8200	3.8200	3.8200	3.8200	3.8200	3.8200
Congestion	0.0000	5.4800	5.4800	5.4800	5.4800	5.4800	5.4800	5.4800	5.4800	5.4800
Sum Externalities	7.43	15.64	15.78	15.56	16.59	16.75	16.50	20.81	20.98	20.72
Total Sum (GWP 1)	7.50	19.36	21.09	15.74	21.06	23.12	16.70	26.37	28.89	20.97
Total Sum (GWP 2)		27.13	28.88		30.38	32.47		37.94	40.49	

Table 5.9: Results of the SLCA assessment (internalization of adverse external effects) for the RPP use phase, displaying respective external costs in €-ct/vkm for all investigated vehicle types and drive technologies.

5.2.3 Impact Assessment

The impact assessment section of this LCSA case study evaluates the potential environmental, economic, and social impacts associated with the introduction of a RPP service. By comprehensively analyzing a range of vehicle types and drive technologies, this section aims to provide a holistic understanding of the resulting impacts, potentials, and consequences, and to contribute essential insights for sustainable practices of RPP.

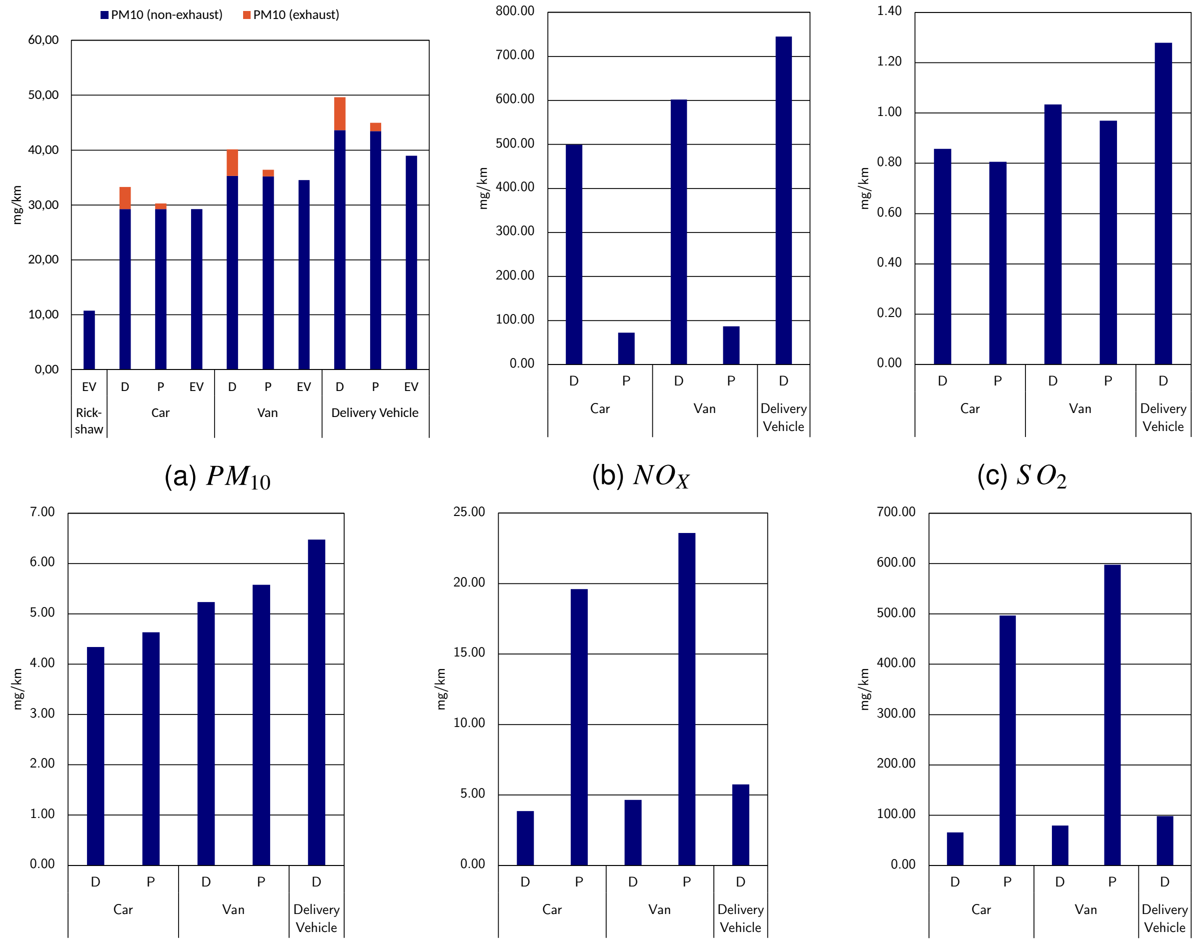
Environmental Evaluation (LCA)

The environmental evaluation of the RPP service is based on a modular approach that first evaluates the different vehicle types and powertrain technologies and then applies these results to the RPP simulation. The results at the vehicle level are related to the entire life cycle of the vehicle and the evaluation of the simulation reflects the respective emissions for one day of operation. A basic distinction is made between the local air pollutants PM_{10}, NO_X, SO_2, $NMHC$, NH_3 and CO and the global climate-relevant emissions measured in CO_2e. The air pollutants are evaluated for the USE phase only and refer to typical emissions for the investigated vehicle types based on urban driving conditions and modeled in the LCSA Fleet Evaluation Tool according to HBEFA emission factors. The GWP, on the other hand, refer to the entire life cycle of the vehicles and were obtained from the LCSA Fleet Evaluation Tool modeling using ecoinvent 3.8 and OpenLCA.

LCA on Vehicle Level:

Figure 5.6a shows the PM_{10} emissions per vehicle category, distinguishing between exhaust and non-exhaust emissions. Exhaust emissions include all PM_{10} emitted from the tailpipes of the vehicles, while non-exhaust emissions are related to abrasion and turbulence effects. In general, it is clear that the non-exhaust PM_{10} emissions have a significantly higher share than the exhaust emissions across all vehicle categories. Furthermore, it becomes clear that the non-exhaust PM_{10} emissions depend mainly on the vehicle weight and the average speed, which leads to significantly lower emissions for the rickshaw.

The NO_X, SO_2, $NMHC$, NH_3, and CO emissions of the modeled vehicles exclude the electric drive, as these air pollutants are assessed only for the USE phase of the RPP service and are produced only in internal combustion engine vehicles. Figures 5.6b, 5.6c, 5.6d, 5.6e and 5.6f show the air pollutant emissions of the considered vehicle types. Regarding NO_X emissions, it is clear that diesel vehicles produce significantly more pollutants than petrol vehicles. This is due to their higher combustion temperatures, which lead to increased formation of nitrogen oxides [Carslaw et al., 2011]. Regarding the different vehicle categories, the emissions scale to the respective fuel consumption. Looking at SO_2 emissions, it is clear that petrol cars emit slightly less than diesel cars, but the vehicle class has a greater influence on total emissions than the engine type. A similar correlation was found for $NMHC$ emissions, but in this case the petrol engine pollutes slightly more than the diesel engine. Looking at NH_3 and CO emissions, it is clear that petrol engines perform significantly worse than diesel engines due to the fuel composition and a less homogeneous fuel-air mixture in the combustion process [Suarez-Bertoa et al., 2017].



(d) $NMHC$ (e) NH_3 (f) CO

Figure 5.6: Air pollutant emissions for different vehicle categories.

Figure 5.7 shows the total GHG life cycle emissions of the introduced vehicle categories and drive technologies assuming German energy (mix and renewable) and fuel emissions. The results are based on data sets from ecoinvent 3.8 (Annex 3.1) and have been validated by Monte Carlo simulation. The results show that the EV variants have significantly lower USE phase emissions, while their RME and PRO emissions are almost twice as high as those of the ICEV vehicles, which is mainly due to the production of the battery [Girardi et al., 2015]. The comparison of EV powered with the German energy mix and purely renewable energies shows a large difference in the USE phase of all vehicle types and suggests that a successful implementation of electric vehicle fleets requires a high share of renewable energies. The differences between diesel and petrol ICEV show that RME, PRO, TRP and EOL are very close for both engine types, only in the USE phase there are small advantages for the diesel engine due to the lower fuel consumption.

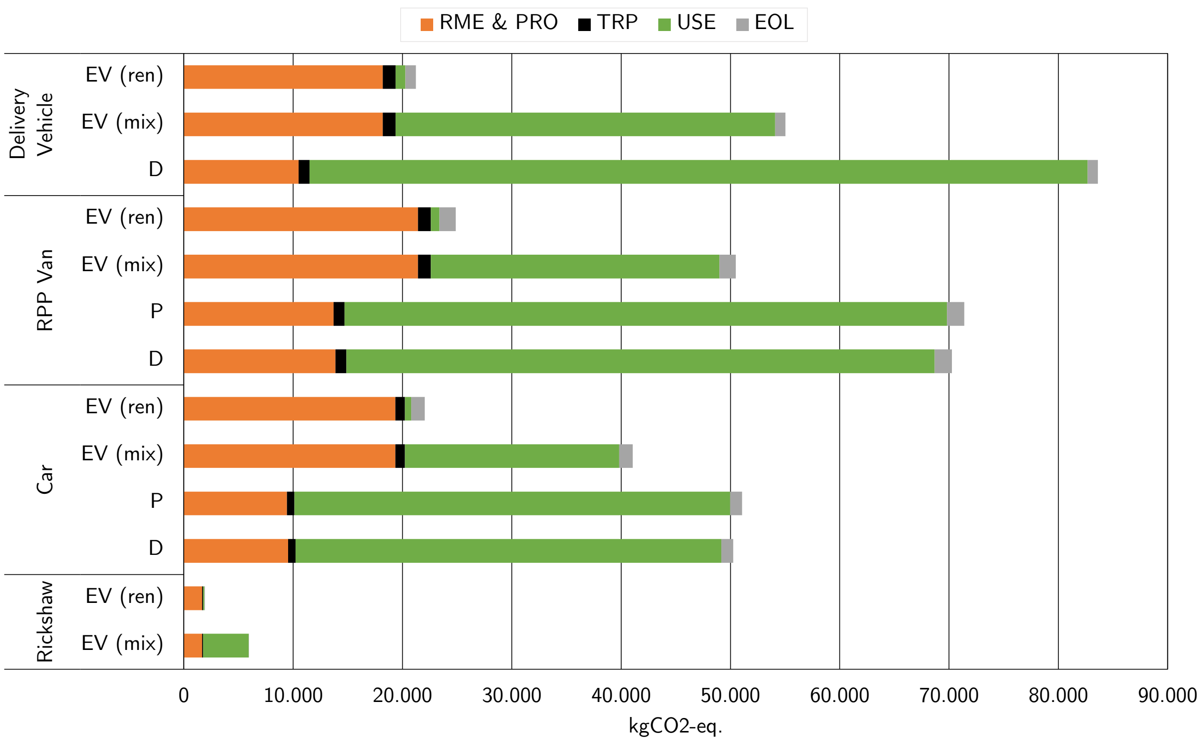
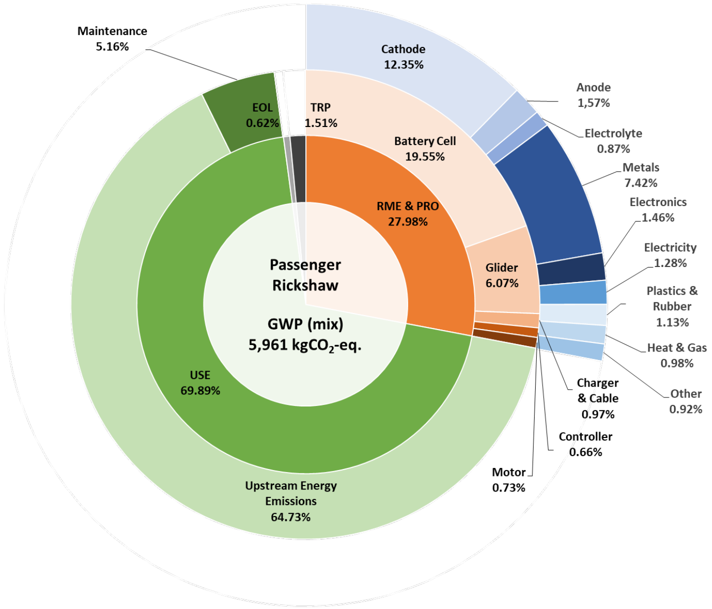


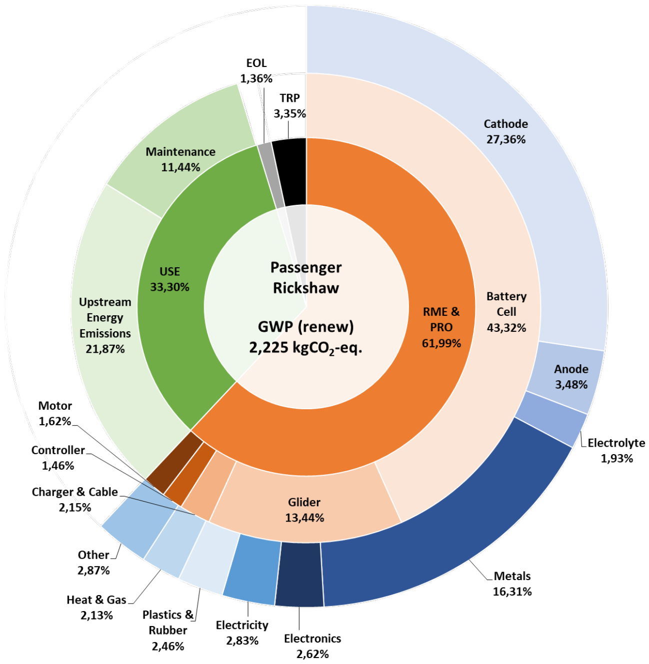
Figure 5.7: GWP of different vehicle types and drive technologies (EV = Electric Vehicle, P = Petrol, D = Diesel), assuming the German energy mix of the year 2018 for USE phase emissions.

The above findings are confirmed by the detailed analysis at component and material level in Figures 5.9a and 5.9b. They show four-section pie charts where the inner circle displays the vehicle type considered and the total GWP of all life cycle phases. The middle circle shows the share of each LCA phase. The outer circle provides information on the component level and the last on the material level. Overall it can be stated that the TRP and EOL phases have a very small share in the total GHG emissions of the vehicles and that the USE phase exceeds the emissions of RME and PRO depending on the fuel and energy mix used.

Figure 5.8a shows that the upstream energy emissions make the largest contribution to the USE phase of electric vehicles. In the RME and PRO phase, the battery production is mainly responsible for the generated GHG emissions. For the rickshaw, the glider production is only one third of the battery production. At the material level, it is clear that the cathode in particular causes high emissions. The second largest contributor is the metals used in all components of the vehicle. Comparing the electric passenger rickshaw powered by the German energy mix of Figure 5.8a with the rickshaw powered only by renewable energy, shown in Figure 5.8b, it becomes clear that the total GWP can be more than halved by powering the rickshaw only with renewable energy. As a result, the share of the USE phase decreases from almost 70% to 33%.

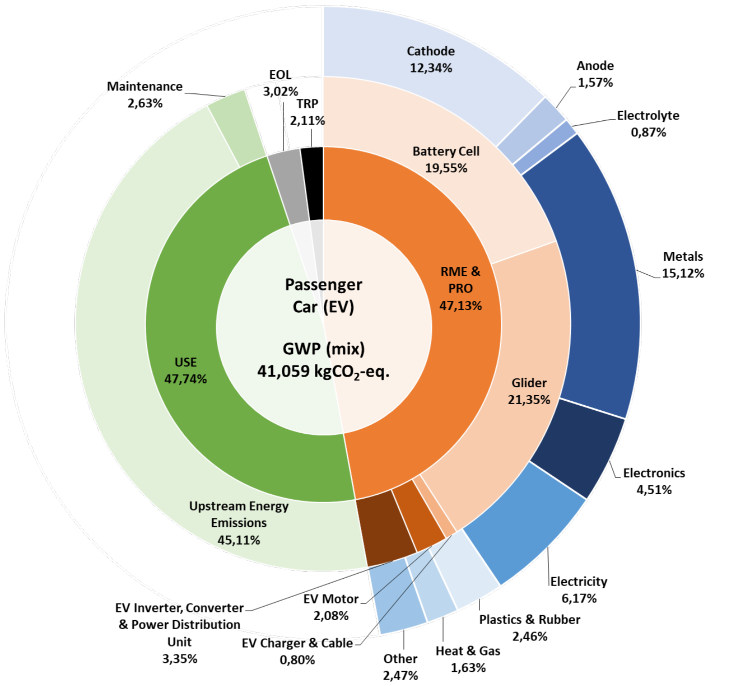


(a) Electric passenger rickshaw, assuming German energy mix of 2018

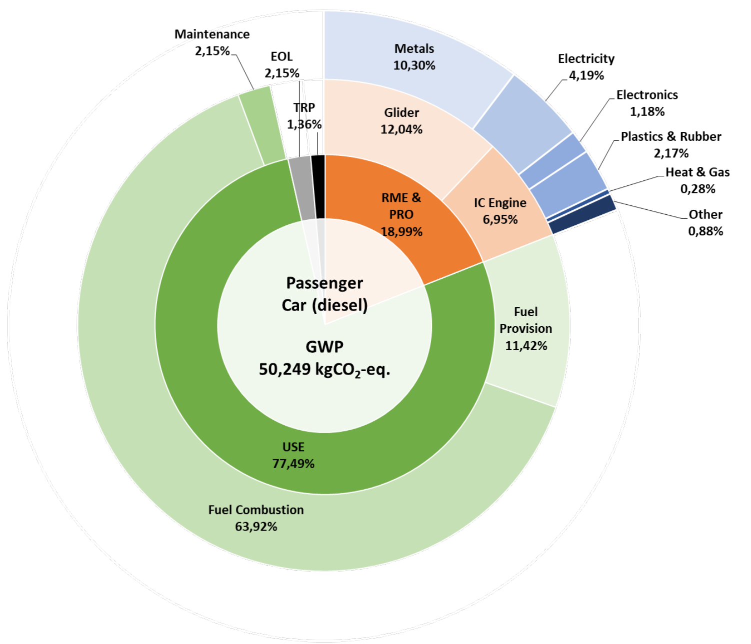


(b) Electric passenger rickshaw, assuming purely renewable energy

Figure 5.8: GWP shares of LCA phases, components, and materials for rickshaw.



(a) Electric passenger car, assuming German energy mix of 2018



(b) Diesel passenger car, assuming German diesel provision

Figure 5.9: GWP shares of LCA phases, components, and materials for car.

Figure 5.9a shows the composition of an electric car powered by the German energy mix, analogous to the rickshaw of figure 5.8a. Compared to the rickshaw, the car has about seven times the GWP value of the rickshaw. In the case of the car, RME and PRO have a much higher share, about 47%, and the GHG emissions for the production of the car, unlike the rickshaw, exceed those for the production of the battery. At the material level, metals account for most of the emissions, followed by the cathode and the electricity used during the RME and PRO phases. If we compare these results with a ICEV driven by a diesel engine (see Figure 5.9b), we can see that the total GWP increases according to Figure 5.7, but the share of RME and PRO decreases considerably compared to the EV, and in the USE phase the combustion of diesel fuel is clearly in the lead with almost 64%.

LCA on RPP Service Level:

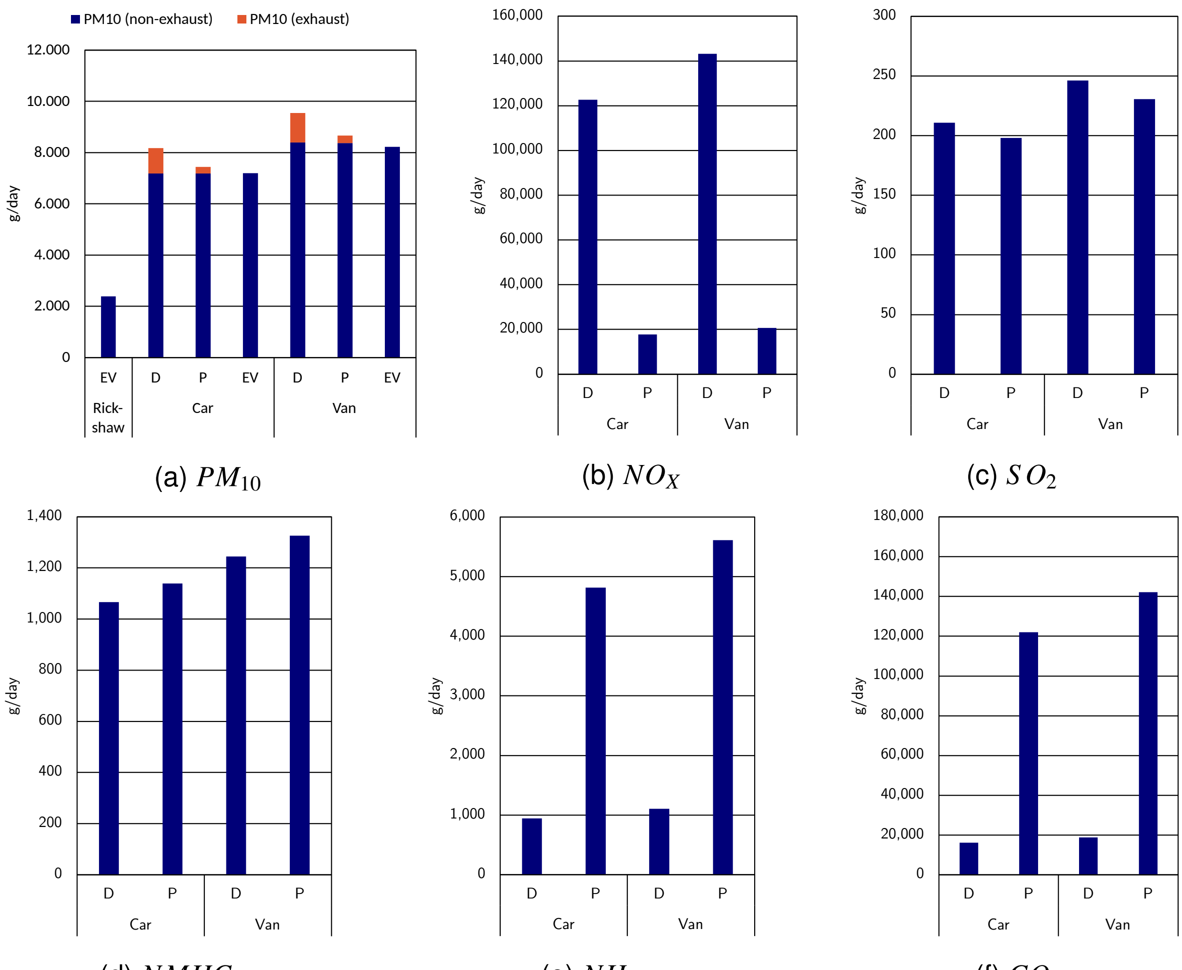
The results on service level were obtained by scaling the results on vehicle level up to respective fleet sizes and total distances driven, resulting in daily emissions over the entire life cycle of the modeled RPP service.

Figure 5.10a shows the total PM_{10} emissions considering exhaust and non-exhaust sources for a full day of RPP service, assuming different vehicle types and drive technologies. It is evident that the EV rickshaw has significant advantages in the area of PM_{10} emissions. The differences between the vehicle types are weighted by the respective fleet distances, resulting in Figure 5.10.

Analysis of the GWP of the different RPP fleets in Figure 5.11 shows that all vehicle types perform better than the *Status Quo* in terms of CO_2e emissions, leading to significant reductions in GWP. It is clear that the higher the parcel penetration rate, the higher the GWP reduction. Figure 5.11a shows the potential CO_2e savings for the RPP rickshaw fleet. Note that only equivalent vehicle types are compared. This means that a RPP electric vehicle is always compared to an electric van in the *Status Quo*, which also applies for ICEV. It can be seen that the savings in covered distance lead to significant savings in air pollution, especially when considering ICEV and EV calculated with the current German energy mix. This is due to the scaling of higher emission values compared to the renewable energy mix. This effect can also be observed for the other two vehicle categories. Looking at the ICEV vehicles in Figures 5.11b and 5.11c we can see that the reduction potential is higher compared to the EV. This is again a scaling effect of the significantly higher CO_2e emissions of ICEV compared to EV, which are multiplied by the constant total fleet distance. Comparing the savings of the different vehicle categories, it is clear that the rickshaw fleet outperforms the car and van fleet despite the larger vehicle fleet, but at high parcel penetration rates (40% and 50%) the van fleet can compete with the rickshaw fleet again.

Economic Evaluation (LCCA)

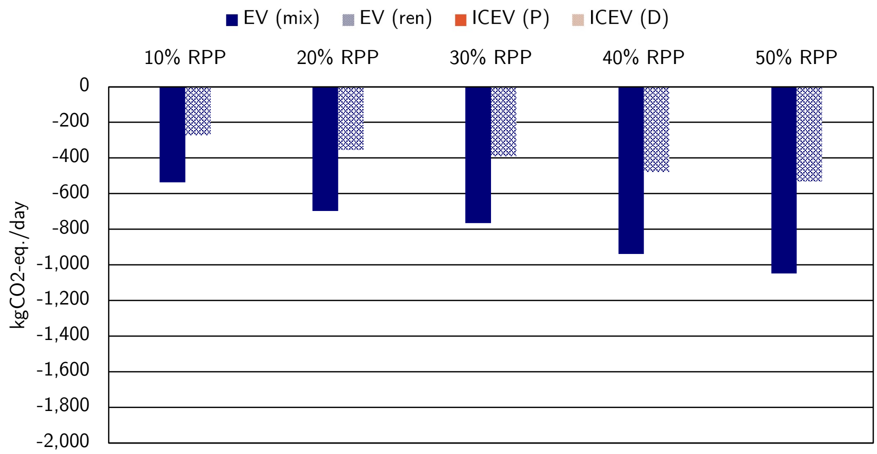
The economic evaluation of RPP investigates the service based on the evaluation metrics introduced in Section 5.1.2. Analogously to the environmental evaluation, the economic evaluation is split into an investigation on vehicle and on RPP service level. However, as stated earlier, the economical and social investigations focus on the USE phase only.



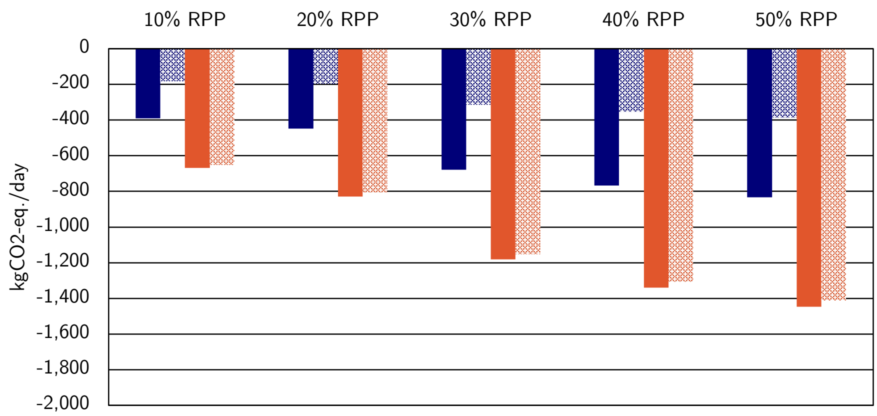
(a) PM_{10} (b) NO_X (c) SO_2

(d) $NMHC$ (e) NH_3 (f) CO

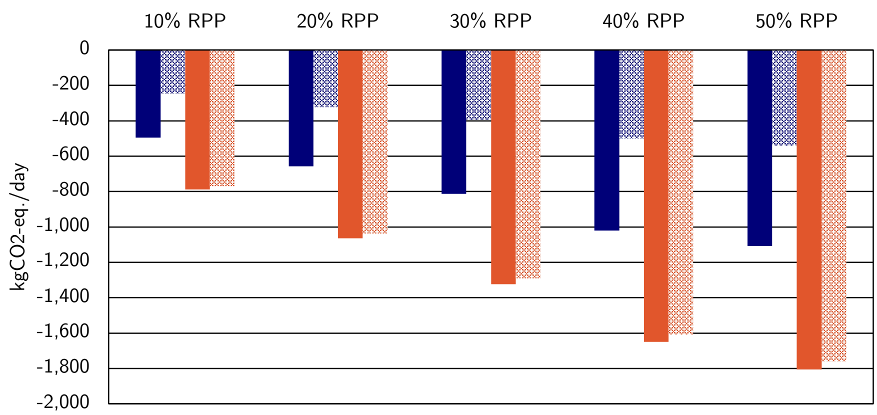
Figure 5.10: Particulate matter, nitrogen oxides, sulfur dioxide, non-methane hydro carbons, ammonia, and carbon monoxide emissions of different vehicle categories emissions for one day of RPP service.



(a) Full RPP Rickshaw vs. Status Quo Scenario



(b) Full RPP Car vs. Status Quo Scenario



(c) Full RPP Van vs. Status Quo Scenario

Figure 5.11: Balance of CO_2e emissions for full RPP scenarios considering different parcel penetration rates and vehicle types (mix = German Energy Mix, ren = Renewable Energy Mix, P = Petrol, D = Diesel).

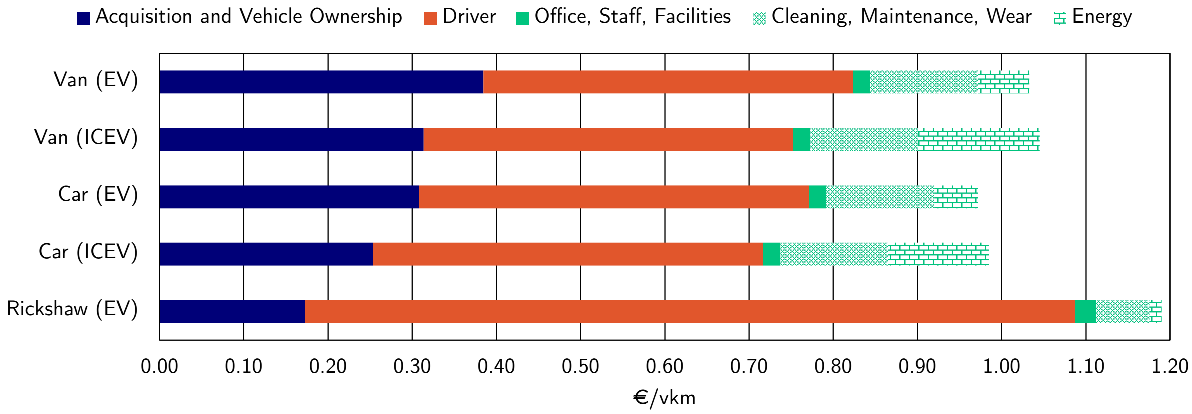


Figure 5.12: Costs in €/vmk for the end-customer for services of the RPP fleet operator.

LCCA on Vehicle Level:

Figure 5.12 displays the cost groups "acquisition and vehicle ownership", "driver", "office, staff, facilities", "cleaning, maintenance, wear", and "energy", which are relevant for the fleet operator. The results reveal that the driver is in all cases the main cost factor, however this is specifically the case for the rickshaw fleet. The acquisition and ownership costs are in turn comparably low for the rickshaw. Office, staff, and facility costs are similar for all investigated fleets and generally make up only for a very small share of the total costs. Energy costs are lower for EV and cleaning, maintenance, and wear is considerably lower for a rickshaw fleet. However, in total the rickshaw fleet has the highest costs with almost 1.20 €/vkm and the EV car the lowest with approximately 0.95 €/vkm.

Figure 5.13 visualizes the platform provider costs of a RPP service. Here the different vehicle types lead to only very small differences, which are mainly due to the different fleet sizes, however the influence of fleet size is not noticeably high for a platform provider, indicating the huge scaling potential of such platforms, which are disconnected from the vehicles and drivers only providing the market place for requests and offers. Overall, the platform provider creates costs of approximately 50 €-cent/vkm which consist of similar shares of "staff, office, and platform", "acquisition, branding, and advertisement", and "payment and fare".

Combining both, the fleet operator and the platform provider costs, leads to total costs of 1.71 €/vkm for the EV rickshaw, 1.47 €/vkm for the ICEV car, 1.45 €/vkm for the EV car, 1.54 €/vkm for the ICEV van, and 1.53 €/vkm for the EV van.

LCCA on RPP Service Level:

Figure 5.14 visualizes the cost savings a RPP service could realize each day of operation. As stated above, for this LCCA only the USE phase was considered. The numbers were obtained by taking into account the saved distances of ride-pooling and delivery fleet compared to the *Status Quo* and adding up the losses (i.e. lower number of transported

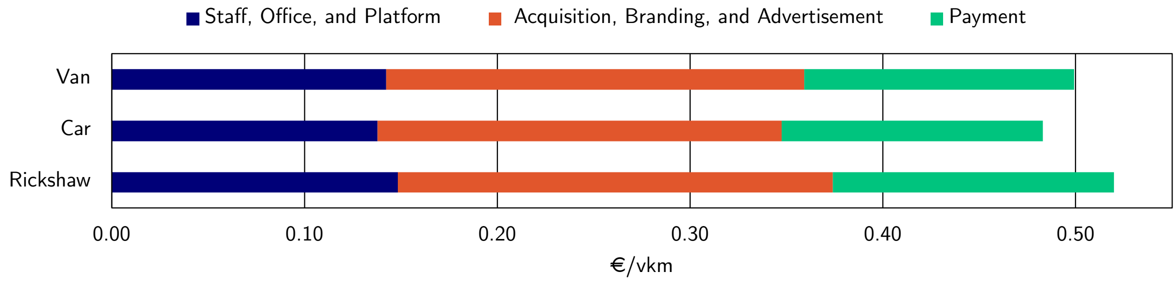


Figure 5.13: Costs in €/vmk for the end-customer for services of the RPP platform provider.

passengers). In the case of ICEV, only diesel vehicles were considered, as the logistics vehicles in the *Status Quo* only exist as EV and ICEV diesel versions.

For all vehicle types and parcel penetration rates, the RPP service could realize cost savings compared to the status quo. The cost for the status quo parcel delivery service was assumed to be 2.50 € per parcel according to Brabänder [2020], however this number will most likely increase significantly in the future up to 4.50 €/parcel in the year 2028, increasing the potential RPP cost savings even further [Brabänder, 2020]. For all RPP fleets, the trend is confirmed that the higher the parcel penetration rate, the higher the absolute savings per day. Looking specifically at Figure 5.14a, it can be seen that at lower parcel penetration rates, the rickshaw fleet can compete with the car and van fleet, despite the clearly higher operating costs. At higher parcel penetration rates, the high-capacity vehicles result in considerably higher savings per operating day.

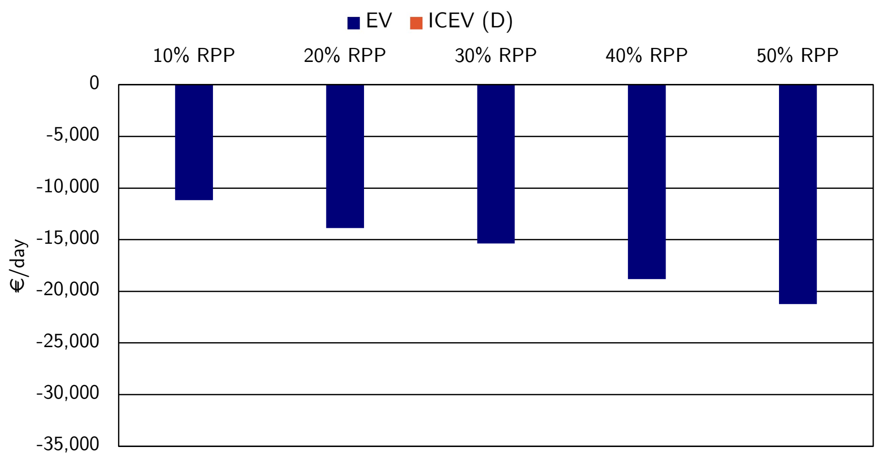
Social Evaluation (SLCA)

The social evaluation of RPP includes the monetization of adverse external effects, comprising GWP, air pollutants, noise emissions, land use and barrier effects, accidents, and congestion. Similar to the two evaluation sections before, the social evaluation is obtained on vehicle and on RPP service level.

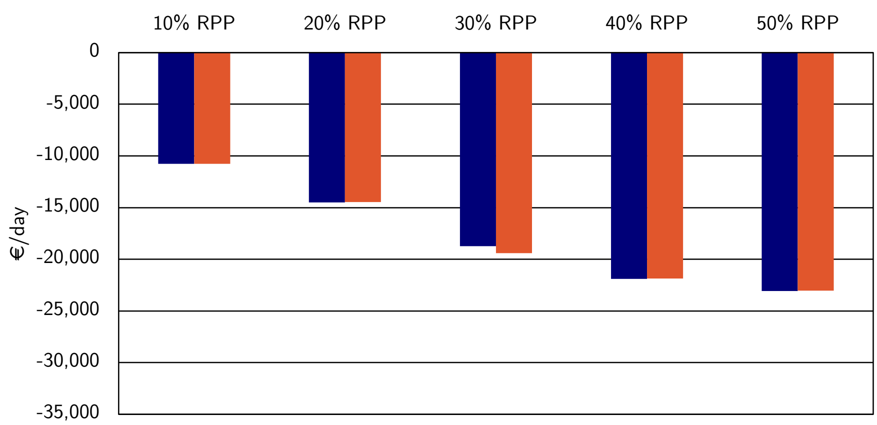
SLCA on Vehicle Level:

Figure 5.15 visualizes the results of the external cost evaluation obtained by applying the formulas presented in the evaluation metrics in Section 5.1.2. It becomes clear that air pollutants and noise emissions have a subordinate role compared to the costs incurred in the areas of GWP, accidents, congestion and, above all, land use and barrier effects. It can also be seen that the EV does not incur costs, especially in the GWP and air pollutants, since they do not emit any emissions in the USE phase considered here. In terms of vehicle categories, it is clear that the delivery vehicle generates the highest external costs, followed by the passenger van and car. The rickshaw generates the lowest external costs.

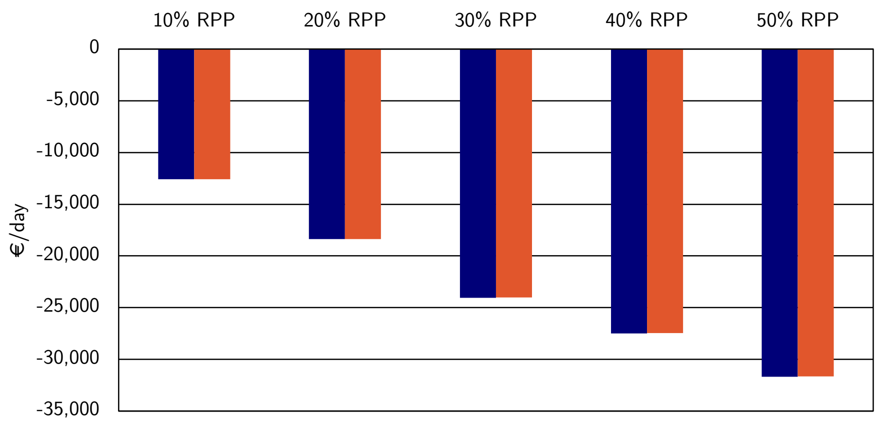
Figure 5.16 is very similar to Figure 5.15, however it visualizes CO_2e monetized assuming a price of 680 $€_{2020}/kgCO_2e$, which has a significant influence on the overall costst per vkm. The comparison of Figure 5.15 and 5.16 shows that if GHG emissions are monetized with a



(a) Full RPP Rickshaw vs. Status Quo Scenario



(b) Full RPP Car vs. Status Quo Scenario



(c) Full RPP Van vs. Status Quo Scenario

Figure 5.14: Balance of LCCA for Full RPP scenarios considering different parcel penetration rates and vehicle types (EV and ICEV (D)).

factor, which weights present and future generation equally, ICEV cause drastically higher costs per vkm than EV.

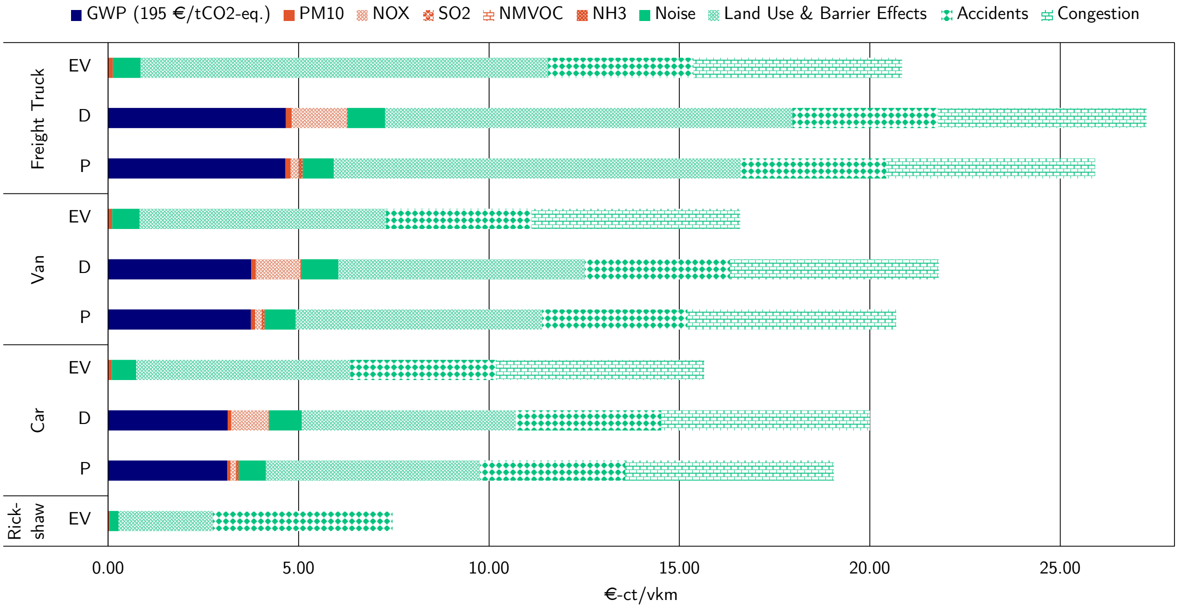


Figure 5.15: External costs for the USE phase in €-ct/vmk per vehicle category and drive technology, assuming a price of 195 $€_{2020}/kgCO_2e$.

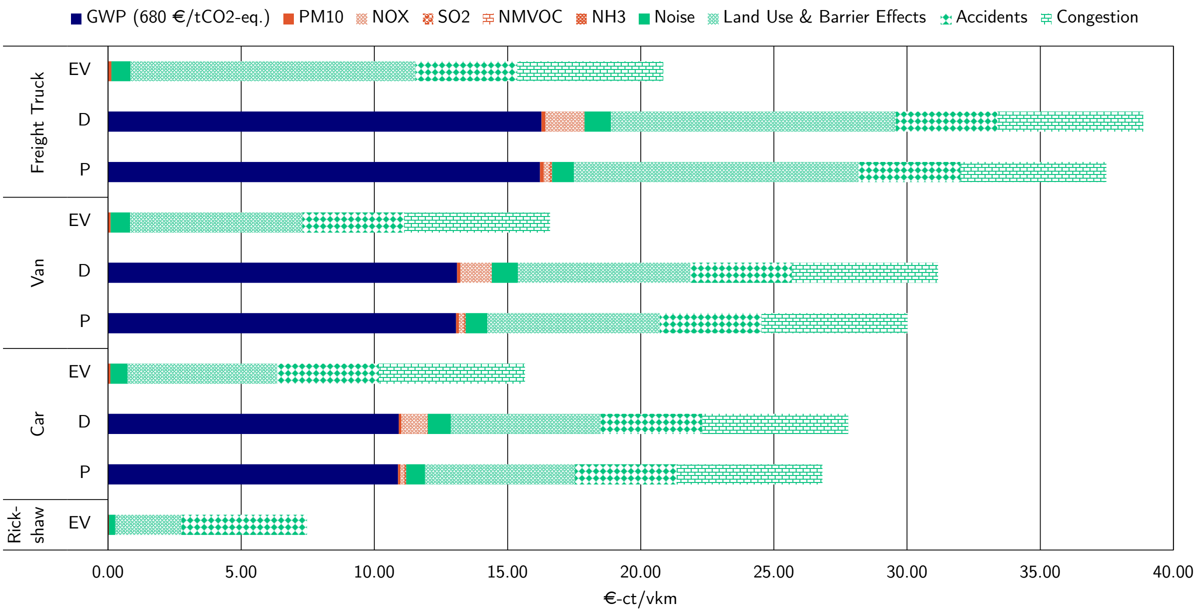


Figure 5.16: External costs for the USE phase in €-ct/vmk per vehicle category and drive technology, assuming a price of 680 $€_{2020}/kgCO_2e$.

SLCA on RPP Service Level:

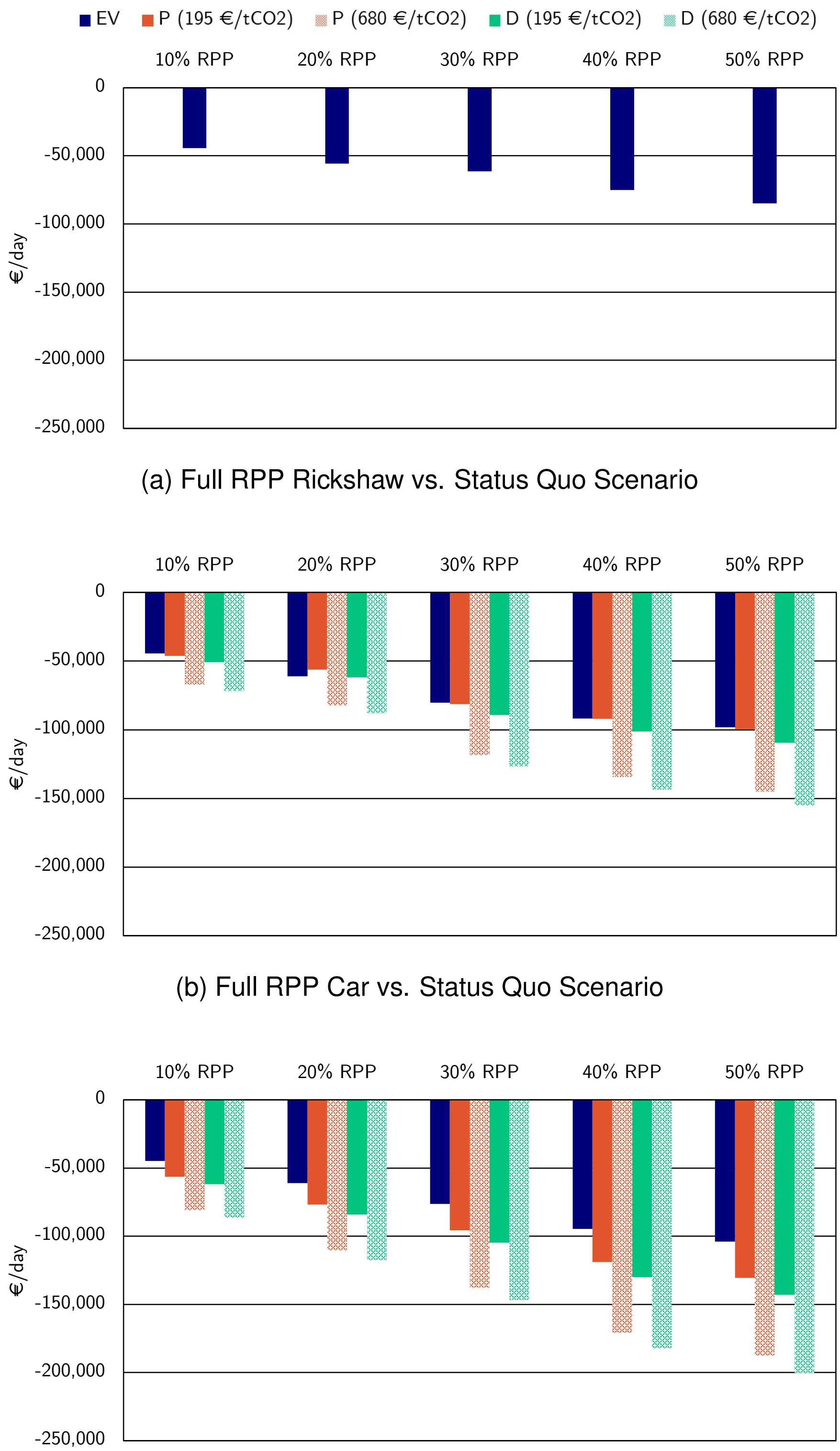
The study of the SLCA of a RPP service results in Figure 5.17. For the rickshaw fleet in Figure 5.17a only EV were considered, because the rickshaw was modeled only for electric drive. It is important to mention that, as mentioned above, this SLCA only considers the USE phase of the RPP service and therefore does not distinguish between different cost rates for the EV, as there are no direct CO_2e emissions associated. It can be seen that the RPP service outperforms the *status quo* for all vehicle types and parcel penetration rates. The external cost savings of RPP per day for the rickshaw fleet range from just under 45,000 (10%) to about 85,000 (50%), see figure 5.17a. Similar to the LCCA, the rickshaw fleet can compete with the other two for the lower parcel penetration rates, and is outperformed by the high-capacity vehicles at higher rates. In general, analogous to the LCCA, it can be seen that the ICEV could realize potentially higher savings due to the scaling effects mentioned above and the additional costs arising from GHG emissions, always assuming that only the same types of drive trains are compared.

Sustainability Evaluation (LCSA)

Taking all three dimensions of sustainability together, namely environmental, economic and social aspects, leads to the LCSA. In the case of this work, the three dimensions were covered by the LCA, LCCA, and SLCA of the RPP service. This section summarizes the results by internalizing all external costs in monetary terms on the vehicle and the RPP service level.

LCSA on Vehicle Level:

Figure 5.18 visualizes the *internal* (LCCA) and *external* costs for all investigated vehicle types assuming a price of 195 $€_{2020}/kgCO_2e$. It is clear that the internal costs of a RPP service provider are significantly higher than the external costs. However, it has to be admitted that the costs of providing ride-sharing services are high compared to private car transport. This is mainly due to the additional cost factor of the driver. Overall, the rickshaw has the highest cost per vkm, but all vehicles are in the range of 1.6 € to 1.8 €/vkm. Figure 5.19 shows the same content as figure 5.18, but assumes a price of 680 $€_{2020}/kgCO_2e$. As a result, the rickshaw no longer has the highest cost per vkm, but is replaced by ICEV vans, and ICEV cars also come very close to the rickshaw cost. At this point, it should be mentioned again that the driver is the main cost factor of the internal costs. If this were to be eliminated, for example by automating the driving functions, this would primarily benefit the rickshaw fleet, which needs more vehicles and therefore more drivers to provide the same quality of service.



(a) Full RPP Rickshaw vs. Status Quo Scenario

(b) Full RPP Car vs. Status Quo Scenario

(c) Full RPP Van vs. Status Quo Scenario

Figure 5.17: Balance of SLCA for Full RPP scenarios considering different parcel penetration rates and vehicle types (mix = German Energy Mix, ren = Renewable Energy Mix, P = Petrol, D = Diesel).

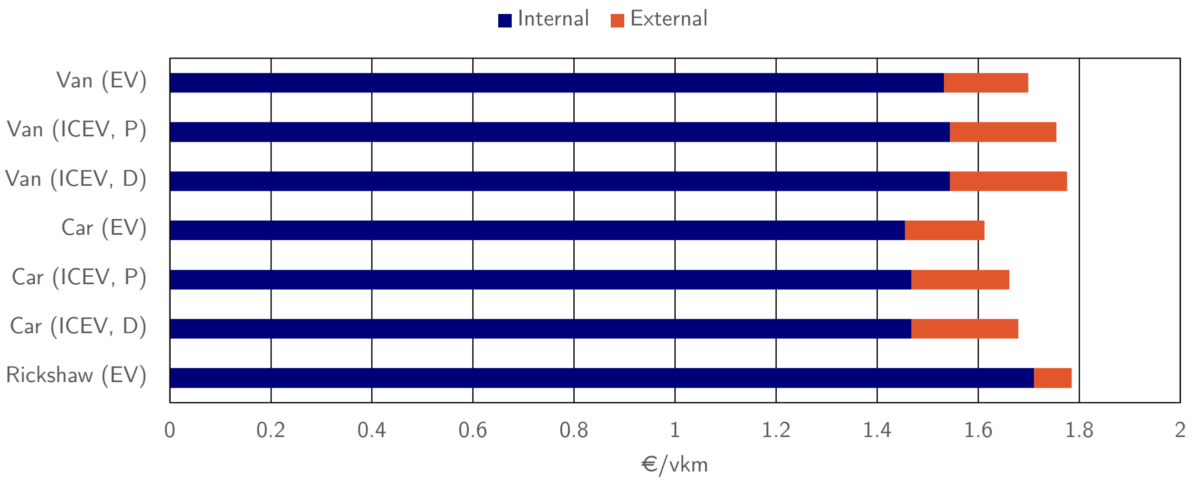


Figure 5.18: LCSA (internalization of all costs) for the USE phase in €-ct/vmk per vehicle category and drive technology, assuming a price of 195 €$_{2020}/kgCO_2e$.

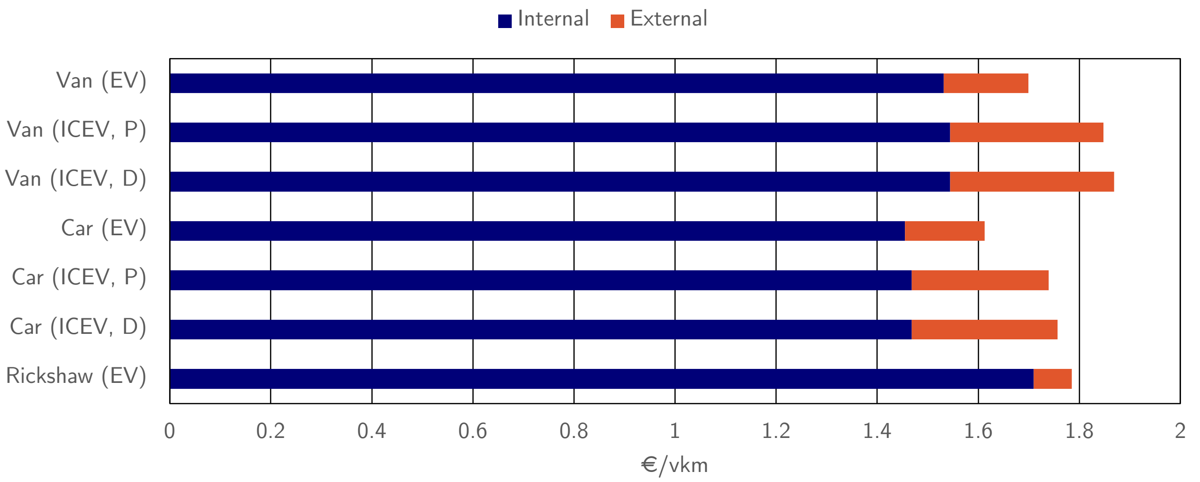
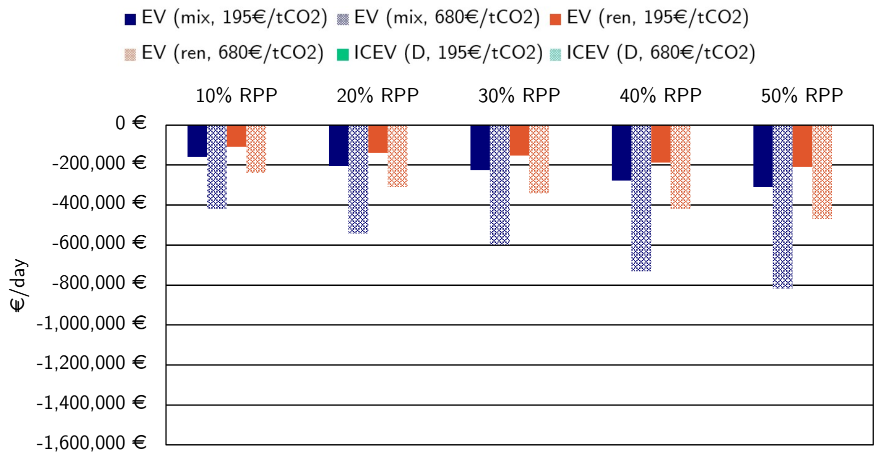


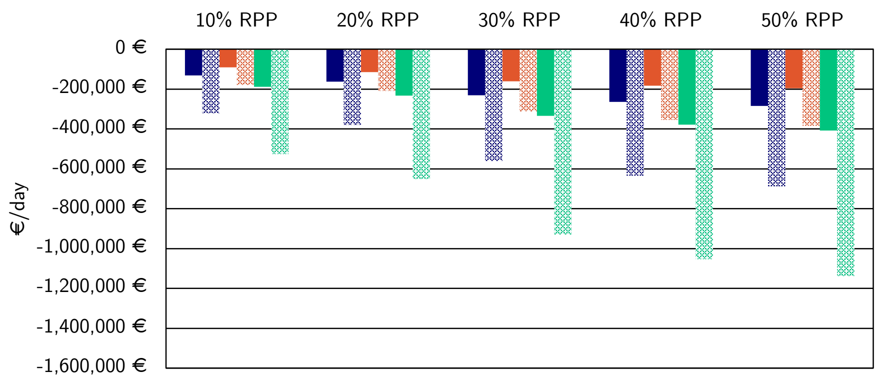
Figure 5.19: LCSA (internalization of all costs) for the USE phase in €-ct/vmk per vehicle category and drive technology, assuming a price of 680 €$_{2020}/kgCO_2e$.

LCSA on RPP Service Level:

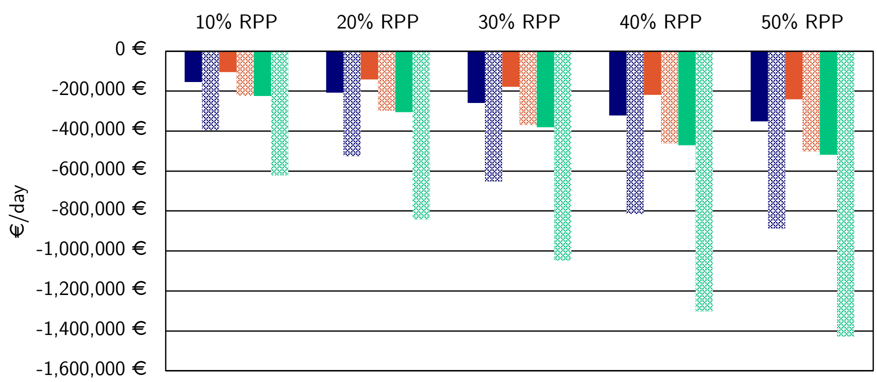
On the mobility service level, the comparison of the *Full RPP Rickshaw* scenario compared to the *Status Quo* in Figure 5.20a shows analogous to the SLCA that the EV charged with the German energy mix and monetized with a price of 680 €$_{2020}/kgCO_2e$ shows the highest savings potential, followed by the renewable energy mix. The two EV cases, where the monetization factor was assumed to be 195 €$_{2020}/kgCO_2e$, show obviously less savings potential. Figure 5.20b, comparing *Full RPP Car* and *Status Quo* scenarios, shows a similar trend, however the ICEV diesel shows the highest savings potential when integrating freight and passenger transport in a RPP service. At this point it should be mentioned again that the status quo is always compared with the equivalent drive systems in the RPP service, which is why the ICEV comparison does not exist as a gasoline engine. A similar picture can be seen in Figure 5.20c.The van vehicles show the highest overall savings potential, but when looking more closely at the 10% or 20% RPP scenarios with EV, the rickshaw fleet can compete with the van fleet.



(a) Full RPP Rickshaw vs. Status Quo Scenario



(b) Full RPP Car vs. Status Quo Scenario



(c) Full RPP Van vs. Status Quo Scenario

Figure 5.20: Balance of the LCSA for Full RPP scenarios considering different parcel penetration rates and vehicle types (mix = German Energy Mix, ren = Renewable Energy Mix, D = Diesel).

In summary, RPP outperforms the *Status Quo* in all three dimensions of sustainability, i.e. environmental, economic and social impacts. It can be seen that the higher capacity vehicle types (i.e. car and van) have an advantage especially for larger parcel volumes, while the rickshaw fleet scores for its relatively short driven distances. The EV has an advantage over the ICEV especially in the dimensions of environment and economy, but also in the social sphere. This is especially true when they turn to charging with a renewable energy mix.

5.2.4 Interpretation of Results

The interpretation of the results of this LCSA includes a sensitivity analysis of the results, as well as a clear communication of the scope and limitations of the developed LCSA Fleet Evaluation Tool, taking into account data quality and uncertainty.

Table 5.10 shows a summary of all assumptions made for the LCSA evaluation of the LCSA Fleet Evaluation Tool and thus the RPP service. The input parameters *vehicle weight* and *average energy consumption* have been used to scale results and data sets and to adapt existing models. Therefore, the sensitivity of the LCSA Fleet Evaluation Tool to these parameters must be considered high, but the parameters have been estimated based on reliable and state-of-the-art references, which limits the uncertainty. The vehicle sizes were used to estimate the land use and barrier effect costs of the SLCA. However, the influence on the results is rather small as other parameters (e.g. vehicle speed, infrastructure costs and parking costs) were also taken into account. In addition, the different vehicle categories can easily be assigned appropriate dimensions, which drastically reduces the uncertainty. The same is true for vehicle speeds, which were verified by microscopic traffic simulation, resulting in a "low" uncertainty, but model sensitivity must be considered "high". Vehicle battery sizes have a significant impact on vehicle LCSA performance, but assumptions have been made based on state of the art vehicle models, resulting in an uncertainty rating of "neutral". The same applies to the purchase price of the vehicles used in the LCCA. However, the vehicle price is only one of many input parameters to the LCCA, so the sensitivity is rated "neutral". The lifetime of the vehicles is input to the LCSA of the LCSA Fleet Evaluation Tool and has a large impact on the results, so the sensitivity is rated "high", but the uncertainty can be limited by referencing the assumptions to state-of-the-art research.

Input Parameter	Uncertainty	Sensitivity
Vehicle Weight	low	neutral
Energy Consumption	low	very high
Vehicle Size	very low	very low
Vehicle Speed	very low	high
Battery Size	neutral	very high
Vehicle Price	very low	neutral
Lifetime	neutral	very high

Table 5.10: Qualitative evaluation of uncertainty and sensitivity of model input parameters.

In addition to the qualitative assessment of the uncertainty and sensitivity of the LCSA Fleet Evaluation Tool model assumptions, a Monte Carlo simulation was performed for the

LCA, which represents the most complex system and should therefore be studied in particular detail. Overall, it can be said that the LCSA Fleet Evaluation Tool is based on very reliable ecoinvent data sets that have been verified several times by independent experts. In addition, the evaluation of the model assumptions, consisting of a combination of uncertainty and sensitivity, promises a very reliable model, which was additionally investigated with respect to stochastic fluctuations by Monte Carlo simulations (Annex 3.5) in the LCA domain. Within the defined scope of application (i.e. the evaluation of vehicle fleets in urban traffic) it can be expected that the results obtained by the LCSA Fleet Evaluation Tool are very reliable. Moreover, the results are consistent with the current state of the art in other research, which will be shown for LCA, LCCA, and SLCA in the next subsections.

Environmental Evaluation (LCA)

As mentioned above, the LCA of the LCSA Fleet Evaluation Tool depends significantly on the input parameters (e.g. vehicle weight, energy consumption, etc.), but the self-assessment of the assumptions in terms of uncertainty and model sensitivity showed that the assumptions are well taken and guarantee good quality and trustworthy results. Overall, the study shows that a ICEV passenger car accounts for approximately 50,000 $kgCO_2e$ and a EV passenger car between 20,000 and 40,000 $kgCO_2e$ over its entire life cycle, which is consistent with other LCA studies in the field [Girardi et al., 2015; Hawkins et al., 2013; Verma et al., 2022]. The obtained air pollutant emissions are also consistent with the results of similar studies [Mitropoulos et al., 2017; Wu & Zhang, 2017]. Furthermore, the Monte Carlo simulations (Appendix 3.5) performed for the LCA domains of the LCSA Fleet Evaluation Tool prove the stochastic robustness of the model results.

The results on vehicle level as well as the RPP evaluation show that, at least in urban traffic scenarios, EVs outperform ICEVs in all domains considered. The GWP of the EV was significantly lower for all vehicle types, the air pollutant emissions during the USE phase were also much lower than ICEV. When analyzing the different vehicle types, it became clear that a RPP service that relies on rickshaws, causes significantly lower GHG emissions and also achieves the best results in terms of air pollutants due to the electric drive. Basically, it became clear that all emissions correlate with the size and weight of the vehicle, and thus the rickshaw is followed by the passenger car, the passenger van, and the delivery vehicle.

Economic Evaluation (LCCA)

The economic evaluation of the RPP USE phase is based on the real world data and literature review of Negro et al. [2021]. The cost components are split between a RPP fleet operator and a platform provider and analyzed accordingly. It was found that the driver is the main cost factor for the fleet operator, which could potentially be replaced by automated systems in the future. Until then, the EV rickshaw, due to its larger fleet size, produces the highest total cost with almost 1.20 €/vkm, followed by the ICEV and EV passenger van and the respective passenger car types. The platform operator costs are very similar for all vehicle types and are around 50 €-ct/vkm. The obtained results are in line with other research studies [Bösch et al., 2018; Compostella et al., 2020; Negro et al., 2021] and represent a typical market cost rate [Uber Technologies Inc., 2023].

Social Evaluation (SLCA)

The SLCA of the RPP service shows that air pollutant and noise emissions have only a minor influence on the valuation of external costs compared to GWP, land use and barrier effects as well as accidents and congestion. According to the current state of research [Schröder et al., 2023], the congestion effects of the rickshaw were evaluated as zero, since the rickshaw is allowed to use the bicycle infrastructure. In addition, this work examined the impact of a rickshaw RPP service on bicycle traffic in Munich. As of 2020, there are approximately 900,000 bicycle trips per day in Munich [Belz et al., 2020], which compared to the 47,500 RPP passenger requests per day would correspond to an increase in bicycle traffic of 5%. Assuming that the main congestion effects would occur at intersections and traffic lights, this would mean that if there was a queue of 20 bicycles, one additional rickshaw would queue, which is assumed not to have a significant impact on the potential congestion effects. Although the rickshaw is difficult to overtake due to its large size compared to a traditional bicycle, it was found to be quite fast with an average speed of about 15 km/h. This high average speed is mainly due to the assistance of the electric motor and further limits potential congestion effects. The remaining results (GWP, air pollutants, land use and barrier effects, accidents, and congestion) are also in line with the scientific state of the art in the field of external cost assessment in transportation research [Choma et al., 2020; Jochem et al., 2016; Mitropoulos et al., 2017; Schröder et al., 2023].

Chapter 6

Real World Test of Ride Parcel Pooling

Chapter Essentials

- The Ride Parcel Pooling web application, consisting of front end, back end, and fleet control is presented, which served as the digital platform for the integrated transportation service for passengers and freight.
- Comprehensive testing procedures were conducted to evaluate the functionality of the vehicle prototype vehicle and ensured its readiness for real world operations.
- The preparation of the real-world field test showed the necessity of marketing campaigns to attract adequate attention of test participants.
- Ride Parcel Pooling was proven to be ready for real-world applications and revealed the necessity of sufficient demand of both, passengers and freight to produce pooled trips.

The methodological structure of this thesis includes a real-world test of the RPP service coupled with the RPP simulation for calibration of the RPP simulation and validation of the whole RPP idea, see Figure 1.3b. To this end, the planning of a RPP real-world field test started in parallel with the RPP service definition and was an integral part of the expert workshops conducted to derive potential use cases and the final simulation scenarios visualized in Figure 3.9. The RPP field test infrastructure consists of a RPP web application running on any type of smartphone, tablet or computer, and a RPP fleet of vehicles. In addition, the field test was accompanied by a small marketing campaign to promote the field test and attract as many test users as possible.

6.1 Ride Parcel Pooling Web Application

The RPP web application was developed in collaboration with students from the Technical University of Munich (TUM) Department of Computer Science, who implemented the front-end and back-end infrastructure. The application consists of a ReactJS front-end for customers, drivers and administrators, which is connected to a back-end via a REST API and is displayed on a website. The Java-based back-end infrastructure is the interface between the front-end and the fleet control infrastructure. It is built for data distribution and storage via MariaDB and provides the representational state transfer for the API connection. The Python-based fleet control (FleetPy), as the third main part of the web application, provides the assignment and routing algorithms and gives feedback to the customers on their requests. Figure 6.1 provides a schematic overview of the web application infrastructure described above.

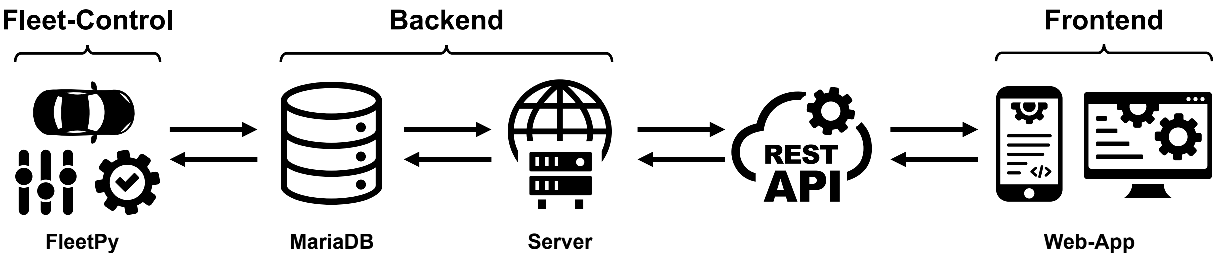


Figure 6.1: Schematic overview of the RPP web application infrastructure.

The back-end of the RPP project communicates with the fleet management software to obtain data about the fleet, drivers, and open requests. It also provides secure REST endpoints that end devices (i.e. front-end) can use to register, log in, submit and update requests, and track the current status of their requests. The server runs on Windows and was hosted on a laptop provided by the Chair of Traffic Engineering and Control during the field test. The server could be connected and controlled using remote desktop software. For offering the web application to the customers, the domain "rideparcelpooling.com" was registered at a web hosting company. Furthermore, a MariaDB database was set up for data storage and connected to a Spring back-end infrastructure. The fleet control application was also run on the back-end in a separate shell and the communication between the back-end and the fleet control happened via so called stream communication objects. Finally, the Spring boot web server serves the front-end React application.

6.1.1 Back-End

Within the RPP back-end, there are three distinct steps in the life cycle of a customer request. First the customer creates the request and fleet control has to decide if the request can be fulfilled or not. If the request can be fulfilled, it sets the state to *accepted*, otherwise to *declined*. In the next step, the customer can read back the information from the back-end and update the set information on his local device. There is also a chance that rescheduling has occurred on the fleet control side. Finally, the request is served by the assigned driver, and fleet control calculates a route for the driver. As soon as the driver reaches the previous step on his route (i.e. the vehicle is now heading to the pick-up location), the state of the request changes to *coming*. This limits the changes that the customer can make to the request and informs them of the imminent arrival. When the driver arrives at the pickup location, the state changes to *waiting* and when the boarding process is finished, either by the customer showing up or the parcel being loaded or the driver having waited long enough, the state changes to *active* or *declined* respectively. Finally, if the request is completed, the state changes to *completed*. The driver information is much more controlled than the customer requests because the back-end uses a very strict state engine for drivers. The state has two parts. The first shows if the driver is in the "driving" loop or the "end shift" loop and the second shows if the driver is currently stopping to pick up/drop off customers/parcels or driving to the next position. There are still three distinct steps in the life cycle. First, the drivers must activate to inform the fleet controller that they are now accepting orders. This changes the state to *active driving*. Then they are put into the "driving" loop. The driver may be given a new route that their front-end application will periodically poll for. When they reach a position, they start the boarding process, which changes to *active boarding*. When the boarding is finished, the state changes back to *active driving*. When the drivers want to stop working, they leave the "driving" loop by deactivating and changing to *end shift driving*. Now they continue driving and go through the boarding process until the assigned vehicle plan for the driver is empty. Then the state changes to *inactive* and the whole cycle can be repeated. The difference between the "driving" loop and the "end shift" loop is that the driver can receive new tasks from the fleet controller. [Saunus & Gruhlke, 2022]

6.1.2 Front-End

The front-end is the point of contact with the RPP software for both customers and drivers. In the following, both the design of the web application and the technical implementation in the front-end environment will be briefly discussed.

Design Aspects

The design of a web application is of utmost importance as it directly impacts the user's experience and overall success of the application. A well-crafted design enhances user satisfaction, fosters engagement, and boosts retention rates. The user interface and user experience design play a crucial role in this process. The user interface design on the one hand focuses on creating visually appealing and intuitive interfaces, ensuring that users can navigate the application effortlessly. On the other hand, user experience design concentrates on understanding user behaviors, needs, and pain points, leading to the creation of user-centric functionalities and features. By integrating effective user interface and user experience design, web applications can deliver a seamless and enjoyable user journey, fostering positive perceptions and encouraging users to return, share their experiences, and contribute to the application's growth. For this reason, and to ensure a systematic approach, a classical design approach was chosen including the steps: problem identification, research and analysis, brainstorming and ideation, concept development , prototyping and iteration, feedback and testing, and refinement.

For the RPP field test, user personas, user journeys, and user flows and task analysis were created. Furthermore, the designs were tested in person and with the help of an online survey to create a pleasurable user interface/user experience experience with the RPP web application during the test phase. Additionally, a competitor analysis was carried out using

(a) Login (b) Account (c) Home (d) Request (e) Approach (f) End Ride

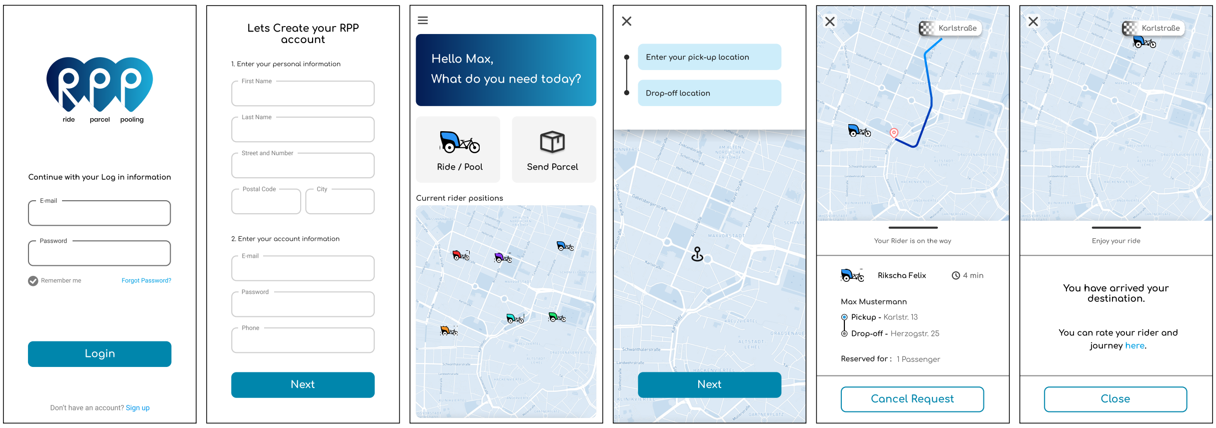


Figure 6.2: Selected customer front-end screen designs for the RPP application.

(a) Login (b) Settings (c) Request (d) Active Jobs (e) Boarding (f) Route

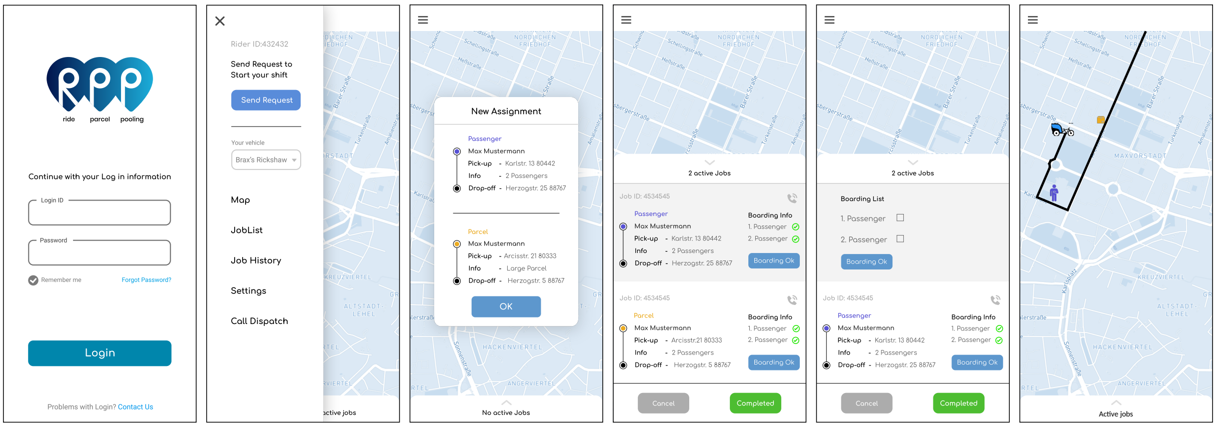


Figure 6.3: Selected customer front-end screen designs for the RPP application.

strength, weaknesses, opportunities, and threats (SWOT) profiles of existing ride-pooling and courier applications. All this resulted in the information and site map architecture and a broad variation of application screens for customers, visualized in Figure 6.2, drivers, visualized in Figure 6.3, and administrators, visualized in Figure 6.4.

Technical Aspects

The goal of the technical RPP front-end is to implement a functional, usable and intuitive way to interact with the back-end and fleet control parts of the project. It provides its users with current relevant information and sends their requests to the back-end. The front-end is written using the Reactjs framework and is therefore a mix of javascript, html and css. React is designed to be fast, responsive and lightweight. In development mode, the page reloads automatically, which speeds up the process, and the deployed version runs on the client side, which reduces the load on the servers. A visualization of the driver and the customer

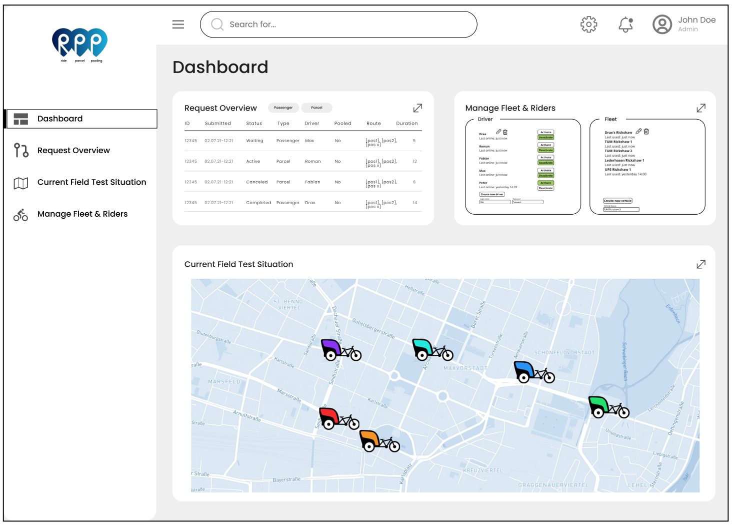


Figure 6.4: Selected administrator front-end screen design for the RPP application.

front-end, which were actually used during the field test, is displayed in Figure 6.8d.

As mentioned at the beginning of this chapter, both the front-end and the back-end were developed in cooperation with students from the Department of Computer Science at the Technical University of Munich. For a detailed insight into the functionalities and infrastructures of the software, the interested reader is referred to the respective Git-lab repositories [Mercier, 2022; Saunus & Gruhlke, 2022].

6.1.3 Fleet Control

The fleet controller, coupled to the RPP back-end infrastructure, is basically an instance of the FleetPy software, slightly adapted to communicate with the back-end using stream communication objects. The fleet control was responsible for assigning requests to active vehicles, updating vehicle schedules, calculating routes, and providing feedback on customer requests. The FleetPy software is also provided open-source and can as well be accessed via a Git-hub [Chair of Traffic Engineering and Control, 2023] or Git-lab repository [Dandl et al., 2023].

6.2 Ride Parcel Pooling Vehicle

The vehicle design and drive technology are essential components of a MoD fleet because they directly impact the overall functionality, efficiency, and user experience of the service. The key feature of the RPP vehicle were adaptability, regulatory compliance, user experience, sustainability, and cost efficiency to make it fit into the project budget, create an appropriate vehicle design, and align it with the project idea of creating a sustainable mobility solution.

6.2.1 Vehicle Prototype

The prototyping process for the RPP vehicle can be divided into technical and design aspects. The first technical and design aspects of the RPP vehicle were already defined at the beginning of the project and went hand in hand with the definition of the RPP service described in Chapter 3. The following main criteria for the prototype were identified during the service definition phase:

- Versatility and flexibility: The vehicle should be versatile enough to accommodate at least two passengers and an appropriate number of parcels.
- Accessibility: The vehicle should be accessible to all passengers, including those with disabilities or mobility impairments.
- Clean and efficient drive technology: Emphasize environmentally friendly and fuel-efficient drive technology.
- Connectivity and communication: Seamless integration with the online platform is important.
- Maintenance: Easy maintenance access, standardized components, and serviceability are important factors for ensuring limited downtime.
- Easy loading and unloading systems: Easy loading and unloading procedure for parcels.

Design Aspects

In the course of designing the RPP app, the vehicle design for the RPP rickshaw was also developed. First, the RPP requirements were defined, followed by research and analysis to gather relevant data (e.g. market research, user surveys). In the next step, a wide range of design concepts to reflect the RPP idea were developed (Figure 6.5), which were subject to a feedback and testing process. Finally, the feedback is incorporated into a refinement of the developed design, before the design gets implemented.

Technical Aspects

The RPP test vehicle is a prototype developed as part of the research for this thesis and consists of a compartment for two passengers, a roof rack, and an optional trailer for transporting parcels, see Figure 6.6. The rickshaw integrates adjustable seating to provide additional space for parcels when the capacity of the roof rack and trailer is exceeded. This allows for varying passenger and parcel loads. The electric rickshaw reaches a top speed of about 25 km/h on a flat, windless road and travels at an average speed of about 15 km/h under normal traffic conditions. In this context, the rickshaw benefits from the classification as a bicycle, with a maximum electric assist speed of 25 km/h in Germany, and is thus allowed to use the bicycle infrastructure, resulting in travel time savings in congested road traffic and zero local emissions. The connectivity and communication of the rickshaw is ensured

(a) Design 1 (b) Design 2 (c) Design 3 (d) Design 4

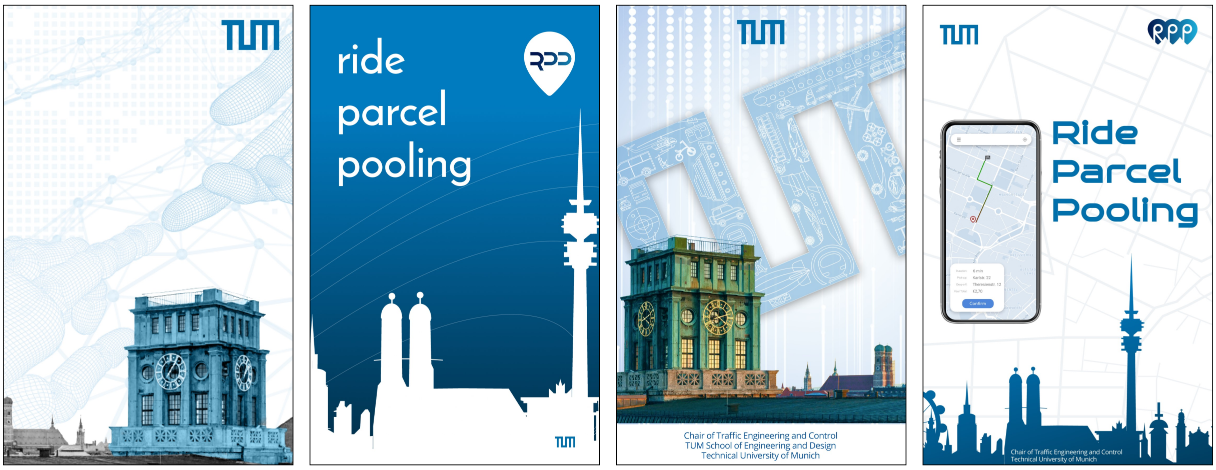


Figure 6.5: Final design proposals for RPP rickshaw.

by the RPP web application, and the drivers can attach their smartphones to the rickshaw handlebars. In addition, the prototype includes a tablet in the passenger compartment to provide an additional device to update passengers who do not have their own smartphones. In addition, the rickshaw offers high accessibility due to its high seating position, however, the transport of passengers in wheelchairs could not be implemented. The maintenance of the rickshaw is also quite simple as all components are standard bicycle parts and can be easily replaced. The trailer provides an easy way to load and unload parcels, and the roof rack and convertible seats provide additional space for transporting parcels.

6.2.2 Fleet Partnership

In order to be able to provide a whole fleet of rickshaws for the test period, a cooperation with a local rickshaw service was established, which provided four additional rickshaws including drivers for the duration of the field test (see Figure 6.7. The drivers were trained in the use of the RPP app and together with the TUM vehicle formed the vehicle fleet of five rickshaws serving all incoming passenger and parcel requests.

6.3 Ride Parcel Pooling Field Test

During the week of Monday, August 22, 2022, to Friday, August 26, 2022, a real-world test of the RPP service was conducted, offering free passenger rides and parcel transport from 10:00 to 19:00. The real-world test of the RPP project consisted of the introduced web application and a fleet of five test rickshaws.

Figure 6.6: RPP rickshaw (prototype for the integrated transportation of passengers and freight).

6.3.1 Goal and Scope

The goal and scope of the RPP field test was to provide a proof of concept of the RPP idea and to gather experience and data on the operation of an integrated on-demand mobility service that simultaneously transports passengers and freight. The test plan included both the web application and the RPP rickshaw concept, and included a feedback loop for the agent-based simulations (e.g., boarding/loading and alighting/unloading times, average travel speed, and customer interaction). The test location and time were selected based on the requirements of an on-demand ride-pooling service area and the vehicle capabilities, i.e. lower maximum speed and no limited weather protection (rickshaw), resulting in a test area of approximately 2 km x 2 km 6.10 including the district 'Maxvorstadt' and parts of the 'English Garden' in Munich during the summer. The real-world field test of RPP aimed to include as many participants as possible, i.e. passengers and parcel shippers. In order to attract a large number of users, marketing campaigns were carried out, including radio and newspaper interviews, as well as the distribution of flyers (see Figure 6.7) and advertising posters. The latter were mainly distributed around the main campus of TUM. In order to maximize the number of parcels transported by the RPP fleet during the field test, in-kind fundraising efforts were also incorporated. Data collection during the field test was done via the web application (Global Positioning System (GPS) traces from cell phones and application interactions) and was accompanied by a short customer feedback survey.

During the real-world field test, the RPP service was offered to the public free of charge. For five consecutive weekdays in August 2022, people could request rides and have the service transport parcels in a predefined area of operation (see blue outlined area in Figure 6.10). In addition to the free rides, in-kind donations of (broken) small appliances, electronics, batteries, and old clothes were collected to create additional parcel demand. Figure 6.8d provides a sample view of the RPP web application, where Figure 6.8a and Figure 6.8b show the customer view, and Figure 6.8c and Figure 6.8d show the driver front-end.

Figure 6.7: RPP rickshaw fleet and flyer for public announcement of the field test.

(a) Customer Login (b) Customer Trip (c) Driver Trip (d) Driver Request

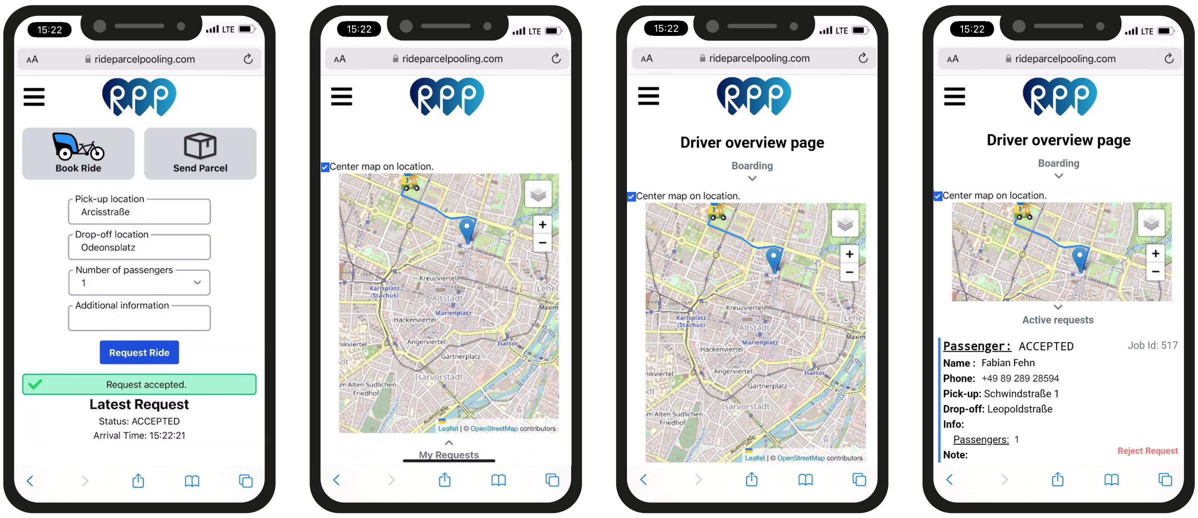


Figure 6.8: Real customer and driver front-end screens from RPP field test.

6.3.2 Results

During the test phase, 54 people created and actively used an account, resulting in a total of 191 valid requests, of which 87% were passenger requests and 13% were parcel requests. The total number of trips served is significantly lower than the number of valid requests. This is for several reasons: First, many requests were canceled by the users themselves, most likely to test the application or due to high waiting time. Second, drivers were able to reject requests if, for example, they could not find the client. Third, technical problems lead to some failures, especially at the beginning of the test. These included system failures and multiple requests for the same trip. In total, 47 valid trips were recorded, 74% of which were passenger trips, 18% parcel trips and 2 shared trips with passenger(s) and parcel(s) on board (see red lines in Figure 6.10). The lengths of the performed trips are shown in Figure 6.9. Self-organized pick-ups and drop-offs by drivers without a ride request via the app were also recorded and may be outside the service area, but are clearly in the minority, see Figure 6.10. The extended operation area included the central "Marienplatz" and northern parts of the "English Garden" and some streets around "Münchner Freiheit".

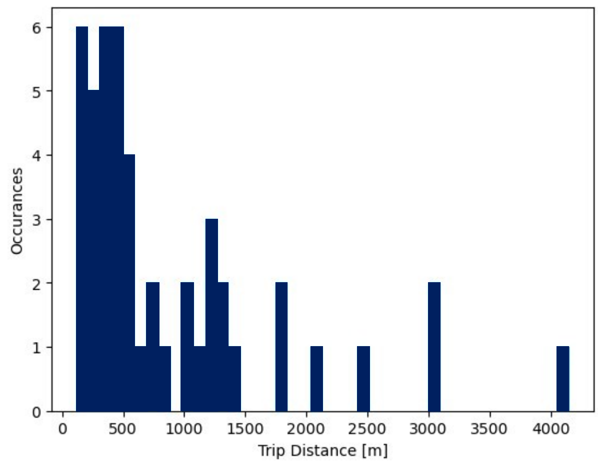


Figure 6.9: Counts of requested trip lengths.

The average speed recorded was 14.1 km/h and the average boarding time was 56.7 seconds. In this study, boarding time describes the time from vehicle arrival to the start of the trip, including vehicle parking, passenger contact, passenger boarding, and preparation for departure. The average occupancy rate of the rickshaws, calculated based on the number passengers per request, was 1.4 passengers. Real 'pooled' passenger trips were not observed during the field test, however there were four passenger trips with at least one parcel on-board. The low pooling rate was probably, due to the low demand, which was far from the system capacity. All relevant values obtained during the field test are shown in Table 6 in Annex 4.

The gathered customer feedback was mostly positive. Most users (93%) found the RPP service pleasant, and around 78% were completely satisfied with the service. 89% of respondents would also be happy to use a paid RPP service and would be willing to pay an average of 4.70 € for a 5 km trip with a duration of about 15 minutes. Users particularly liked the RPP application, the nice drivers, the sustainable travel, the price and the RPP rickshaws. Suggestions for improvement included automated address completion during the booking process, entertainment options while riding, and charging options for electronic devices.

In conclusion, the real-world testing of RPP included a web application, a RPP vehicle concept, and the RPP real-world field test. The web application comprised back-end, front-end and fleet control functionalities and respective design and technical aspects. The development of the web application proofed that a MoD application serving passengers and freight is possible and that the software 'FleetPy' is capable of real-time decision making for the respective use-case. The RPP vehicle prototype also proofed real-world applicability and was evaluated positively by the field test participants and drivers. The five-day field trial of the RPP service demonstrated the viability of the RPP concept and its readiness for real-world implementation. It also provided evidence that rickshaws are a viable and accepted mode of transport for urban ride-pooling services, even in Western European countries. However, more extensive field testing is needed to fully assess long-term customer acceptance.

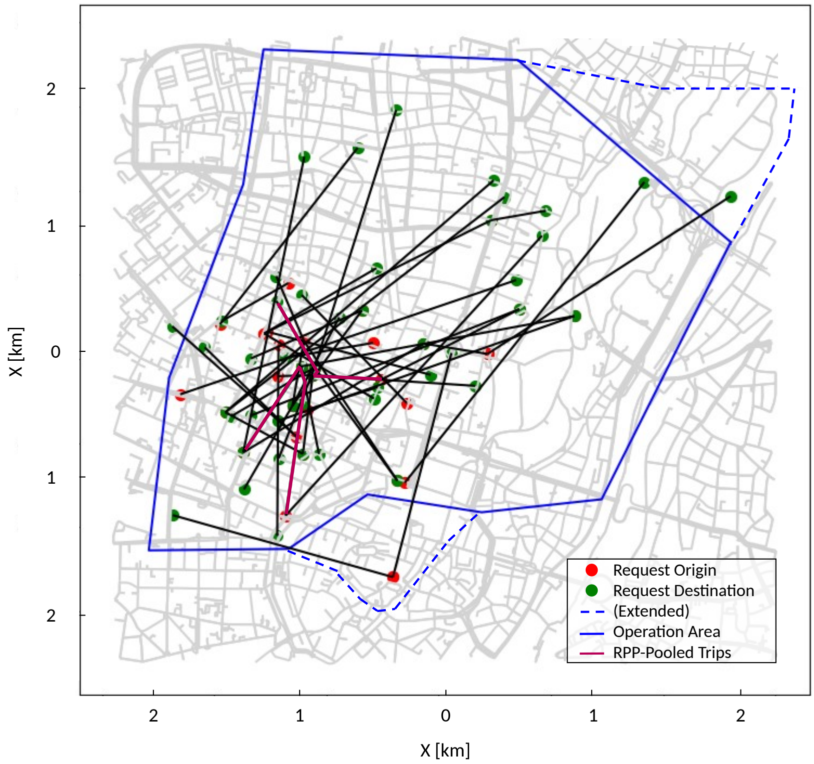


Figure 6.10: Visualization of service area and all recorded trips (including origins and destinations) and two RPP trips of passengers and parcels sharing rides.

Chapter 7

Conclusion, Limitation, and Future Work

7.1 Summary and Discussion

The overall objective of this dissertation was to comprehensively investigate and assess the potential benefits and feasibility of integrating urban passenger and freight transportation services to promote the development of more sustainable and efficient urban transportation ecosystems. This research aimed to understand how the convergence of passenger and freight transportation systems can mitigate environmental impacts, reduce traffic congestion, improve resource utilization, and enhance the overall quality of urban livability. By investigating the state of the art, developing a RPP service definition, simulating and evaluating the RPP service, and finally testing the service in real-world conditions, this dissertation created a holistic picture of RPP from the initial idea, over service definition, simulation and evaluation, to proof of concept.

The literature review defines the solution space by considering various forms of urban passenger and freight transportation, including public, private, and on-demand mobility options, as well as courier, parcel, and cargo services. Research in this area has uncovered different models and methodologies for integrating these modes. In particular, public transportation appears to be well suited for parcel and freight feeder services, while individual and mobility-on-demand options could include courier and parcel services. Existing practical applications of integrated passenger and freight transportation tend to favor mobility-on-demand systems and individual transportation, but with a predominant focus on maximizing profits rather than minimizing travel distances. Although LCA methods are applicable, they have not been widely used to evaluate urban vehicle fleets and integrated mobility concepts. To address these gaps, this research introduced the LCSA Fleet Evaluation Tool to holistically evaluate the concept of Ride Parcel Pooling, which aims to minimize vehicle miles traveled by combining mobility-on-demand ride-pooling and urban parcel transport. This concept, defined through expert workshops and customer surveys, highlights the potential for positive acceptance and identifies key service parameters for simulation (see Chapter 3).

Research Questions

Conceptualization:

Against this background, this thesis answers the research question on RPP service definition:

- Which service characteristics and use cases contribute to a sustainable change of the existing transportation system by integrating urban passenger and freight transport?

The RPP service has been defined as a combination of a mobility-on-demand ride-pooling service and parcel transportation. The assignment of parcels to passenger trips is designed in line with the RPP idea of minimizing detours in order to keep the total driven distance as low as possible and deteriorating the customer and operator KPIs as little as possible. The use case "Prioritized Ride Parcel Pooling", was selected for further in-depth analysis in an agent-based simulation, as it perfectly meets the requirements mentioned above.

Modeling:

The simulation study involves the adaptation of the agent-based simulation framework "FleetPy" and its integration with three heuristic parcel assignment strategies to form a comprehensive ride-pooling fleet control algorithm. By evaluating different integration scenarios in combination with these assignment strategies compared to the status quo, it is observed that the "Combined Decoupled Parcel Assignment (CDPA)" strategy is best suited to the goal of integrating freight transportation into ride-pooling services, resulting in the lowest traveled distances. In addition, the study introduces three different vehicle categories, namely rickshaws, cars, and vans, each characterized by different fleet sizes, capacities, and operational constraints. The results indicate that the integration of logistics services into ride-pooling is feasible and can efficiently utilize underutilized system capacity without compromising the quality of passenger transportation. Depending on the chosen assignment strategies and vehicle categories, it is possible to serve almost all parcels up to a parcel-to-passenger demand ratio of 1:10, while reducing the overall fleet mileage compared to the status quo. The evaluation of RPP points out the necessity of conducting a comprehensive life cycle sustainability assessment to systematically evaluate the impacts of RPP. It introduces the LCSA Fleet Evaluation Tool, designed to offer a novel approach for assessing urban vehicle fleets throughout their entire life cycle, encompassing environmental, economic, and social considerations. Through a detailed case study of the *"Full RPP Integration"* scenario, significant benefits become evident, including substantial reductions in GWP, fleet operating costs, and positive social implications when compared to the *Status Quo*. The choice of vehicle types becomes pivotal, with larger parcel volumes favoring high-capacity options like cars and vans, while rickshaws excel in minimizing travel distances. Moreover, the analysis highlights the advantages of electric vehicles, particularly in terms of environmental, economic, and social dimensions, reinforcing the validity of model assumptions and results in the overall interpretation. By that, the following two research questions regarding the modeling of RPP were answered:

- How could an on-demand Ride Parcel Pooling service look like and what are suitable control strategies?

- How could a holistic life cycle assessment for urban vehicle fleets look like and which parameters should be included?

Evaluation:

As mentioned above, the applied control and assignment strategies were tested assuming different parcel volumes applied to the RPP system. The CDPA strategy was found to lead to the lowest driven distances, which was the fundamental idea of RPP, without compromising on passenger and operator KPIs. This led to a novel mobility service that incorporates parcel transportation into the systems of a ride-pooling operator, resulting in lower driven distances compared to the status quo with two separate fleets. In this context, the evaluation of RPP in Chapter 5 of this dissertation tried two answer the following two research questions:

- Is a Ride Parcel Pooling service economically competitive compared to the status quo (separate state of the art ride-pooling and last mile freight transport)?
- Can Ride Parcel Pooling cause a sustainable change of urban mobility-on-demand vehicle fleets?

The LCSA Fleet Evaluation Tool, designed to evaluate mobility fleets in urban environments, was implemented based on a LCSA approach, taking into account environmental, economic and social impacts and comparing them with the status quo. The evaluation of the RPP service showed a significant reduction of negative impacts in all three dimensions of sustainability, i.e. environmental, economic and social, compared to the status quo. In terms of the environment, the RPP service could save significant amounts of CO_2 and local air pollutants. From a financial perspective, the integrated mobility service can already today be economically attractive for both, ride-pooling providers and parcel transportation enterprises. This is especially true for larger, low-capacity fleets that currently require a higher number of drivers. In the social dimension, RPP creates substantial positive changes in all evaluated indicators, i.e. GWP, local air pollution, noise, land use and barrier effects, accidents, and congestion.

Lastly, the RPP field test implemented a RPP web application, followed by rigorous testing of the RPP prototype vehicle. Subsequently, the service was investigated in a real-world field test and proofed the concept, as well as the applicability of the RPP idea.

7.2 Limitations

This thesis has three main limitations especially regarding the modeling and evaluation of the proposed RPP service. First, there is limited real-world input data for the FleetPy simulation and the LCSA Fleet Evaluation Tool, especially for emerging mobility concepts such as RPP. This mainly concerns the passenger and parcel demand input data for the simulation. Since the simulated RPP service does not yet exist in reality, certain assumptions had to be made. In this case, these were the replacement of 5% of the private car trips in Munich by ride-pooling trips and the assumption that the parcel service providers would make their parcels available to the service. In the case of the LCSA Fleet Evaluation Tool, the input data was based on peer-reviewed publications and databases, but there could still be minor inaccuracies, especially where the model used generic data sets. This could slightly affect the accuracy and robustness of the analyses. Second, the integration of passenger and freight transport involves very complex logistics and decision-making processes. Simplifying assumptions and modeling this complexity can lead to an oversimplified or generalized representation of the system. This includes the behavioral assumptions for ride-pooling passengers, as well as shippers and receivers of parcels, and the data sets and inputs used for the LCSA evaluation of the RPP service. Third and finally, the comparative analysis of RPP versus the status quo includes existing transportation systems and alternatives, which can be complex. Obviously, the criteria for comparison and the availability of relevant benchmarks can vary, and were estimated for the scope and constraints of the Munich urban case study. This means that the results obtained could be different when evaluating the RPP service in another location with different circumstances.

7.3 Implications

Integrating passenger and freight transport in urban transportation systems can have various political, legal, and social implications. In the case of RPP, i.e. integration of parcel transport into a MoD ride-pooling service, all three implication dimensions are of relevance and decide on the success of this novel transportation service.

7.3.1 Political Instruments

Political measures comprise both "pull" and "push" strategies to influence how people choose and use transportation options and by that the success or failure of new transportation solutions. The former describe measures that seek to "force" change, while the latter seek a desired development by creating "new opportunities" for stakeholders. Pull measures include investments, prioritization, public awareness campaigns, and government partnerships [Transformative Urban Mobility Initiative, 2023]. Investments can be carried out in infrastructure (e.g. establish new mobility offers, improve existing services), or service operation (e.g. increase service duration or frequency). Furthermore, certain transportation means can be prioritized (e.g. longer green times at traffic lights) over others. Additional to monetary pull measures, awareness campaigns, marketing, and participation can increase social acceptance of mobility solutions. Lastly, governmental partnerships, like concessions with certain conditions, can lead to more a sustainable urban mobility network. Push measures on the other hand include taxes, restrictions, and bans [Transformative Urban Mobility Initiative, 2023]. These comprise congestion and road charges and tax incentives, area-wide parking management, restricted zones, and speed reductions, and finally permanent or temporary bans of certain modes of transportation. Lastly, there are measures, which cannot clearly be assigned to pull or push measures and are kind of in between both. These include the redistribution of road space: e.g. cycle or bus lanes, planting buffers, infrastructure for new mobility solutions, or pedestrian connections.

In order to promote integrated transport solutions such as RPP, financial support for infrastructure and operational improvements could be considered. However, the evaluation of the simulation results showed that a RPP service can already be financially viable.

Therefore, supportive measures such as government partnerships, awareness campaigns, restricted zones, or tax incentives could be of greater benefit in creating a fertile landscape for integrated transportation solutions. In transportation planning, possible push measures to support the idea of RPP could be on the one hand: tolls or (temporary) access restrictions for conventional, private or delivery vehicles in the city center, an increase in parking fees or a city toll. On the other hand, the pull measure could be: lanes for high-occupancy vehicles, pick-up and drop-off zones for MoD services that allow an easy transition from private to pooled transport, improved Mobility as a Service solutions, or financial support (comparable to public transport). The latter would only be applied if the service cannot be profitable on its own under the given circumstances.

7.3.2 Legal Aspects

In August 2021, the German government's reform of the Passenger Transport Act (PBefG) has come into force [Deutscher Bundestag, 2021]. With this, Germany has created the legal basis for ride-sharing and taken a pioneering role in international comparison. Of central importance are the new Sections 44 and 50 of the PBefG [Personen-Beförderungs-Gesetz, 2021a, 2021b], which define what constitutes "scheduled on-demand transportation" and "pooled on-demand transportation" and the conditions under which they may be operated. These conditions include certain emission standards for the vehicles used, as well as targets for certain vehicle occupancy rates.

In the case of RPP, where passengers and freight share rides, the regulatory situation is less clear. The law governing the contract of carriage, which in Germany regulates the carriage of passengers and freight, is relevant. The contract of carriage is a special form of contract for work and services in the sense of §§ 631 ff. BGB (German Civil Code) [Bürgerliches Gesetzbuch, 2023], since the success of the transportation constitutes the work. This success includes not only the safe but also the punctual transportation of persons and/or goods. The other party to the contract, e.g. the passenger, is obliged to pay the agreed remuneration. Special emphasis should be placed on safe transportation conditions. These should always be observed, e.g. by transporting the freight separately (e.g. in the trunk). Of particular interest is the contractual relationship to be established between the logistics provider and the MoD operator, as damage or loss of parcels must be legally covered and insured. A solution could be similar to the one already in place between contract access points and the logistics provider. Such access points accept shipments that could not be delivered on behalf of the consignee and, as a third party, organize local storage and delivery of the parcel. This could involve a similar set of contracts between the MoD service operator and the logistics provider, as the relationship appears to be very similar. In addition, the RPP vehicles should be designed so that passengers cannot access the parcels being transported to prevent vandalism or theft. The Federal Ministry of Digital Affairs and Transport is currently discussing the future legal framework for the carriage of freight in public transport vehicles [Bammerlin, 2021].

7.3.3 Societal Acceptance

Hand in hand with political instruments and legal aspects, social acceptance is one of the main drivers for the successful implementation of new mobility concepts. It is important to engage the public through consultations, education, and demonstration projects to convey the benefits and gather feedback, as this thesis did in the field test of RPP. Prioritizing accessibility, inclusivity, environmental and health advantages, and cost savings while ensuring safety is essential to the potential customers of a RPP service. In the case of RPP, a clear vision aligned with urban development goals and the publication of case studies fosters social acceptance. The evaluation of RPP showed that such an integrated transportation service has positive effects on all three dimensions of sustainability and during the service definition phase the potential customer survey revealed great acceptance for the RPP idea among the respondents. Finally, the real-world field test proofed the concept and also received very positive feedback.

From the perspective of logistics service providers, there is currently little willingness to break up established supply chains and logistics processes in order to consolidate flows of goods or combine them with existing flows of people [Bundesverband Paket und Expresslogistik e. V., 2019]. One reason is that each service provider has its own well-established system that would be disrupted by consolidation, and another is that service providers do not want to reveal their data to a third party. However, the analyses in Chapter 4 show that RPP is able to generate significant economic benefits that could make these concerns disappear in the longer term.

At a higher level, there is also the question of whether we can afford the status quo in its current form for much longer. The introduction to this doctoral thesis clearly showed that the transportation sector is one of the main emitters of CO_2 and therefore has an increased responsibility to mitigate climate change. In order to comply with one of the principles of social coexistence, namely that the current generations must not endanger the future of the next generations, it is indicated to steer the status quo in a way that ensures its continuation, even if this means that we can no longer afford the status quo in its current form. For this reason, integrating passenger and freight traffic in cities is a sensible step in the right direction, all the more so if service quality hardly deteriorates as a result, which is the case for the defined RPP service.

7.3.4 Transportation Objectives

The objectives of urban transport systems are diverse, ranging from smooth traffic flow to high accessibility and affordable mobility for all. Economic as well as environmental and social components play an important role. High levels of road traffic, especially in urban areas, cause negative externalities such as longer travel times, increased emissions and congestion. These effects could be exacerbated if the trends of increasing road traffic and growing demand for parcel delivery continue. Urban transport infrastructure consumes about 17% of available land in the city of Munich [Geisser & Lenk, n.d.]. Current urban development efforts advocate a redistribution of established land uses and support more space for social interaction and encounters as well as environmentally friendly forms of transportation [Gössling, 2016]. The redistribution of space should result in a more livable urban environment and promote sustainable transportation solutions (e.g., pick-up and drop-off zones for MoD). The planned RPP service could be part of the solution by replacing private car parking and double-parking of large logistics vehicles. In addition, urban travel and freight transport are responsible for about 23% of total transport-related CO_2 emissions [Joint Research Center European Commission, 2023], and also produce a considerable amount of noise and local pollutants such as PM, SO_2, CO and NO_X emissions [Handbook of Emission Factors for Road Transport (HBEFA), 2023], thereby harming the health of citizens. The only way to avoid these negative effects of traffic is to reduce the overall road-based traffic volume and increase the share of electric vehicles.

This thesis has shown that using existing MoD ride-pooling passenger trips for urban parcel logistics could reduce road traffic and make the city more attractive to its citizens and visitors. Overall, the integration of passenger and freight flows could be a promising solution to maintain a functioning urban transport system and prepare it for the future challenges of growing transport demand. RPP could provide both a solution to reduce overall traffic by reducing travel distances and a significant contribution to the electrification of urban road transport through a centralized decision to have a fully electric vehicle fleet. Furthermore, the idea of RPP could encourage the emergence of a low-cost distribution system, allowing local shops, retailers and citizens to establish a local delivery system for their local shipments or to start e-commerce. This is especially relevant today as many cities face the problem of local shops and retailers struggling financially because they are unable to compete with online stores. The policy aspects of RPP require a collaborative effort between public authorities, industry stakeholders and community representatives. Developing effective policies that balance fostering innovation with ensuring public and consumer safety, and environmental protection requires dialogue and consultation to understand the needs and concerns of all stakeholders.

7.4 Outlook

The RPP service studied in this thesis showed great potential in meeting urban transportation goals and could be well supported by political, legal, and social implications. In addition, the real-world field test proved the concept of RPP. Additionally, RPP could gain enormous market share with the introduction of automated driving and the associated elimination of the driver cost factor. Nevertheless, there are some crucial issues to be considered on the way to market maturity, and the scientific consideration of integrated transportation systems for passengers and freight has not yet been fully told. For this reason, the following subsections provide an outlook on future research areas, as well as an insight into the possible market introduction of the outlined RPP service.

7.4.1 Future Research

This doctoral thesis presented the idea of RPP and developed it into a mobility service, which was successfully tested under real-world conditions. Future research could focus on a couple of areas connected to this research, which were out of scope for this thesis. Those can be presented according to the dissertation structure 1.3, reaching from the service conceptualization over modeling and evaluation to testing of the envisioned service.

Service Conceptualization

The envisioned RPP mobility service was conceptualized as a combination of an on-demand ride-pooling service that additionally transports parcels on top of any existing passenger trips. This service definition was chosen to best fit the RPP idea of a sustainable urban mobility service, but all of the other combinations explored could potentially provide a sustainable service. Furthermore, this research focused on urban applications, but RPP could potentially also work in rural areas if there is enough demand and supply density to actually pool trips, which is usually easier in urban environments [MOIA, 2023]. The service studied involved traditional parcel delivery in particular, but other last-mile logistics services (e.g. time critical food delivery) may be worth exploring in future studies. Furthermore, the RPP service could include delivery robots that enter and exit the vehicles like passengers, covering the very last mile of delivery trips and then returning to the MoD vehicles. In addition, the use cases presented in Chapter 3 that were excluded from this analysis ("Parcel Hopping", "Mobile Parcel Lockers", and "In-Vehicle Delivery") may be worth exploring.

Modeling and Evaluation

Regarding the modeling and evaluation of RPP, more sophisticated and optimal operation and assignment strategies could be developed that more accurately estimate the potential distance savings of RPP. In this context, exact optimization approaches or artificial intelligence-based algorithms could be used for optimized routing and matching of passengers, parcels, and vehicles. In addition, demand forecasting based on historical or real-time data could improve the efficiency of RPP in general and the SDPA and SCPA assignment strategies in particular. In addition, this study did not investigate which parcel constraints (e.g. delivery time windows, size, weight, special requirements) promote or prevent the integratability of parcels into a MoD ride-pooling service. In this context, future studies could investigate which parcel demand is particularly suitable for integration with existing passenger trips, and which combinations of passenger and freight transportation work best from an operational perspective.

Real-World Testing

The RPP field test investigated the real-world applicability of the RPP service. Future research could develop more sophisticated front-end, back-end, and fleet control solutions for a RPP customer and driver platform. In addition, more elaborate vehicle prototyping, customer testing, and the integration of delivery robots into the concept could be of scientific interest.

7.4.2 Go to Market Strategy

In order to initiate a RPP service, certain steps and considerations involved in commercializing the scientific innovation must be considered. According to Osterwalder and Pigneur [2010], these include key partners, key activities, value proposition, customer relationships, customer segments, key resources, distribution channels, cost structures, and revenue streams. In the following the respective elements are evaluated for a potential RPP service in the European context. The points reflect the insights of this dissertation from the literature research, service definition, modeling and evaluation, and field test activities, which are relevant for the go to market strategy of a potential RPP service.

Collaboration with a variety of partners is critical to the success of the RPP service. Government agencies and municipalities play a critical role in regulatory compliance, funding, and integration into urban planning. Transportation providers, including public transit agencies and ride-sharing platforms, offer opportunities to expand the user base. Logistics and delivery companies are essential for the efficient movement of freight. Local shops and retailers can benefit from RPP's local distribution system. Vehicle manufacturers and technology providers provide the necessary resources and innovation. Environmental organizations and academic institutions support sustainability and research efforts, enhancing RPP's credibility and innovation. Successful implementation of RPP requires a series of key activities. Building the technology platform is paramount, enabling user interaction, route optimization, and parcel tracking. Fleet acquisition and management, driver recruitment, and dynamic route planning are essential for efficient operations. Navigating regulatory compliance, data management, and marketing are ongoing activities. Additionally, expansion and scaling efforts should identify new markets and regions for growth. RPP offers a compelling value proposition to multiple user segments. Passengers benefit from cost savings, convenience, reduced traffic congestion, greener travel, and dynamic route planning. Businesses and shippers benefit from cost-effective logistics, optimized parcel routes, enhanced delivery services, and sustainability initiatives. For society and the environment, RPP contributes to reduced traffic and emissions, optimized urban space, reduced energy consumption, support for local businesses, and sustainable urban mobility. Building strong customer relationships is central to RPP's success. User on-boarding and support ensure a smooth start for new users. Feedback mechanisms foster a sense of involvement and responsiveness. Security and trust are essential elements to gain user confidence. User education helps users understand and maximize the benefits of RPP. Privacy, security, and transparency are paramount to building trust. RPP targets a variety of customer segments, including daily commuters seeking reliable transportation, occasional travelers looking for convenient options, the elderly and disabled needing accessible transportation, tourists exploring new cities, and local shops, restaurants and businesses looking for efficient deliveries. To operate effectively, RPP relies on key resources, including a fleet of vehicles capable of carrying both passengers and freight, a robust technology platform, advanced routing and optimization algorithms, and a pool of expertise in transportation logistics, technology, and regulatory compliance. The RPP service reaches users through mobile applications, web platforms and call centers. Users can access services through dedicated apps or websites, and some may prefer to book by phone for added convenience. RPP incurs various costs, including vehicle acquisition and depreciation, driver and operator expenses, fuel and energy costs, maintenance and repairs, insurance and liability coverage, technology and software development, marketing and advertising, and administrative and overhead costs. RPP generates revenue from a variety of sources, including passenger rides, parcel deliveries, advertising and sponsorships, delivery partnerships, and government and public funding. Each stream contributes to the financial sustainability and growth of the service.

Taken together, these elements form a comprehensive framework for the development, implementation and operation of a RPP service that addresses the needs and interests of various stakeholders while delivering value to passengers, shippers and society as a whole. Already today, however, MoD fleets of vehicles used exclusively for passenger transport could be converted to integrated operations. Today, the Munich taxi fleet consists of about 3,000 vehicles [Bundesverband Taxi, 2019], which is five times the size of the simulated fleet in Chapter 4. Scaling the simulation results, which were derived under the premise that passenger transport is hardly affected, this would result in a RPP volume of 25,000 parcels per day, which corresponds to a market share of approximately 11.5% in Munich [Bundesverband Paket und Expresslogistik e. V., 2017].

7.4.3 Emerging Technologies

The convergence of artificial intelligence, vehicle automation, and drone delivery has the potential to significantly impact the concept of ride-pooling and RPP in the future.

Artificial intelligence can potentially be used to better optimize route, dynamic fleet sizing, and predict demand for both passengers and parcels in real-time. Vehicle automation allows for efficient ride-sharing, reducing the number of vehicles on the road, and lowering overall transportation costs, as the main cost factor, the driver, can be saved. Drones can handle last-mile delivery of parcels, further reducing costs and increasing efficiency. Artificial intelligence could also be used to implement dynamic pricing models that incentivize users to share rides and include parcels during off-peak hours or in less congested areas. This can help to balance supply and demand and to increase overall transportation efficiency. Vehicle automation and drones can furthermore enable flexible transportation models. During off-peak hours, autonomous vehicles could for example be used primarily for parcel delivery, and during peak hours, they can switch to ride-sharing mode.

While these advancements hold significant promise, they also come with challenges such as regulatory hurdles, safety concerns, and the need for robust cybersecurity measures. Additionally, public acceptance and trust in these technologies will play a crucial role in their successful integration into the transportation and delivery ecosystem.

In the future, the integration of vehicle automation and artificial intelligence could open up new opportunities for RPP and further improve the business case. Currently, the driver remains a significant cost factor in these mobility systems, often leading to the adoption of high-capacity vehicle systems. In addition, automation of the parcel delivery process, possibly using delivery robots or parcel lockers, could facilitate the seamless integration of a logistics system into large-scale MoD systems, ensuring efficient operations.

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List of Terms and Abbreviations

MoD Mobility On Demand 4, 5, 9, 14, 21–24, 27–29, 39, 40, 43, 44, 46, 47, 52, 59, 60, 64, 67–69, 75, 77, 78, 80, 81, 86, 88, 89, 97, 105, 109, 110, 137, 143, 148, 149, 151, 152, 154, 155, 159, 160, 191

OD Origin-Destination 3, 60, 68, 77

OR Operations Research 14, 19, 22

PRO Production 31, 95, 96, 103, 106, 108, 113, 114, 117, 195–198

PuT Public Transportation 2–5, 7, 8, 14–16, 18, 19, 22, 24, 26–29, 39, 44–46, 48, 155

RME Raw Material Extraction 31, 95, 96, 103, 106, 108, 113, 114, 117, 195–198

RPP Ride Parcel Pooling 12, 30, 31, 39, 40, 44, 46–64, 66–69, 72, 73, 76–82, 86, 88, 89, 91–94, 96, 103, 105–107, 109, 112, 117–122, 124–131, 133–143, 145–157, 159, 160

SCPA Subsequent Coupled Parcel Assignment 75, 79, 81, 82, 84–87, 152

SDPA Subsequent Decoupled Parcel Assignment 73, 79, 81, 82, 84, 86, 152

SLCA Social Life Cycle Assessment 31, 33, 34, 94–96, 103, 105, 107, 110, 121, 124–126, 129–131, 157

TRP Transport Processes 94, 113, 114

TUM Technical University of Munich 133, 139, 140

USE Use 31, 94–96, 103, 105–108, 112–114, 117, 120, 121, 123, 124, 126, 130, 156, 157, 195–198

vkm Vehicle Kilometers 102, 107, 110, 120, 121, 123, 124, 130, 160

Relevant Publications for this Thesis

Chapter 3: Service and Scenario Definition

Fehn, F., Hamm, L., Engelhardt, R., & Bogenberger, K. (2022). Ride-Parcel-Pooling: Insights to Integrated Passenger and Freight Transportation through a Customer Survey. In hEART 2022-10th Symposium of the European Association for Research in Transportation.

Chapter 4: Modeling and Simulation of Ride Parcel Pooling

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Chapter 6: Real World Test of Ride Parcel Pooling

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Statement on the Use of Generative AI

The author acknowledges that he used generative AI (ChatGPT 3.5 & 4, Grammarly) exclusively for spell-checking and for revising and shortening his own texts.

Annexes

1 Thesis Color Codes

Category	Colors and HEX Codes					
Main Plot Colors	Main Color 1 #000078	Main Color 2 #E1562C	Main Color 3 #00C47E			
Trip Classification	Passenger #5751D4	Parcel #EBAB21	Pooled #B80057			
Assignment Strategies	CDPA #00BAAB	CDPA #B8ECE8	SDPA #008AF8	SDPA #BDE1FD	SCPA #B04500	SCPA #EBCFBD
Vehicle Types	Van #00A66B	Car #00598A	Rickshaw #CF61E6			
Life Cycle Phases	RME #1F77B4	PRO #FF7F0E	USE #4DAF4A	EOL #A6A6A6		

Table 1: Colors used in the visualizations throughout the thesis.

2 On-demand Mobility Simulation Model

2.1 List of Symbols

Symbol	Description
G	Street network, consisting of nodes (N) and edges (E)
N	Network nodes
E	Network edges
r_i^c	Request of customer i
o_i^c, d_i^c, t_i^c	Origin, destination, and request time of MoD customer i
r_i^p	Request of parcel i
o_i^p, d_i^p	Origin, and destination of parcel i
v	MoD vehicle
V	MoD vehicle fleet
c_v^c, c_v^p	Vehicle capacity for customers, and parcels
t_{max}^{wait}, t_{max}^{travel}	Maximum waiting, and travel time for a customer
Δ	Detour factor
tt_i^{direct}	Direct travel time for request i
ψ_k	Feasible vehicle schedule
R_ψ, P_ψ	Set of customer and parcel requests
t_b	Time needed for boarding and alighting
$\phi(\psi_k)$	Objective function for the rating of vehicle schedule ψ_k
$d(\psi_k)$	Distance to drive to complete vehicle schedule ψ_k
P	Assignment reward to prioritize passenger transport
T_p^{max}	Time when remaining parcels in the vehicles are delivered
τ_{th}	Parcel detour threshold parameter for assignment

Table 2: List of symbols in the modeling section.

2.2 FleetPy Algorithms

Algorithm 1 Passenger insertion for new customer r_i^c.

ψ_{best} = None
v_{best} = None
for all $v \in V^{ca}$ **do**
  $\psi_{\tilde{k}}(v; R_\psi \cup \{r_i^c\}, P_\psi)$ = insert($\psi_k(v; R_\psi, P_\psi), r_i^c$)
  if $\phi(\psi_{\tilde{k}}(v; R_\psi \cup \{r_i^c\}, P_\psi) < \phi(\psi_{best})$ **then**
    $\psi_{best} \leftarrow \psi_{\tilde{k}}(v; R_\psi, P_\psi \cup \{r_i^p\})$
    $v_{best} \leftarrow v$
  end if
end for
if $v_{best} \neq None$ **then**
  assignSchedule(v_{best}, ψ_{best})
end if

Algorithm 2 CDPA Insertion

for all $r_i^p \in P_u$ **do**
  ψ_{best} = None
  v_{best} = None
  for all $v \in V^{ca}$ **do**
    $\psi_{\tilde{k}}(v; R_\psi, P_\psi \cup \{r_i^p\})$ = insert($\psi_k(v; R_\psi, P_\psi), r_i^p$)
    if $d(\psi_{\tilde{k}}(v; R_\psi, P_\psi \cup \{r_i^p\})) - d(\psi_k(v; R_\psi, P_\psi)) < (1 - \tau_{th}) d(o_i^p, d_i^p)$ **then**
      if $\phi(\psi_{\tilde{k}}(v; R_\psi, P_\psi \cup \{r_i^p\}) < \phi(\psi_{best})$ **then**
        $\psi_{best} \leftarrow \psi_{\tilde{k}}(v; R_\psi, P_\psi \cup \{r_i^p\})$
        $v_{best} \leftarrow v$
      end if
    end if
  end for
  if $v_{best} \neq None$ **then**
    assignSchedule(v_{best}, ψ_{best})
    $P_u \leftarrow P_u \setminus \{r_i^p\}$
  end if
end for

Algorithm 3 S-PA Origin Insertion

for all $r_i^p \in P_u$ **do**
  ψ_{best} = None
  v_{best} = None
  for all $v \in V^{ca}$ **do**
    $\psi_{\tilde{k}}(v; R_\psi, P_\psi \cup \{o_i^p\})$ = insertOrigin($\psi_k(v; R_\psi, P_\psi), r_i^p$)
    if $d(\psi_{\tilde{k}}(v; R_\psi, P_\psi \cup \{o_i^p\})) - d(\psi_k(v; R_\psi, P_\psi)) < (1 - \tau_{th}) d(o_i^p, d_i^p)/2$ **then**
      if $\phi(\psi_{\tilde{k}}(v; R_\psi, P_\psi \cup \{o_i^p\}) < \phi(\psi_{best})$ **then**
        $\psi_{best} \leftarrow \psi_{\tilde{k}}(v; R_\psi, P_\psi \cup \{r_i^p\})$
        $v_{best} \leftarrow v$
      end if
    end if
  end for
  if $v_{best} \neq$ None **then**
    assignSchedule(v_{best}, ψ_{best})
    $P_u \leftarrow P_u \setminus \{r_i^p\}$
    $P^a_{v_{best}} \leftarrow P^a_{v_{best}} \cup \{r_i^p\}$
  end if
end for

Algorithm 4 SDPA Destination Insertion

for all $v \in V^{ca}$ **do**
  ψ_{best} = None
  r_{best} = None
  for all $r_i^p \in P_v^a$ **do**
    $\psi_{\tilde{k}}(v; R_\psi, P_\psi \cup \{r_i^p\})$ = insertDestination($\psi_k(v; R_\psi, P_\psi \cup \{o_i^p\}), r_i^p$)
    if $d(\psi_{\tilde{k}}(v; R_\psi, P_\psi \cup \{r_i^p\})) - d(\psi_k(v; R_\psi, P_\psi \cup \{o_i^p\})) < (1 - \tau_{th}) d(o_i^p, d_i^p)/2$ **then**
      if $\phi(\psi_{\tilde{k}}(v; R_\psi, P_\psi \cup \{r_i^p\})) < \phi(\psi_{best})$ **then**
        $\psi_{best} \leftarrow \psi_{\tilde{k}}(v; R_\psi, P_\psi \cup \{r_i^p\})$
        $r_{best} \leftarrow r_i^p$
      end if
    end if
  end for
  if $r_{best} \neq$ None **then**
    assignSchedule(v, ψ_{best})
    $P_v^a \leftarrow P_v^a \setminus r_i^p$
  end if
end for

Algorithm 5 SCPA Destination Insertion

for all $r_i^c \in R_t^{new}$ **do**
  $\psi_{best,u}$ = None
  $v_{best,u}$ = None
  for all $v \in V$ **do**
    $\psi_{\tilde{k}}(v; R_\psi \cup \{r_i^c\}, P_\psi)$ = insert($\psi_k(v; R_\psi, P_\psi), r_i^c$)
    if $\phi(\psi_{\tilde{k}}(v; R_\psi \cup \{r_i^c\}, P_\psi)) < \phi(v_{best,u})$ **then**
      $\psi_{best,u} \leftarrow \psi_{\tilde{k}}(v; R_\psi \cup \{r_i^c\}, P_\psi)$
      $v_{best,u} \leftarrow v$
    end if
  end for
  $\psi_{best} = \psi_{best,u}$
  $v_{best} = v_{best,u}$
  r_{best} = None
  for all $v \in V$ **do**
    $\psi_{\tilde{k}}(v; R_\psi \cup \{r_i^c\}, P_\psi)$ = insert($\psi_k(v; R_\psi, P_\psi), r_i^c$)
    for all $r_i^p \in P_v^a$ **do**
      $\psi_l(v; R_\psi \cup \{r_i^c\}, P_\psi \cup \{r_i^p\})$ = insertDestination($\psi_{\tilde{k}}(v; R_\psi \cup \{r_i^c\}, P_\psi), r_i^p$)
      if $d(\psi_l(v; R_\psi \cup \{r_i^c\}, P_\psi \cup \{r_i^p\})) - d(\psi_{best,u}) < (1 - \tau_{th}) d(o_i^p, d_i^p)/2$ **then**
        if $\phi(\psi_l(v; R_\psi \cup \{r_i^c\}, P_\psi \cup \{r_i^p\})) < \phi(\psi_{best})$ **then**
          $\psi_{best} \leftarrow \psi_l(v; R_\psi, P_\psi \cup \{r_i^p\})$
          $r_{best} \leftarrow r_i^p$
          $v_{best} \leftarrow v$
        end if
      end if
    end for
  end for
  if $v_{best} \neq$ None **then**
    assignSchedule(v, ψ_{best})
    if $r_{best} \neq$ None **then**
      $P^a_{v_{best}} \leftarrow P^a_{v_{best}} \setminus \{r_{best}\}$
    end if
  end if
end for

3 Life Cycle Sustainability Model

3.1 Ecoinvent Dataset Documentation

The detailed data-set descriptions and connected technosphere and biosphere information can be found on the Ecoinvent 3.8 Database Search. In the following all flows utilized in OpenLCA for the case study are listed:

Passenger Rickshaw

RME and PRO Phase:

- market for electric scooter, without battery | electric scooter, without battery | Cutoff, U - GLO
- market for thermoforming of plastic sheets | thermoforming of plastic sheets | Cutoff, S - GLO
- market for battery cell, Li-ion, NCA | battery cell, Li-ion, NCA | Cutoff, U - GLO

USE Phase:

- market for maintenance, electric scooter, without battery | maintenance, electric scooter, without battery | Cutoff, S - GLO
- market for electricity, low voltage | electricity, low voltage | Cutoff, S - DE
- market for electricity, low voltage, renewable energy products | electricity, low voltage, renewable energy products | Cutoff, S - CH

EOL Phase:

- market for manual dismantling of electric scooter | manual dismantling of electric scooter | Cutoff, S - GLO
- market for transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, S - RER

Passenger Car

RME and PRO Phase:

- market for passenger car, diesel | passenger car, diesel | Cutoff, U - GLO
- market for passenger car, petrol/natural gas | passenger car, petrol/natural gas | Cutoff, U - GLO
- market for passenger car, electric, without battery | passenger car, electric, without battery | Cutoff, U - GLO
- market for battery cell, Li-ion, NCA | battery cell, Li-ion, NCA | Cutoff, U - GLO
- transport, freight train | transport, freight train | Cutoff, S - DE
- market for transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, S - RER
- market for transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, S - GLO

USE Phase:

- maintenance, passenger car | passenger car maintenance | Cutoff, S - RER
- diesel production, low-sulfur, petroleum refinery operation | diesel, low-sulfur | Cutoff, S - Europe without Switzerland
- petrol production, 5% ethanol by volume from biomass | petrol, 5% ethanol by volume from biomass | Cutoff, S - CH
- market for electricity, low voltage | electricity, low voltage | Cutoff, S - DE
- market for electricity, low voltage, renewable energy products | electricity, low voltage, renewable energy products | Cutoff, S - CH

EOL Phase:

- market for manual dismantling of used passenger car with internal combustion engine | manual dismantling of used passenger car with internal combustion engine | Cutoff, S - GLO
- market for manual dismantling of used electric passenger car | manual dismantling of used electric passenger car | Cutoff, S - GLO
- market for transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, S - RER

Passenger Van

RME and PRO Phase:

- market for passenger car, diesel | passenger car, diesel | Cutoff, U - GLO
- market for passenger car, petrol/natural gas | passenger car, petrol/natural gas | Cutoff, U - GLO
- market for passenger car, electric, without battery | passenger car, electric, without battery | Cutoff, U - GLO
- market for battery cell, Li-ion, NCA | battery cell, Li-ion, NCA | Cutoff, U - GLO
- transport, freight train | transport, freight train | Cutoff, S - DE
- market for transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, S - RER
- market for transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, S - GLO

USE Phase:

- maintenance, passenger car | passenger car maintenance | Cutoff, S - RER
- diesel production, low-sulfur, petroleum refinery operation | diesel, low-sulfur | Cutoff, S - Europe without Switzerland
- petrol production, 5% ethanol by volume from biomass | petrol, 5% ethanol by volume from biomass | Cutoff, S - CH
- market for electricity, low voltage | electricity, low voltage | Cutoff, S - DE
- market for electricity, low voltage, renewable energy products | electricity, low voltage, renewable energy products | Cutoff, S - CH

EOL Phase:

- market for manual dismantling of used passenger car with internal combustion engine | manual dismantling of used passenger car with internal combustion engine | Cutoff, S - GLO
- market for manual dismantling of used electric passenger car | manual dismantling of used electric passenger car | Cutoff, S - GLO
- market for transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, S - RER

Logistics Truck

RME and PRO Phase:

- market for light commercial vehicle | light commercial vehicle | Cutoff, U - GLO
- market for battery cell, Li-ion, NCA | battery cell, Li-ion, NCA | Cutoff, U - GLO
- transport, freight train | transport, freight train | Cutoff, S - DE
- market for transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, S - RER
- market for transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, S - GLO

USE Phase:

- maintenance, light commercial vehicle | maintenance, light commercial vehicle | Cutoff, U - RER
- diesel production, low-sulfur, petroleum refinery operation | diesel, low-sulfur | Cutoff, S - Europe without Switzerland
- petrol production, 5% ethanol by volume from biomass | petrol, 5% ethanol by volume from biomass | Cutoff, S - CH
- market for electricity, low voltage | electricity, low voltage | Cutoff, S - DE
- market for electricity, low voltage, renewable energy products | electricity, low voltage, renewable energy products | Cutoff, S - CH

EOL Phase:

- market for manual dismantling of used passenger car with internal combustion engine | manual dismantling of used passenger car with internal combustion engine | Cutoff, S - GLO
- market for manual dismantling of used electric passenger car | manual dismantling of used electric passenger car | Cutoff, S - GLO
- market for transport, freight, lorry >32 metric ton, EURO6 | transport, freight, lorry >32 metric ton, EURO6 | Cutoff, S - RER

3.2 Assumptions for Life Cycle Cost Assessment

Acronym	Relevant cost components for fleet operator and platform provider
c^{SMD}	smartphone with GPS: 392€, monthly smartphone contract: 25€
c^{VO}	one-time registration fees: 41€, one-time taxi-specific inspection: 12€, annual general inspection: 95€, monthly vehicle concession with fees: 7€, monthly radio fees: 6€, annual taxes: 132€, annual insurance: 5,815€
c^{DS}	hourly driver salary: 12€ (German minimum wage)
c^{S}	monthly salary of a fleet operator (responsible for 80 vehicles): 4,670€, monthly administrator salary (responsible for 400 vehicles): 3,967€
c^{OF}	monthly costs for rent and utilities per square meter office (15 sqm/employee): 61€, office equipment (per month and employee): 80€, fleet management software (per vehicle per month): 5€
c^{IC}	interior cleaning (every 40 trips): 17€
c^{EC}	exterior cleaning (every 380km): 13€
c^{MS}	yearly maintenance and repair costs (ICEV): 2,150€, yearly maintenance and repair costs (EV): 1,505€
c^{ES}	monthly salary of research and development employee (0.021 employees/vehicle): 6,875€, monthly salary of marketing and sales employee (0.007 employees/vehicle): 5,241€, monthly salary of general administration employee (0.011 employees/vehicle): 5,967€, monthly salary of operations and support employee (0.043 employees/vehicle): 3,377€
c^{OUE}	monthly costs for rent, utilities, and equipment (per month and employee): 1001€
c^{P}	yearly smartphone applications, website maintenance, and data security costs (per trip): 0.007€
c^{ADC}	yearly costs for acquisition of drivers and customers (per trip): 0.45€
c^{VB}	yearly vehicle branding costs (per trip): 0.6€
c^{AD}	yearly advertisement costs (per trip): 0.5€
c^{TF}	transaction fare (per trip): 0.1€
c^{PF}	pickup fare (per trip): 6€
c^{RF}	ride fare (per kilometer): 1.50€

Table 3: Cost components of the fleet operator and platform provider, according to Negro et al. [2021]. The cost components were rounded wherever applicable.

3.3 Inputs to LCSA Model from Simulation

	Logistics Trucks								Ride-Pooling Vehicles					
Simulation Scenarios	Mode/ Scenario	Missing Parcels	Needed Trucks	Extra Distance		Saved Distance		Saved Trucks	Passenger Rickshaw		Passenger Car		Passenger Van	
Status Quo	10%	0	34	2,614	km	0	km	0	230,985	km	248,622	km	240,528	km
Separate	20%	0	67	4,183	km	0	km	0						
Passenger	30%	0	101	5,570	km	0	km	0	47,668	pas.	48,245	pas.	46,596	pas.
and Parcel	40%	0	134	6,863	km	0	km	0						
Fleet	50%	0	166	7,997	km	0	km	0	0	par.	0	par.	0	par.
RPP Full	Rickshaw	577	2	261	km	1,697	km	32	231,641	km	249,597	km	241,094	km
10% parcel	Car	165	1	148	km	1,491	km	33	47,553	pas.	47,982	pas.	46,460	pas.
demand	Van	1	1	23	km	2,025	km	33	5,106	par.	5,518	par.	5,682	par.
RPP Full	Rickshaw	3,386	7	1,057	km	1,826	km	60	232,285	km	250,710	km	241,933	km
20% parcel	Car	2,010	3	523	km	1,572	km	64	47,484	pas.	47,737	pas.	46,292	pas.
demand	Van	420	1	148	km	2,630	km	66	7,980	par.	9,356	par.	10,946	par.
RPP Full	Rickshaw	7,746	14	2,133	km	2,004	km	87	232,418	km	250,603	km	242,556	km
30% parcel	Car	5,089	5	1,033	km	2,556	km	96	47,466	pas.	47,589	pas.	46,127	pas.
demand	Van	1,860	2	316	km	3,226	km	99	9,303	par.	11,960	par.	15,189	par.
RPP Full	Rickshaw	12,795	20	2,651	km	2,449	km	114	232,747	km	250,966	km	242,607	km
40% parcel	Car	9,363	9	1,649	km	2,869	km	125	47,422	pas.	47,591	pas.	45,981	pas.
demand	Van	4,352	3	694	km	4,090	km	131	9,937	par.	13,369	par.	18,380	par.
RPP Full	Rickshaw	17,752	26	3,336	km	2,959	km	140	232,687	km	251,015	km	243,294	km
50% parcel	Car	14,199	14	2,463	km	3,141	km	152	47,398	pas.	47,484	pas.	45,948	pas.
demand	Van	7,684	4	834	km	4,397	km	162	10,663	par.	14,216	par.	20,731	par.

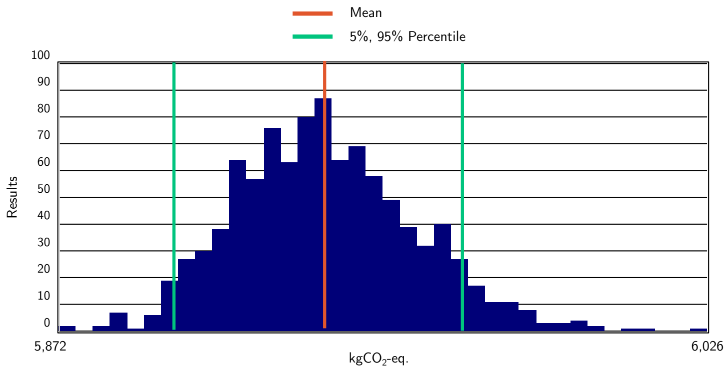
Table 4: Simulation results, including *Status Quo* and *Full RPP* scenarios, varying parcel penetration rates (10-50%), and vehicles (freight truck, rickshaw, car, van). Left part of the table displays the logistics trucks and the right part the ride-pooling operation, including served passengers (pas.), parcels (par.) and traveled kilometers (km).

3.4 Inputs to LCSA Model from HBEFA

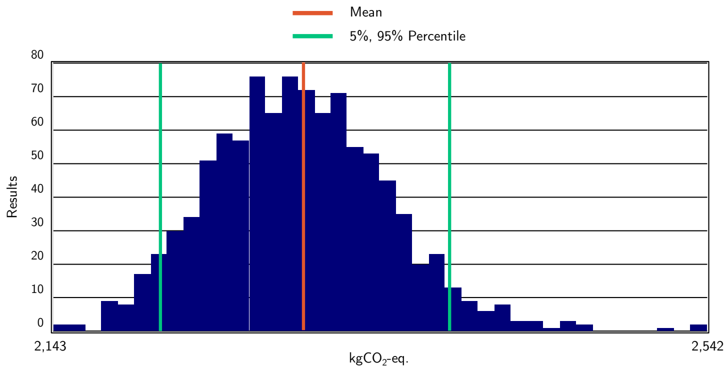
	Rickshaw	Car			Van			Freight Truck		
Emission Factor [Unit]	electric	petrol	diesel	electric	petrol	diesel	electric	petrol	diesel	electric
Fuel [g/km]	-	55.70	53.60	-	66.84	64.32	-	82.10	79.87	-
Calorific Values [kWh/kg]	-	12.72	12.64	-	12.72	12.64	-	12.72	12.64	-
Fuel [kWh/km]	0.05	0.71	0.68	0.18	0.85	0.81	0.21	1.04	1.01	0.24
$CO_2 - eq.$ [g/km]	0.00	160.01	160.59	0.00	192.12	192.71	0.00	238.55	239.28	0.00
SO_2 [mg/km]	0.00	0.86	0.81	0.00	1.03	0.97	0.00	1.28	1.20	0.00
CO [mg/km]	0.00	65.86	496.79	0.00	79.42	597.64	0.00	98.26	738.24	0.00
NO_X [mg/km]	0.00	499.30	72.48	0.00	602.16	87.20	0.00	744.96	107.71	0.00
PM_{10} (non-exhaust) [mg/km]	10.75	29.25	29.25	29.25	35.28	35.19	48.76	43.64	43.47	38.99
PM_{10} (exhaust) [mg/km]	0.00	4.03	1.02	0.00	4.85	1.23	0.00	6.01	1.51	0.00
$NMVOC$ [mg/km]	0.00	4.34	4.63	0.00	5.23	5.57	0.00	6.47	6.89	0.00
NH_3 [mg/km]	0.00	3.85	19.60	0.00	4.64	23.58	0.00	5.74	29.13	0.00

Table 5: Scaled emission factors [Handbook of Emission Factors for Road Transport (HBEFA), 2023], fuel consumption [Handbook of Emission Factors for Road Transport (HBEFA), 2023], and calorific values [European Automobile Manufacturers' Association, 2023] for all investigated RPP vehicle types including different drive technologies. ($NMVOC$ of electric vehicles were corrected to "0.00", according to Bebkiewicz et al. [2021], as HBEFA values were faulty.)

3.5 Monte Carlo Simulations

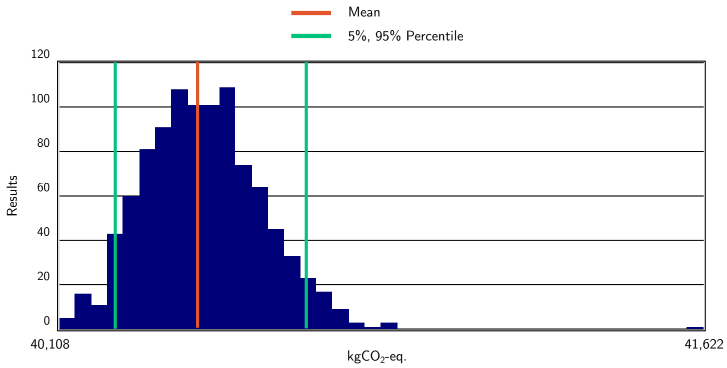


(a) Rickshaw EV German energy mix (σ = 53.14).

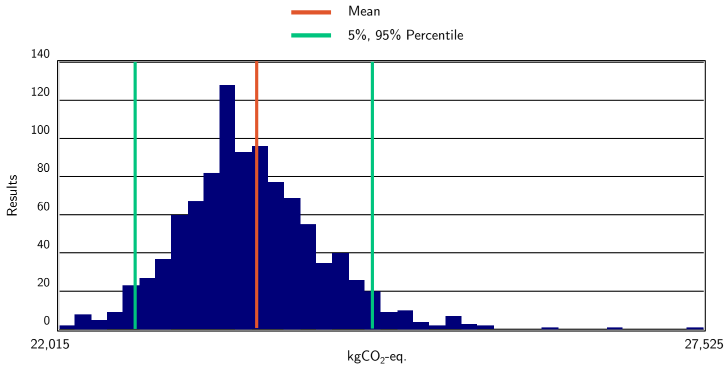


(b) Rickshaw EV renewable energy mix (σ = 54.84).

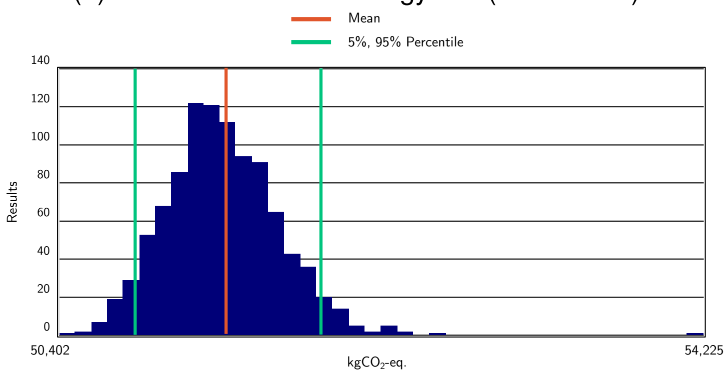
Figure 1: Histograms of Monte Carlo simulations for all modeled rickshaw types introduced to the case study.



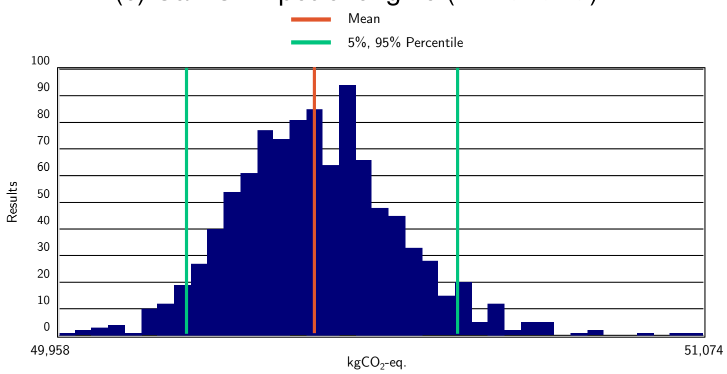
(a) Car EV German energy mix (σ = 635.36).



(b) Car EV renewable energy mix (σ = 625.85).

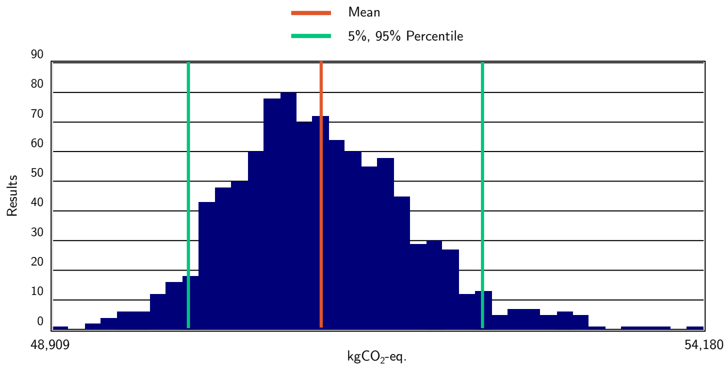


(c) Car ICEV petrol engine (σ = 348.73).

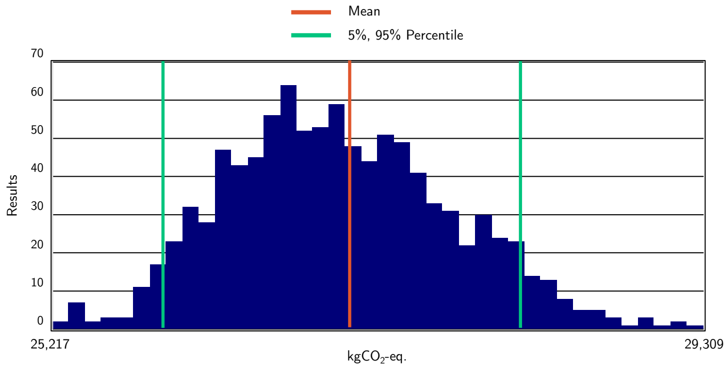


(d) Car ICEV diesel engine (σ = 343.49).

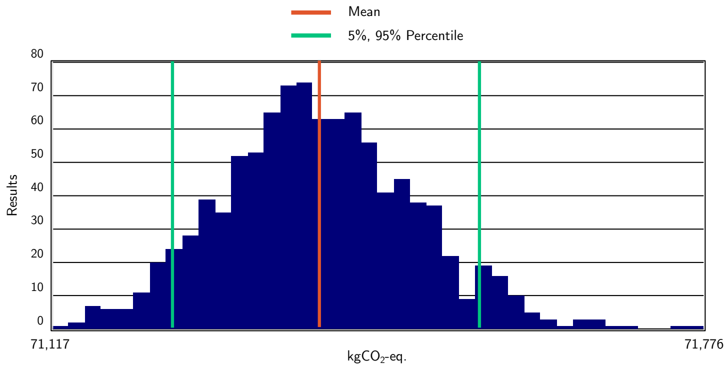
Figure 2: Histograms of Monte Carlo simulations for all modeled car types introduced to the case study.



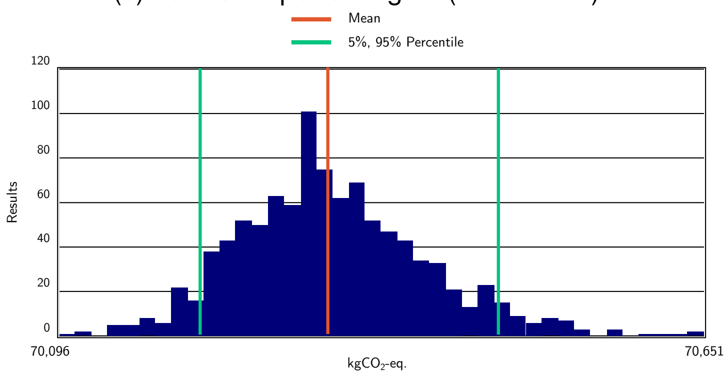
(a) Van EV German energy mix (σ = 744.94).



(b) Van EV renewable energy mix (σ = 708.06).

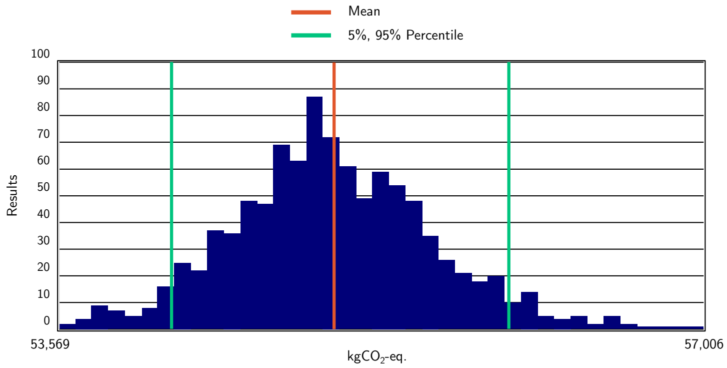


(c) Van ICEV petrol engine (σ = 493.29).

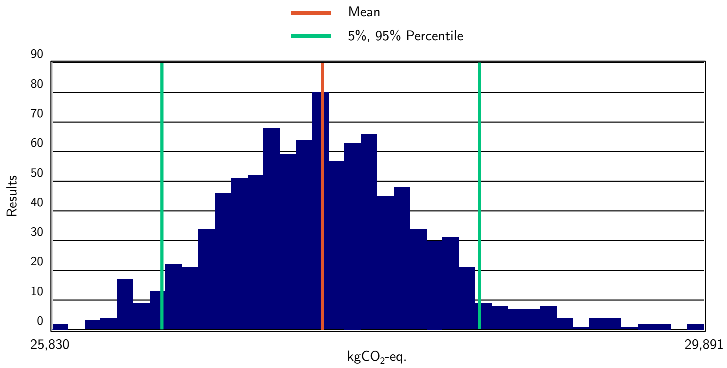


(d) Van ICEV diesel engine (σ = 516.03).

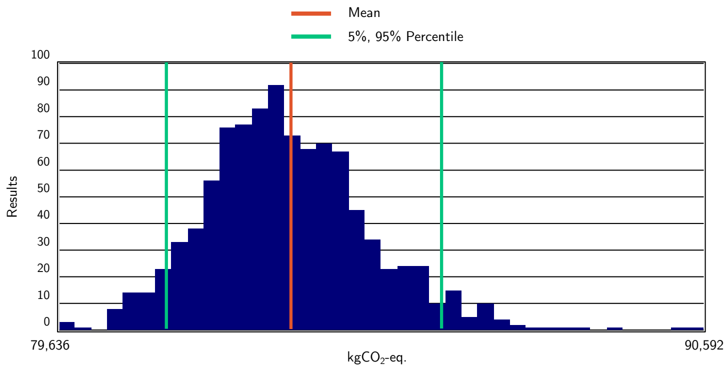
Figure 3: Histograms of Monte Carlo simulations for all modeled van types introduced to the case study.



(a) Delivery Vehicle EV German energy mix (σ = 507.83).



(b) Delivery Vehicle EV renewable energy mix (σ = 552.00).



(c) Delivery Vehicle ICEV diesel engine (σ = 483.92).

Figure 4: Histograms of Monte Carlo simulations for all modeled delivery vehicle types introduced to the case study.

4 Field Test Service Parameters

Parameter	Value
Active Unique User Accounts	54
Total Number of Requests	191
Share of Passenger Requests	87%
Share of Parcel Requests	13%
Total Number of Served Trips	47
Share of Passenger Trips	74%
Share of Parcel Trips	18%
Share of Combined Trips	8%
Average Trip Length	0,88 km
Min. Trip Length	0,12 km
Max. Trip Length	4,15 km
Average Vehicle Speed	14,1km/h
Average Passenger Occupancy	1,4
Average Boarding Time	56,7s

Table 6: Service parameters derived from the field test.