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TRANSPORT FINDINGS

Substituting Car Trips: Does Intermodal Mobility Decrease External Costs and How Does It Affect Travel Times? An Analysis Based on GPS Tracking Data

Felix Gotzler[1], Nico Nachtigall[1], Konstantin Krauss[2]

[1] School of Engineering and Design, Institute of Automotiv Technology, Technical University of Munich, [2] Fraunhofer Institute for Systems and Innovation Research

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Findings

This study quantifies the reduction in external costs and changes in travel times resulting from the shift from car use to intermodal travel in Munich, based on real-world tracking data. By re-routing all car trips and calculating the travel times, distances, and externalities of alternative modes, we demonstrate that without increasing travel time, external costs can be reduced by 21 %, and by up to 77 % if a doubling of travel time is accepted. These findings highlight the significant benefits of intermodal mobility for urban transportation planning and underline its importance as a viable alternative to the private car.

1. Questions

Public transit (PT) and active mobility are widely recognized as sustainable transportation modes - in contrast, private cars and e-scooters, although popular, are associated with significant environmental and societal costs (Gössling et al. 2019; Felipe-Falgas, Madrid-Lopez, and Marquet 2022). It is often argued that the latter may be used on the first and last mile of intermodal trips (Shaheen and Chan 2016; Li et al. 2024; Yin et al. 2024; Krauss et al. 2024), and overall environmental impact, compared to the private car, thus can be reduced. This positive effect of intermodal travel has been substantiated in theory (Edel, Wassmer, and Kern 2021) but not based on actual GPS tracking data.

Travel time is known to be a critical factor in (intermodal) mode choice (Oostendorp and Gebhardt 2018). We, therefore, investigate the general questions of whether the substitution of car trips with intermodal combinations reduces external costs and how travel times are affected by examining the following:

1. How are modes of transport empirically combined in intermodal trips?
2. What trip-based external costs arise from intermodal combinations?
3. Can external costs be reduced by shifting to intermodal travel while limiting the increase in travel time for the individual?

2. Methods

We employ an app-based tracking dataset encompassing 1,096 participants over a 13-month period to empirically assess mobility behaviors within Munich's PT network, which was recorded in the scope of the Mobilität.Leben study (Loder et al. 2024). This dataset allows for a precise calculation of traveled distances and associated external costs, enhancing the accuracy over traditional approaches such as conventional travel diaries, usually completed by study participants retrospectively by naming one (primary) mode per trip and estimating the distance. External costs of intermodal trip chains can be computed accurately this way. To provide context and to facilitate the interpretation of our results, the recorded mode shares are listed in table 1.

Table 1. Distance-based modal shares recorded by the sample.

Mode	Modal Share
Car	38.5 %
PT	36 %
Bicycle	13.8 %
Walking	11.3 %

We limit the tracking data to trips within the area of service of the local PT provider Münchner Verkehrsverbund (MVV). The dataset, initially consisting of individual legs, is processed to construct comprehensive trips for subsequent routing. Specifically, two legs are combined into a trip if the time gap between them is under ten minutes, or a stay with purpose 'wait' with a duration of less than an hour is between two legs. Consequently, a trip can comprise multiple legs.

We apply external cost rates, constructed from seven categories, determined specifically for Munich (Schröder et al. 2023) as listed in table 2. Costs are computed for each leg of the trip rather than aggregating costs to a primary mode per trip (in contrast to studies relying on primary-mode-based travel diaries).

To assess the potential of substituting car trips, we re-route all car trips with open trip planner (OTP) (Morgan et al. 2019). The routing graph is based on OpenStreetMap (OSM) (OpenStreetMap contributors 2023) and GTFS data for Germany (Brosi 2023) and Munich (Münchner Verkehrsgesellschaft 2023). This setup supports intermodal routing, enabling the calculation of door-to-door travel times and distances across various transportation modes. A comparison of tracking data and routing results validates both the distance and duration computed by the router. To evaluate the potential to substitute car trips of different modes (and intermodal combinations), we subsequently analyze resulting modal splits at limited increases of travel time. We heuristically select the alternative associated with the lowest external costs for each percentage and all trips and obtain the respective modal share for each

Table 2. External cost rates applied to the respective legs of the tracking data in Euro-Cent per person-kilometer for different modes of transports (Schröder et al. 2023)

	Air pollution	Climate	Noise	Land use	Congestion	Accidents	Barrier Effects	**Total**
Motorcycle	0.56	2.15	3.44	1.17	3.10	4.10	2.10	**16.56**
Bicycle	0	0	0	0.84	0	5.72	0.16	**6.72**
Bus	1.16	1.94	0.18	2.76	2.94	2.14	0.24	**11.37**
Tram	0.04	0.03	1.20	2.74	1.17	0	0	**8.01**
Regional Train	0.03	0.03	0.03	2.74	1.63	0	0	**4.63**
Electric Car	0.23	1.11	0.19	4.90	3.65	2.55	1.51	**14.15**
Car (Combustion)	0.48	2.61	0.19	4.90	3.65	2.55	1.51	**16.97**
Shared e-scooter	0.02	0.13	0.29	0.52	0	18.10	0.16	**19.21**
Walking	0	0	0	0	0	0.70	0	**0.7**
Subway	0.01	0.03	0.03	2.74	2.60	1.39	0	**3.99**
Pedelec	0.01	0.08	0	0.84	0	7.07	0.16	**8.17**
Car-Sharing	0.57	3.12	0.23	2.67	4.36	3.04	1.81	**15.80**

hypothetically accepted proportional increase in travel time. For this analysis, we assume the external costs to be constant, which is valid for relatively small changes to the overall modal split of a city. As our sample is small compared to the population of Munich, we consider this a valid assumption. However, if this analysis were to be extended to a whole city, dynamic changes in external cost rates should be modeled.

3. Findings

Figure 1 shows the external costs per passenger-kilometer (pkm) for all occurring singular modes and intermodal trip chains. Costs are depicted across three trip distances, highlighting the differing impacts of modal combinations on the overall costs for varying lengths of trips. The secondary (right) y-axis belongs to the dotted bars and indicates the respective relative shares of the three trip lengths (e.g., for walking, we see that roughly 90 % of trips are shorter than 1km). This visualization offers a new angle on the cost-efficiency per pkm, allowing us to evaluate the frequency of each distance segment traveled and assess the practical potential for reducing external costs through intermodal travel.

The study reveals that intermodal travel significantly lowers external costs, particularly for longer journeys. While not changing much for short and medium-distance trips, the combination of car and PT reduces externalities by about 40 % for trips longer than 5 km (which account for about 90 % of all trips for this combination) compared to car trips. Combining PT with e-scooters yields similar reductions in external costs (compared to monomodal travel with e-scooters). On medium-length trips, costs per km decrease from 19 to 11 Cent/pkm, and on long trips to 5 Cent/pkm and therefore less than the bicycle. Empirical evidence shows that the distance traveled by e-scooters remains constant for short, medium, and long intermodal routes, but the proportional share decreases. Trips over 5 km account for almost 90

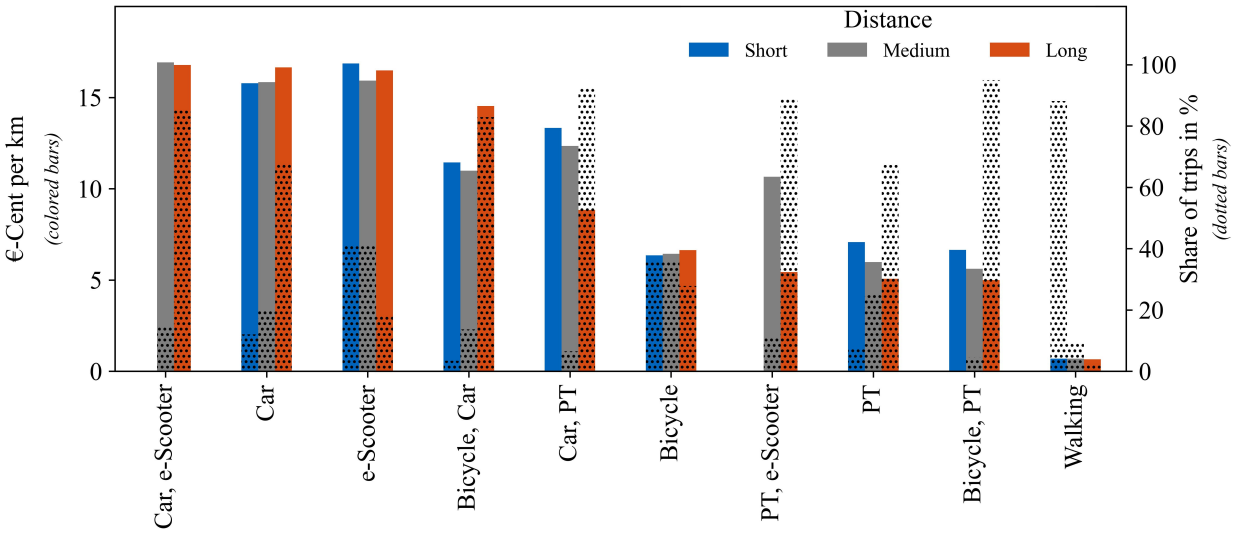

Figure 1. Cost per pkm for different mono- and intermodal trips with respective trip distances and relative shares of trip lengths (short: < 1 km, medium: 1-5 km, long: > 5 km). Dotted bars indicate relative shares of trip lengths within each mode/modal combination (right y-axis).

% of all intermodal PT and e-scooter trips, proving that the claimed merits of e-scooters as a first-/last-mile feeder for PT are indeed leveraged through the samples' mobility behavior. Of all trips involving e-scooters (intermodal and monomodal), trips combining e-scooters and PT that are longer than 5 km account for 30.3 %, underlining the importance of intermodal trips for shared micromobility. To evaluate the potential for modal shifts, we re-route all car trips in the dataset, considering the constraint of maximum additional travel time. This provides travel times and distances of alternative modes (or combinations) for the same trips, which we use to calculate external costs. Figure 2 shows the remaining share of external costs when accepting a percentual increase in travel time and the resulting modal split under external-cost-optimal choice.

The hypothetically accepted increase in travel time is shown on the x-axis. For each percentage value, we heuristically select the alternative with the lowest external costs under the condition that the travel time increases by a maximum of x %. The primary (left) y-axis indicates the remaining share of external costs, with regard to the initial external costs of car trips, and corresponds to the black line. The secondary (right) y-axis shows the trip-based modal split resulting from this time-constrained, cost-optimal mode choice, corresponding to the stacked areas. For instance, a hypothetical 50 % increase in travel time results in 48 % of the initial costs with a modal distribution comprising 10 % bicycle, 15 % combined car and PT, 16 % PT and bicycle, 2 % walking, 26 % PT, and 31 % remaining car trips. The analysis indicates that substituting car trips with alternative modes, even without any increase in travel time, could reduce external costs by 21 %. Most trips that could be replaced without time loss (18 %) are shifted towards intermodal

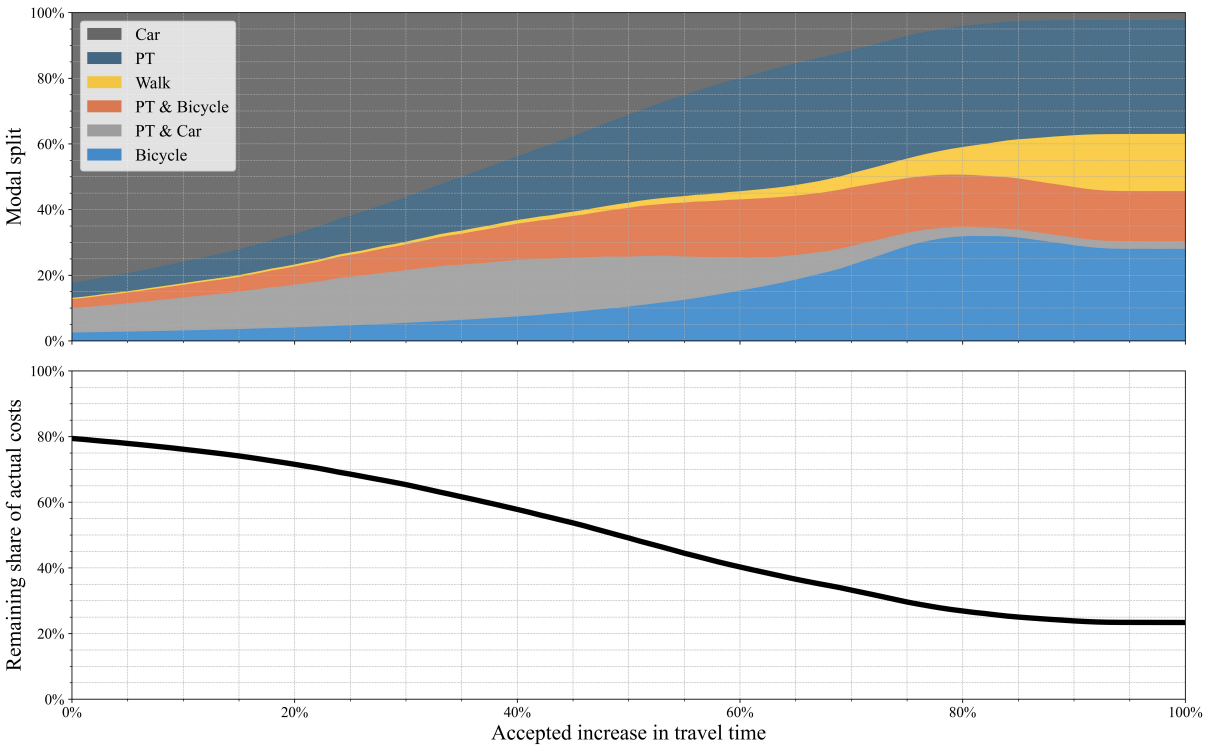

Figure 2. Modal distribution optimized for minimal external costs (upper graph) along with the resulting residual external costs after factoring in an accepted percentage increase in travel time (lower graph).

trips combining car and PT (7.5 %). While some trips could be conducted by bicycle or PT alone (2.5 % each), walking is merely an option when little or no increase in travel time is accepted. External costs progressively decrease with accepted increases in travel time up to 85 %. Only a marginal share of 2.2 % of all car trips cannot be replaced by other modes, even if double the travel time is accepted. The potential walking share remains below 3 % until 63 % of accepted additional time and gradually increases from there on towards a final share of 17.5 %. Cycling starts with a modest share, peaking at 18 % for a 63 % time increase, and stabilizes around 15 %. The share of PT first gradually increases over the accepted additional time, reaches a peak of 17 % modal share at 69 % time increase, and converges to a share of 34 %. While the intermodal combination of car and PT is relevant until 50 % of the accepted time penalty with a modal share of 19 %, its share becomes marginal thereafter. Conversely, the combination of bicycles and PT holds steady at 15 % beyond a 50 % time increase.

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Supplemental Information

Validation of routing

OTP allows the router to be parametrized to meet the needs at hand. To validate the chosen parametrization, we compare the re-routed results with the actual travel times and distances recorded by the participants. Figure 3 shows the probability density of absolute errors. For all modes and both distance and time, the deviations are centered around zero, meaning there is a roughly equal amount of over- and underestimated trips. Overall, the induced error, therefore, is neutralized, and the estimated distances and times are valid.

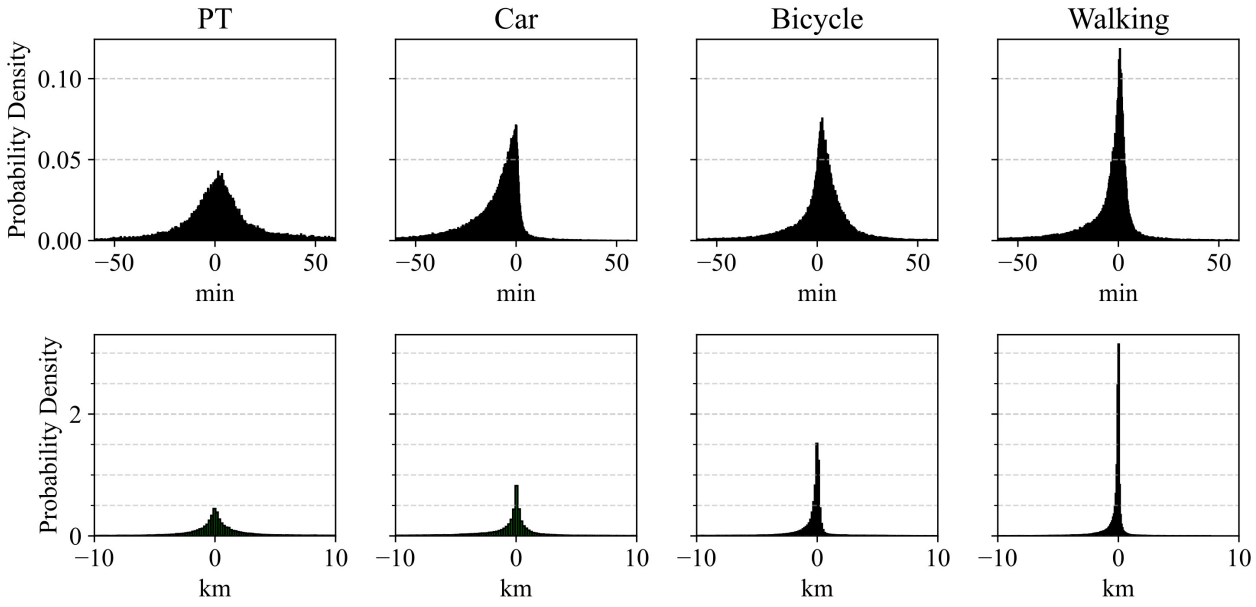

Figure 3. Analysis of deviations of distance and duration between recorded trips and routed trips for different modes.

SUPPLEMENTARY MATERIALS

Supplemental Information

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