Data-driven analysis of urban logistics policies based on vehicle traces in the Copenhagen capital region

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Short summary

This paper presents an analysis of stop sequence data of nine logistics operators from different sectors that are active in the Copenhagen area. Based on these data, an easily adaptable and transposable data-driven modeling pipeline based on trajectory rerouting is presented. It allows to rapidly assess the potential impact of different urban logistics policies on the respective operators. Using the model, an estimation of energy and emission reductions due to the implementation of three different Zero Emission Zone proposals and a Microhub in the City of Copenhagen is presented.

1 Introduction

Cities across Europe are encouraged to lower emissions of their transportation systems. While some insights can be generalized, individual measures and policies are more efficient in some cities than others. Therefore, individual Sustainable Urban Logistics Plans (SULPs) are being developed all over Europe (Fossheim & Andersen, 2017). A valuable tool for exploring the efficiency of such a plan or for deciding between various options, are simulations and scenario-based modeling approaches. While system-level modeling tools for logistics systems are emerging (de Bok et al., 2022; Sakai et al., 2020; Toilier et al., 2018), they require substantial knowledge about the characteristics of the local transport system and ideally data from many local operators. However, access to relevant data remains a challenge for those modeling approaches (Buldeo Rai & Dablanc, 2023) and synthetic data often rely on strong assumptions (Hörl & Puchinger, 2023; Hörl et al., 2024). The present paper, hence, introduces a more light-weight, data-driven approach for obtaining insights into the efficiency of certain urban logistics policies based on a small sample of local operator data.

2 Available data

For the present study, data has been collected by the City of Copenhagen on nine operators performing food, beverage, and parcel deliveries in the Copenhagen capital region (Table 1). Each operator provided about two weeks worth of data covering the daily sequence of stops performed by each of their active vehicles. Each stop is defined by its longitude and latitude. For some operators, timestamps for each delivery are attached to the stop sequence. In total, the data sets cover 158,582 shipments for the tracked periods with 11,911 per day. They are delivered by around 266 vehicles on an average day. As shown in Table 1, the operators show a large variety in terms of the number of shipments performed per vehicle and day, ranging from 235 for the operator transporting the smallest to 8 for the operator transporting the largest items.
Additionally to the operator data, a planning road network of the Copenhagen Capital Region has been provided, which, however, could also be replaced using public data from OpenStreetMap.

3 Methodology

Our goal is to study two urban logistics policies: the introduction of a Zero Emission Zone (ZEZ) in the city of Copenhagen and the deployment of an Urban Microhub in the Medieval center of the city. The ZEZ defines that no ICV (Internal Combustion Vehicles) are allowed to enter the

	Op.	Days	Vehicles per d	Shipments total	per d	per veh/d	Distance [km] per d	per veh/d	per shipm.
F&B	#1	15	11	37,288	2,486	235	2,110	199	0.85
	#2	14	56	29,833	2,131	38	6,755	120	3.17
	#3	14	84	20,645	1,475	18	3,189	38	2.16
	#4	10	28	3,051	305	11	306	11	1.00
	#5	12	2	311	26	12	119	55	4.60
	$\sum$	-	181	91,128	6,422	35	12,479	69	1.94
P/P	#6	12	17	37,910	3,159	190	2,272	136	0.72
	#7	10	33	15,786	1,579	48	970	30	0.61
	#8	13	17	7,852	604	35	463	27	0.77
	#9	13	18	1,906	147	8	250	14	1.71
	$\sum$	-	85	63,454	5,488	65	3,955	47	0.72
Total	$\sum$	-	266	154,582	11,911	45	16,435	62	1.38

Table 1: Operator data and *estimated* distances (F&B: Food & Beverage, P/P: Parcels / Postal)

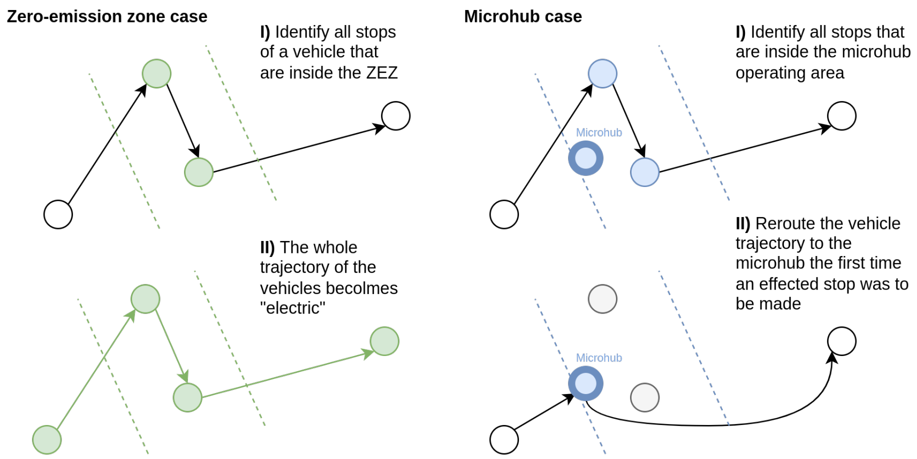

Figure 1: Application of transport policies to the trajectory data

specified zone. The Microhub requires operators willing to perform deliveries in a specified area to route them through a local distribution center, which manages the last mile of the delivery process using low emission vehicles.

Route reconstruction

The first step in our data-driven analysis pipeline is the reconstruction of individual vehicle routes. As mentioned above, for each operator, day, and vehicle, a sequence of stops with coordinates is given. Based on this information, we reconstruct the link-by-link routes through the Copenhagen road network. Hence, for each segment between two stops, we obtain the specific trajectory, the traveled distance, and the travel time.
The routed trajectories allow us to estimate the overall driven distance per day and other indicators for the baseline situation. Note that, in reality, routes may not be as optimal as obtained from our shortest-path routing and most operators only include deliveries, but no stops at the depots for backhauls. The obtained values should, hence, be understood as lower bound estimates.

Zero emission zone

For a first potential analysis of the ZEZ policy, we assume that all vehicles used today are ICV except if they are explicitly indicated as being electric in the operator data. While this is an approximation for operators that don't provide this information, the assumption is acceptable given the low rate of electrification in reality. The key idea behind our data-driven approach for understanding the ZEZ is that operators will be forced to switch to EV (Electric Vehicles) as soon as they interact with the ZEZ (Figure 1, left).
Technically, we examine the stop sequences of all vehicles found in our data set. As soon as one

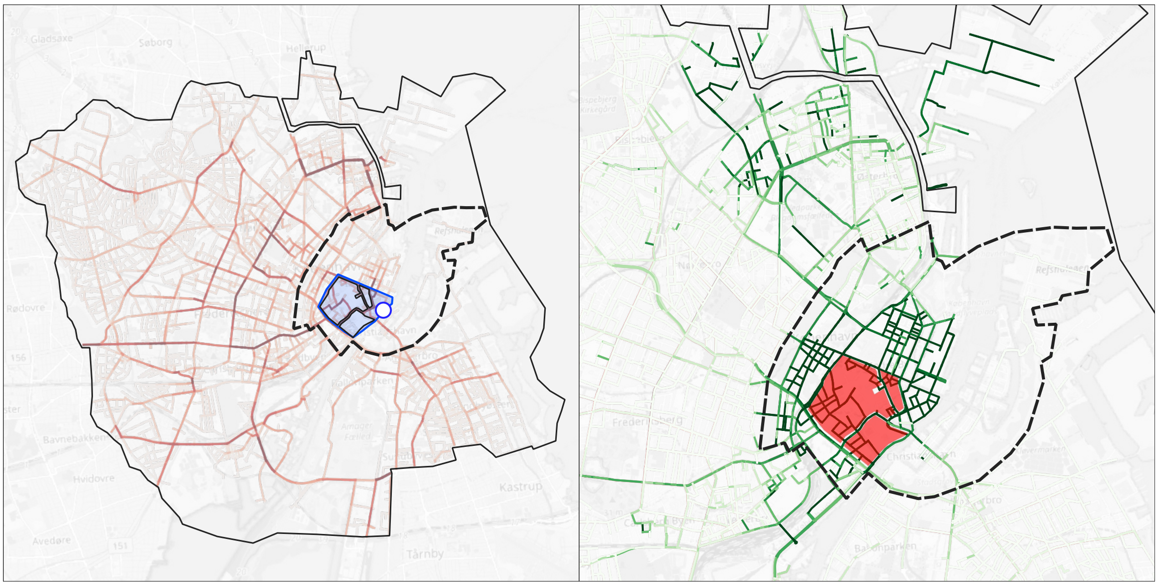

Figure 2: Left: Environmental zone (solid) and Inner city (dashed) perimeters with microhub and its operating area (blue). Baseline logistics flows in red. Right: Medieval city perimeter (red) and EV flows (green).

stop inside the ZEZ perimeter is found, the vehicle is tagged as *electric*. In consequence, all stops performed by that vehicle become electric. All vehicles that don't perform any stop inside the ZEZ are rerouted such that they need to perform detours in case their connecting trajectories touch the ZEZ at any point during the day.
After processing all data sets, we can calculate the driven distance, travel time for both ICVs and EVs. By assuming specific factors for emissions and energy consumption, we can assess the ecological effects of introducing the ZEZ policy.
Note that this data-driven approach comes with a range of implications. (1) Implementing a ZEZ has a network effect on surrounding areas. Because certain vehicles need to become electric, they have a positive impact along their whole trajectory. Hence, despite the relatively simple approach, the complex spatial impact of implementing a ZEZ policy can be assessed. On the contrary, in reality, operators would reassess their vehicle fleet and reassign deliveries and routes such that their overall cost is minimized. Those surrounding gains, hence, might be lower in reality than estimated.

Microhub

The Microhub policy is implemented by first defining the spatial perimeter of the area that is to be served by the Microhub as well as the location of the Microhub itself.
We then identify all deliveries along the vehicles' stop sequences that are located within the Microhub perimeter. The first stop inside the perimeter is replaced with a visit to the Microhub while all subsequent stops are removed (Figure 1, right). This implies that the vehicle delivers all relevant items to the Microhub, which then processes them further.
Note that we don't model the final delivery, which could be done using a dedicated Vehicle Routing Problem set up for the Microhub operator. Since we assume that the final delivery would be performed using low-emission vehicles, we don't consider them in our energy and emission analysis. However, it should be noted, that in reality, those last-mile operations would have an impact on the overall assessment.

4 Results

To analyze the policy effects, we calculate the driven distance, emissions and energy demand for ICVs and EVs on three analysis perimeters: the Medieval city, the Inner City, and today's Environmental Zone (Figure 2). For the estimation of GHG emissions, we assume an average of 260 gCO2eq/km for ICVs and 37 gCO2eq/km for EVs (based on Denmark's energy mix). To estimate the energy demand, we assume 800 Wh/km for ICVs and 300 Wh/km for EVs. Table 2

Policy	Baseline	Microhub	ZEZ Med.	ZEZ Inn.	ZEZ Env.
Analysis: Medieval city					
ICV Distance [km]	469	-	-	-	-
EV Distance [km]	94	-	(+500%) 563	(+500%) 563	(+500%) 563
Total Distance [km]	563	-	(0%) 563	(0%) 563	(0%) 563
Energy [kWh]	403	-	(-58%) 169	(-58%) 169	(-58%) 169
GHG [gCO2eq]	126	-	(-82%) 23	(-82%) 23	(-82%) 23
Analysis: Inner city					
ICV Distance [km]	1,629	(-22%) 1,264	(-47%) 856	-	-
EV Distance [km]	253	(-40%) 150	(+306%) 1,026	(+645%) 1,882	(+645%) 1,882
Total Distance [km]	1,882	(-25%) 1,414	(+0%) 1,883	(-0%) 1,882	(-0%) 1,882
Energy [kWh]	1,379	(-23%) 1,056	(-28%) 993	(-59%) 564	(-59%) 564
GHG [gCO2eq]	434	(-23%) 335	(-39%) 264	(-83%) 75	(-83%) 75
Analysis: Environmental zone					
ICV Distance [km]	5,880	(-6%) 5,528	(-9%) 5,365	(-49%) 2,974	-
EV Distance [km]	824	(-12%) 721	(+63%) 1,340	(+356%) 3,756	(+714%) 6,704
Total Distance [km]	6,704	(-7%) 6,249	(+0%) 6,705	(+0%) 6,730	(+0%) 6,704
Energy [kWh]	4,951	(-6%) 4,639	(-5%) 4,694	(-29%) 3,506	(-59%) 2,011
GHG [gCO2eq]	1,562	(-6%) 1,466	(-7%) 1,449	(-41%) 923	(-83%) 268

Table 2: Analysis of the policy implementation scenarios in average values per day

shows the relevant system indicators in the baseline and policy cases, grouped by analysis perimeter. The documented policies are the implementation of a Microhub with its respective operating area as shown in Figure 2 (left) and the implementation of a Zero Emission Zone on successively larger perimeters that coincide with the analysis perimeters (Medieval city, Inner city, Environmental Zone).

Starting with the Microhub policy, one can see that implementing the facility removes the ICV distance completely from the Medieval area, which is the expected outcome given its definition. Zooming out to the perimeters of the Inner city and the Environmental Zone, this policy reduces distance, emissions and energy still by 23% and 6%, respectively. Clearly, emissions caused by the operations of the Microhub are not included in this analysis and would need to be modeled additionally.

Passing on to the environmental zone, the first case that is examined is its implementation in the Medieval city. In that case no ICV distance is present anymore, but electric vehicles are allowed to operate. In consequence, a reduction in emissions by 58% is achieved in the Medieval context and a reduction of 82% in GHG emissions. Zooming out to the largest scope of the Environmental zone, implementation of the Medieval ZEZ yields an overall reduction in energy consumption of 5% and a reduction in GHG emissions by 7%.

Keeping the analysis parameter of today's Environmental Zone, implementing a ZEZ in the Inner city would yield larger reductions of 29% and 41% for energy and emissions, respectively. This is more than threefold the effect of the Medieval ZEZ. Finally, implementing the ZEZ on the perimeter of the Environmental Zone leads to an energy reduction of 59% and emission reactions of 83% which is again two times more impactful than the Inner City ZEZ.

It should be noted that more detailed spatial analyses can be performed using the model output. Figure 2 (right), for instance, qualitatively shows the use of the road network by newly introduced electric vehicle as a consequence of implementing the Inner City ZEZ. Once can clearly see how the policy has an impact on surrounding areas due to the transformation of vehicles that are directly interacting with the respective ZEZ.

5 Discussion and Outlook

The presented data-driven methodology is relatively simple to implement, but already provides interesting and policy-relevant information. It, in particular, helps to assess the magnitude of the impact that can be expected of implementing specific urban logistics policies that act on the trajectories and selection of transport vehicles.

In (Green Mile, 2023) estimations on the overall logistics traffic in the city of Copenhagen have been performed. Based on the reported numbers, the number of observed active vehicles represent about 0.05% of daily transport vehicles in the city. With respect to distance, the comparison with

(Green Mile, 2023) yields that about 0.42% of the overall daily distance driven by logistics vehicles in the zone is covered by our sample.

Furthermore, it should be noted that the results should be regarded as *optimistic* in terms of impact as operators are expected to adapt more dynamically to policy changes, and, for instance, would both adapt their vehicle fleet and route assignment to optimally (with the lowest cost) respond to the imposed constraints.

For that reason, the next step in our research will be to model the obtained operators in a more flexible way. Specifically, our goal is to model each operator (with given stop sequences) as a Vehicle Routing Problem (VRP) with fleet composition, for which vehicle and distance costs, as well as capacities and daily activity times are calibrated such that the solution to the respective VRP yields the observed vehicle counts (for the entirety of the given days) and stays within a plausible driven distance compared to the reference data. The respective solutions can be obtained using out-of-the-box open-source solvers such as VROOM (Coupey et al., 2024). After calibration, we can then impose highly flexible policies on those operators by adding additional constraints to the VRP. In the case of the Microhub, individual stops would be deleted from the shipments that are to be fulfilled by an operator's fleet, and additional ones at the Microhub would be added, potentially including a time constraint for their latest arrival on the delivery day. For the Zero Emission Zone, specific *vehicle skills* (i.e., being electric) would be required for the fulfillment of certain shipments in the ZEZ area. On top, other policies such as off-hour deliveries (imposing time constraints on shipments) can be modeled. A major advantage of this modeling approach will then be to flexibly combined multiple policies and to observe their effect when applying them intelligently to specific operator types.

Another pathway of further research is to estimate spatial distribution models for the stops that are contained in the data set. This way, regression models can be set up that allow generating artificial demand data sets for the operator categories observed in the data. As a result, it would be possible to set up an arbitrarily large set of stereotypical synthetic operators and estimate the impact of the proposed policies on a larger scope of operation.

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