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Transport-related effects of rail-based urban parcel transport: scenario analysis and policy implications

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Abstract

The rapid growth of e-commerce has led to increased parcel volumes, posing challenges for sustainable city logistics. This study evaluates the potential of a combined cargo and passenger tram system as an alternative to light commercial vehicle (LCV) shipments. Empirically extending the agent-based freight demand model 'logiTopp', transport-related effects are analyzed through scenario simulations. Results show that a cargo tram can shift LCV mileage to sustainable modes, though the overall shift exceeds saved LCV mileage. The study highlights operational challenges like missing rail access at distribution centres and emphasizes the need for policy incentives to foster the cargo tram's potential.

Keywords: urban rail-based transport; cargo tram; parcel shipments; freight demand model; agent-based modelling; sustainable city logistics

1. Introduction and Related Work

In recent years, e-commerce has grown rapidly worldwide. Between 2012 and 2022, sales volumes tripled in Germany, leading to a sharp rise in parcel volumes and, hence, in courier, express, and parcel (CEP) shipments (BIEK, 2023). Although current studies show that CEP traffic accounts for only ~1 % of the urban traffic volume (Kummer et al., 2021), light commercial vehicles (LCVs), typically used by CEP service providers (CEPSPs), e.g., emit significantly more pollutants than passenger vehicles (Allekotte et al., 2020). Their larger size and longer presence in cities also increase public space consumption and congestion, often caused by second-row parking during deliveries (Behrends, 2011). To prevent CEPSPs from simply scaling fleets in response to growing demand, sustainable city logistics concepts must be explored, prioritizing environmental responsibility and resource efficiency.

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A potentially sustainable alternative is using urban rail systems for parcel deliveries with so-called cargo trams (Behiri et al., 2018). As outlined in Browne et al. (2014), this approach can be effective if integrated into an intermodal system, where rail infrastructure is used to transport goods from distribution centres to centralized locations in urban cores (city hubs). From there, goods are shipped using sustainable road vehicles such as cargo bikes. The basic idea behind a cargo tram is the utilization of passengers' unused capacity of rail-based public transit for freight transport (De Langhe et al., 2019; Van Duin et al., 2019). De Langhe et al. (2019) distinguish three operational modes: dedicated freight trams using the existing urban rail infrastructure, freight wagons coupled with passenger trams, and combined passenger and freight transport within the same tram, each with advantages and limitations.

Comparing the scarce number of real-world implementations of cargo tram systems, past pilot projects in European cities such as Paris, Amsterdam, and Vienna predominantly applied dedicated freight tram systems. While the system is the most flexible regarding logistical operations, a major bottleneck is the limited urban rail network capacity, causing failure of some of those projects (Arvidsson and Browne, 2013). Freight wagons coupled with passenger trams have not been realized yet. Although less capacity-intensive, conceptual studies also expect capacity issues (Cochrane et al., 2017). Moreover, challenges could arise from coupling and decoupling processes. In contrast, combined passenger and freight transport within the same tram vehicle utilizes existing transport capacities while conserving resources. Pilots of this type of system have only started recently, such as in Karlsruhe, Germany (LogIKTram, 2023). With studies suggesting economic benefits due to reduced personnel costs (Bektaş et al., 2017), significant operational challenges persist through the full integration in the passenger transport, particularly time-sensitive manual loading and unloading processes (Arvidsson and Browne, 2013). Pilots like Karlsruhe aim to solve this by integrating automated handling technologies to boost transshipment efficiency and ensure schedule reliability, both of which are critical to the success of cargo trams (Regué and Bristow, 2013).

Reviewing different studies and pilot projects on cargo tram systems reveals that these can be effective city logistics measures, though the socio-economic benefits outweigh the business-economic gains (De Langhe et al., 2019). Beyond the technical and operational feasibility of city logistics innovations such as a cargo tram, their success also depends on governance frameworks and the active involvement of all relevant stakeholders (Marcucci et al., 2023). For example, Marcucci et al. (2017) showed that collaborative governance models foster stakeholders' support and commitment of new city logistics solutions, and consequently leading to a more effective realization. Moreover, Le Pira et al. (2017) emphasized the importance of accounting for stakeholders' preferences and behavioral analysis to foster an effective participatory policy-making process for city logistics solutions.

However, a key limitation is the lack of detailed consideration of a cargo tram's transport-related effects and intermodal integration. Existing studies evaluating the effectiveness of a cargo tram system are either qualitative in nature (Arvidsson and Browne, 2013; Strale, 2014) or, in the case of quantitative studies, have a solid economic focus, e.g., cost-benefit analyses (De Langhe et al., 2019; Van Duin et al., 2019), monetizing transport-related effects in rough projections based on aggregated key figures. Although a precise knowledge of those effects, like changes of freight vehicle kilometers travelled, is essential for policymakers to assess the effectiveness of such a system and to implement targeted measures, detailed analyses, e.g., through freight demand models, still do not exist. This paper addresses this research gap by simulating the transport-related effects of a cargo tram system using logiTopp, a microscopic, agent-based urban freight demand model. The simulations are based on a pilot project in Karlsruhe, Germany, depicting combined passenger and freight transport within the same tram and focusing solely on parcel shipments rather than freight in general.

2. Modeling Framework

2.1. Agent-based freight demand model logiTopp and its consideration of a cargo tram

This study uses the agent-based urban freight demand model logiTopp, which simulates all parcel shipments of private and business customers on the first and last mile within a designated planning area over a one-week simulation period (Barthelmes et al., 2023, 2025b; Reiffer et al., 2023). The base of the model framework builds the synthetic population of private and business agents, representing inhabitants and establishments within a designated planning area. The framework consists of three modules: a long-term, mid-term, and short-term module.

In the long-term module, the parcel demand model estimates each agent's weekly in- and outgoing parcel quantities. Furthermore, each parcel's delivery/pick-up day and size are modelled based on empirical distributions. A delivery type (home, work and parcel lockers) is determined for private parcels based on a logit model. Moreover, for private parcels, a distinct CEPSP and the corresponding distribution centre (DC) are arbitrarily chosen based on market shares. The choice of a CEPSP for business parcels is more complex and takes place in the mid-term module. Here, contractual relationships between business agents and CEPSPs are modelled as the base for choosing a CEPSP for each business parcel. A Greedy algorithm is applied for the selection process, considering the contractual relationship and market shares (Kübler et al., 2023). In the short-term module, private and business agents, as well as CEPSPs, are simulated. Each CEPSP operates a fleet of LCVs, with parcel capacities drawn from a normal distribution. At each DC, delivery/pick-up tours are planned, considering the vehicle fleet and parcel demand using a route-first cluster-second heuristic (Beasley, 1983). While running the simulation, each planned tour is executed, and the parcels are delivered to and picked up from all agents.

Initially, logiTopp considers only LCVs. Consequently, no explicit mode choice takes place; it is deterministically predefined. However, to consider a cargo tram system, which only works as an intermodal solution using transport chains, logiTopp's mode choice logic must be adapted. Barthelmes et al. (2025a) have already developed a conceptual methodology to reflect a cargo tram system within logiTopp tailored to the requirements of a combined passenger and freight tram transport within the same tram vehicle, being the operational mode for this study's exemplary pilot site in Karlsruhe, Germany. They proposed a two-stage transport chain selection model that reflects the mode choice between different transport chains and traditional LCV delivery, comprising a rule- and utility-based stage, and demonstrated its proof-of-concept. The transport chains relevant to this study are illustrated in Figure 1 (left).

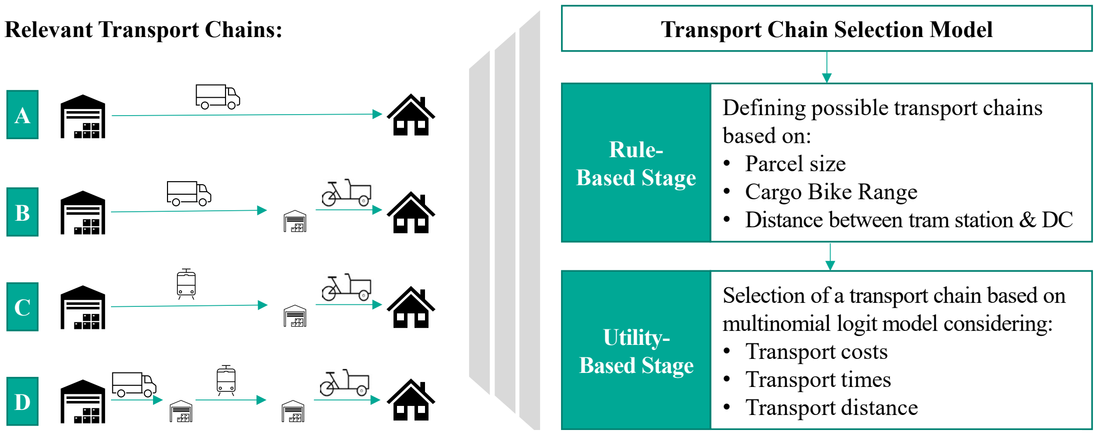

Fig. 1: Relevant transport chains and existing implementation of logiTopp's transport chain selection model; own illustration based on Barthelmes et al. (2025a)

Each transport chain starts at a CEPSP's DC and ends at a recipient, either a private or business agent (last mile). The first mile is also considered in the modelling framework. However, for clarity the following description only refers to the last mile. Transport chain A represents the status quo with direct delivery using LCVs. Transport chains B to D are intermodal transport chains involving at least one transshipment at city hubs located at tram stops within the urban centre. In transport chain B, parcels are packed to LCVs at CEPSPs' DCs and are transported to city hubs, from where they are delivered by cargo bikes. Transport chains C and D comprise the cargo tram. Transport chain C uses cargo trams directly from the DC to the city hub, while transport chain D accounts for CEPSPs without direct rail access. Here, parcels are first transported by LCV to the nearest tram stop, loaded onto the tram, and then transported to city hubs. In both transport chains, delivery between the city hub and recipients is done by cargo bikes.

Figure 1 (right) illustrates the two-stage transport chain selection model developed by Barthelmes et al. (2025a). First, for each parcel, the general suitability of a transport chain is checked within the rule-based stage. Hereby, the choice set of possible transport chain options is determined for each parcel. For instance, large parcels are excluded from transport chains comprising cargo bikes due to the limited transport capacity, reducing the number of stops and making cargo bike tours inefficient. Moreover, recipients must be within a distinct range of a city hub to receive deliveries by a cargo bike. Subsequently, the specific transport chain for each parcel is chosen within the utility-based stage. A multinomial logit model (MNL) is developed, considering transport costs, times, and distance. Aiming solely at the demonstration of a proof-of-concept for the methodology itself, Barthelmes et al. (2025a) set all beta parameters in the utility function deterministically to the same value. Since this limits the practical applicability of the methodology and the interpretation of the results, they advocate an empirical foundation of the parameters for future research, which is addressed in the next subsection of this paper.

2.2. Relevant adaptations of logiTopp and its transport chain selection model

The utility-based stage of the transport chain selection model requires support and adjustments using empirical data. Since the number of CEPSPs is limited, standard approaches like stated choice surveys are unsuitable. Alternatively, expert interviews were conducted with four major German CEPSPs, incorporating an 'analytical hierarchy process' (AHP) following the method introduced by Saaty (1977). In the first part, experts identified relevant factors for first- and last-mile mode choice in a cargo tram system. All agreed that, beyond transportation costs, times, and distance, other aspects also matter when selecting an appropriate transport chain. These include environmental friendliness, the necessity of transshipment processes, the size of the transported parcels, and the recipient type. For example, business parcels are more likely to be shipped solely by LCVs due to reduced time flexibility in the shipment process. Moreover, the bigger a parcel, the more likely it is to be exclusively shipped using LCVs.

In the second part, the AHP was conducted independently with each expert to evaluate the importance of the relevant factors for the transport chain selection. Each expert evaluated all factors in pairwise comparisons based on a scale from 1 to 9, with 1 for equal importance and 9 for the absolute importance of one factor over another (Saaty, 1977). The pairwise comparisons of all experts were aggregated using the geometric mean. Based on the aggregated evaluation matrix, the importance of the decision factors was determined in an iterative process using the eigenvalue method. A consistency index of 0.12 confirms the matrix's reliability, remaining below the threshold of 0.2. The results of the AHP are presented in Table 1.

Table 1. Importance values of relevant factors for the transport chain selection model.

decision factor	importance value	variable type
transportation costs	0.3767	numeric
transportation distance	0.1264	numeric
transportation time	0.1243	numeric
environmental friendliness	0.1133	binary
transshipment process	0.1029	binary
parcel size	0.0916	categorial
business agent	0.0647	binary

The importance values obtained in the AHP are transferred to the MNL model in the transport chain selection model, replacing the utility function proposed in Barthelmes et al. (2025a). This procedure is justified by the additive utility structure of an AHP comparable to those in conventional discrete choice models and the proof that the stochastic formulation of AHP yields preference probabilities of the same mathematical form as a logit model (Hahn, 2006, 2003). Accordingly, the AHP-derived utilities are used in the logit equation to obtain theoretical, preference-based choice probabilities. Environmental friendliness, transshipment processes, parcel size, and recipient type are added as further variables compared to Barthelmes et al. (2025a). As the importance values don't reflect the value range, all variables were normalized to their respective ranges to ensure scale consistency and comparability across variables. Moreover, coefficient signs were assigned to maintain consistent utility interpretation. This approach is supported by Danner et al. (2017), who demonstrated that transforming AHP-derived weights to match variables' value ranges enables the results of AHP and discrete choice theory to be directly comparable.

Moreover, the tour planning method of logiTopp must be adapted to correspond to planning for intermodal first and last-mile urban freight trips. Therefore, an intermodal tour planning algorithm was developed, starting with a capacity coordinator that allocates (shared) cargo tram space among DCs. Transport chains using the same cargo tram ride require arbitration, while non-cargo tram chains are assigned immediately as they do not require shared transportation resources. The transport chain selection model determines the preferred option for each parcel, while storing probabilities for viable alternatives if the available tram capacity is exceeded. Then, DCs request tram slots proportional to demand, and available slots are allocated via weighted random assignment. With this, each DC is allocated a set of cargo tram-based transport chains and an unrestricted number of default LCV tours. Based on these allocations, last-mile cargo bike tours are initially planned using the route-first cluster-second heuristic (Beasley, 1983), considering a travelling salesman problem round-trip algorithm respecting cargo bike capacities. If planned bike tours exceed tram capacity, surplus parcels are reassigned to alternative preferences or LCV delivery as the default fallback. A final round of tour planning computes the last-mile delivery of LCV tours for all remaining parcels.

3. Scenario Analysis and Results

LogiTopp, with its aforementioned adaptations, is applied to Karlsruhe, Germany, simulating about 500,000 parcels shipped to or from private or business agents over one week. Taking the example of the LogIKTram project in Karlsruhe (LogIKTram, 2023), the following analysis depicts a combined passenger and parcel transport within the same vehicle. Illustrations of the concept are shown in Figure 2 (right). To avoid costly reloading, parcels for intermodal transport chains are pre-packed into cargo bike boxes at the CEPSPs' DCs and loaded onto passenger trams alongside passengers. However, this design leads to operational restrictions: Firstly, according to passenger count data, transport of cargo bike boxes is limited to off-peak hours – before 6 a.m. and after 6 p.m. Secondly, only two cargo bike boxes can be transported simultaneously within a tram due to space restrictions.

Fig. 2: Spatial representation of cargo tram concept (left) and graphical impressions (right)

Considering these conditions, a base scenario for combined passenger and parcel transport is defined. This includes, amongst others, selecting one tram line that allows cargo bike box transport as a starting point for the concept and the location of two city hubs for transshipments at appropriate tram stops with sufficient space and near the urban centre. The DCs of CEPSPs are represented based on their actual locations within the Karlsruhe study area. As no CEPSP has direct rail access, the nearest tram stop is defined as a transfer stop for cargo bike boxes for each DC. A spatial representation is illustrated in Figure 2 (left). Additional DCs are not visible in the figure due to the chosen map section, but are included in the model. Other assumptions for defining the base scenario relate to parameters affecting the transport chain selection model. First, it is assumed that the cargo bikes, starting from their respective city hubs, can only reach destinations within a radius of 3 km. For destinations beyond this radius, an intermodal transport chain is not feasible. Second, the utility function and parameters obtained in the AHP are applied to the utility-based transport chain decision.

Further assumptions regarding network-specific distance, time, and cost related variables for parcel transport had to be made to apply the utility-based transport chain decision properly. The distances are based on calculations from the mode-specific network and are available as an origin-destination matrix for all connections between traffic analysis zones. The same holds for the transportation times, whereas time surpluses are considered for possible transshipment process. Costs for LCV are determined based on the distance-dependent vehicle and fuel costs. Tram costs are set to 0 as only existing passenger tram rides are considered, and, at least in the early stage of the project, additional costs can be subsidized by public funds. Moreover, labor costs are introduced for all human resource-demanding activities (driving LCVs and cargo bikes, handover processes) within a transport chain. For further details of the underlying assumptions, we refer to Barthelmes et al. (2025a).

Figure 3 presents the results of the model simulations compared to the status quo, i.e., exclusive LCV shipments. As the goal associated with the cargo tram is to reduce motorized vehicles' mileage, the evaluations of the transport-related effects are based on the freight vehicle kilometers travelled (VKT) relative to the LCVs' VKT in the status quo. Hence, for simplicity, all results are shown as a percentage relative to the VKT in the status quo.

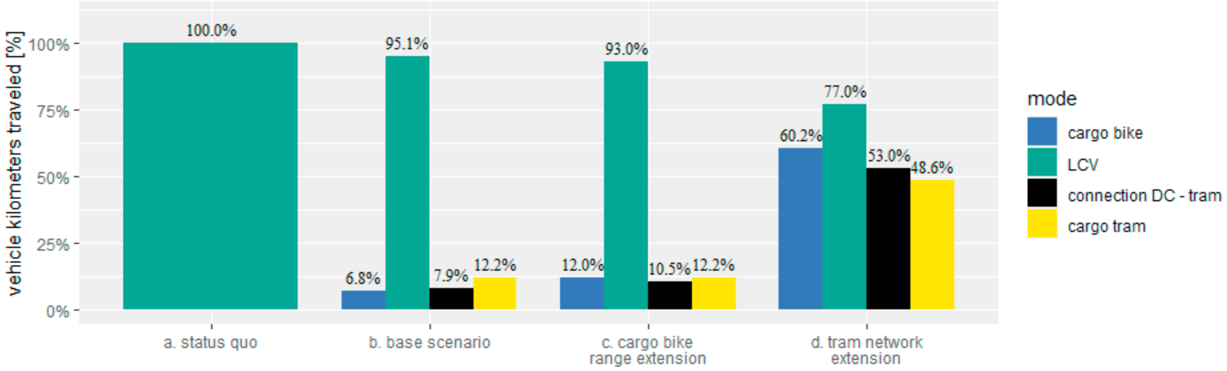

Fig. 3. Analysis of freight vehicle kilometres travelled of selected cargo tram scenarios.

Based on the simulation results, a reduction in LCVs' VKT of 4.9% compared to sole LCV delivery and pick-up tours can be expected when a cargo tram is introduced (b. base scenario). At the same time, the shift to intermodal transport chains with a cargo tram will induce VKT on other modes. The deliveries and pick-ups of parcels by cargo bikes induce VKT of 6.8% of the size of LCV mileage in the status quo. This is caused by the smaller capacity of cargo bikes, which transport an average of 53 parcels with 38 stops per tour, compared to LCVs, with around 150 parcels and 87 stops per tour. As a result, more tours with cargo bikes are necessary than solely with LCVs.

Since only existing tram rides based on the passenger timetable are considered for the combined transport, the share of cargo tram mileage can be disregarded in the evaluation, but is shown for completeness. However, the cargo bike boxes' necessary access/egress trips between CEPSPs' DCs and the nearest tram stops are critical. In the base scenario, these trips cumulate 7.9% of the size of LCV mileage in the status quo, assuming that two cargo bike boxes are transported per trip. Presuming these trips would be done with LCVs, the total mileage of LCVs would be higher than in the status quo, as 7.9% exceeds the previous reduction of 4.9%.

Further scenarios support those tendencies. Increasing the cargo bike radius from 3 km to 5 km (c. cargo bike range extension) allows more customers to be reached by cargo bikes from the city hubs and thus serviced through a transport chain that includes the cargo tram. According to Barthelmes et al. (2025a), increasing the cargo bike range from 3 km to 5 km increases the number of parcels that can be shipped via an intermodal transport chain by a factor of about 1.33. Hence, the simulation results indicate a further reduction in LCV mileage to 93% of the VKT in the status quo, accompanied by a parallel increase in the mileage of cargo bikes and access/egress trips between a DC and tram stop compared to the base scenario. The VKT of cargo tram rides remains nearly the same as in scenario b. This is due to the maximum transport capacity of the cargo tram being reached, which is determined by the maximum number of scheduled rides within the time windows allowed for freight transport.

Extending the cargo tram concept to additional tram lines and thus increasing the maximum rail-based parcel transport capacity is investigated in another scenario (d. tram network extension). In addition to more tram lines on which parcel transport is feasible, further city hubs close to the additional lines needed to be defined and considered in logiTopp. The simulation shows that a massive service expansion significantly decreases the VKT of LCVs and, consequently, increases the VKT of all other modes. However, the results indicate that the previously discussed problem of access and egress trips between the DCs and the closest tram stops is further exacerbated.

Besides VKT, we also analyzed the effects of the cargo tram system on transportation time, which correlates with labor work times and, hence, the system's economic impact. In the base scenario, the transport time requiring human resources is 6.8% higher than in the status quo, mainly caused by more time-consuming cargo bike tours. Additionally, the access and egress trips between a DC and the nearest tram stop also contribute to a higher transportation time. Transportation times within the cargo tram are not included, as cargo bike boxes are shipped unaccompanied during the tram ride. This effect is amplified in the other scenarios, as the VKT of cargo bikes also increases, e.g., in scenario c, the transportation time that requires human resources is 8.2% longer than in the status quo.

4. Conclusion

This study quantifies the transport-related effects of rail-based urban parcel shipments utilizing the agent-based freight demand model logiTopp to analyze whether a combined passenger and cargo tram system can contribute to a more sustainable city logistics. Relevant features, such as an empirical foundation for cargo tram usage through an AHP, are considered, aiming for the most realistic and reliable modeling of a not yet established system.

The simulation results show, for the example of Karlsruhe, Germany, that a combined cargo and passenger tram can positively affect the urban transport system as the VKT of LCVs is shifted to more sustainable modes. Although the VKT of cargo bikes induced is higher than the saved VKT on LCVs, this is not considered a disadvantage due to the lower space consumption and emission-neutral transportation of cargo bikes. The effect's strength depends on the trams' maximum possible transport capacity, deduced from the number of possible cargo tram lines and available time slots in existing passenger tram rides. Generally, the simulation results emphasize that the combined system can only be seen as a supplement to sustainable city logistics and not its backbone, facing low savings on VKT of LCVs compared to the induced VKT on cargo bikes. This is also confirmed by the fact that the available cargo tram capacity is only sufficient for a small part of the parcel transport, first and foremost, ensuring undisrupted passenger operations by restricting possible transport times. An expansion of capacity, e.g., through expanding the service to other tram lines, is accompanied by the construction of new city hubs, causing additional costs and infrastructure requirements, which must be weighed against the possible savings in LCV mileage.

In line with existing literature, the simulations indicate that the transport costs with a cargo tram-based urban parcel shipment system are expected to exceed those in a solely LCV-based system, even when there are no costs for the transport within the cargo tram. Therefore, transport planners and politicians must prepare a suitable incentive system to ensure a competitive and attractive operation. While the introduction of push measures, such as road closures for motorized vehicles, would be possible, a balanced mix with pull measures should be chosen to foster the system's acceptance. In addition, based on the findings of Marcucci et al. (2017) or Le Pira et al. (2017), a thorough integration of all stakeholders, namely, shippers, carriers, citizens and planners, is necessary to introduce a feasible set of policy measures and, hence, foster the acceptability of a cargo tram.

However, transporting cargo bike boxes between CEPSPs' DCs and the nearest tram stop remains the biggest challenge. To unfold the concept's full potential, these trips must be eliminated, e.g., through direct rail connections. This could further reduce operational hurdles through additional handling and storage processes and costs. From a political perspective, establishing a joint DC for all CEPSPs would also be conceivable to achieve further economies of scale. However, as a first step of the implementation, it may be reasonable to restrict participation in the cargo tram system only to CEPSPs with particularly high modal shift potential. These are CEPSPs with their DCs as close as possible to rail infrastructure and as far as possible from city hubs. Hereby, induced mileage to the DC's nearest tram stop is minimized, and the shift of mileage from LCVs to the cargo tram is maximized.

Still, the simulations in this study rely on logistical experts' stated preferences and are therefore subject to uncertainty. To reassess the results, the AHP interviews should be repeated after initial experiences with the combined cargo tram system. In addition, while integrating AHP weights into Logit models offers a theoretically grounded approach, further research is needed to validate and refine this hybrid framework in empirical applications. Moreover, the transferability of the findings to other urban contexts remains limited and is subject to future research, as city logistics systems and tram infrastructure differs substantially across European cities.

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