Modeling the ecological and economic footprint of last-mile parcel deliveries using open data: A case study for Lyon

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SHORT SUMMARY

The amount of parcels delivered in the urban space is steadily increasing and is often expected to double by 2030. At the same time rising energy prices and policies towards sustainable development affect the business models and distribution schemes in the sector. The present study uses open data to approximate today's parcel volumes for the specific case of Lyon and estimated how those parcels are delivered in terms of used vehicles, covered distances and ecological impacts. The first part describes our data collection process which hypothesizes market shares and cost structures of the parcel operators. In the second part, we solve Heterogeneous Vehicle Routing Problems to uncover the likely distribution schemes. This way, the study provides rough estimates on the total daily emissions and energy used for parcel deliveries outlined pathways for future modeling efforts and data collection.

Keywords: parcels, urban, last-mile, logistics, optimization, VRP

1 INTRODUCTION

The amount of parcels delivered in the urban space is expected to increase strongly in the coming years. Today, cities already reflect upon strategies to regulate urban logistics, understanding the complex interplay between its economic, ecological and social impacts becomes ever more important. While ideas and research efforts on sustainable urban logistics policies are gaining traction (Mucowska, 2021; Neghabadi et al., 2019; Patella et al., 2021). Recent advances in transport simulation aim to model urban logistics on a systemic level (de Bok et al., 2022; Sakai et al., 2020; Toilier et al., 2018), but reliable data remains scarce. The present short paper is an attempt to model one specific sector of urban logistics - home parcel deliveries - solely based on open data for a use case of Lyon.

2 METHODOLOGY

Our approach follows various steps from generating the parcel demand for a territory and defining the supply in terms of operators and distributions center. We then define cost structures to obtain the used vehicles and driven distances to deliver all parcels based on a cost-minimization and vehicle-routing approach. The individual steps are described below.

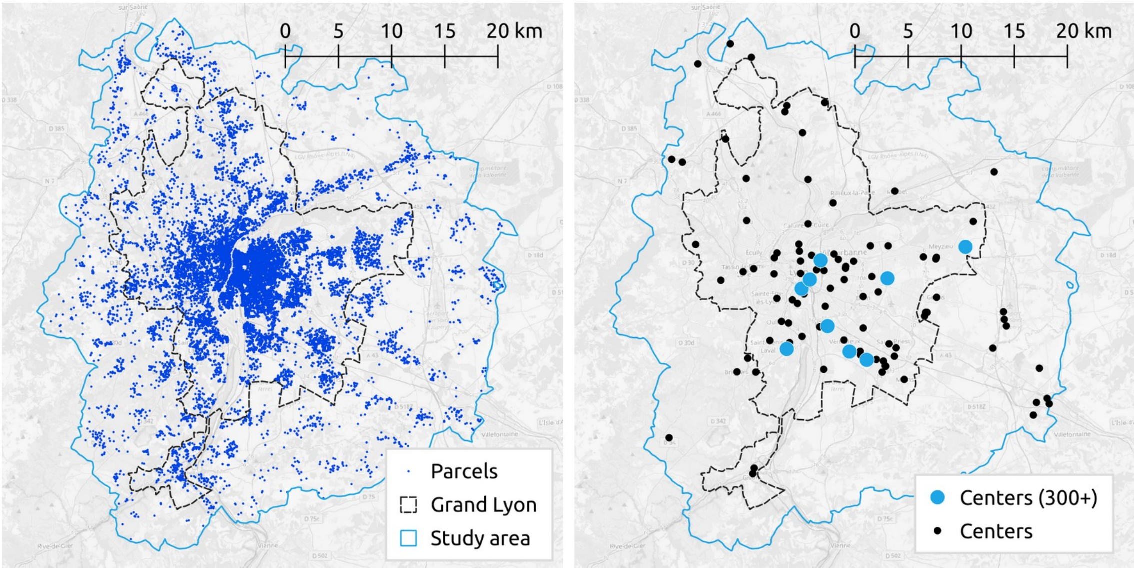

Figure 1: Map of the study area, generated parcels, and distribution centers (Background: OpenStreetMap)

Demand data

Our demand generation process is based on a synthetic population for the Rhône-Alpes region around Lyon. Such a synthetic population, which is a digital representation of households and persons in a region, along with their socio-demographic attributes can be generated based on open data in France. We make use of a replicable data processing pipeline that can be applied anywhere in France (Hörl & Balac, 2021). For the present study, we only consider households in our study area, which comprises the city of Lyon, the Grand Lyon metropolitan region and bordering municipalities with relevant logistics infrastructure (Figure 1). For this perimeter, the population synthesis pipeline generates 1.6 million persons in about 795,000 households.

We fuse the synthetic population data with surveys on the purchasing behavior of the local population. Specifically, (Gardrat, 2019) provides statistics on the annual number of orders made per household based on various socio-demographic characteristics. In (Hörl & Puchinger, 2022) we have proposed a method to make use of this information to generate the probable daily parcel demand for the synthetic households using Iterative Proportional Fitting. Applying the model to our study area yields 16,252 geolocated parcels to be delivered during an average day (Figure 1).

Operator model

The goal of our methodology is to let operators minimize their cost by choosing relevant vehicle types for delivering their assigned parcels and optimizing the vehicle routes. Unfortunately, information on the cost structures of parcel operators is scarce. However, we can assume that the main cost components for offering their service are salaries, vehicle maintenance and investment costs, and per-distance costs. A substantial part of our research was to collect information from gray literature on these cost components. While a detailed analysis of our sources and aggregation procedures exceed the scope of this paper, they will be detailed in an extended publication.

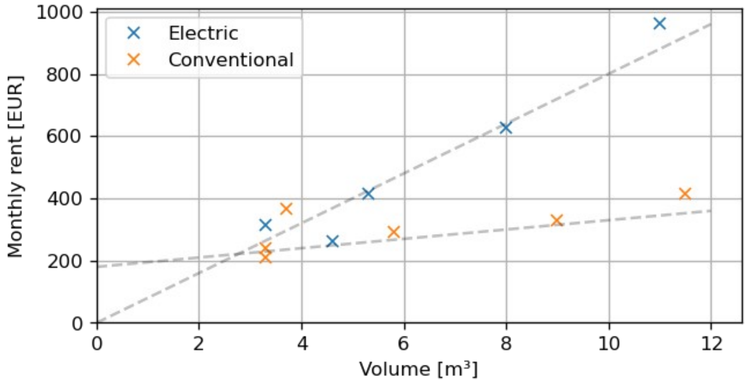

Figure 2: Monthly rent versus transport volume

For personnel costs, we assume an effective net salary of 1,300 EUR per month per driver, leading to an approximate gross salary of 1,700 EUR, and to monthly costs of about 3,400 EUR per full-time employee and month for the operator. Divided by 25 operating days, we arrive at daily salary costs of 136 EUR.

In terms of per-vehicle costs, we have examined the long-term rental offers of the major French vehicle manufacturers, along with the characteristics of the advertised vehicles. This analysis has yielded distinct vehicle classes (of about $3.3m^3$, $5m^3$, $10m^3$) for which costs increase linearly with the transport volume. This is true for thermal and electric vehicles while the slope of the latter is higher (Figure 2). We document the daily unit costs per prototypical vehicle that are used in our model in Table 1 ranging from 210 EUR for a small thermal vehicle up to 800 EUR for large electric truck. In the final optimization we divide these cost by 25 active days per month.

The per-distance costs depend strongly on the consumption of the individual vehicle types. Based on our analysis of manufacturer offers, we have attached representative values for thermal vehicles (in L/100km) and electric vehicles (in Wh/km) to our prototypical vehicle types in Table 1. The per-distance costs are calculated by multiplying the driven distance per vehicle type with the respective consumption factor and the price for fuel (in EUR/L) and electricity (in ct/kWh), respectively.

Additionally, we have noted down representative CO_2 equivalent emissions rates (in g_{CO2eq}/km) for each vehicle type. The rates for thermal vehicles are based on our manufacturer analysis, while the rates for electric vehicles are based on the French average of $90g_{CO2eq}$/kWh for electricity production[1].

Finally, Table 1 shows the values for a prototypical cargo-bike (Be) based on current rental offers in France and typical consumption rates.

[1]https://www.rte-france.com/eco2mix

Table 1: Operator model

Vehicle type	St	Mt	Lt	Se	Me	Le	Be
Size	S	M	L	S	M	L	S
Propulsion	T	T	T	E	E	E	E
Capacity	33	50	100	33	50	100	14
Fuel consumption [L/100km]	5	6	8	-	-	-	-
Electricity consumption [Wh/km]	-	-	-	160	200	300	42
Unit cost [EUR/month]	210	260	370	260	400	800	160
Distance cost* [EUR/100km]	304.5.00	377.00	522.00	14.00	18.00	27.00	3.80
Emissions** [g_{CO2eq}/km]	130	160	215	14.4	18	27	3.8

Be: Cargo-bike; Size: S – Small, M – Medium, L – Large; Propulsion: T – Thermal, E – Electric;
*Indicative distance costs based on 1.45 EUR/km and 9ct/kWh; **Electric vehicle emissions based on 90g_{CO2eq}/kWh

Operator assignment

To link the demand and the operators, we need to assign an operator to each generated parcel in the synthetic population. For that, we perform weighted random draws from the set of operators based on their market shares. Those market shares have been elaborated from gray literature and a dedicated model. These steps cannot be covered in detail but will be explained in an extended publication. Table 2 shows the resulting parcels assigned to each operator.

Table 2: Operator statistics

Operator	Distribution centers	Market share [%]	Parcels
La Poste (Colissimo)	72	40.08	6,384
Chronopost	6	14.98	2,430
UPS	2	13.55	2,210
DPD	3	9.94	1,632
DHL	8	8.95	1,477
GLS	2	6.93	1,169
Colis privé	2	5.36	917
Fedex	9	0.21	33
Total	**104**	**100**	**16,252**

Distribution centers

To know from where parcels are dispatched, we make use of the SIRENE database[2], which lists all enterprises and their facilities in France, along with their address and the number of employees. From this database we have extracted all facilities belonging to any of the parcel distributors listed in Table 2. The resulting distribution centers are shown in Figure 1 and Table 2 indicates the number of centers per operator.

For each parcel, we select the distribution center of the respective operator that is the closest in terms of road distance. These road distances are calculated using a network extracted from

[2]https://www.sirene.fr

OpenStreetMap data[3] and the `osmnx` library (Boeing, 2017). The process results in nine distribution centers out of 104 with more than 300 assigned parcels (Figure 1).

Heterogeneous Vehicle Routing Problem

Based on the inputs above, we define a Heterogeneous Vehicle Routing Problem (HVRP) *per distribution center* with the following characteristics:

- The goal is to minimize the overall cost which is the sum of the unit costs and a daily salary per chosen vehicle and the total distance-based cost of the vehicle trajectories.
- The operator can vary the number of vehicles of each of the seven types (Table 1) and the individual vehicle routes.
- Vehicles start at the distribution center and must return before the end of the day. Their total active time cannot exceed a daily duration of 10h. It consists of the travel times between parcels and depot; service times of 120s at delivery; and service times of 60s per pick-up.
- Vehicles cannot carry more parcels than their capacity allows. We assume 10 parcels per m^3 in Table 1. We allow multiple tours per vehicle during one day.

For each distribution center, we obtain a distance matrix and a travel time matrix from our extracted OpenStreetMap network using the `osmnx` library (Boeing, 2017). Since `osmnx` calculates travel times based on the speed limits of the road segments, we further inflate these values using averaged factors from the TomTom Congestion Index (Cohn et al., 2012) factors of Lyon to arrive at approximately congested travel times.

Finally, we solve the resulting Heterogeneous Vehicle Routing Problems using the open-source VRP solver VROOM[4].

3 RESULTS AND DISCUSSION

We define three individual scenarios:

- **Baseline**: The scenario is based on our synthetic population for 2022. The prices are chosen such that they reflect the long-term cost structures of the operators that have given rise to the distribution schemes that we see today.
- **Today**: The scenario considers recent increases in energy prices beginning of 2023 with fuel prices of about 1.90 EUR/L[5] and 14 ct/kWh[6]. It hence shows how the distribution system could develop in case prices stay at this level in the long term.
- **Future**: The scenario is a future scenario in which we consider an updated synthetic population that considers population growth[7] and a general increase of parcels per capita by a factor of two. We assume that prices have increased by +80% for fuel and +60% for electricity.

[3]https://download.geofabrik.de

[4]https://github.com/VROOM-Project/vroom

[5]Diesel, France, 09/01/2023, https://www.tolls.eu/fuel-prices

[6]EUROSTAT, Non-household, S2 2022, https://ec.europa.eu/eurostat/cache/infographs/energy_prices/enprices.html

[7]Based on INSEE prediction scenarios https://www.insee.fr/fr/information/6536990

The results are shown in Table 3. For the **Baseline** case, we obtain 139 thermal vehicles being used, but only eight electric vehicles and 24 cargo bikes. This reflects today's reality where electric vehicles do not have a large share in the transport system. In terms of vehicle sizes, large vehicles (133) dominate, followed by smaller ones (24) of which the majority are cargo-bikes. Medium-sized vehicles are rarely used. The total distance driven for last-mile deliveries is almost 10,000 km per day for thermal vehicles, the distance for electric vehicles and cargo-bikes is ten times smaller. Only 7% of all parcels are delivered by electric vehicles or cargo-bikes. In terms of consumption, 780 liters of fuel are needed and 236 kWh of electricity. This consumption translates into about 2100 kg of CO_2 equivalents emitted for the last-mile deliveries during one day which makes 131g per parcel. To calculate the total consumed energy we assume a conversion rate of 10 kWh/L and arrive at a total of 8000 kWh per day with 497 Wh per parcel.

For the **Today** scenario with adjusted prices (increase of 30% for fuel and 55% for electricity), we see a slight shift of electric vehicles from eight to 14. Still, this shift represents a doubling of the driven distance of electric vehicles and a doubling in parcels delivered by electric vehicles while their overall percentage remains low with 7% for electric transporters and 12% for cargo-bikes. Accordingly, electricity use doubles while fuel consumption drops by 10%. These shifts lead to a reduction in emissions by 8% in total to 120g per parcel. Total energy use is also reduced by 5% while no large shifts in the cost structures can be observed. Despite electricity prices having increased stronger than fuel prices, the observed shifts can be explained by the different ratios of capital expenses versus operational expenses between thermal and electric vehicles. The latter have higher vehicle prices with lower per-distance costs. In the **Baseline** case, the break-even daily distance at which a single electric vehicle becomes cheaper in total is at about 34 km, while the point shifts to 26 km in the **Today** scenario (see Figure 3).

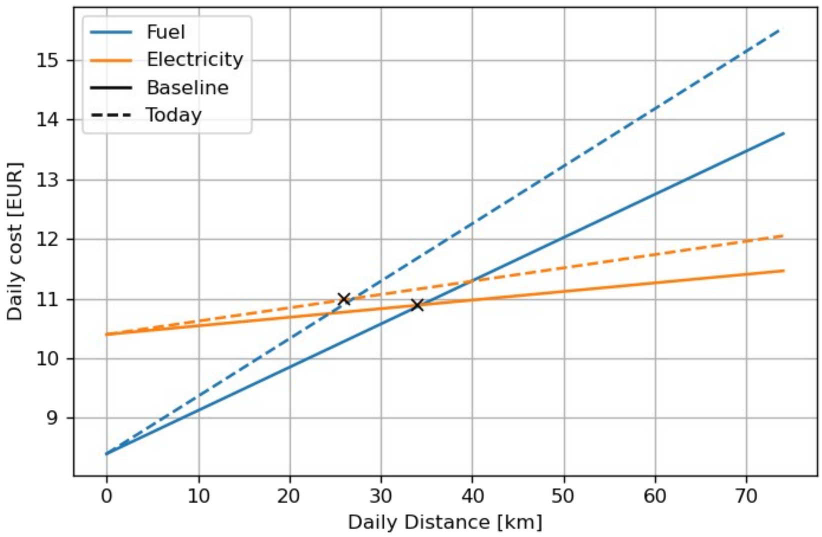

Figure 3: Break-even points for a small electric vehicle

In the **Future** scenario, both the numbers of thermal and electric vehicles increase because of the higher demand. However, electric vehicles increase strongly from 8 to 101. In terms of vehicle size especially large vehicles double in count. At the same time the distance for thermal vehicles goes down and the distance for electric vehicles increases tenfold. Interestingly, the total distance is not doubled, but increases by only 50%, which shows that there are scale effects with

Table 3: Optimization results

	Baseline	**Today**	**Future**
Scenario			
Population	2022	2022	2030
Demand factor	1.0	1.0	2.0
Fuel price [EUR/L]	1.45	1.90	3.40
Electricity price [EUR/kWh]	0.09	0.14	0.23
Vehicles by type			
Thermic	139	133	164
Electric	8	14	101
Cargo-bike	24	24	21
Vehicles by size			
Small (S)	32	33	32
Medium (M)	6	6	8
Large (L)	133	132	246
Distances [km]			
Thermic	9,835	8,916	6,185
Electric	1,194	2,294	11,438
Cargo-bike	750	785	861
Total	*11,778*	*11,995*	*18,484*
Parcels			
Thermic	15,001	14,493	21,926
Electric	500	1,009	11,236
Cargo-bike	751	750	761
Total	*16,252*	*16,252*	*33,923*
Consumption			
Fuel [L]	783	710	494
Electricity [kWh]	236	546	3,261
Environment			
Emissions [kg_{CO2eq}]	2,127	1,956	1,622
Per parcel [g_{CO2eq}]	*131*	*120*	*48*
Energy [kWh]	8,071	7,642	8,205
Per parcel [Wh]	*497*	*470*	*242*
Cost [EUR]			
Salaries	23,256	23,256	38,896
Vehicles	2,217	2,302	5,416
Distance	1,159	1,426	2,427
Total	*26,632*	*26,985*	*46,740*
Per Parcel	*1.64*	*1.66*	*1.38*

respect to the transported parcel volumes. While parcels delivered by electric vehicles are rare **Today** they make up 50% of all flows in the **Future** scenario. In the latter, fuel consumption goes down by 37% while electricity use increases by a factor of 13 and total used energy by a factor of 10. On the contrary, total emissions decrease, but only by 24% despite a reduction of 63% *per parcel*. This effect is due to the generally increased demand. Total costs increase by 75% but not equally on all cost components (67% on salaries, 144% on vehicles, 109% on distance), which puts a higher influence on operational costs on the overall costs. Per parcel, there is a margin of 26ct per parcel between the **Today** and **Future** scenario.

In all scenarios, we see that cargo-bikes are rarely used because of their limited capacity.

4 CONCLUSION

In this paper we have documented a model on the economic and ecological characteristics of last-mile parcel deliveries in a city. While the model makes use of a multitude of assumptions, its main value lies in the comparison of scenarios. In the future, more detailed and distinct scenarios should be evaluated. In terms of validation, system-level reference data is not likely to emerge in the near future. Hence, we are engaging actively in discussing our operational assumptions with domain experts and practitioners to compile a comprehensive list of limitations and future improvements, which will be detailed in an extended publication on the model.

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