TODAY'S TECHNICAL FEASIBILITY OF HEAVY-DUTY BATTERY ELECTRIC TRUCKS FOR URBAN AND REGIONAL DELIVERY - A REAL-WORLD CASE STUDY

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OSL2022

Fraunhofer Institute for Systems and Innovation Research ISI

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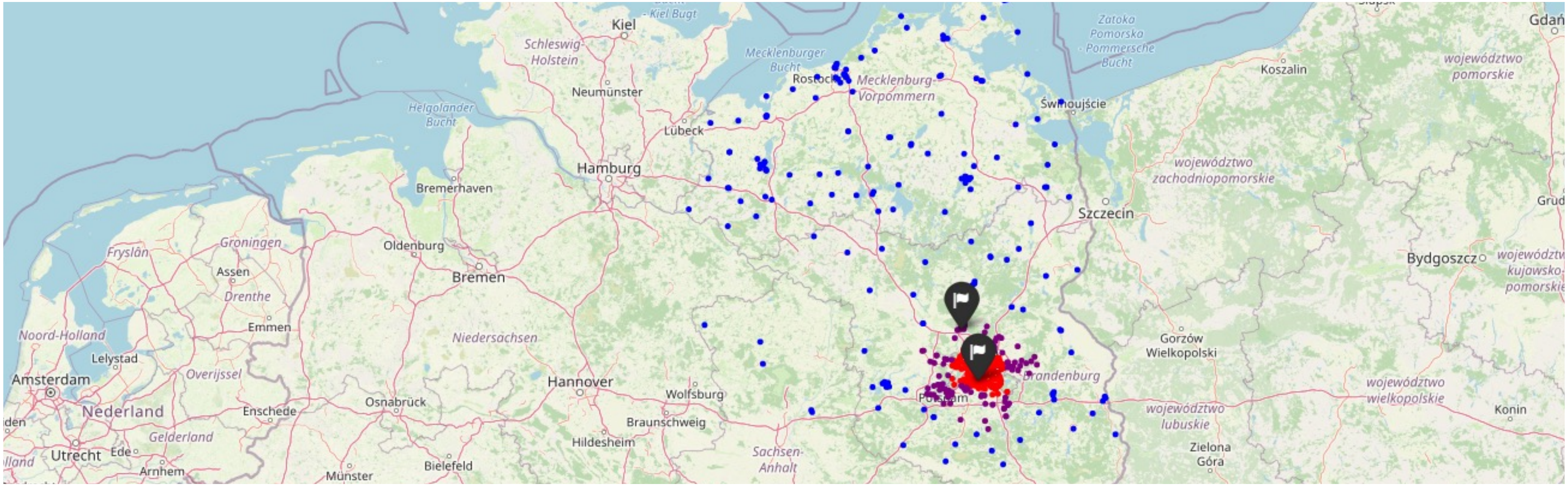

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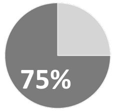
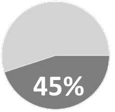
Motivation: European transport emissions: Dramatic reduction required to comply with reduction targets in 2045/2050

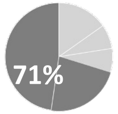
Total transport GHG emissions in Europe



Road transport ⇨

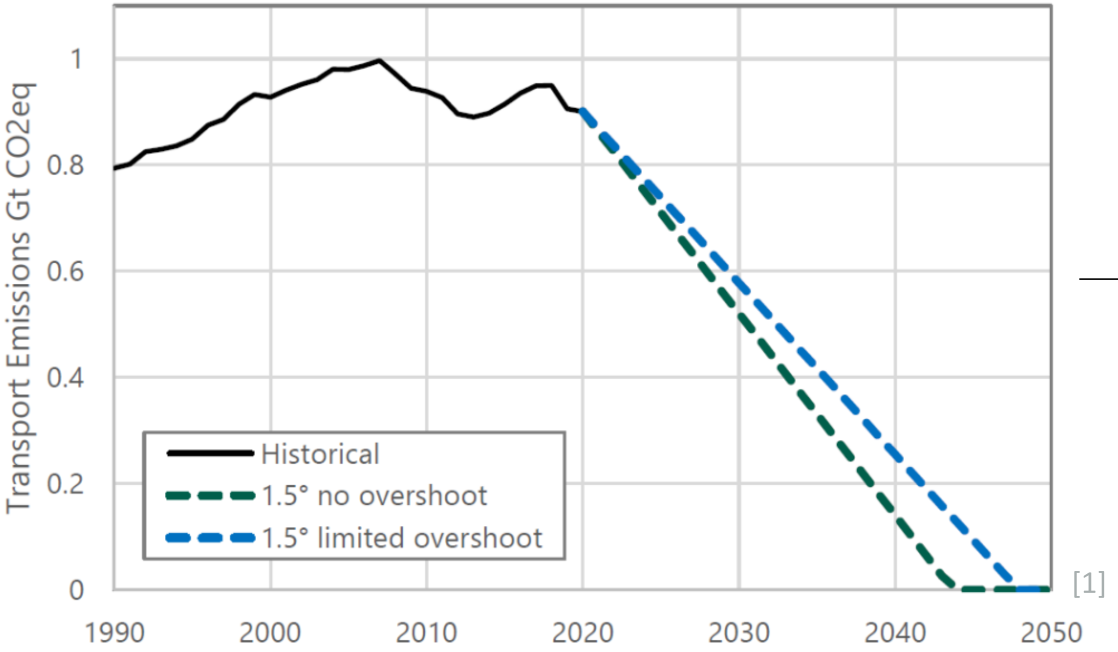


Freight transport ⇨



Trucks > 12t

[2], [3]



Total transport GHG emissions in Europe around **0.9 Gt/a**, with **25% being emitted from heavy duty vehicles >12t** (equals approx. **8%** of total EU GHG emissions)

Technological Pathways

Direct use of electricity

- *Battery electric trucks (BET)*
- *Caternary battery electric hybrid*

Indirect use via synthetic energy carriers

- Caternary hybrid with IC engine
- ICE Vehicles with synthetic fuels
- Fuel Cell Electric Vehicles
- Hydrogen IC engine vehicles

[1] Plötz et al. (2021): Net-zero-carbon transport in Europe until 2050 – Targets, technologies and policies for a long-term EU strategy. Karlsruhe: Fraunhofer ISI

[2] Wietschel et al. (2017): Machbarkeitsstudie zur Ermittlung der Potentiale des Hybrid-Oberleitungs-Lkw. *Studie im Rahmen der Wissenschaftlichen Beratung des BMVI zur Mobilitäts- und Kraftstoffstrategie.*

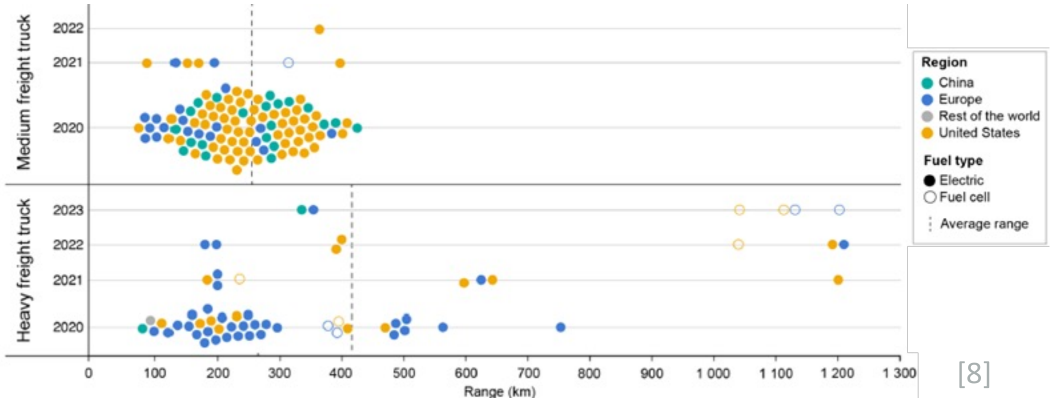
[3] European Commission (EC) (2020): "EU Transport in figures: Statistical Pocketbook 2020," European Commission (EC), Luxembourg, Sep. 2020.

Status quo: Truck fleet owners are still questioning the technical feasibility of BETs for their individual application

Literature

- Broad consent implies a great potential for **urban and regional delivery** with a daily mileage **lower than 400 km** [4,5,6,7]
- Most recent studies even see **long-haul transport (> 500 km)** close to a threshold where BETs become feasible [5,6,7]
  - by taking the required driving break (45 min) for recharging (assuming availability of charging infrastructure).
- Findings based on **high-level fleet analyses**, **survey data**, synthetic operating schedules, **standardized driving profiles** (e.g. VECTO Long-Haul) or **generic use patterns**.

Market Outlook (IEA, 2021)



[8]

- Growing model availability with vehicle ranges from 200 to 500 km expected.

✓ ***General literature-proofed feasibility*** ❯

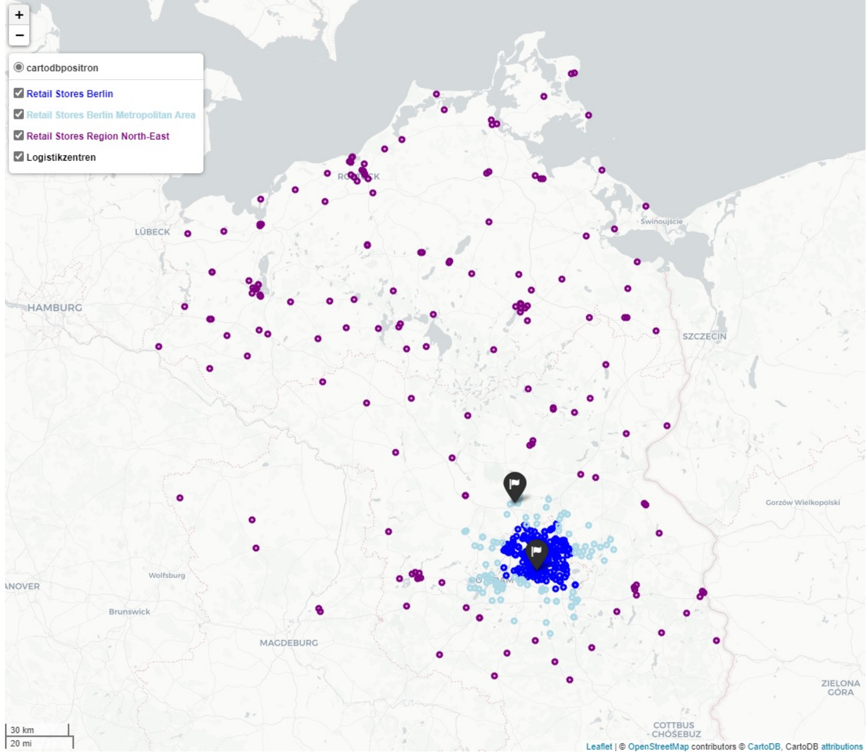
Spotlight on individual applications with real-world and per-vehicle data

❮ ✓ ***Model availability (caution on delivery times)***

[4] I. Mareev, J. Becker, and D. Sauer, "Battery Dimensioning and Life Cycle Costs Analysis for a Heavy-Duty Truck Considering the Requirements of Long-Haul Transportation," Energies, vol. 11, no. 1, p. 55, 2018, doi: 10.3390/en11010055.
[5] A. Phadke, A. Khandekar, N. Abhyankar, D. Wooley, and D. Rajagopal, "Why Regional and Long-Haul Trucks are Primed for Electrification Now," Lawrence Berkeley National Laboratory, 2021.
[6] B. Nykvist and O. Olsson, "The feasibility of heavy battery electric trucks," Joule, vol. 5, no. 4, pp. 901–913, 2021, doi: 10.1016/j.joule.2021.03.007.
[7] H. Basma, Y. Beys, and F. Rodriguez, "Battery electric tractor-trailers in the European Union: A vehicle technology analysis," International Council on Clean Transportation (ICCT), 2021.
[8] International Energy Agency (IEA), "Global EV Outlook 2021: Accelerating ambitions despite the pandemic," International Energy Agency (IEA), 2021.

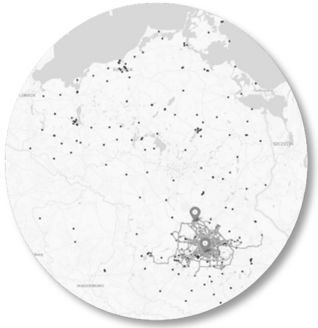
Data: 9,500 commuting tours (incl. time stamp & payload) to 543 retail stores with 224 N3 cooling trucks over one month

Overview



543 stores, 220 km radius from Berlin

4 truck classes (N3) within 1 month



18t solo, n = 25

26t solo, n = 56

Truck-Trailer, n = 35

Tractor-Trailer, n = 108

224 trucks, 9.500 tours, 1 million vkm

Own illustrations

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Method: Vehicle modeling with tour-specific parameter values and Monte-Carlo simulation to deal with uncertainty

Energy consumption and battery sizing

- **Simplified mathematical-physical model** adjusted from [9] to account for
  - Vehicle dynamics & driving forces – Eq.1
  - Energy need by accessories – Eq.2, f(t)
  - Energy need for refrigeration (4°C) – Eq.2, f(t)
  - Depth of discharge (DoD) limits – Eq.2
  - Safety buffer / residual capacity – Eq.2

$$E_{Driving} = \left[\frac{\left(\frac{1}{2} \cdot \rho \cdot C_D \cdot A \cdot v_{rms}^3 + c_{rr} \cdot m_T \cdot g \cdot v_{av} + \partial_\alpha \cdot m_T \cdot g \cdot v_{av}\right)}{\eta_{bw}} + \partial_{Reku} \cdot m_T \cdot a_{av} \cdot v_{av} \cdot \left(\frac{1}{\eta_{btw}} - \eta_{btw} \cdot \eta_{brk}\right) \right] \cdot \frac{D}{v_{av}} \quad (Eq. 1)$$

$$E_{total} = \frac{E_{Driving} + P_{Aux} \cdot t_{Driving} + P_{Cool} \cdot (t_{Driving} + t_{Stopp}) + E_{Residual}}{\eta_{DoD}} \quad (Eq. 2)$$

tour-specific parameters *general parameters*

Evaluation

- Battery sizes: 100 – 800 kWh (50 kWh increment)
- **Monte-Carlo Simulation**:
  - n = 100 per daily trip; 95% treshold
  - **PERT-distribution** for major parameters (e.g. curb weight, energy density, DoD limit, efficiencies, ...)

Scenario definition

- Assumption: BET mimics current diesel schedule

  Comply with GVW limits
- Base: Overnight depot charging (ONC – slow 50kW)
- S1: Intermediate depot charging (fast[1]); ONC – slow (50 kW)
- S2: Intermediate depot (fast[1]) + retail store charging (150 kW); ONC – slow (50 kW)

[9] S. Sripad and V. Viswanathan, "Performance Metrics Required of Next-Generation Batteries to Make a Practical Electric Semi Truck," ACS Energy Lett., vol. 2, no. 7, pp. 1669–1673, 2017, doi: 10.1021/acsenergylett.7b00432.
1: Range from 50 kW to 1000 kW

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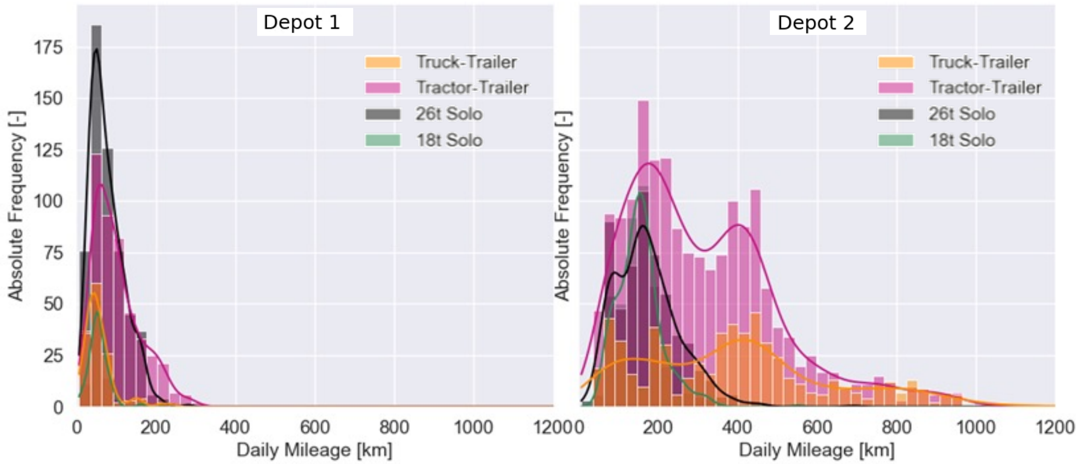
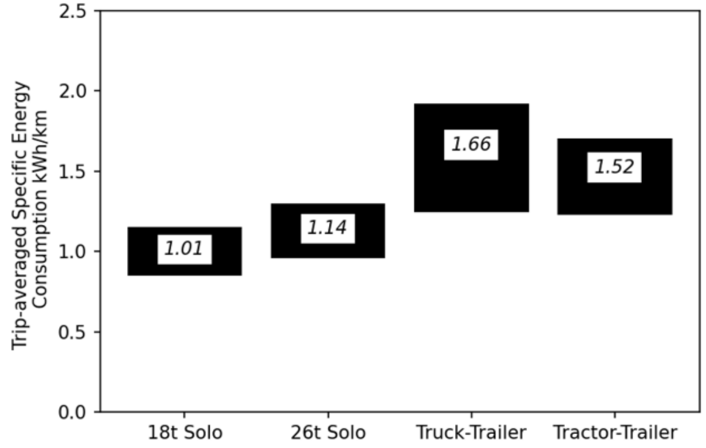
Results (1/3): High variance in operating behavior and energy need – from daily 200 km (urban) to 700 km (regional)

Daily driving ranges



- 1-5 tours per day; 1-4 stops at retail stores per tour
- **Daily mileage:**
  - **Mostly below 200 km for urban delivery**
  - Solo trucks usually under 400 km
  - **500 – 700 km for regional delivery**
- Mean annual mileage: 56,000 km[1]

Simulated energy consumption



- Simulated battery-to-wheel energy consumption (median values):
  - *18 t Solo:* *1.01 kWh/km*
  - *26 t Solo:* *1.14 kWh/km*
  - *Tractor-Trailer:* *1.52 kWh/km*
  - *Truck-Trailer:* *1.66 kWh/km*

1: range from 15,000 to 124,000 km (10%-90% quantile)

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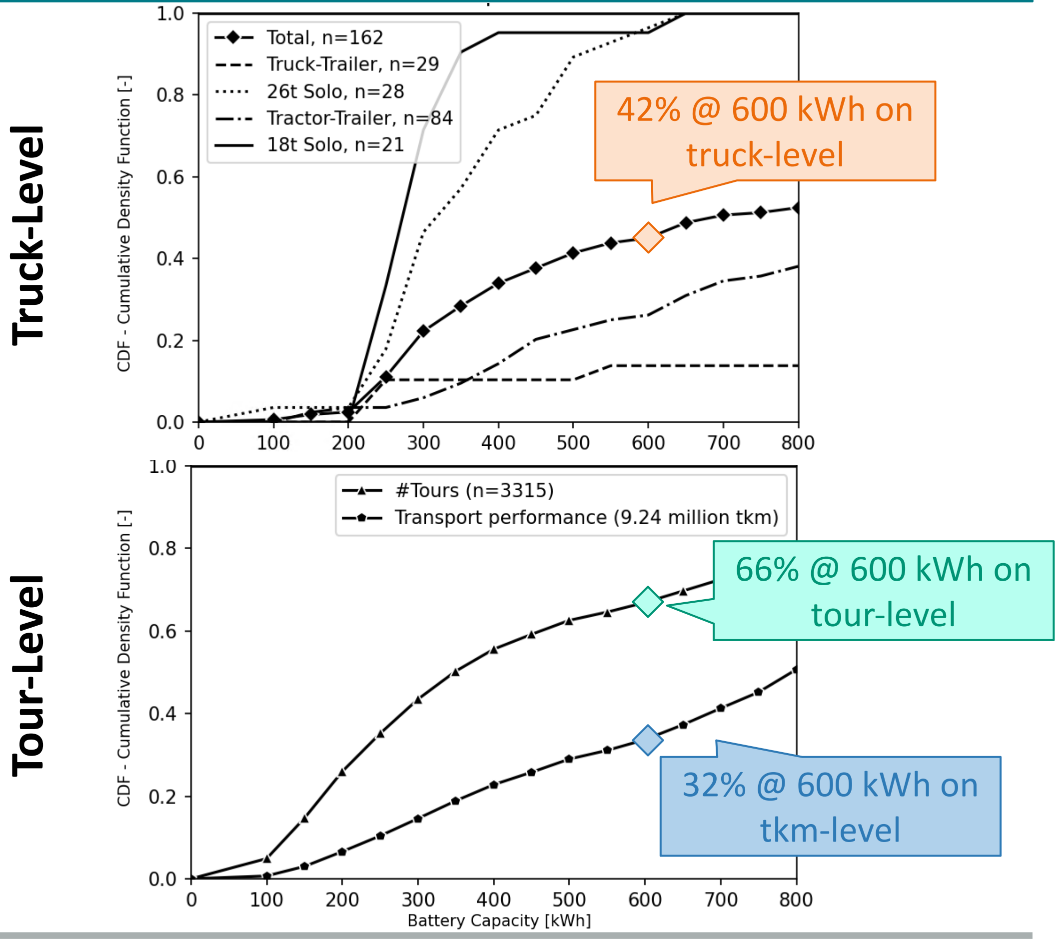
Results (2/3): Base scenario - getting the right battery capacity per truck and optimize tour & truck allocation

Central findings

1. **No right battery capacity per truck class,**
   - **Vehicle-specific examination** for the right battery capacity that ideally matches the vehicle's operating profile.
   - **Over 40% of the fleet** might be replaceable with BET **with up to 600 kWh**.
2. If the vehicle allocation is neglected, tour feasibility is significantly higher than on truck-level (**few unfeasible tours are the crunch**)
   - **High potential by re-allocating daily tours** within the truck fleet (e.g. SoC based)
   - **Mixed fleet considerations**, where most tours are done with BETs, and minor shares remain for (already existing) diesel trucks
3. **Long and / or heavy tours** are most challenging (delta tour-level and tkm-level)

Depot 2: trucks, tours and tkm

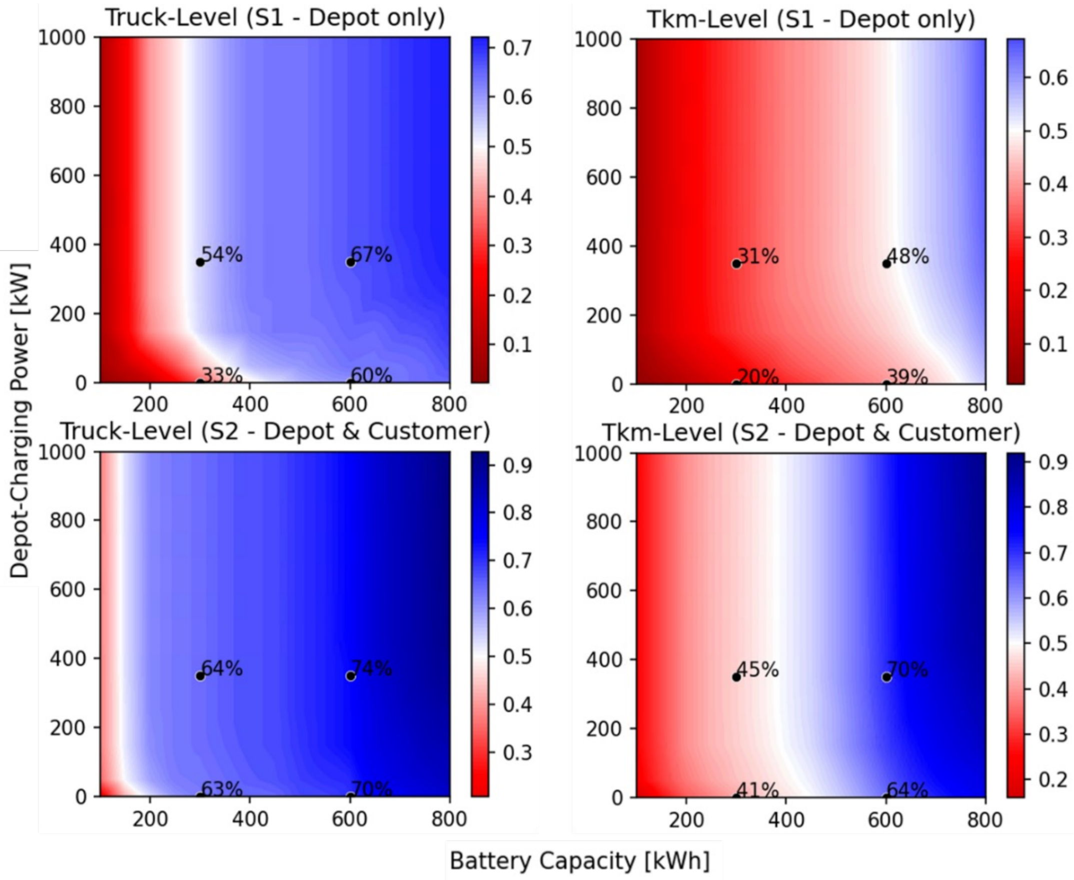


Results (3/3): Scenarios S1 & S2 – advanced fleet electrification might need several simultaneous measures

Central findings

1. **Higher intermediate charging power** leads to higher feasibility with smaller batteries. **Effect saturates beyond 350 kW** (observe the median (50% threshold))
2. **Higher sensitivity towards installed battery capacity** rather than charging power given long trip segments and distances (x-axis versus y-axis gradient – **saturation over 650 kWh (GVW limit)**
3. Intermediate charging options at (selected) retail stores (***coincides with the 45 min break***) enable an increase of roughly **20% of electrified tkm**.
4. **Full electrification fails in any scenario** so that further combined actions are required - e.g.
    1. **Fleet operator:** tour optimization, adjusted scheduling (e.g., SoC-based)
    2. **Manufacturer:** Higher battery energy density, (FCET)

Feasibility heatmaps



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Discussion and limitations: Conditional generalization of our findings and more in-depth modelling needed

- Tours and vehicle allocation are presumed to be exactly as of February 2021 so that potential BET would **mimic the existing diesel truck schedule**. We assume that **all trips must be technically feasible** to classify one truck as technically replaceable with an BET.

- **Data representativeness and particularities of the food retail industries** (e.g. additional energy needs from commodity cooling, milk-run concept and return-home application).

- **Uncertainties for our simulated energy consumption** resulting from our simplified simulation approach (e.g. without trip dynamics, ...) -> balance complexity versus speed

- We assume that **intermediate fast charging (depot, retail store) is available at any time** so that all cargo terminals (depot plus retail stores) are equipped with charging infrastructure. Possible occupancy and potential constraints (e.g., costs, available space, and grid connection) are neglected.

- **No battery aging effects** (i.e., cyclic and calendar) that would impact technical feasibility with decreasing State-of-Health (SoH).

Conclusion: High BET feasibility with available and announced battery capacities, yet custom real-word pitfalls likely remain.

- We analyzed over **9,000 real-world commuting tours** to 543 retail stores with 224 heavy-duty cooling trucks (4 different truck classes) operating **within only 220 km around Berlin** for two use cases: (1) urban and (2) regional delivery.

- We find **high potential for BET feasibility** even if we **exactly mirror the existing operating** schedules
  - With up to 600 kWh and no additional intermediate fast-charging infrastructure, we reach **39% of electrified tkm** and **may replace nearly 60% of all trucks (Depot1 and Depot2)**.

- We emphasize the necessity of:
  - **finding the right battery capacity** per truck by analyzing its operational patterns
  - **high ad-hoc potential through tour optimization and variable truck-tour allocation** (i.e., SoC- and SoH-based).

- Given some literature-proofed general feasibility, further research should focus on **more case studies from other relevant industries**, to **highlight custom real-world pitfalls** in daily operations (e.g. limited 45min driving break charging potential for some regional use cases, multi-shift operations), and enhance to **techno-economic evaluations**.

THANK YOU FOR YOUR ATTENTION

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References

- [1] Plötz et al. (2021): Net-zero-carbon transport in Europe until 2050 – Targets, technologies and policies for a long-term EU strategy. Karlsruhe: Fraunhofer ISI
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Truck-class-specific simulation parameters. Ranges indicate the PERT distribution's minimum, most likely, and maximum values. Individual parameters are constant values.

Parameter		18t	26t	Truck-Trailer	Tractor-Trailer	Source
m_{Curb_D}	[kg]	5,761 -6,475 - 7,125	8,239 - 8,679 - 9,073	8,239 - 8,679 - 9,073	5,761 - 6,475 - 7,125	Q25-Q50-Q75 [17]
$m_{Trailer}$	[kg]	-	-	6,500 ± 20%	8,500 ± 20%	derived from [15]
$C_D \cdot A$	[m²]	5.559 -5.698 - 5.837	5.463 - 5.997 - 5.737	6.557 - 7.839 -9.179	5.559 - 5.698 - 5.837	Q25-Q50-Q75 [17]
c_{rr}	[N/kN]	5.5 - 5.7 - 6.9	5.0 - 5.6 - 6.8	5.0 - 5.6 - 6.8	4.9 - 5.1 - 6.5	Q25-Q50-Q75 [17]
P_{Aux}	[kW]	2.97 ± 20%	3.39 ± 20%	4.32 ± 20%	4.11 ± 20%	[15, 16]
P_{Cool}	[kW]	3.11 ± 20%	3.11 ± 20%	5.90 ± 20%	5.14 ± 20%	ATP/DIN 8959
P_{Motor}	[kW]	200 - 228 - 265	265 - 323 -350	265 - 323 -350	331 - 355 - 368	Q25-Q50-Q75 [17]
v_{Std}	[m/s]	0.413	0.417	0.744	0.677	[-]

Other simulation parameters. Ranges indicate the PERT distribution's minimum, most likely, and maximum values. Individual parameters are constant values.

Parameter		Value / Value range	Source
η_{DoD}	[%]	90% ± 5%	[13]
ρ_{Bat}	[Wh/kg]	150 - 175 - 225	[13, 14, 20]
∂_{Reku}	[%]	50% ± 10%	[14]
a_{av}	[m/s²]	Urban: 0.331 ± 20%, Regional: 0.160 ± 20%	Q25-Q75 [19]
η_{BTW}	[%]	$= \eta_{BTW}$ (95% ± 2.5%) · η_{PT} (90% ± 2.5%)	[13, 14]
η_{brk}	[%]	97%	[14]
v_{RMS}	[m/s]	$= \sqrt{v_{av}^2 + v_{std}^2} + v_{Wind}$ (3 ± 20%)	Modelled based on [14] and VECTO [21]
$E_{Residual}$	[kWh]	30	Own assumption
p	[kg/m³]	1.15 - 1.225 - 1.3	Own assumption
m_{Emot}	[kg/kW]	1.43	[22]
m_{DPT}	[kg]	$= m_{Gearbox}$ (300 kg) + m_{Tank} (108 kg) = 408 kg	Own calculation based on [2]
m_{ICE}	[kg/kW]	3.3	[23]
m_{PL}	[kg]	Base value from truck schedule (± 20%)	Own assumption
$P_{Charge,Dep}$	[kW]	$\in \{50,150,250,350,450,1000\}$	Own assumption based on common charging standards
$P_{Charge,CR}$	[kW]	150	Own assumption
r_{NCP}	[%]	75% ±10%	Own assumption
η_{NCP}	[%]	68.1% (184/270) - 82% (164/200) - 92.6 % (250/270)	[24]

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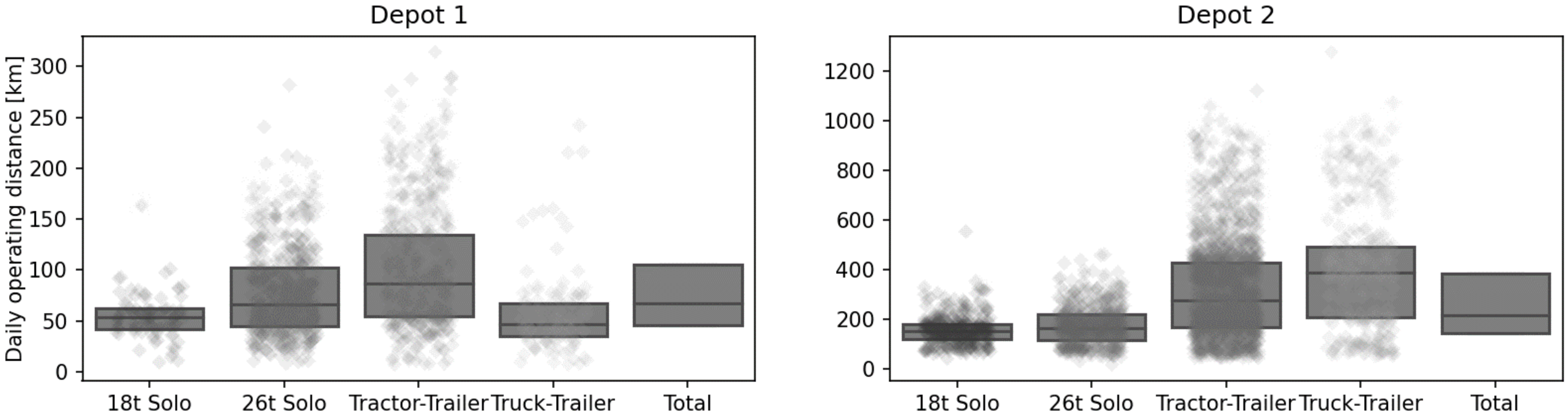
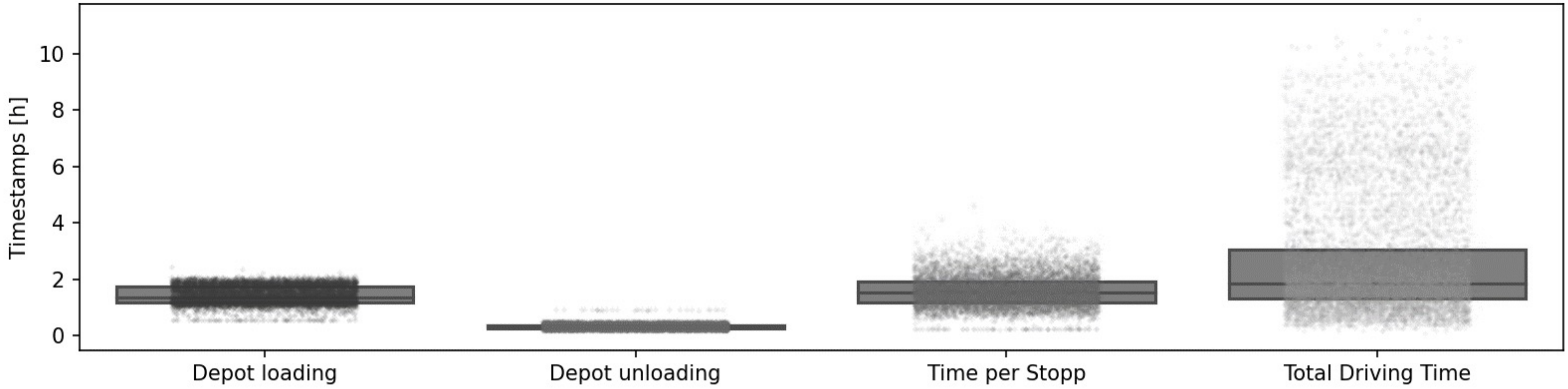
Evaluation of daily operating distances per truck class and per depot location. Sample points are scattered, whereas the boxplots indicate the lower quartile, median, and upper quartile. Own illustration



Evaluation of vehicle operating times across both depots. Sample points are scattered, whereas the boxplots indicate the lower quartile, median, and upper quartile. Own illustration.



Vehicle scheduling specifies four timestamps, from vehicle loading at the cargo terminals within the depots (*tLoading*), driving time (*tDriving*), stop time at customer retail stores (*tStopp*), and eventually vehicle unloading at the cargo terminals to complete one single commuting tour. An evaluation including single values and boxplot per category is shown in ***Figure 3***, combining both depots. While **vehicle loading typically takes 70-105 minutes**, **customer stops last similar (71-114 minutes)**, yet **unloading takes only 15-22 minutes**. As mentioned earlier, additional breaks such as the mandatory 4.5h driving break are not scheduled as these are covered at customer stops.

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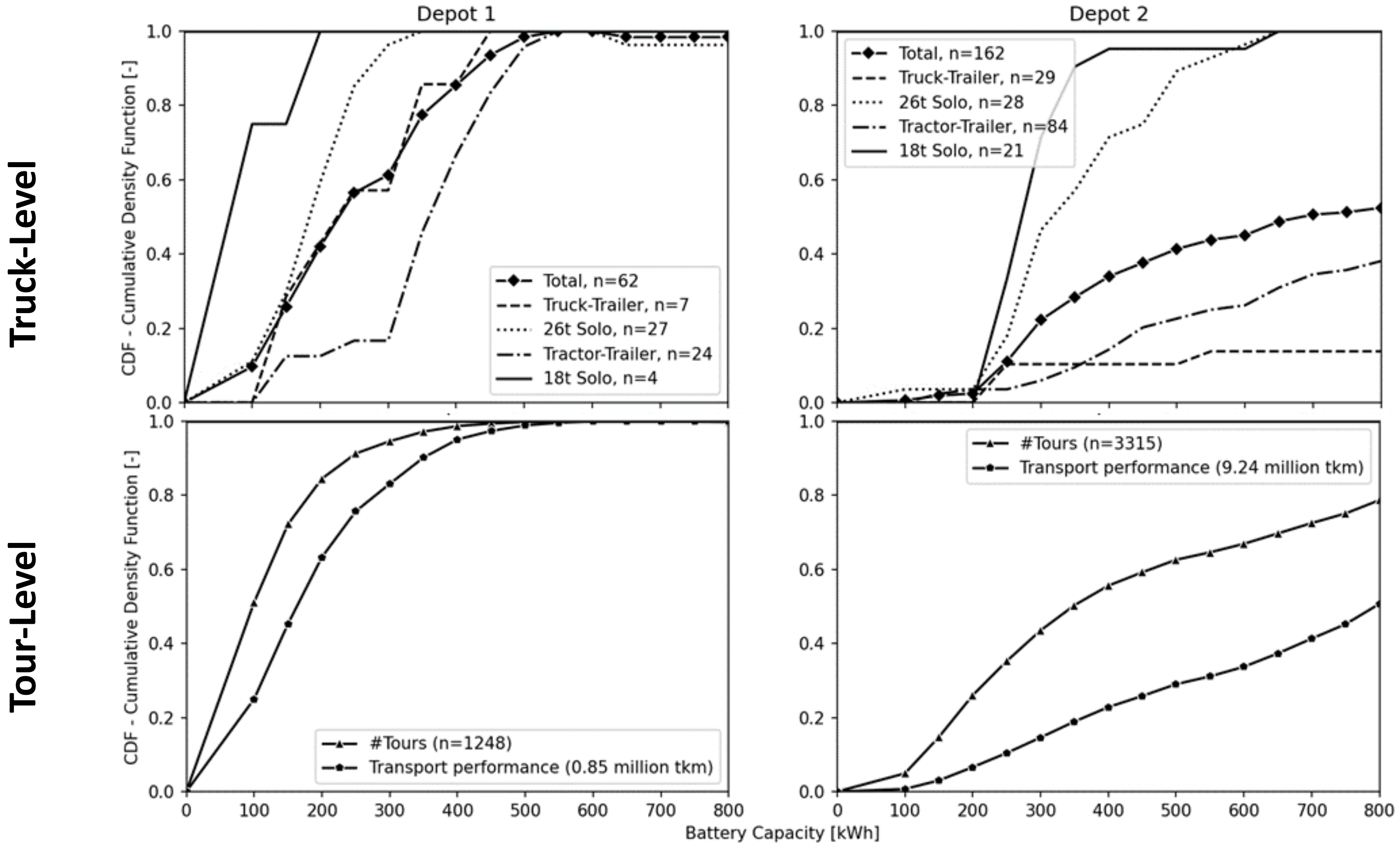
BET feasibility per truck class (on truck-level) Left: CDF over battery capacity for Depot 1. Right: CDF over battery capacity for Depot 2. Own illustration.



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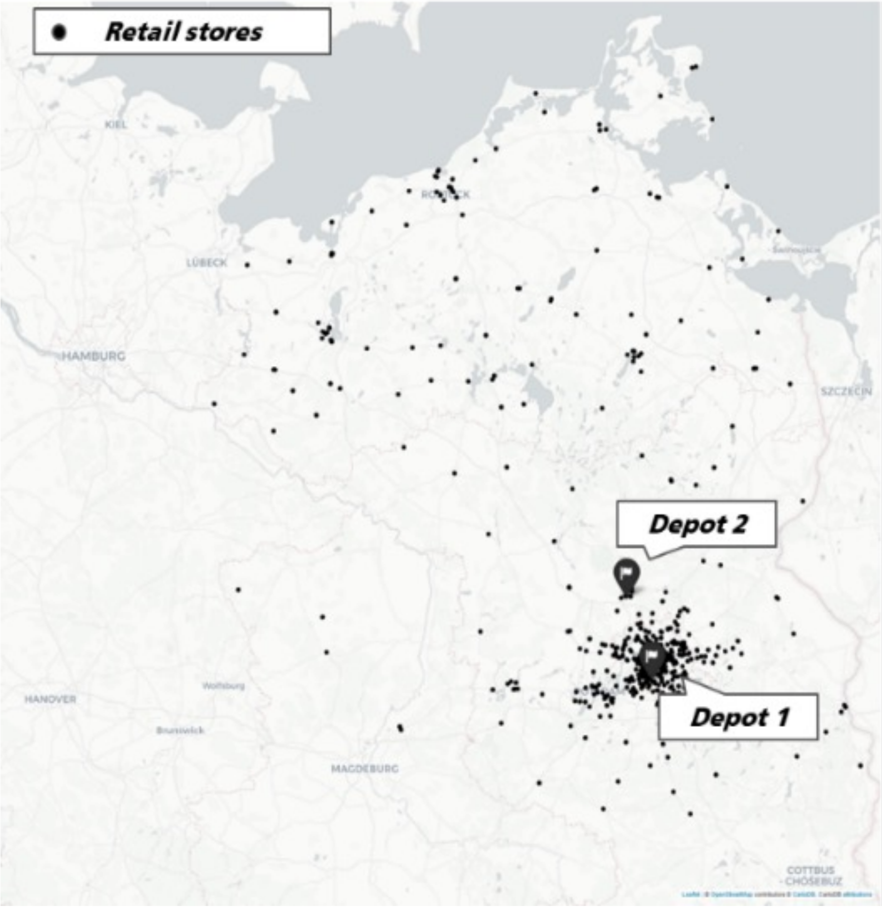
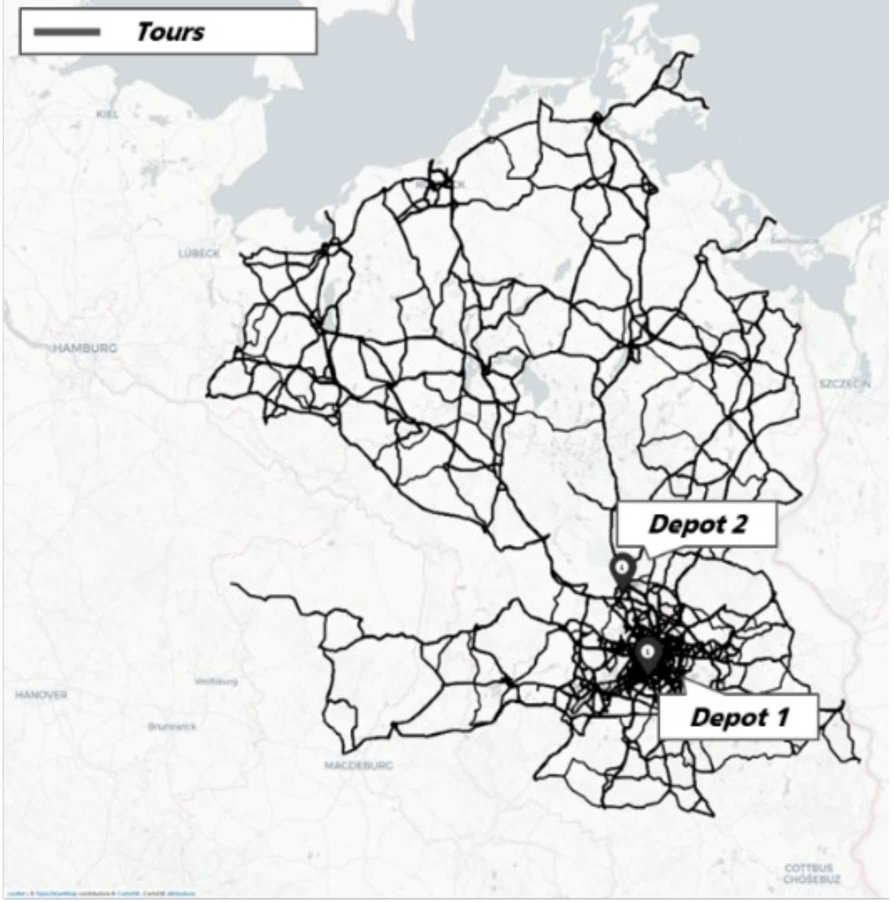
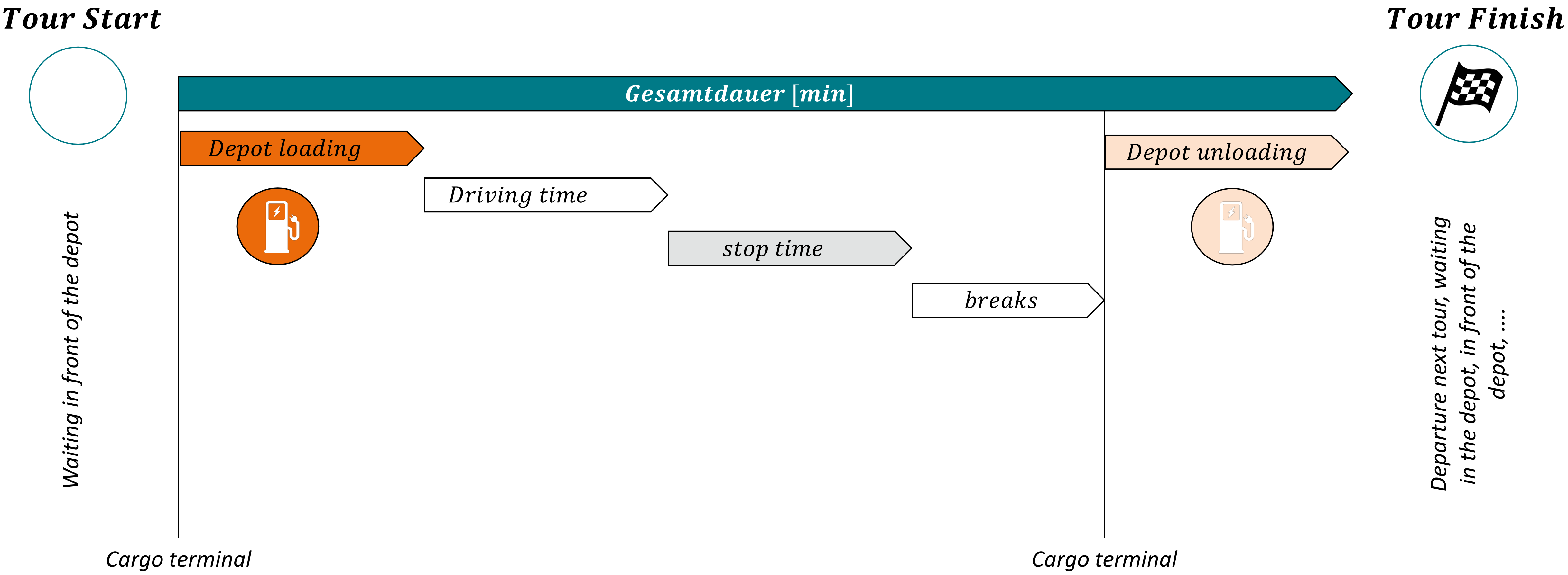
Data sample - Northeast Region: Customers (Left) and Tours (Right)





Data sample – time stamps



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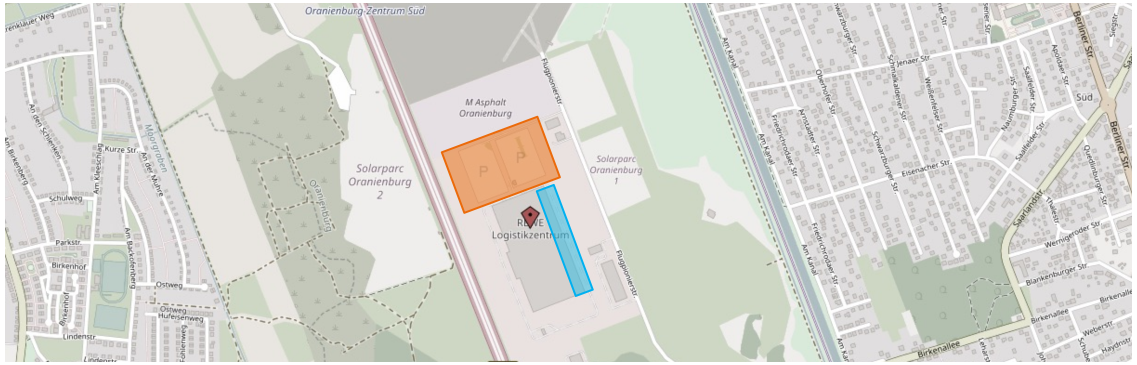
Depot overnight loading in the parking lot; optional intermediate charging at the cargo terminals

Description

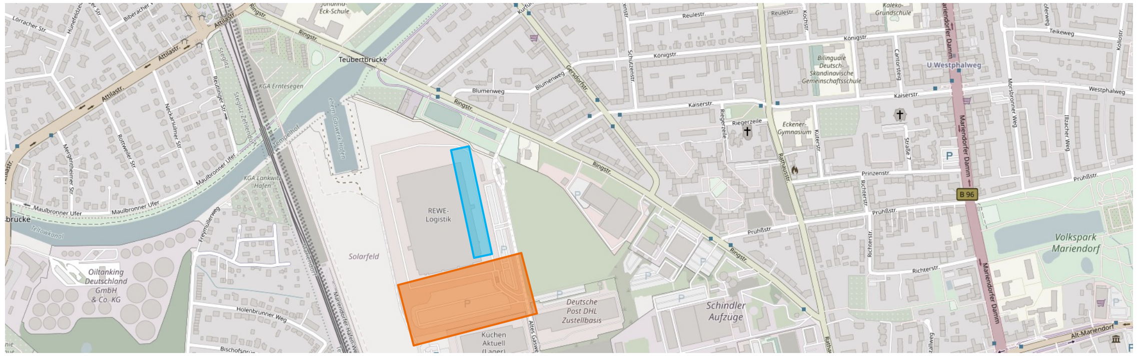
- Overnight depot charging in the parking lot in front of the site
  - 162 vehicles in Oranienburg
  - 62 vehicles in Mariendorf

- Intermediate depot charging at the depot ("depot loading") directly at the cargo terminals within the logistics center in focus

Depot Oranienburg (urban and regional)



Depot Mariendorf (urban)



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