Integration of Passenger and Freight Transportation using Autonomous Shuttles: A Simulation Study on Sustainability-Related KPIs

Johannes Staritz, research assistant and PhD student,
Faculty IV – Business and Informatics, Hochschule Hannover, Hannover

Helen Sand, research assistant,
Faculty IV – Business and Informatics, Hochschule Hannover, Hannover

Marvin Auf der Landwehr, post-doctoral research assistant,
Faculty IV – Business and Informatics, Hochschule Hannover, Hannover

Christoph von Viebahn, professor,
Faculty IV – Business and Informatics, Hochschule Hannover, Hannover

Maylin Wartenberg, professor,
Faculty IV – Business and Informatics, Hochschule Hannover, Hannover

Extended Abstract

Summary. Autonomous and integrated passenger and freight transport (APFIT) is a promising approach to tackle both, traffic and last-mile-related issues such as environmental emissions, social and spatial conflicts or operational inefficiencies. By conducting an agent-based simulation, we shed light on this widely unexplored research topic and provide first indications regarding influential target figures of such a system in the rural area of Sarstedt, Germany. Our results show that larger fleets entail inefficiencies due to suboptimal utilization of monetary and material resources and increase traffic volume while higher amounts of unused vehicles may exacerbate spatial conflicts. Nevertheless, to fit the given demand within our study area, a comparatively large fleet of about 25 vehicles is necessary to provide reliable service, assuming maximum passenger waiting times of six minutes to the expense of higher standby times, rebalancing effort, and higher costs for vehicle acquisition and maintenance.

Keywords. integrated passenger and freight transport, rural transport simulation, sustainability, key performance indicators, agent-based simulation

1. Introduction

Within rural areas, points of interests and supply are generally located far away from the inhabitant's residences, thus travel distances are comparatively long (e.g. Poltimäe et al. 2022). Due to the low local population density, rural transport operators struggle to establish economically feasible transport services that satisfy the local mobility needs (e.g. Cavallaro and Nocera 2023). Therefore, transportation service coverage is low, which is why inhabitants have to rely on privately-owned cars for their mobility needs (Mounce et al. 2020; Poltimäe et al. 2022). However, this transportation mode is related to negative effects such as high emissions as well as social and spatial conflicts (Nieuwenhuijsen and Khreis 2016; Urry 2004). Making transport more sustainable is high on the agenda for transportation planners and has become a relevant concern for policy makers across the globe (e.g. Bauchinger et al. 2021). Additionally, the first and the last leg of freight transport movements is also a highly challenging aspect (Macioszek 2018). Over the last years, reinforced by the expansion of e-commerce and the COVID-19 pandemic, the number of parcel deliveries has continuously risen (e.g. Romano Alho et al. 2021). This has led to smaller and spatially as well as temporally more fragmented shipments that involve a wide range of interacting users, resulting in multiple and sporadic exchanges (Bruzzone et al. 2021; Romano Alho et al. 2021). Moreover, the provision of express and return services contributes to operational inefficiencies and potentially increases negative traffic-related externalities (Bruzzone et al. 2021; Cavallaro and Nocera 2023; Romano Alho et al. 2021).

To tackle both, mobility- and last-mile-delivery-related problems, the integration of passenger and freight flows in a single transport service fleet is a promising approach (Cavallaro and Nocera 2023). Emerging technologies such as autonomous and electrified driving further increase the potential to minimize negative externalities and operational costs, e.g. by reducing personnel requirements (Bucchiarone et al. 2021). Combining their benefits with the operational benefits of integrated transportation systems for passengers and freight may be suitable to increase the efficiency of last mile deliveries but also to reduce negative traffic-related impacts on economic, environmental, and social performance metrics (Sun et al. 2020). However, research on integrated passenger and freight transport using autonomous vehicle is scarce and lacks approaches that compare different specifications and parameter constellations to find environmentally, socially and economically valuable scenarios of APFIT under given demand structures within rural areas. To close this gap and to shed first light on tradeoffs between influential target figures, we apply an agent-based simulation using the software *AnyLogic*. This method is suitable to illustrate and analyze highly complex systems with a large degree of non-linear interdependencies and components (Auf der Landwehr et al. 2020). Furthermore, simulation helps to mimic and analyze systems with highly intricate interrelationships, various design variants, and operational properties that have not yet been piloted in practice (e.g. APFIT; Wenzel 2018). In doing so, we aim to compare the performance of different scenario variations of APFIT regarding relevant key performance indicators (KPIs) within the rural area of Sarstedt, Germany. Hereby, we shed light on this widely unexplored research topic and provide valuable information for future research. By providing details of parameter variations and their effects and tradeoffs, we additionally contribute a conceptual decision base for future implementations of APFIT in practice.

2. Related Work

In order to evaluate potential improvements of integrated passenger and freight flows, compared to the current (separate) transport schemes, Bruzzone et al. (2021) propose a set of operational, environmental and social key performance indicators (KPIs). They defined the variation in average daily traffic, in distance covered, and in load factors to be critical performance measures. Furthermore, they emphasize freight service frequency, used energy, air pollution and external as well as labor costs to be important benchmarks. Additionally, the results of two case studies indicate that integrated passenger and freight transport is particularly effective in cases where reduced freight volumes, limited freight pickup/delivery locations and comparatively low elasticity of travel demand reduce the constraints to the adoption of this integrated scheme. Cavallaro and Nocera (2022) provide a sound overview about research in the field of integrated passenger and freight transport. They identified 69 relevant contributions to this topic and provide insights about applied approaches, means of transport, and the territorial scale of the studies reviewed. They revealed that a vast majority of research focuses on urban areas while rural areas are widely unexplored. Furthermore, they identified only two studies, considering autonomous vehicles for the integration of passenger and freight transport. The first, a study conducted by Schlenther et al. (2020) proposes a methodology to simulate the behavior of privately-owned autonomous vehicles that are hired for parcel delivery by the service provider. Using the software MATSim, they investigated the impacts of resignation from fleet ownership by a transport service company operating on a city-wide scale in Berlin, Germany. They revealed promising cost reductions of the operator due to resignation from fleet ownership and the lowering of driver costs to the expense of an increase of vehicle miles travelled and of en-route vehicles throughout the day. The second study that was identified by the literature review of Cavallaro and Nocera (2022) was conducted by Manchella et al. (2021). They propose a distributed model-free algorithm for joint ride-sharing of passengers and goods that uses deep neural networks and reinforcement learning. The results show that the introduced algorithm paired with multi-hop transfer of goods is able to achieve significantly higher operational efficiency as well as a lower environmental footprint compared to a case where goods are delivered directly from pick-up to drop-off locations without transit (no hoptrips) or a case where passengers and freight are transported in separate vehicles, respectively. Sun et al. (2020) explored an integrated public transport system deploying the Toyota e-palette or an exchangeable capsule design as described in Ulrich et al. (2019). They introduced an illustrative example of the system, summarize its technical challenges, and describe typology and components to model such an integrated mobility system for urban areas. Furthermore, the issues concerning business model and governance intervention to promote such an urban integration were explicitly discussed. Beirigo et al. (2018) researched autonomous shuttles with compartments for simultaneously moving passengers and parcels and formulated a mathematical routing problem for this mode of transport. They implemented a mixed-integer linear programming formulation and compared the performance of single-purpose and mixed-purpose fleets on 216 transportation scenarios. They revealed that mixed-purpose fleets perform in average 11% better than single-purpose fleets and found that the performance of the mixed-purpose fleet improves as logistic demand increases.

Yet, to the best of our knowledge, there is a dearth of research that explores operational trade-offs of APFITs in rural areas, particularly when it comes to sustainability-related KPIs. This study is a first attempt to generate meaningful insights on the operational implications of such systems and opts to pave the ground for additional research in this emerging and promising domain.

3. Methodology

In order to compare the performance of different scenario variations of APFIT regarding relevant KPIs, we develop an agent-based simulation model for the exemplary rural area of Sarstedt in Germany. This study area is located between the cities of Hanover and Hildesheim in Lower Saxony and is characterized by high commuter traffic into bordering regions. Nevertheless, for their daily traffic, inhabitants of this region highly depend on privately owned vehicles as public transport coverage is comparatively weak. Thus, using the multimethod software *AnyLogic*

(Version 8.8.1), we illustrate and evaluate the concept of APFIT for this area by applying 27 different parameter variations in order to reveal tradeoffs between influential target figures (see Figure 1). We thereby measure total fleet kilometers driven, average customer waiting time, and the vehicle utilization related KPIs mean vehicle time at service, mean vehicle time in standby, and total vehicle time spend rebalancing. Additionally, we explore the number of cancelled mobility requests due to exceeded maximum passenger waiting time. These KPIs provide insights about related sustainability metrics such as energy and space consumption, the use of material and financial resources, as well as the service reliability, vehicle utilization, and related abrasion.

We simulate and compare the results of the scenarios on a daily basis (from 00:00 a.m. to 12:00 p.m.). For our concept of APFIT, parcel deliveries, thus the actual simultaneous transport of passenger and freight takes place only between 08:00 a.m. and 07:00 p.m. During that time, mixed routes occur where the delivery of parcels to households and the fulfilment of mobility demand at the stopping points alternate. To achieve a preferably realistic mobility demand scenario, a list of mobility requests is generated based on traffic-flow information that have been extracted from mobile communication traffic data and secondary studies on penetration rates for on-demand transports in rural areas. Traffic flows are mapped based on a total of 50 mobility clusters within the area of investigation with a maximum size of 800×800 meters. Based on the resulting list of mobility requests, a pick-up-and-delivery problem is defined and subsequently solved by means of *Google OR Tools*. The objective function of this mathematical problem is to minimize the total distance driven. Regarding the start to destination relationships, the only constraint of the problem is that the destination point must be located after the starting point. As APFIT includes shared rides, the destination point does not have to follow directly after the starting point. Instead, several starting points may be lined up before the destination points follow. From the simulation model, a distance matrix with linear distances (beeline) and start to destination relationships is overhanded to *Google OR Tools*.

For each vehicle, the necessary detour to serve a request is determined. A mobility request is assigned to the vehicle that has the shortest detour. To enhance vehicle utilization, ride-sharing is applied and empty vehicles are prioritized. The vehicle, a request has been assigned to, always moves directly towards the stopping point which is ranked first in its mobility order list. This list is vehicle-specific and contains only the orders that were assigned to the vehicle. After the vehicle has arrived, it will be checked, which mobility requests belong to the given stopping point and passengers embark or disembark the vehicle. Subsequently, the vehicle consults its mobility order list again for further requests. If further requests exist, the vehicle moves directly towards the next stopping point on the list. Otherwise, the vehicle will be redistributed to areas where demand is expected. To predict the total number of journeys from a specific mobility cluster into another at a specific weekday at a specific time, we implemented a machine learning model (ML-model) into the agent-based simulation that was trained using the aforementioned mobile communication data. Vehicles are initially loaded with parcels. We assume the delivery order list to be known in advance and do not apply any parcel reloading to vehicles during the day. Based on the order list, a capacitated-vehicle-routing problem is formulated, whose constrain is the maximum capacity. The assignment of routes to vehicles is also conducted using *Google OR Tools*. In order to deliver parcels, the vehicle always moves to the receiving household which is ranked first on the delivery order list and unloads/delivers the designated parcels. A vehicle conducting a delivery order while a new mobility request occurs will finish the delivery order and subsequently serve the new mobility request. Upcoming mobility requests are always prioritized over outstanding delivery orders and will be served first to reduce customer waiting times. Upon arrival at a destination of a current order or request, vehicles iterate over their list of mobility requests and delivery orders to check which request is assigned to this stopping point or which order belongs to this household.

4. Results and Discussion

To assess APFIT regarding relevant KPIs within the area of Sarstedt, Germany, the proposed simulation model has been employed for 27 different simulation experiments. For each experiment, the input parameters fleet size, parcel capacity per vehicle and maximum passenger waiting time were set in varying constellations, which were determined based on state-of-the-art literature and expert feedback from local mobility and logistics providers (see Figure 1 and Figure 2). Assuming 2% of all mobility requests (419 in total) and 25% of all delivery requests (192 in total) to be fulfilled by the fleets, we determined mean kilometers per vehicle driven and mean vehicle time at service, standby, or rebalancing. Furthermore, we assessed the number of canceled mobility requests, the average customer waiting time, and total fleet kilometers driven. Those KPIs are representative for ecological, economic and social performance metrics such as consumption of energy and space, or the use of material and financial resources. Furthermore, they provide insights about reliability of the provided service, vehicle utilization and related abrasion.

Our results show that larger fleets lead to higher mean vehicle times in standby and accordingly to lower mean vehicle times at service. This indicates that larger fleets may imply inefficiencies due to suboptimal utilization of monetary and material resources. Furthermore, unused vehicles may exacerbate spatial conflicts due to increased parking demand. While a higher number of employed vehicles slightly decreases the mean vehicle time spend rebalancing, the total time for rebalancing increases and potentially leads to higher overall traffic volume. In line with lower vehicle utilization when employing a larger fleet, the mean kilometers per vehicle driven decrease with an increase of fleet size (see Figure 1). This relives single vehicles from work load, potentially minimizes material abrasion, and may facilitate time windows for maintenance and repair.

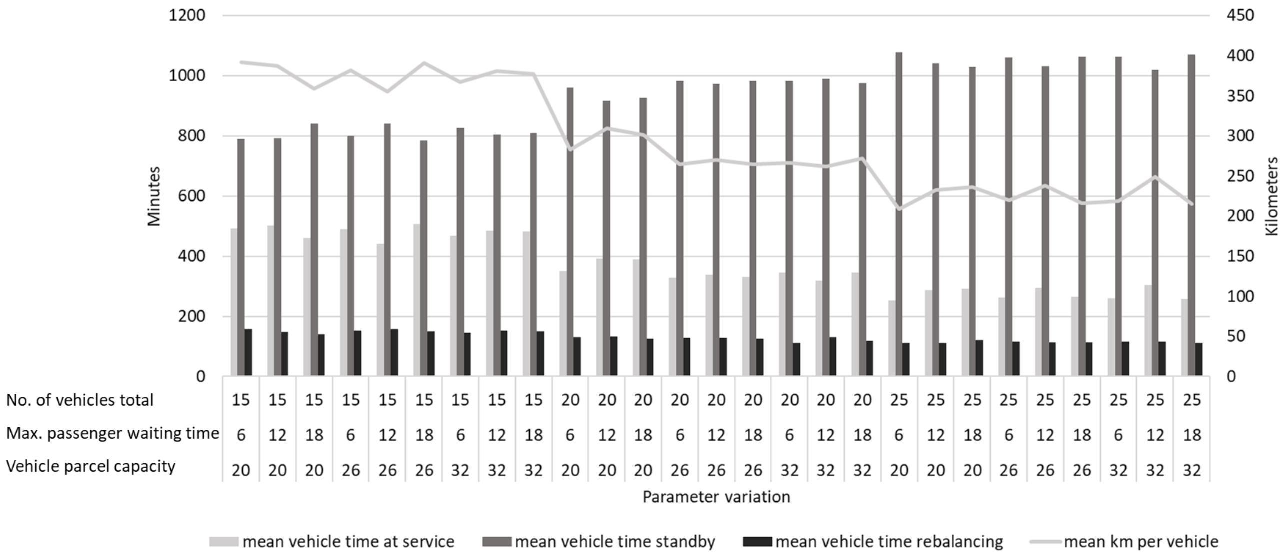

Figure 1. Vehicle utilization KPIs and mean kilometers driven per parameter variation

Nevertheless, the total fleet kilometers driven do not increase with the number of vehicles employed as less vehicles need to drive longer distances to serve a given demand (see Figure 2). Thus, larger fleets seem to have no direct influence on traffic volume per se. Instead, negative traffic-related effects of larger fleets seem to be caused by higher vehicle times in standby and total time spend for vehicles rebalancing resulting in increased consumption of parking space, congestion, accidents and energy consumption. We found that the maximum passenger waiting time is less influential to the number of unserved (cancelled) request compared to the fleet size. This suggests that in terms of reliable service provision, the time sensitivity of passengers is less important than the number of employed vehicles. Thus, future research may focus on optimizing fleet sizes rather than on in-depth analyses of passenger time sensitivity. The number of cancelled requests reliably reaches zero when a fleet of 25 vehicles is employed. This suggest that under the given demand structures in the area of Sarstedt, Germany a fleet of about 25 vehicles fits the demand. This number of vehicles enables reliable service provision assuming comparatively sensitive maximum passenger waiting times of six minutes to the expense of higher standby times, traffic volume due to rebalancing, and higher costs for vehicle acquisition and maintenance. Additionally, we found indications that even slightly higher parcel carrying capacities significantly decrease the total fleet kilometers driven. Thus, future research may focus on the expansion of vehicle parcel capacities from a conceptional and design point of view to further enhance vehicle utilization and to contribute to the reduction of resource requirements.

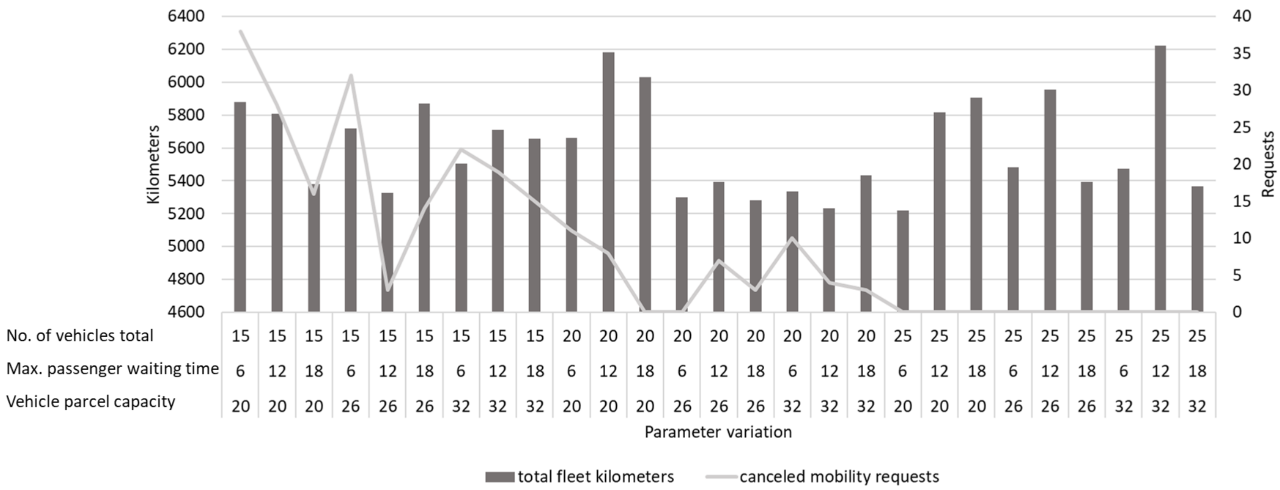

Figure 2. Total fleet kilometers driven and number of unserved requests per parameter variation

Our proposed simulation approach provides first insights on the widely unexplored research topic of integrated passenger and freight transport using autonomous shuttles. By conducting 27 simulation experiments we provide first details about parameter variations and their effects on specific target figures. Our approach supports future (simulation) studies by providing a sound model for application of APFIT in rural areas. Furthermore, we contribute a conceptual decision base for future implementations of the concept in practice. Nevertheless, and similar to the insights of Beirigo et al. (2018), the results are still highly dependent on the parameters assumed and further research is needed to find an equilibrium between the most influential factors (tradeoffs) to provide sound parameter options for fleet operators. Additionally, to simplify our approach we made several assumptions and excluded a number of aspects from our examination, which may serve as fruitful amendments for future research. We did not consider any environmental factors such as congestion, accidents or other traffic-related disorders. Furthermore, the process of loading parcels into vehicles was not illustrated by our simulation. Instead, we assumed all parcels to be initially loaded to vehicles at the depot. Similarly, we assumed that all recipients are actually encountered for delivery and did not consider varying parcel sizes and their influence on vehicle capacities. Moreover, we did not consider a detour factor limiting the passenger travel time and detours caused by pooling of different requests.

Ultimately, further research is needed to expand our approach to assess the economic feasibility by implementing monetary cost models or the environmental impact by applying models to measure the actual amount of energy consumption of APFIT.

Acknowledgement

The authors would like to thank the German Federal Ministry for Digital and Transport (BMDV) for its financial support and the project sponsor TÜV Rhineland for supervision of the research project *Kombinom_2* with the funding code 19F2187B.

References

Auf der Landwehr, Marvin, Maik Trott, and Christoph von Viebahn. 2020. „Waste of Time and Money? Constructing an Applicability Framework for Organizational Use of Simulation Studies and Digital Twins." In *International Conference on Information Systems* 41, no. 9: 1-9.

Bauchinger, Lisa, Anna Reichenberger, Bryonny Goodwin-Hawkins, Jurij Kobal, Mojca Hrabar, and Theresia Oedl-Wieser. 2021. "Developing Sustainable and Flexible Rural–Urban Connectivity through Complementary Mobility Services." In *Sustainability* 13, no. 3: 1-23. https://doi.org/10.3390/su13031280.

Beirigo, Breno, Frederik Schulte, and Rudy Negenborn. 2018. „Integrating People and Freight Transportation Using Shared Autonomous Vehicles with Compartments." In *IFAC-PapersOnLine* 51, no. 9: 392–397. https://doi.org/10.1016/j.ifacol.2018.07.064.

Bruzzone, Francesco, Federico Cavallaro, and Silvio Nocera. 2021. "The integration of passenger and freight transport for first-last mile operations." In *Transport policy* 100: 31–48. https://doi.org/10.1016/j.tranpol.2020.10.009.

Bucchiarone, Antonio, Sandro Battisti, Teresa Galvao Dias, and Philip Feldman. 2021. "Guest Editorial Diversification in Urban Transportation Systems and Beyond: Integrating People and Goods for the Future of Mobility." In *IEEE Transactions on Intelligent Transportation Systems* 22, no. 4: 2008–2012. https://doi.org/10.1109/TITS.2021.3067410.

Cavallaro, Federico, and Silvio Nocera. 2022. "Integration of passenger and freight transport: A concept-centric literature review." In *Research in Transportation Business & Management* 43: 1-11. https://doi.org/10.1016/j.rtbm.2021.100718.

Cavallaro, Federico, and Silvio Nocera. 2023. "Flexible-route integrated passenger–freight transport in rural areas." In *Transportation Research Part A: Policy and Practice* 169: 1-20. https://doi.org/10.1016/j.tra.2023.103604.

Macioszek, Elżbieta. 2018. "First and Last Mile Delivery – Problems and Issues." In *Advanced Solutions of Transport Systems for Growing Mobility*, ed. by Grzegorz Sierpiński, 147–154. Cham: Springer International Publishing.

Manchella, Kaushik, Abhishek Umrawal, and Vaneet Aggarwal. 2021. "FlexPool: A Distributed Model-Free Deep Reinforcement Learning Algorithm for Joint Passengers and Goods

Transportation." In *IEEE Transactions on Intelligent Transportation Systems* 22, no. 4: 2035–2047. https://doi.org/10.1109/TITS.2020.3048361.

Moerner, Moritz von. 2019. "Demand-oriented mobility solutions for rural areas using autonomous vehicles." In *Autonomous Vehicles and Future Mobility* ed. by Pierluigi Coppola, and Domokos Esztergár-Kiss, 43–56, Elsevier.

Mounce, Richard, Mark Beecroft, and John Nelson. 2020. "On the role of frameworks and smart mobility in addressing the rural mobility problem." In *Research in Transportation Economics* 83: 1-9. https://doi.org/10.1016/j.retrec.2020.100956.

Nieuwenhuijsen, Mark, and Haneen Khreis. 2016. "Car free cities: Pathway to healthy urban living." In *Environment International* 94: 251–262. https://doi.org/10.1016/j.envint.2016.05.032.

Poltimäe, Helen, Merlin Rehema, Janika Raun, and Age Poom. 2022. "In search of sustainable and inclusive mobility solutions for rural areas." In *European Transport Research Review* 14, no. 1: 1-17. https://doi.org/10.1186/s12544-022-00536-3.

Romano Alho, André, Takanori Sakai, Simon Oh, Cheng Cheng, Ravi Seshadri, Wen Han Chong, Yusuke Hara, Julia Caravias, Lynette Cheah, and Moshe Ben-Akiva. 2021. "A Simulation-Based Evaluation of a Cargo-Hitching Service for E-Commerce Using Mobility-on-Demand Vehicles." In *Future Transportation* 1, no. 3: 639–656. https://doi.org/10.3390/futuretransp1030034.

Schlenther, Tilmann, Kai Martins-Turner, Joschka Bischoff, and Kai Nagel. 2020. "Potential of Private Autonomous Vehicles for Parcel Delivery." In *Transportation Research Record: Journal of the Transportation Research Board* 2674, no. 11: 520–531. https://doi.org/10.1177/0361198120949878.

Sun, Shanshan, Yiik Wong, Xiaodong Liu, and Andreas Rau. 2020. "Exploration of an integrated automated public transportation system." In *Transportation Research Interdisciplinary Perspectives* 8: 1-9. https://doi.org/10.1016/j.trip.2020.100275.

Ulrich, Christian, Horst Friedrich, Jürgen Weimer, and Stephan Schmid. 2019. "New Operating Strategies for an On-the-Road Modular, Electric and Autonomous Vehicle Concept in Urban Transportation." In *World Electric Vehicle Journal* 10, no. 4: 1-16. https://doi.org/10.3390/wevj10040091.

Urry, John. 2004. "The 'System' of Automobility." In *Theory, Culture & Society* 21 no. 4-5: 25–39. https://doi.org/10.1177/0263276404046059.

Wenzel, Siegrid. 2018. „Simulation logistischer Systeme". In *Fachwissen Logistik. Modellierung logistischer Systeme* ed. by Horst Tempelmeier, 1-34, Berlin, Heidelberg: Springer

This paper could be cited as:

Johannes Staritz, Helen Sand, Marvin Auf der Landwehr, Christoph von Viebahn, Maylin Wartenberg. 2023. "Integration of Passenger and Freight Transportation using Autonomous Shuttles: A Simulation Study on Sustainability-Related KPIs." In *2023 International Scientific Symposium on Logistics: Conference Volume*, ed. by Thorsten Schmidt, Kai Furmans, Bernd Hellingrath, René de Koster, Anne Lange, and Hartmut Zadek, 131–138. Bremen: Bundesvereinigung Logistik. https://nbn-resolving.org/urn:nbn:de:bsz:14-qucosa2-855859. https://doi.org/10.25366/2023.129.