# *Electric Vehicle Thermal Conditioning: Energy Demand Implications under Climate Change*

***Jan 30, 2026***

***2026 Transportation Engineering, Economics, and Policy Workshop***

**Anna Stefanopoulou**
**William Clay Ford Professor of Technology**
**Mechanical Engineering**
**University of Michigan– Ann Arbor**

**Edson Severnini**
**Associate Professor of Economics**
**Boston College**
**(previously at CMU)**

**Youngki Kim**
**Associate Professor**
**Mechanical Engineering**
**University of Michigan – Dearborn**

**Jingchen Ma (Fellow)**
**Phd candidate, Mechanical Engineering**
**University of Michigan – Ann Arbor**

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***Thanks to Sloan Foundation (Interdisciplinary Transportation Fellowship)***

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# External Advisors

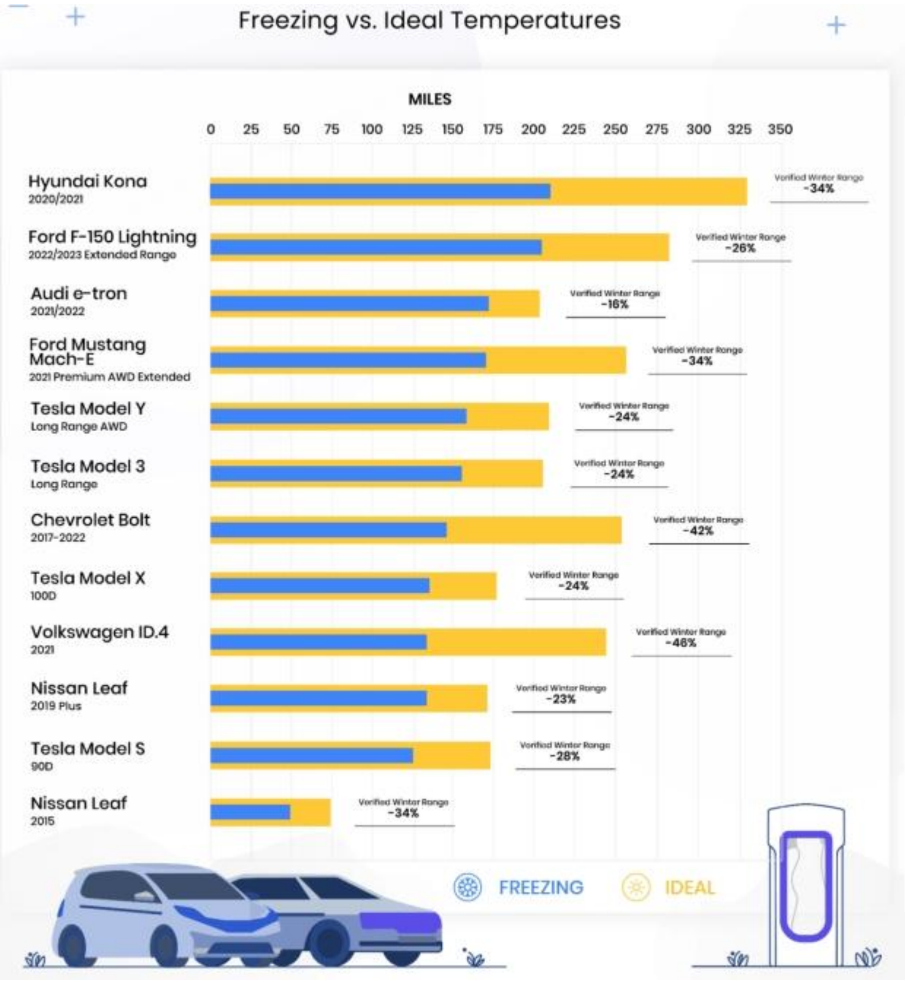
**Caldwell, Robert**
US EPA
Office of Transportation and Air Quality,
Transportation & Climate Division, LFIAC

**Kyoung Pyo Ha**
Research Fellow
Hyundai Kia America Technical Center, Inc. (HATCI)

**Stephen Dolen**
Assistant Vice President
Logistics, Transportation and Parking operations
University of Michigan

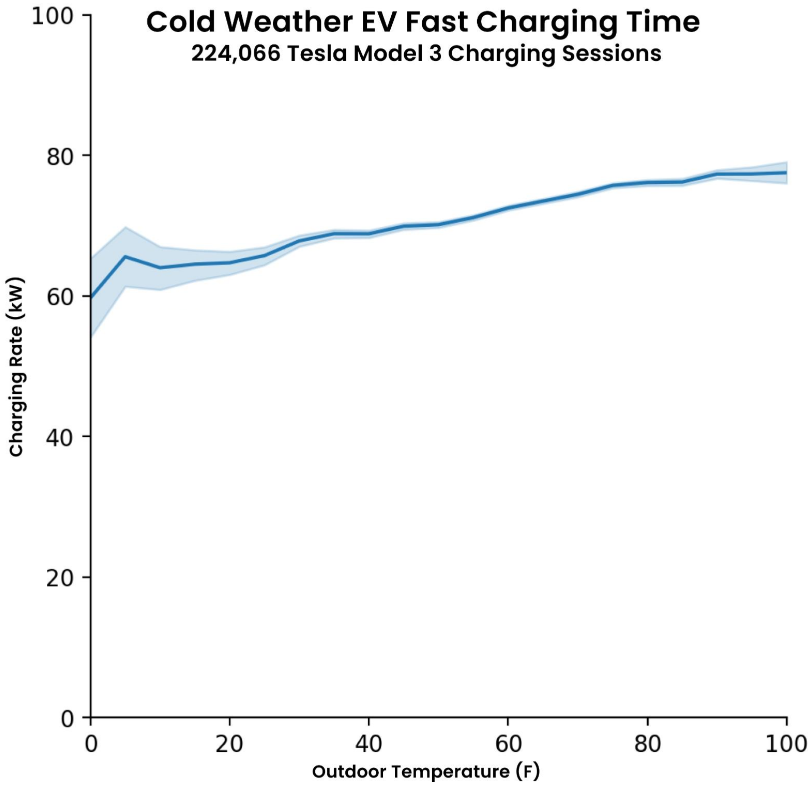
# Cold Weather Negative Impacts on Electric vehicles

1. Driving range ↓

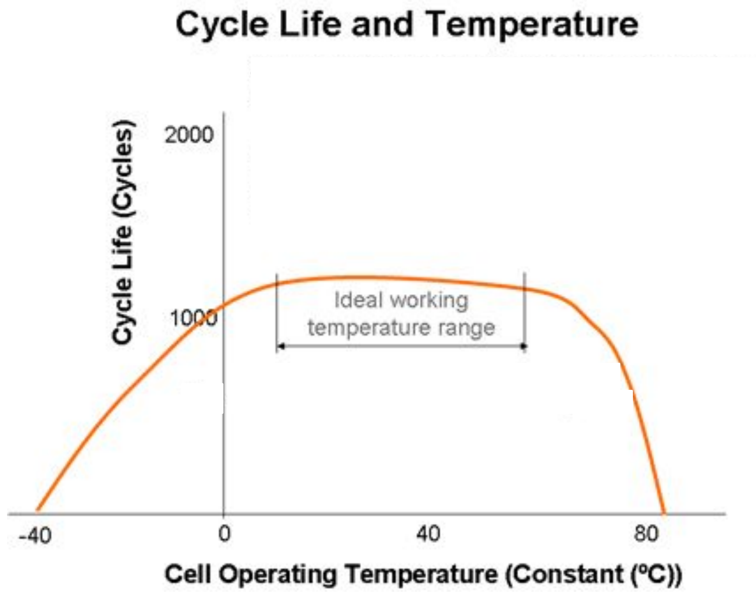



https://www.recurrentauto.com/

2. Charging time ↑




3. Battery lifetime ↓




Shahjalal, Mohammad, et al. "A review of thermal management for Li-ion batteries: Prospects, challenges, and issues." *Journal of energy storage* 39 (2021): 102518.

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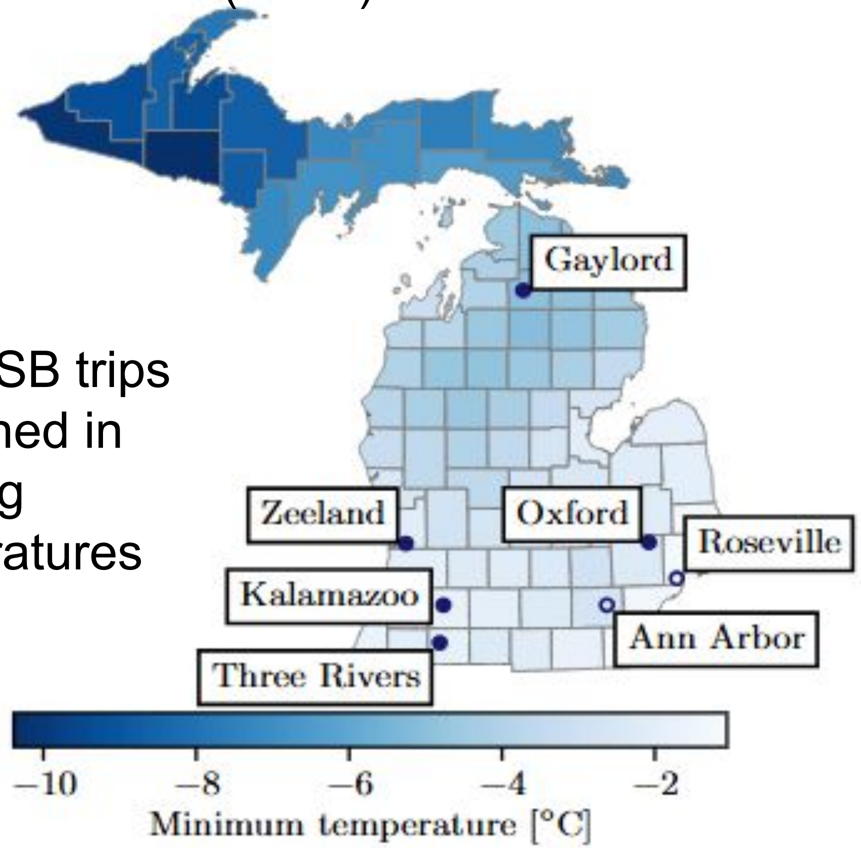
# Field Winter Data Study of MI Electric School Buses

Michigan daily lows map for 17 Electric school buses (ESBs) in 7 school districts




50% ESB trips happened in freezing temperatures

| SCHOOL DISTRICTS | ELECTRIC BUSSES | QUANTITY |
|---|---|---|
| Ann Arbor | Saf-T-Liner C2 Jouley | 4 |
| Roseville | Saf-T-Liner C2 Jouley | 2 |
| Gaylord | LionC | 2 |
| Kalamazoo | LionC | 1 |
| Oxford | LionC | 2 |
| Three Rivers | LionC | 2 |
| Zeeland | LionC | 4 |

Tran, V. V., **Ma, J.**, Siegel, J. B., & Stefanopoulou, A. G. (2024). Fighting the cold: The impact of preconditioning on electric school bus performance.

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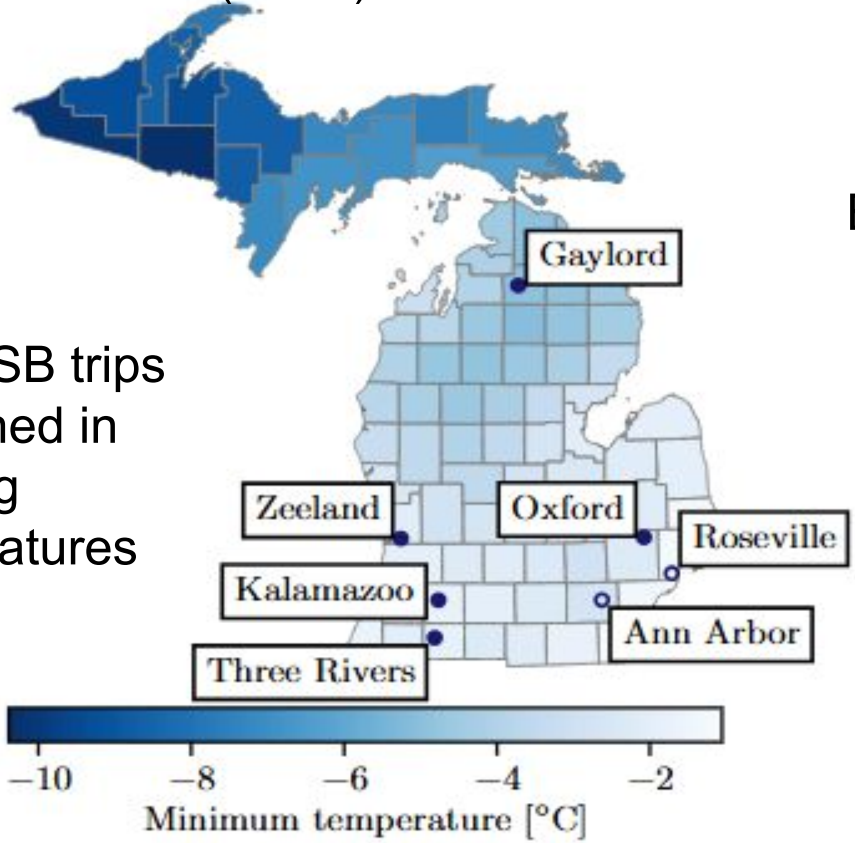


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Electric bus with electric cabin heater

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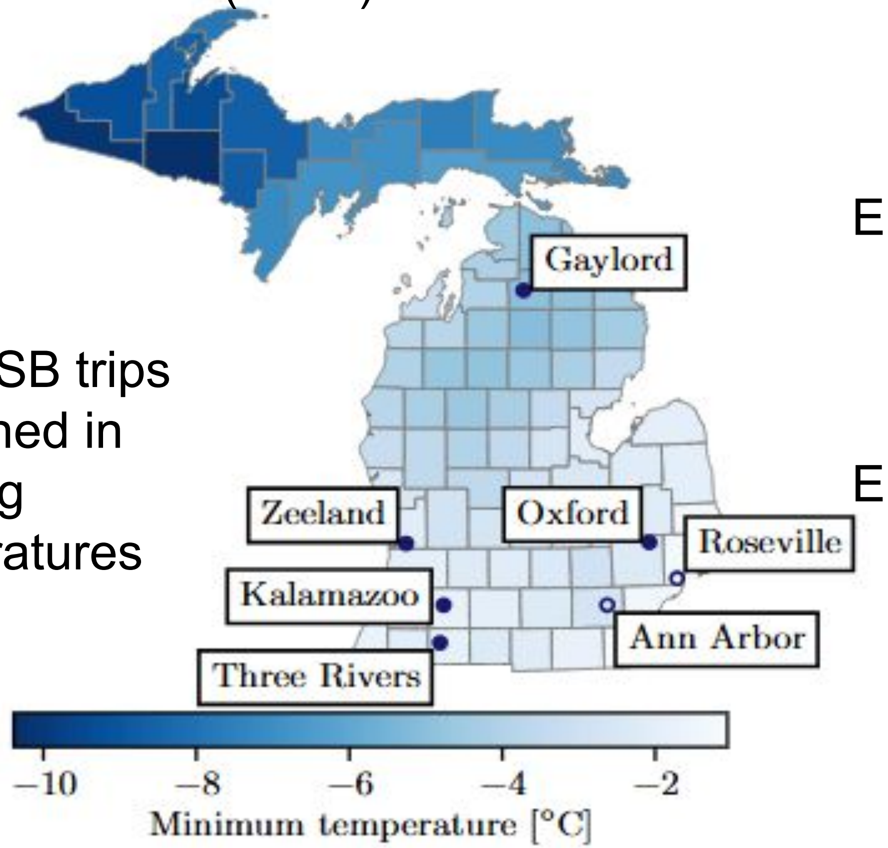


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Electric bus with electric cabin heater

Electric bus with diesel cabin heater

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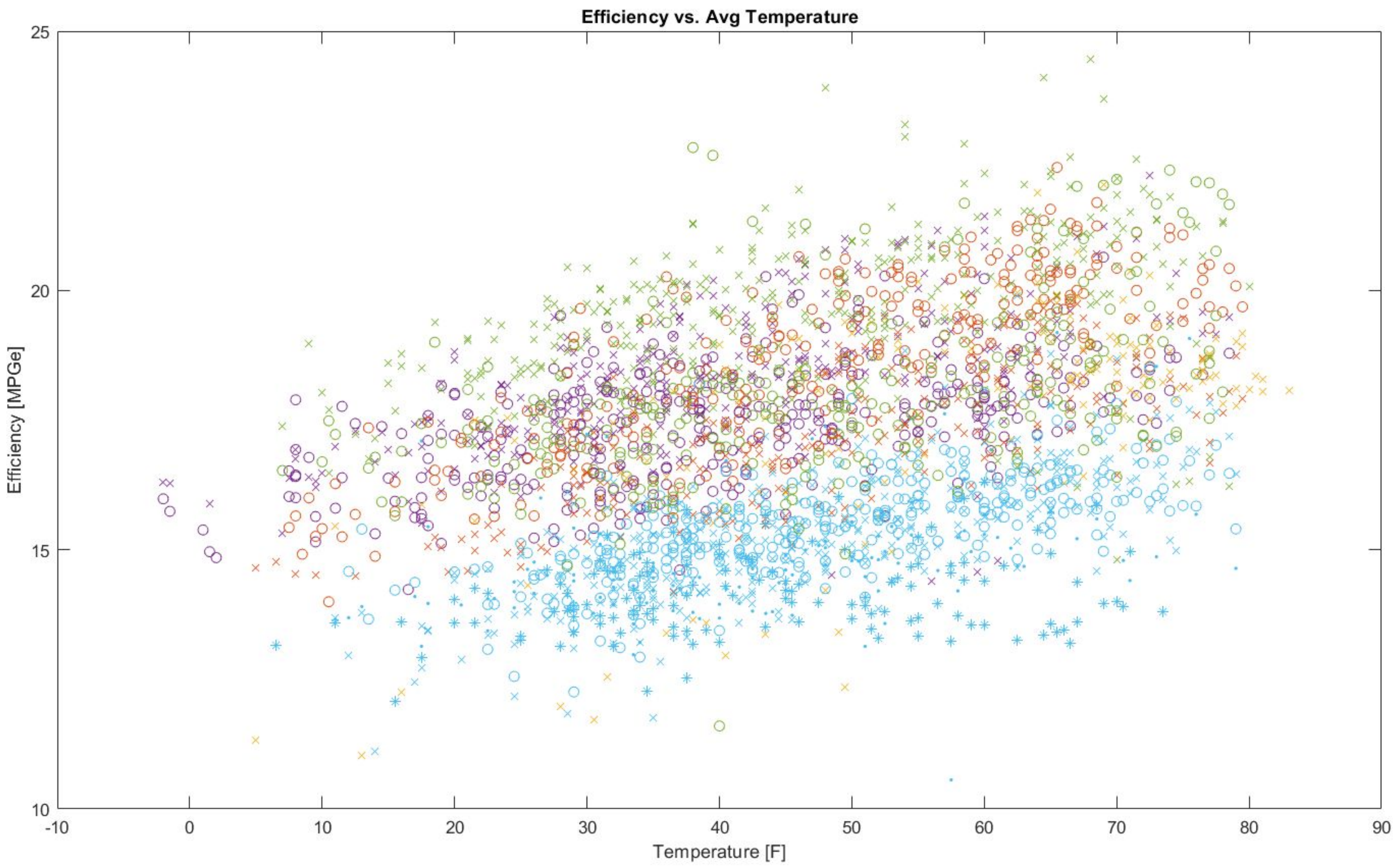
# Combined Efficiency vs. Temperature

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# Non-Cold Weather Data (2022-23)

**Non-cold weather efficiency (April 2022 - Sept 2022)**

Data based on days where more than 10 miles were driven and 1 kWh net was consumed between 4/01/2022-09/30/2022

| | School districts | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **LionBeat/Valence Data** | **Gaylord** | | **Oxford** | | **Three Rivers** | | **Kalamazoo** | **Zeeland** | | | | **Average** | **Ann Arbor** | | | | **Roseville** | | **Average** |
| **Vehicle Level** | **1** | **2** | **1** | **2** | **1** | **2** | **1** | **1** | **2** | **3** | **4** | | **1** | **2** | **3** | **4** | **1** | **2** | |
| Total miles | 1168 | 1283 | 4375 | 3008 | 4062 | 4877 | 2653 | 3256 | 3541 | 2268 | 5364 | | 2185 | 1603 | 2134 | 2274 | 2060 | 243 | |
| KWh consumed | 1577 | 1848 | 6290 | 5025 | 5408 | 6195 | 3910 | 4950 | 5561 | 4220 | 8321 | | 3513 | 2493 | 3474 | 3989 | 3969 | 347 | |
| **Efficiency (mi/kWh)** | **0.74** | **0.69** | **0.70** | **0.60** | **0.75** | **0.79** | **0.68** | **0.66** | **0.64** | **0.54** | **0.64** | **0.67** | **0.62** | **0.64** | **0.61** | **0.57** | **0.52** | **0.70** | **0.61** |
| **Electric MPGe** | **28.07** | **26.32** | **26.36** | **22.69** | **28.47** | **29.84** | **25.71** | **24.93** | **24.13** | **20.37** | **24.43** | **25.57** | **23.58** | **24.37** | **23.28** | **21.60** | **19.67** | **26.56** | **23.18** |

Electric buses with diesel cabin heater

Electric buses w/o diesel cabin heater with electric cabin heater

# Non-Cold Weather Data (2022-23)

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0.7(mi/kWh)
25.6 MPGe

0.6(mi/kWh)
23.2 MPGe

**All types of electric school buses achieve very high efficiency (nearly 5x of the traditional combustion engine bus)**

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Typical Sedan EV

3-4.2(mi/kWh)
100-140 MPGe

0.7(mi/kWh)
25.6 MPGe

0.6(mi/kWh)
23.2 MPGe

**All types of electric school buses achieve very high efficiency (nearly 5x of the traditional combustion engine bus)**

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| **Electric MPGe** | 28.07 | 26.32 | 26.36 | 22.69 | 28.47 | 29.84 | 25.71 | 24.93 | 24.13 | 20.37 | 24.43 | 25.57 | 23.58 | 24.37 | 23.28 | 21.60 | 19.67 | 26.56 | 23.18 |

**Non-cold efficiency**

**(5x of the traditional combustion bus)**

**Winter efficiency (Oct 2022 - Mar 2023)**

Data based on days where more than 10 miles were driven and 1 kWh net was consumed between 10/01/2022-03/31/2023

| LionBeat/Valence Data | School districts | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gaylord | | Oxford | | Three Rivers | | Kalamazoo | Zeeland | | | | Average | Ann Arbor | | | | Roseville | | Average |
| **Vehicle Level** | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 2 | 3 | 4 | | 1 | 2 | 3 | 4 | 1 | 2 | |
| Total miles | 1992 | 1730 | 4684 | 3833 | 4366 | 7539 | 4053 | 4702 | 5145 | 5842 | 7580 | | 1001 | 2033 | 1412 | 2365 | 854 | 528 | |
| KWh consumed | 2872 | 2601 | 6983 | 5843 | 5827 | 9889 | 6802 | 8308 | 9273 | 10443 | 12873 | | 2349 | 4588 | 3378 | 5123 | 1856 | 1044 | |
| **Efficiency (mi/kWh)** | 0.69 | 0.67 | 0.67 | 0.66 | 0.75 | 0.76 | 0.60 | 0.57 | 0.55 | 0.56 | 0.59 | 0.64 | 0.43 | 0.44 | 0.42 | 0.46 | 0.46 | 0.51 | 0.45 |
| **Electric MPGe** | 26.29 | 25.20 | 25.42 | 24.86 | 28.40 | 28.90 | 22.58 | 21.45 | 21.03 | 21.20 | 22.32 | 24.33 | 16.15 | 16.80 | 15.85 | 17.49 | 17.44 | 19.17 | 17.15 |

**Winter electric efficiency**

**24 MPGe with diesel heater (4x)**

**17 MPGe with electric heater (3x)**

# Considering the Diesel used for Heater

**Non-cold weather efficiency (April 2022 - Sept 2022)**

Data based on days where more than 10 miles were driven and 1 kWh net was consumed between 4/01/2022-09/30/2022

| | School districts | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
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| **Efficiency (mi/kWh)** | 0.74 | 0.69 | 0.70 | 0.60 | 0.75 | 0.79 | 0.68 | 0.66 | 0.64 | 0.54 | 0.64 | 0.67 | 0.62 | 0.64 | 0.61 | 0.57 | 0.52 | 0.70 | 0.61 |
| **Electric MPGe** | 28.07 | 26.32 | 26.36 | 22.69 | 28.47 | 29.84 | 25.71 | 24.93 | 24.13 | 20.37 | 24.43 | 25.57 | 23.58 | 24.37 | 23.28 | 21.60 | 19.67 | 26.56 | 23.18 |

**Non-cold efficiency**

**(5x of the traditional combustion bus)**

**Winter efficiency (Oct 2022 - Mar 2023)**

Data based on days where more than 10 miles were driven and 1 kWh net was consumed between 10/01/2022-03/31/2023

| | School districts | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LionBeat/Valence Data | Gaylord | | Oxford | | Three Rivers | | Kalamazoo | Zeeland | | | | Average | Ann Arbor | | | | Roseville | | Average |
| **Vehicle Level** | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 2 | 3 | 4 | | 1 | 2 | 3 | 4 | 1 | 2 | |
| Total miles | 1992 | 1730 | 4684 | 3833 | 4366 | 7539 | 4053 | 4702 | 5145 | 5842 | 7580 | | 1001 | 2033 | 1412 | 2365 | 854 | 528 | |
| KWh consumed | 2872 | 2601 | 6983 | 5843 | 5827 | 9889 | 6802 | 8308 | 9273 | 10443 | 12873 | | 2349 | 4588 | 3378 | 5123 | 1856 | 1044 | |
| **Efficiency (mi/kWh)** | 0.69 | 0.67 | 0.67 | 0.66 | 0.75 | 0.76 | 0.60 | 0.57 | 0.55 | 0.56 | 0.59 | 0.64 | 0.43 | 0.44 | 0.42 | 0.46 | 0.46 | 0.51 | 0.45 |
| **Electric MPGe** | 26.29 | 25.20 | 25.42 | 24.86 | 28.40 | 28.90 | 22.58 | 21.45 | 21.03 | 21.20 | 22.32 | 24.33 | 16.15 | 16.80 | 15.85 | 17.49 | 17.44 | 19.17 | 17.15 |
| Gallons diesel consumed | 159 | 158 | 118 | 103 | 131 | 226 | 115 | 133 | 146 | 165 | 215 | | — | — | — | — | — | — | |
| **Total MPGe** | 8.49 | 7.63 | 16.29 | 14.08 | 15.34 | 15.48 | 13.77 | 13.35 | 13.18 | 13.25 | 13.67 | 11.62 | 16.15 | 16.80 | 15.85 | 17.49 | 17.44 | 19.17 | 17.15 |

**Winter total efficiency**

**12 MPGe with diesel heater (2x)**

**17 MPGe with electric heater (3x)**

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# Summary: Average Annual Data (2022-23)

**Annual efficiency (April 2022 - Mar 2023)**

Data based on days where more than 10 miles were driven and 1 kWh net was consumed between 4/01/2022-03/31/2023. Recalculated for these dates rather than summing above. They're close but there's a small discrepency but the effect on efficiency is <0.04MPGe

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
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| **Vehicle Level** | **1** | **2** | **1** | **2** | **1** | **2** | **1** | **1** | **2** | **3** | **4** | | **1** | **2** | **3** | **4** | **1** | **2** | |
| Total miles | 3180 | 3040 | 9059 | 6905 | 8509 | 12496 | 6706 | 8011 | 8738 | 8206 | 13049 | | 3186 | 3636 | 3546 | 4638 | 2914 | 771 | |
| KWh consumed | 4478 | 4491 | 13272 | 10968 | 11352 | 16197 | 10712 | 13354 | 14924 | 14838 | 21374 | | 5862 | 7080 | 6852 | 9112 | 5825 | 1391 | |
| **Efficiency (mi/kWh)** | **0.71** | **0.68** | **0.68** | **0.63** | **0.75** | **0.77** | **0.63** | **0.60** | **0.59** | **0.55** | **0.61** | **0.65** | **0.54** | **0.51** | **0.52** | **0.51** | **0.50** | **0.55** | **0.52** |
| **Electric MPGe** | **26.91** | **25.65** | **25.87** | **23.86** | **28.41** | **29.24** | **23.73** | **22.74** | **22.19** | **20.96** | **23.14** | **24.79** | **20.60** | **19.46** | **19.62** | **19.29** | **18.96** | **21.01** | **19.82** |
| Gallons diesel consumed | 159 | 158 | 141 | 117 | 131 | 226 | 115 | 133 | 146 | 165 | 215 | | — | — | — | — | — | — | |
| **Total MPGe** | **11.48** | **10.99** | **18.44** | **16.98** | **19.77** | **19.12** | **16.87** | **16.50** | **16.20** | **14.73** | **16.76** | **14.47** | **20.60** | **19.46** | **19.62** | **19.29** | **18.96** | **21.01** | **19.82** |

## Annual total efficiency
## 14 MPGe with diesel heater (>2x) with no range impact
## 20 MPGe with electric heater (>3x) with 18% range reduction

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# Focus on the ESBs with Diesel Cabin Heater

Previous studies and data campaigns tracked EV winter efficiency

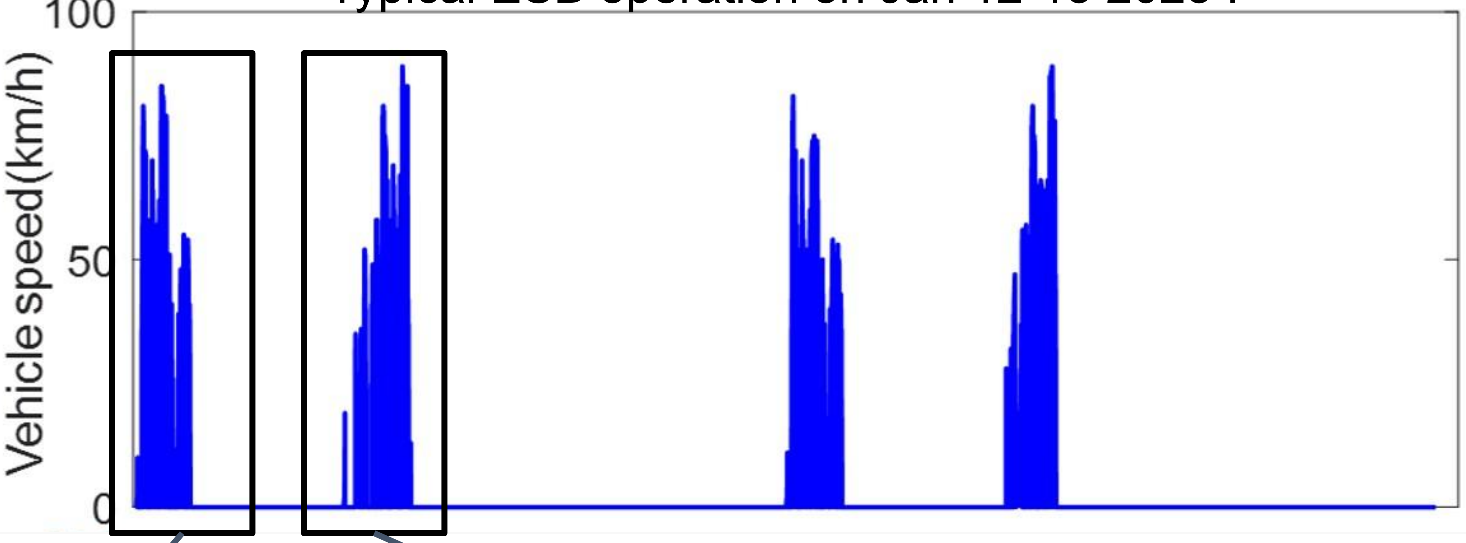
- Could not decouple losses from **cabin heating** versus **battery thermal conditioning**

This study:

- Analyses data from ESBs with diesel cabin heater
- Isolates the benefits/need for battery thermal conditioning (increased range/decreased driving losses)
- Clarifies the losses from pack thermal conditioning

# Trickle Thermal Conditioning (TTC) on ESBs during the Cold

Typical ESB operation on Jan 12-13 2023 :




Morning transportation: taking students to school

Afternoon transportation: taking students back home

ESB operation features:

- Frequent stops
- Low utilization
- Long parking duration

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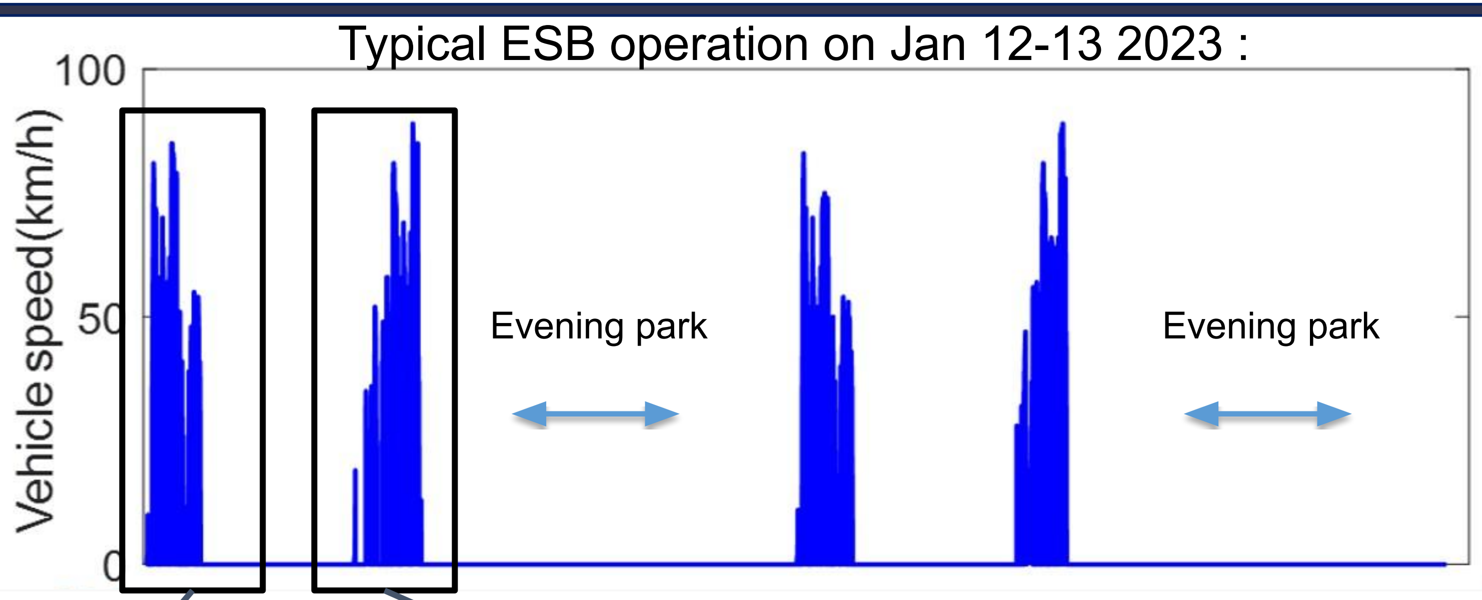


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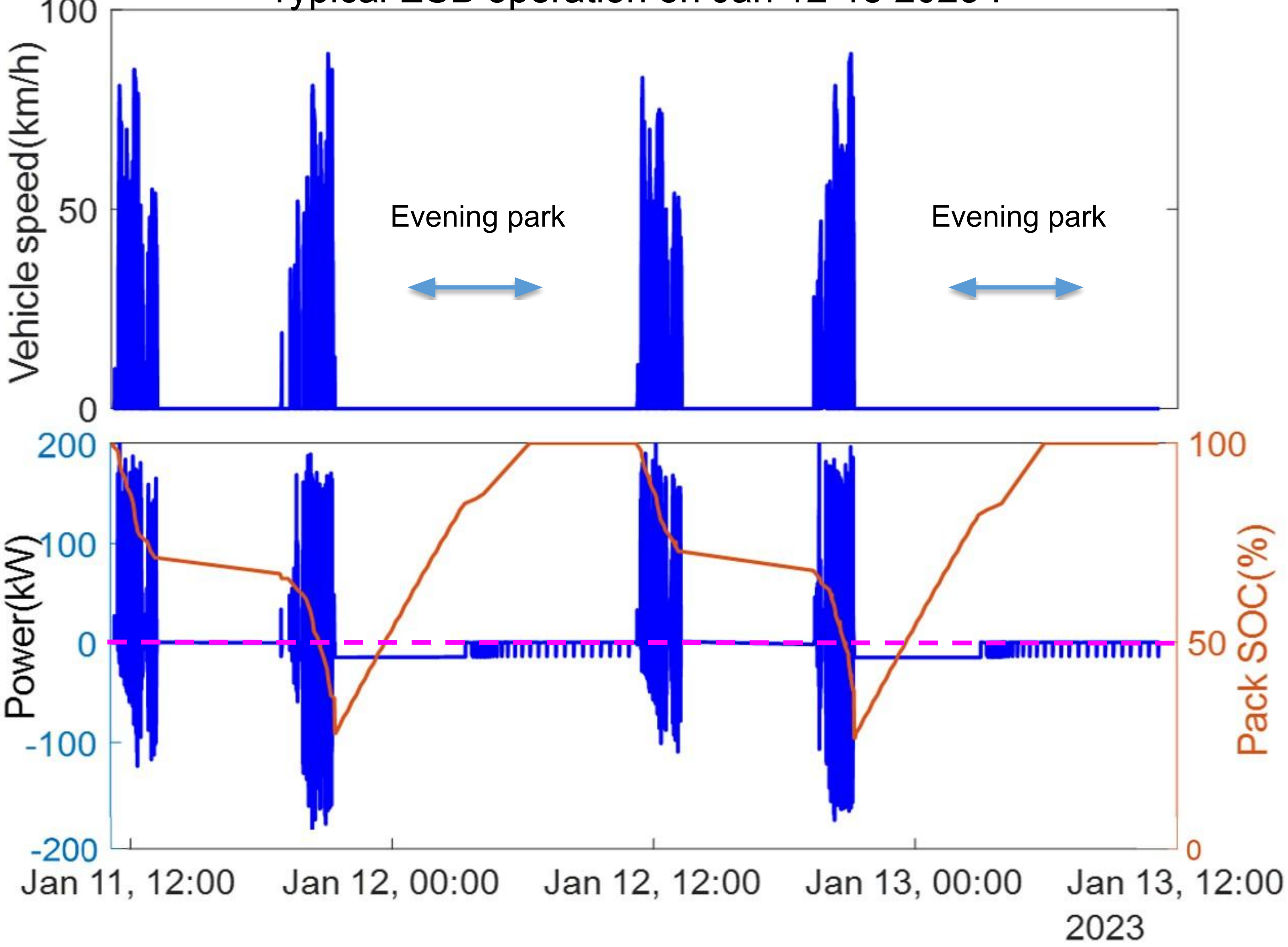


Power>0:
battery discharging

Power<0:
regen brake /
battery charging /
TTC

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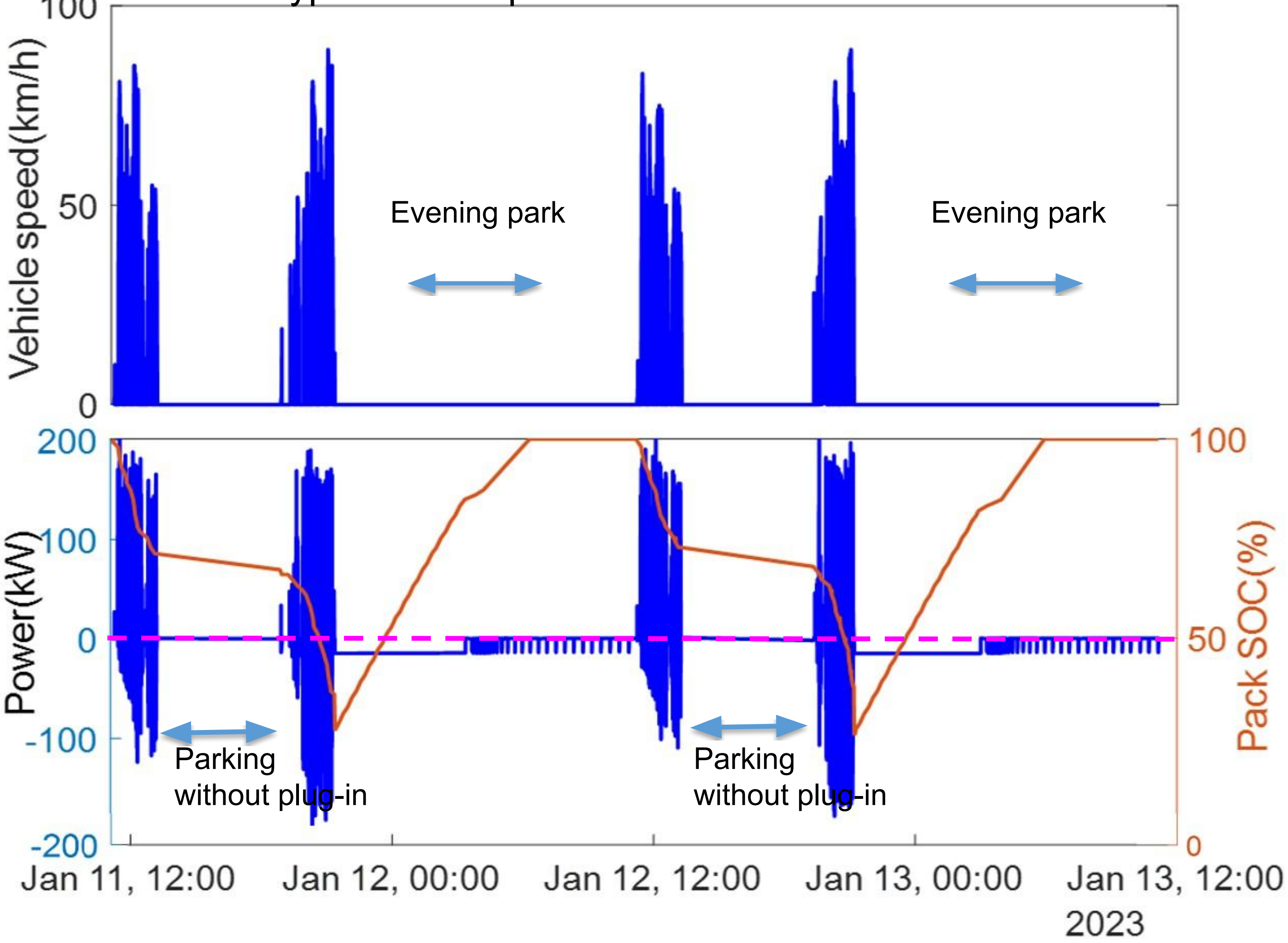


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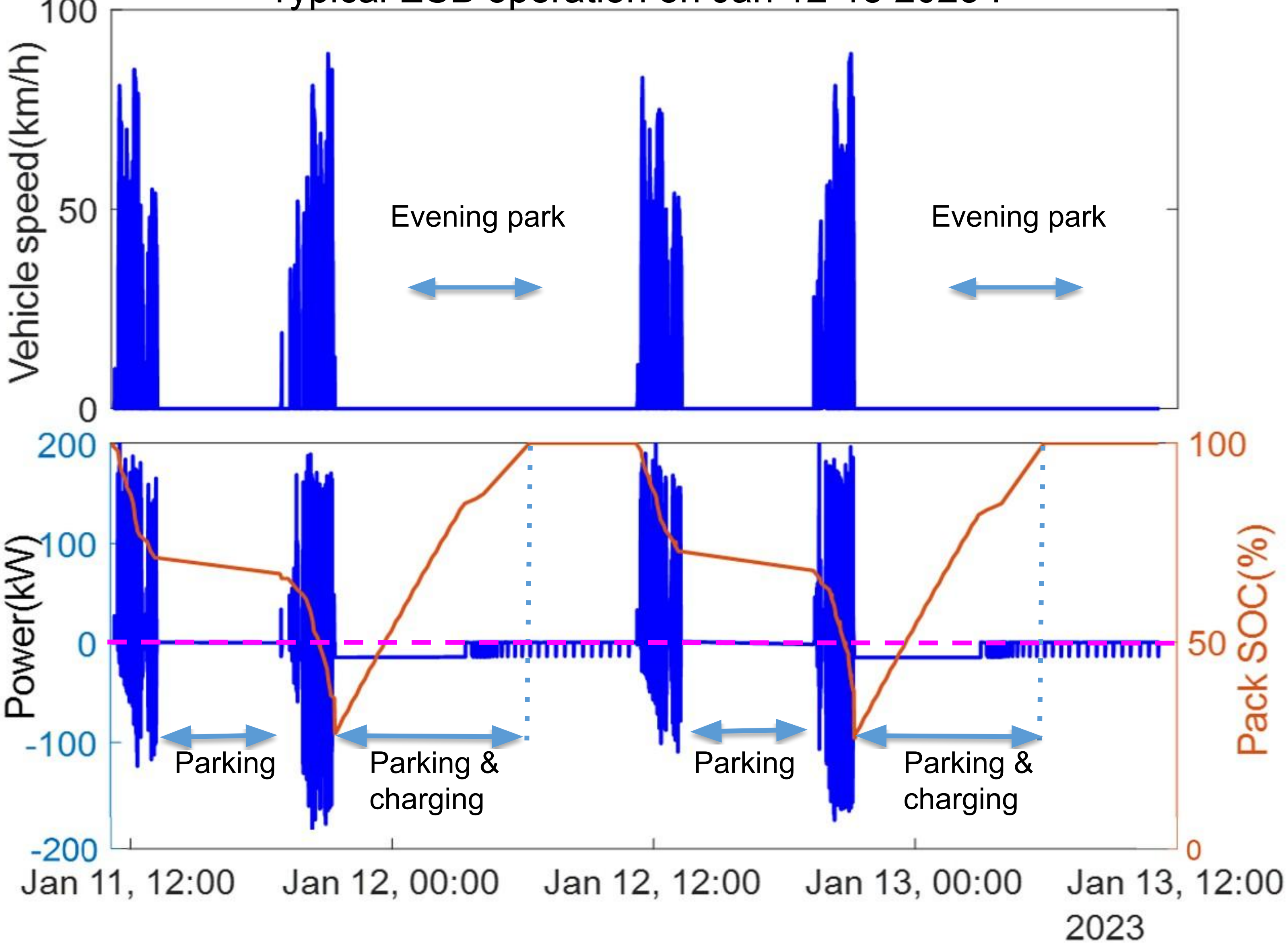


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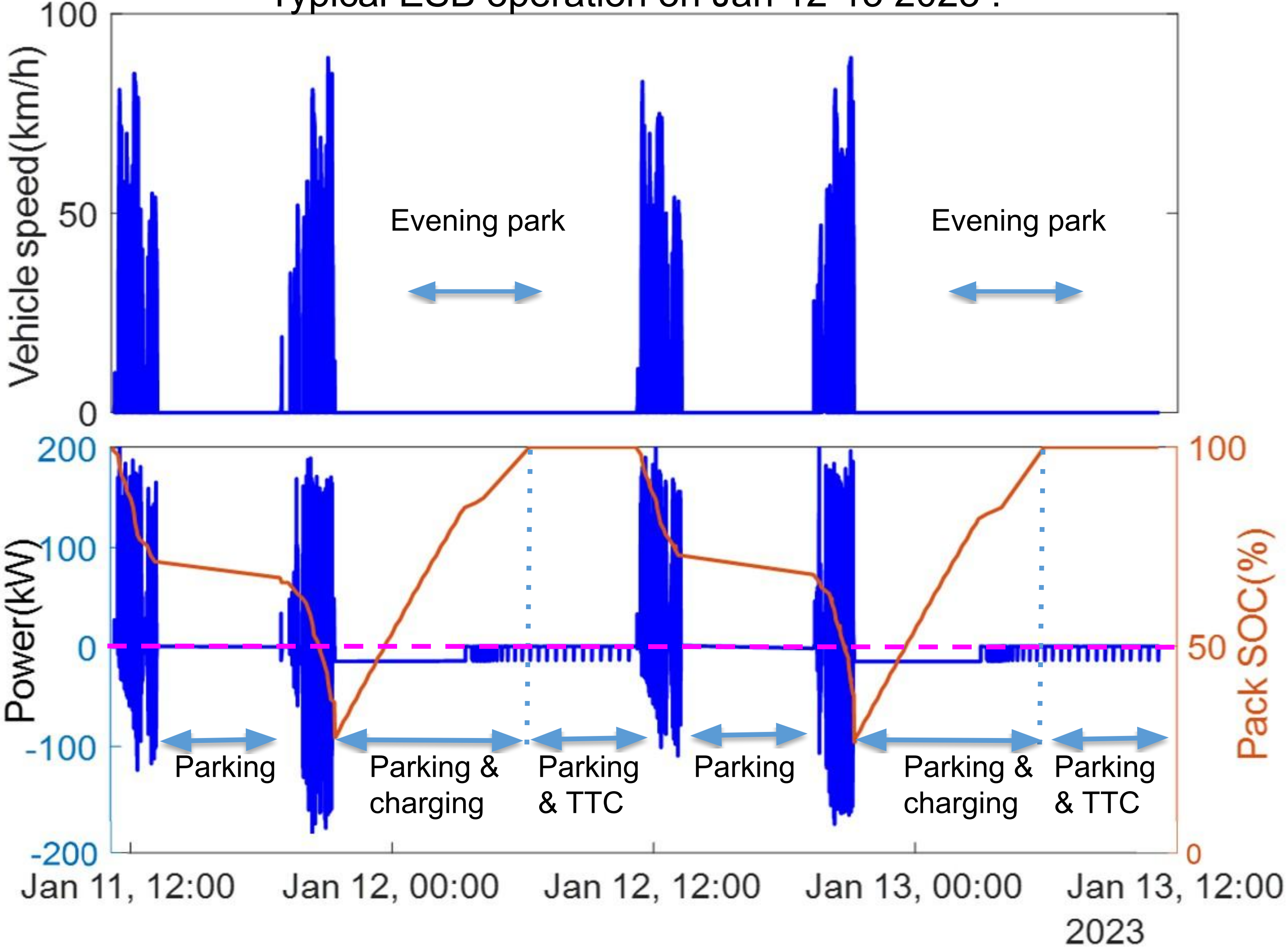


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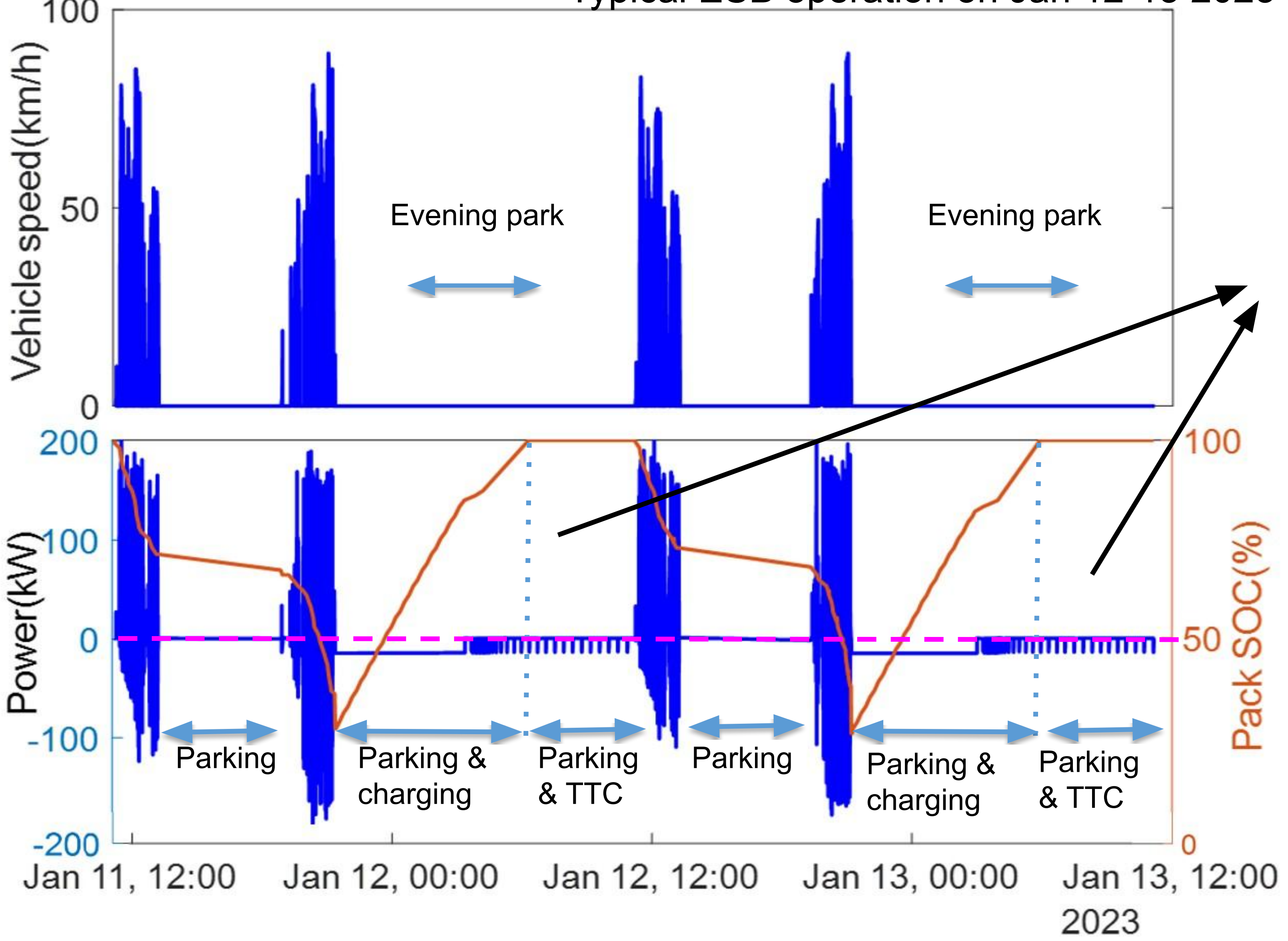


**Trickle thermal conditioning (TTC) happens after fully charged and during the cold and parking**

Power>0: battery discharging

Power<0: regen brake / battery charging / TTC

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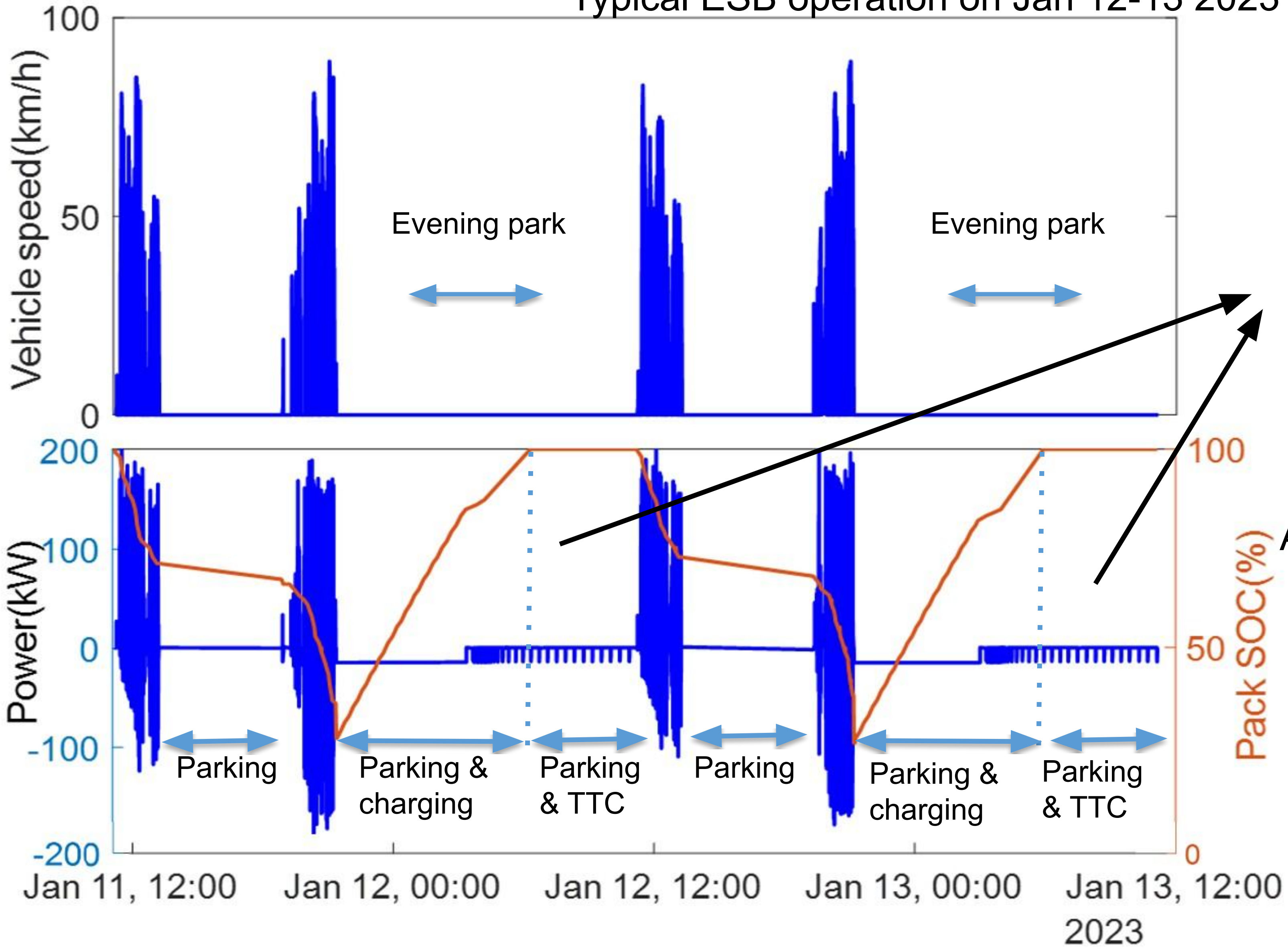
# Trickle Thermal Conditioning (TTC) on ESBs during the Cold

Typical ESB operation on Jan 12-13 2023 :




**Trickle thermal conditioning (TTC) happens after fully charged and during the cold and parking**

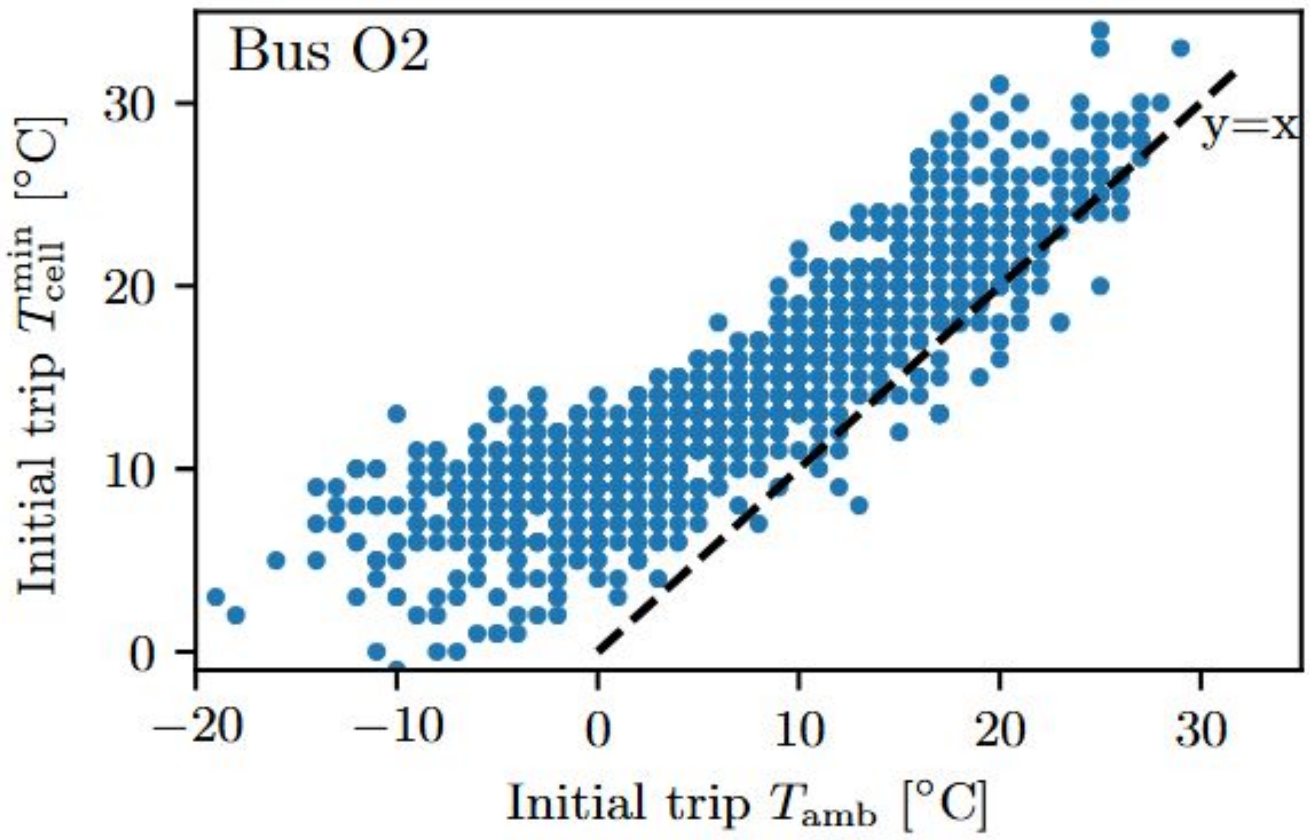
Ambient temperature below freezing (0 °C):

- In total of 4296 trip sessions
- 2405 TTC sessions
- ~65 days on average below freezing per year

3 years,
11 buses
5 districts

# Temperature maintained above 0°C by TTC

Starting trip battery temperature versus ambient temperature:




TTC keeps the battery above 0 °C at drive start, even in subzero temperatures.

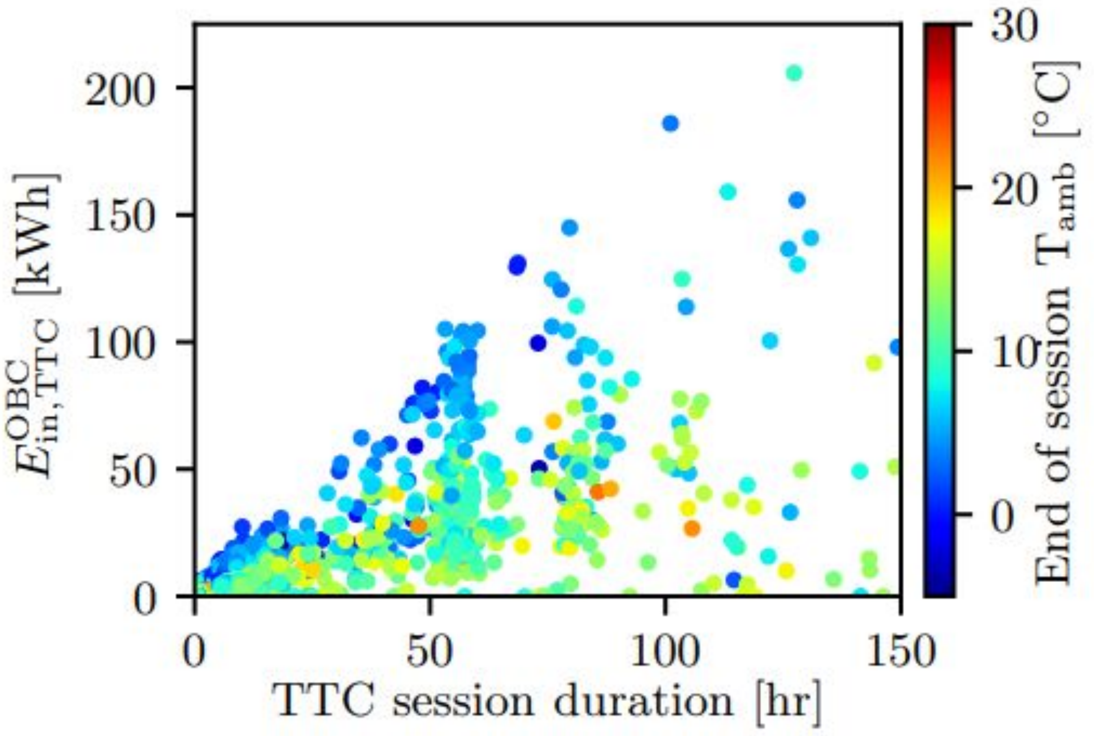
Tran, V. V., **Ma, J.**, Siegel, J. B., & Stefanopoulou, A. G. (2024). Fighting the cold: The impact of preconditioning on electric school bus performance.

# 33 MWh energy used by TTC for 11 buses for 3 years

ESB operation features:

- Frequent stops
- Low utilization
- Long parking duration

Energy into the bus during TTC




- Overnight TTC can use up to 25 kWh at -5°C

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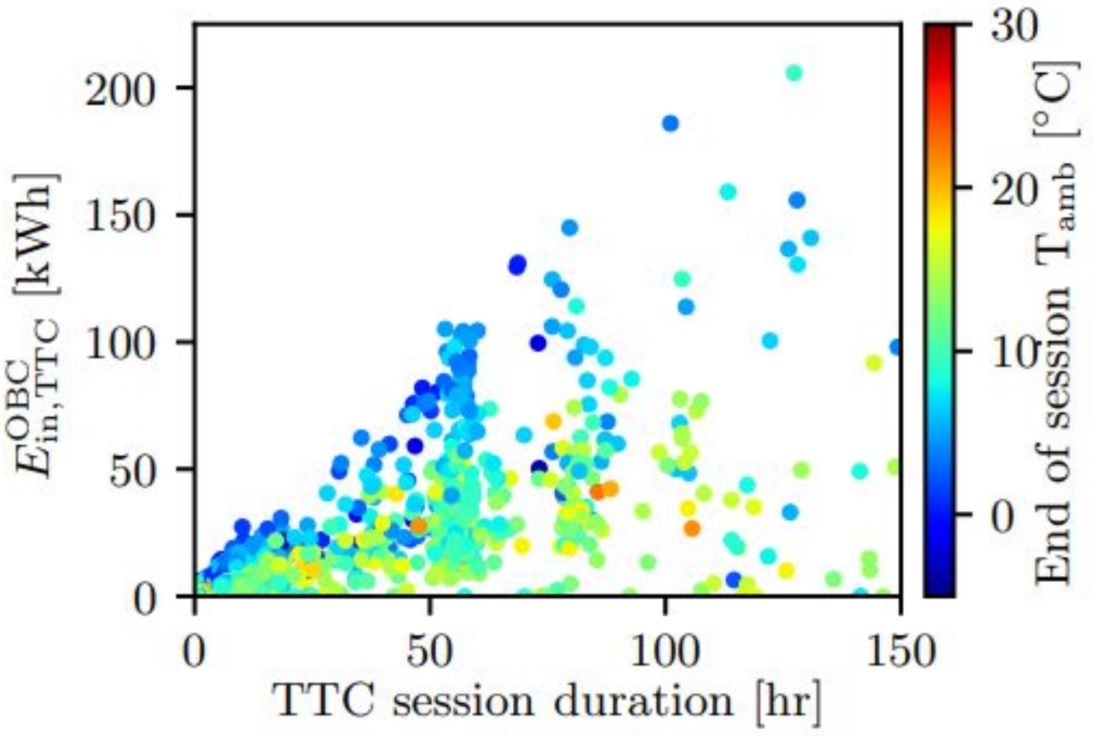


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- Extended TTC during breaks can consume up to 168 kWh, comparable to pack capacity

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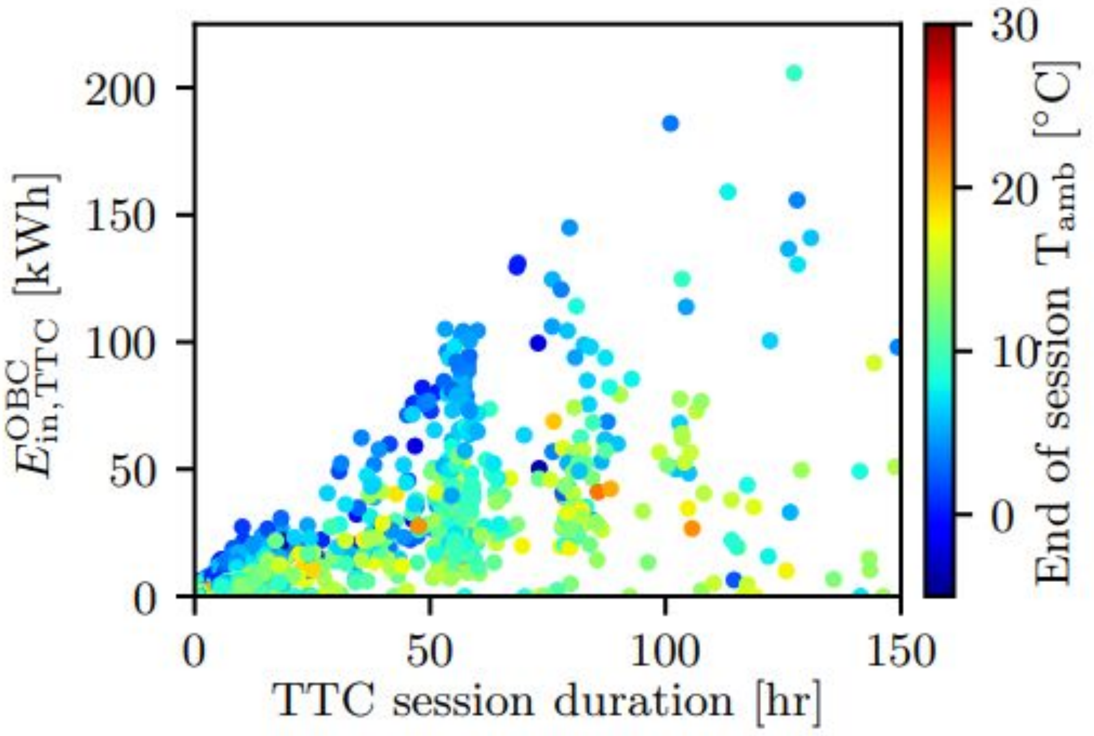


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- Annual TTC cost ≈ $1000/bus at $0.1/kWh

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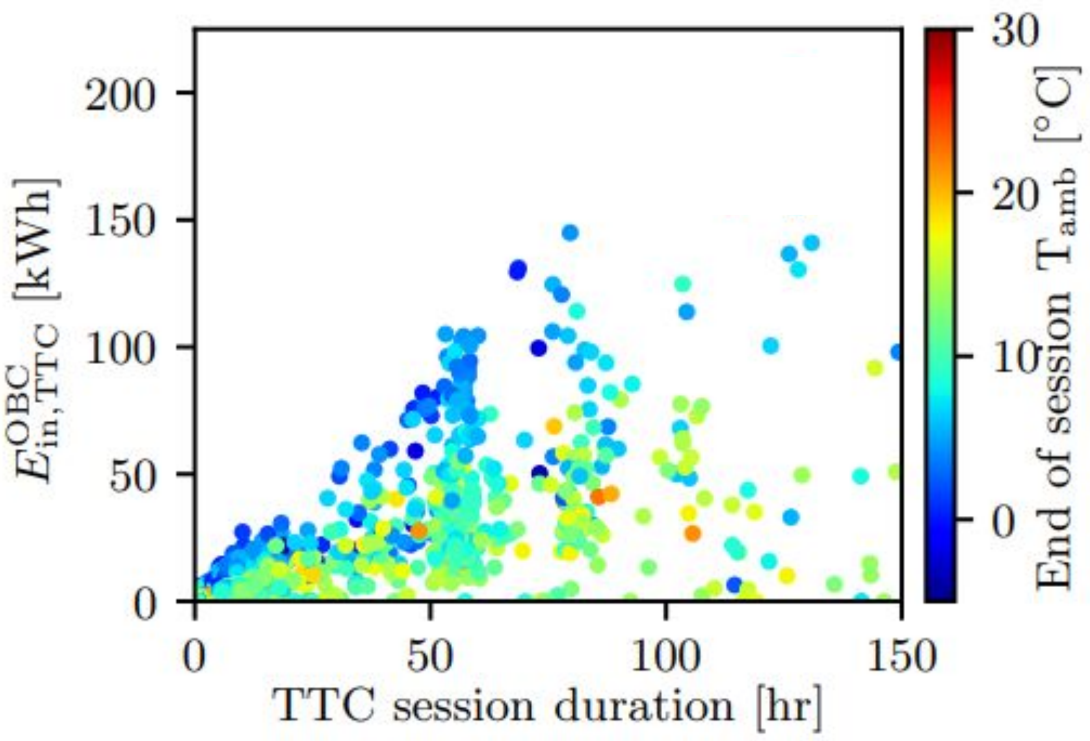
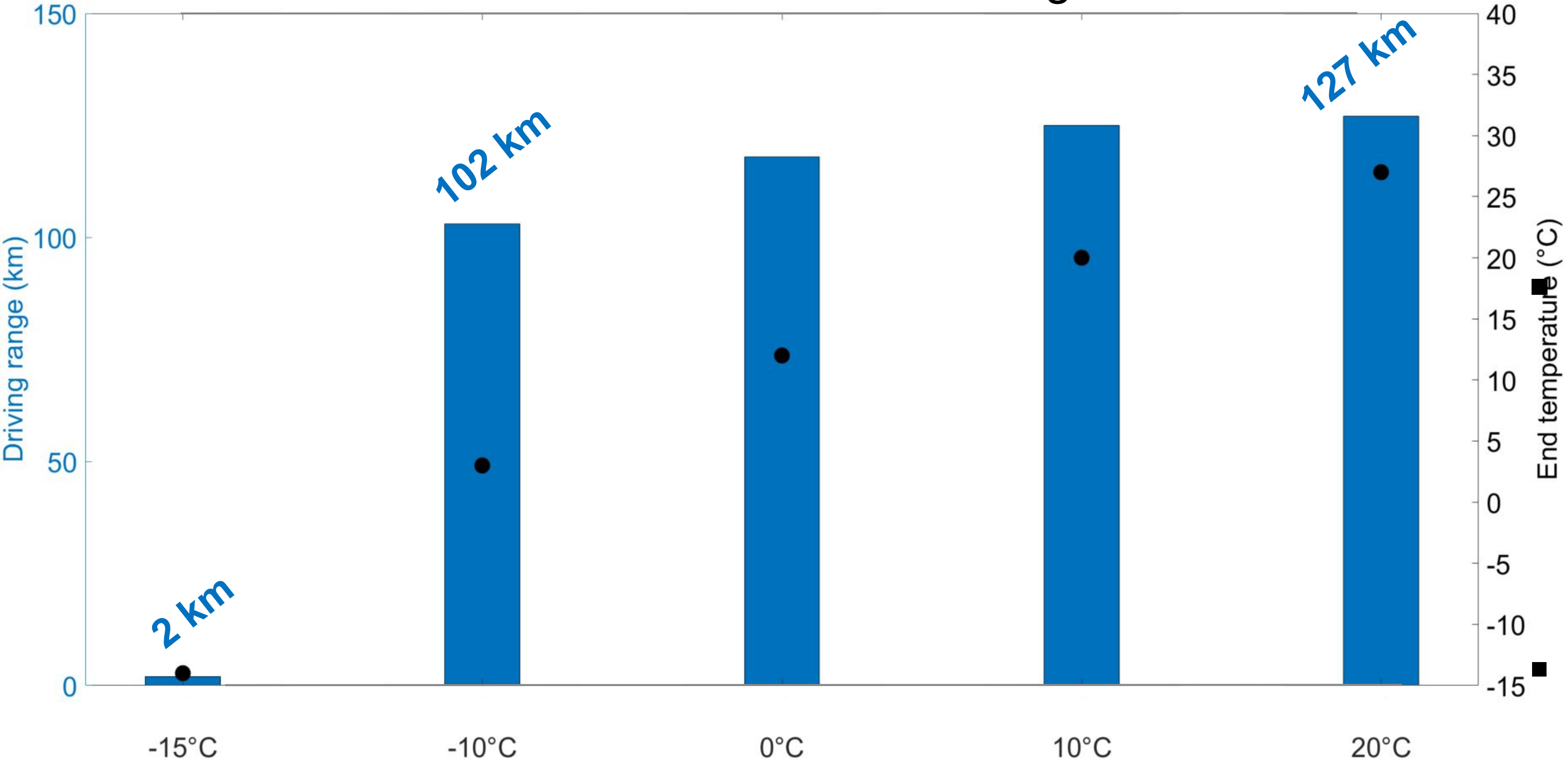



- Overnight TTC can use up to 25 kWh at -5°C
- Extended TTC during breaks can consume up to 168 kWh, comparable to pack capacity
- Annual TTC cost ≈ $1000/bus at $0.1/kWh
- **Driving energy reductions by having TTC can partially or fully offset this extra energy use**

# Thermal Conditioning Increase Driving Range

Baseline: no TC implemented

Driving range versus ambient temperature without thermal conditioning:




3 days | 17 days | 78 days | 96 days | 168 days | 7 days

in 2019 in Gaylord

- Driving range decreases up to 25 km between 20 °C and -10 °C due to increased internal resistance at low temperatures.
- The driving range at -15°C is only 2 km, because the cold start voltage hits the battery minimum voltage.
- The substantial winter range loss in pure battery electric vehicles (BEVs) should be attributed to the cabin heating rather than the battery heating.

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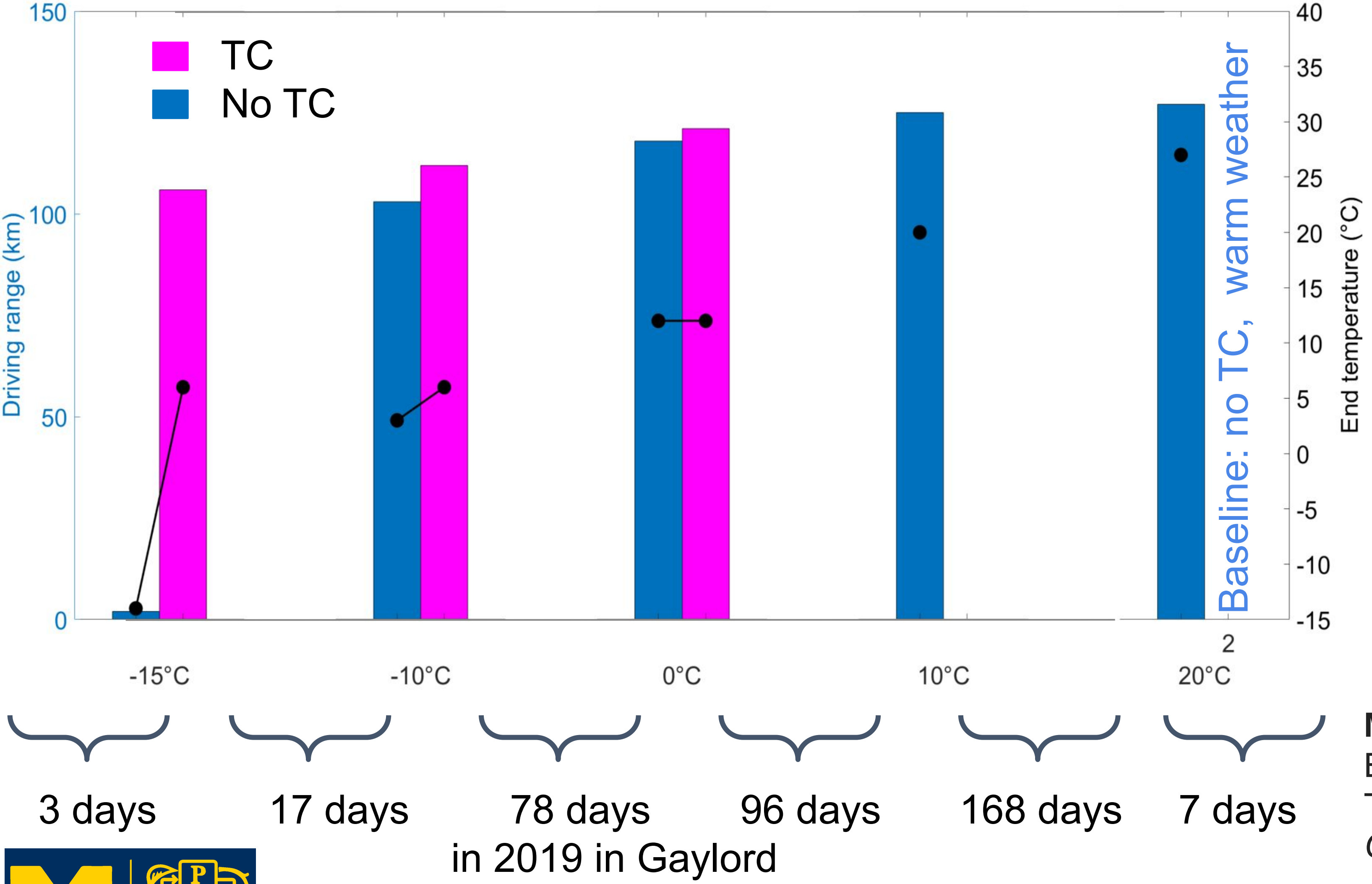
# Thermal Conditioning Increase Driving Range



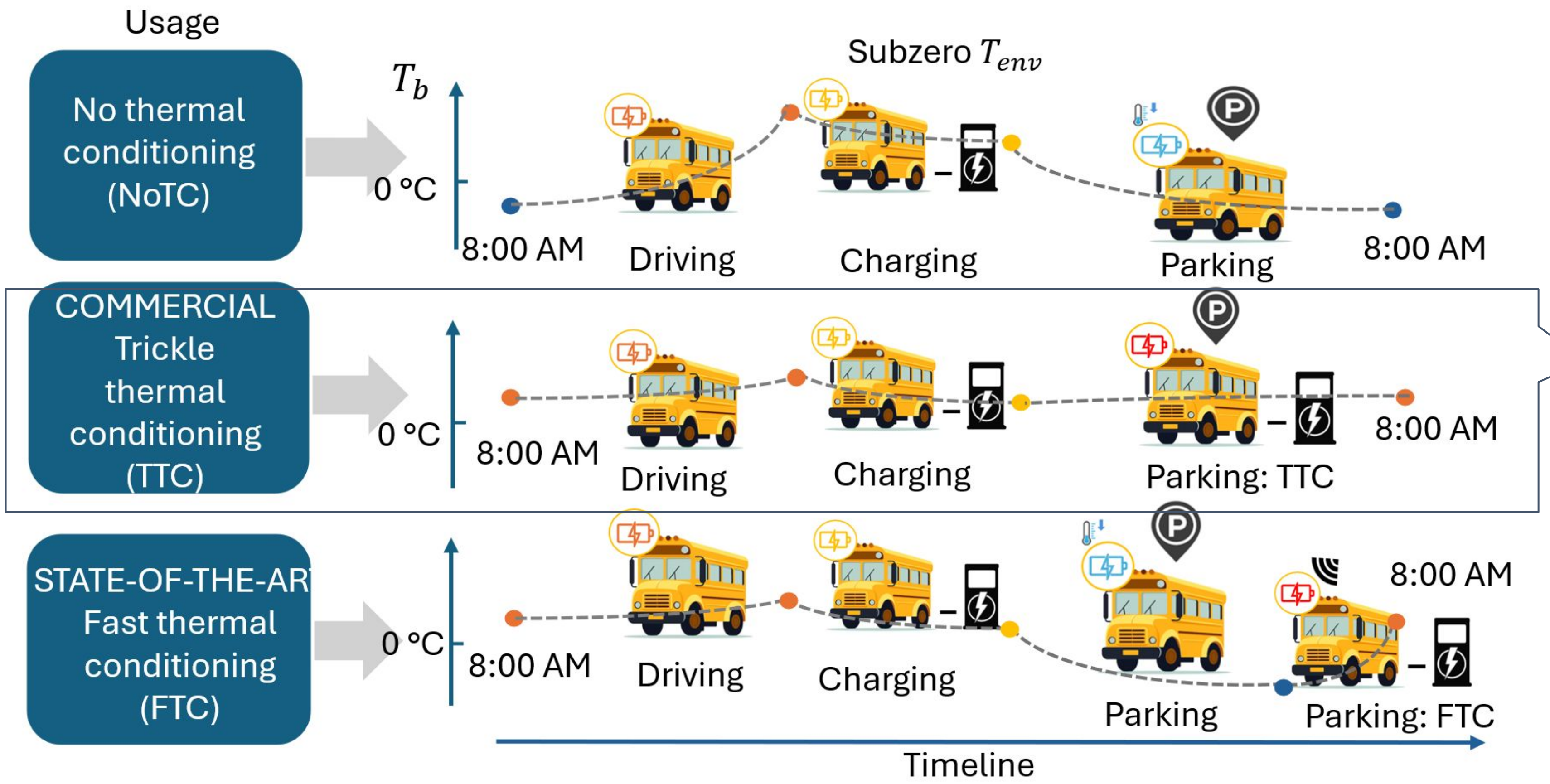

- TC enables 112 km range at -10°C , which recovers ~**40%** of the range lost in cold conditions.

**Ma, Jingchen,** et al. "Energy Consumption in Electric School Buses at Cold Conditions: A Study of Thermal Conditioning Strategies." *2025 American Control Conference (ACC)*. IEEE, 2025.

# Alternative approach: Fast thermal conditioning

Three ESB winter thermal conditioning scenarios

- Plugged in and fully charged
- Temperature maintenance to >5 °C throughout parking




Realized on the current ESB models

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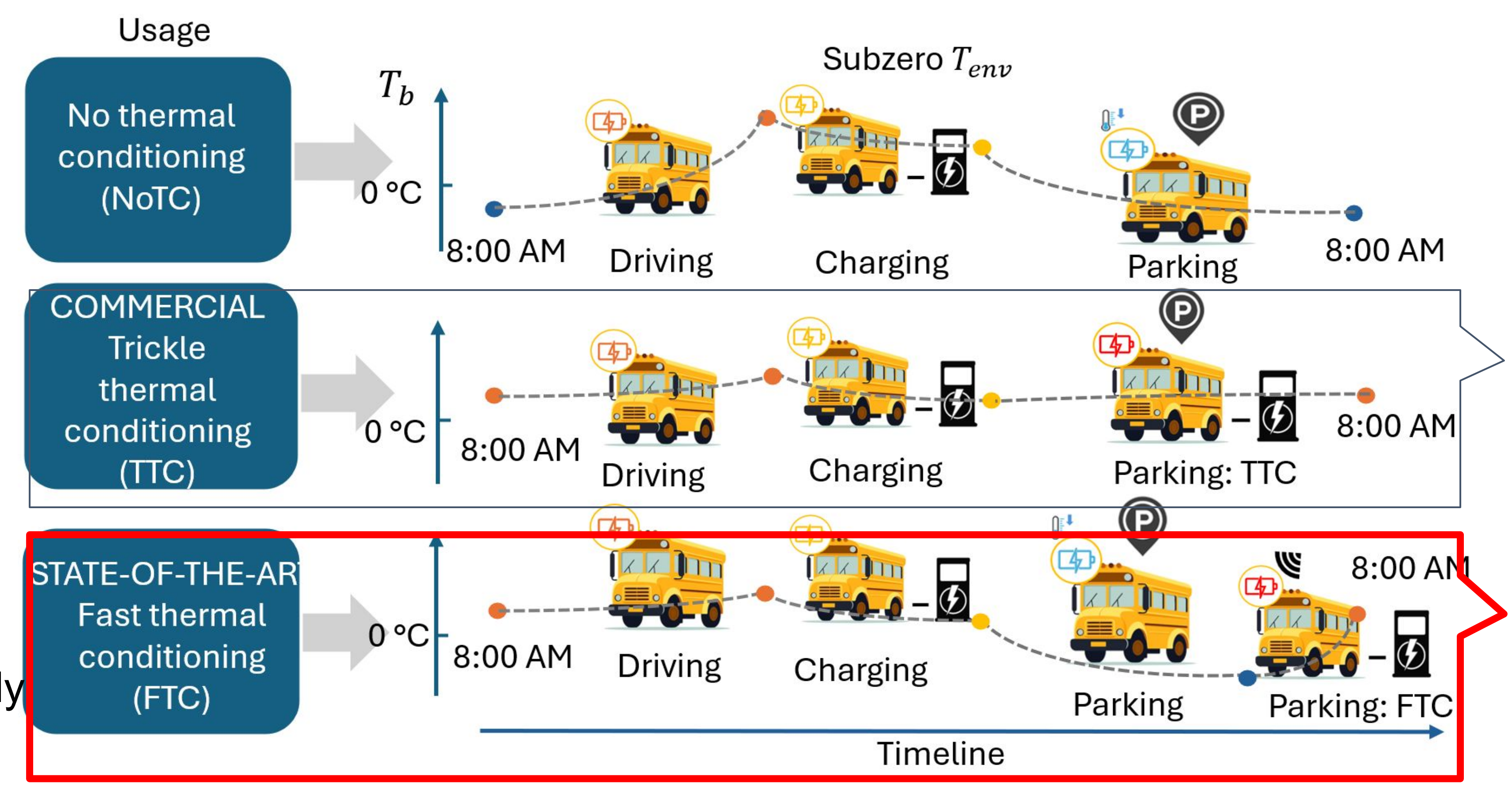


- Plugged in and fully charged
- Temperature maintained >5 °C throughout parking

Realized on the current ESB models

- Battery allowed to cool below freezing
- Rapid preheating shortly before operation

Advanced method that reduces extra energy usage



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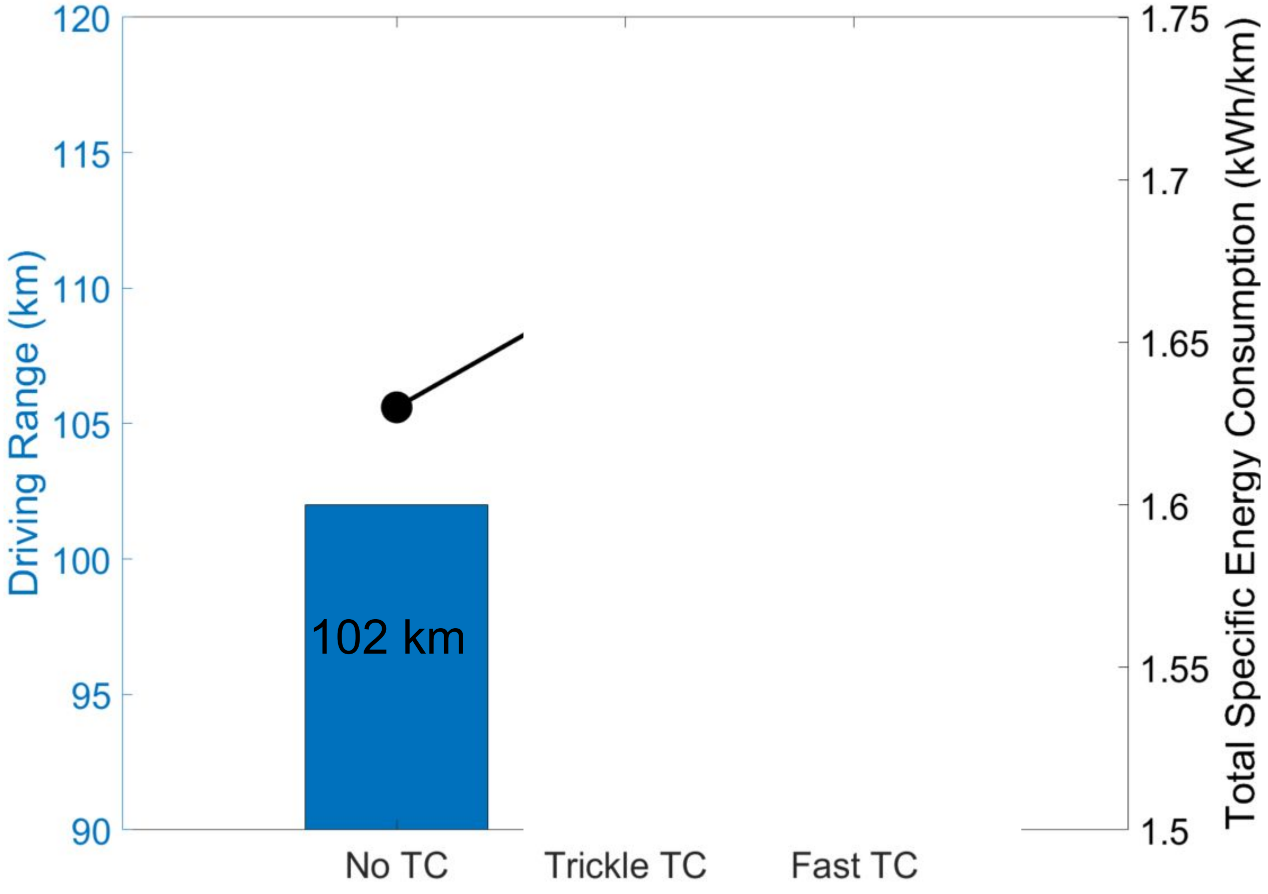
# Thermal Conditioning Impacts on Energy Consumption




Simulation at
-10 °C environmental temperature

- Lowest specific consumption
  (FTC: 1.58 kWh/km)
- Highest Specific consumption
  (TTC: 1.67 kWh/km → 8-hour overnight parking)

- **FTC effective regardless of parking duration**

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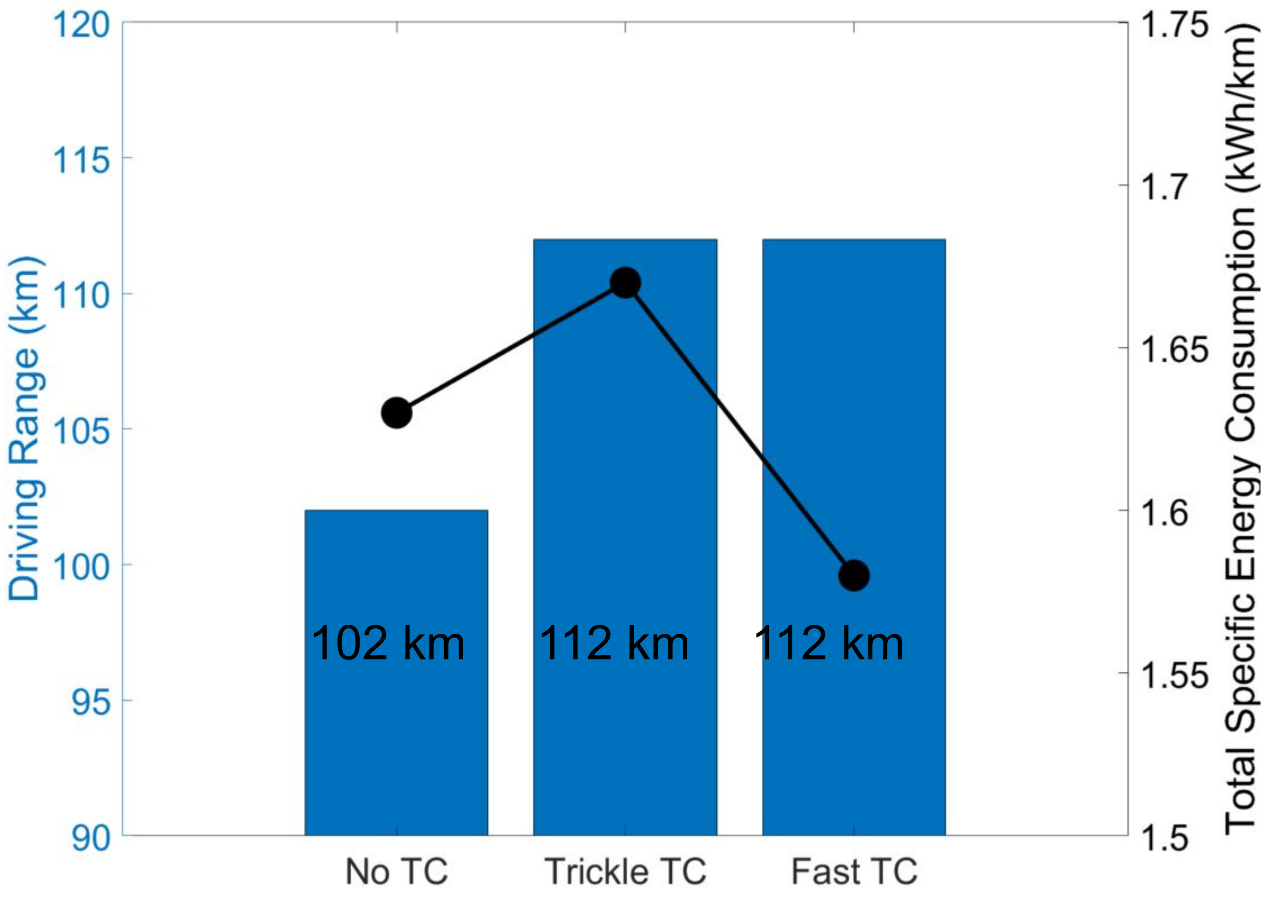


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# Conclusions

- Michigan ESBs field data spans 3 years, 11 buses and 5 districts.
- Thermal conditioning can improve driving range by 40%.
- We analysed 3 TC scenarios: no TC, Trickle TC and Fast TC.
- Fast TC has the least total specific energy consumption.
- **Fast TC reduces the need for extended overnight heating.**
  **Has the potential, if scheduled correctly, to lower $CO_2$ emissions from electricity generation.**

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# Thank you!

# Supplementary Slides

# Fighting the Cold: Thermal Conditioning

## What is thermal conditioning: definition and trends

- Classification by lasting length:

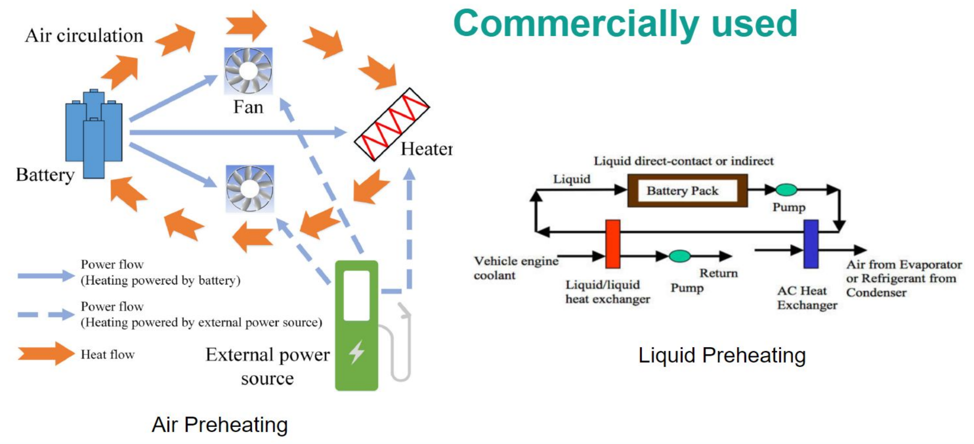
Thermal Conditioning (TC)

- Conventional trickle thermal conditioning (TTC) — Whole parking duration
  - Realized on current **Electric School Bus** (ESB) model.
  - TTC is initiated after the ESB is plugged in and fully charged, maintaining the battery temperature before the subsequent trip.
- Fast thermal conditioning (FTC) — Short duration
  - Realized on **Light Duty Vehicles**, Tesla Model 3, Audi Etron and Porsche Taycan, etc.
  - Not realized on ESB.
  - FTC preheats the battery from low ambient temperature to a pre-specified temperature in a very short time before vehicle operation (charging or driving).

- Classification by heat transfer pattern:

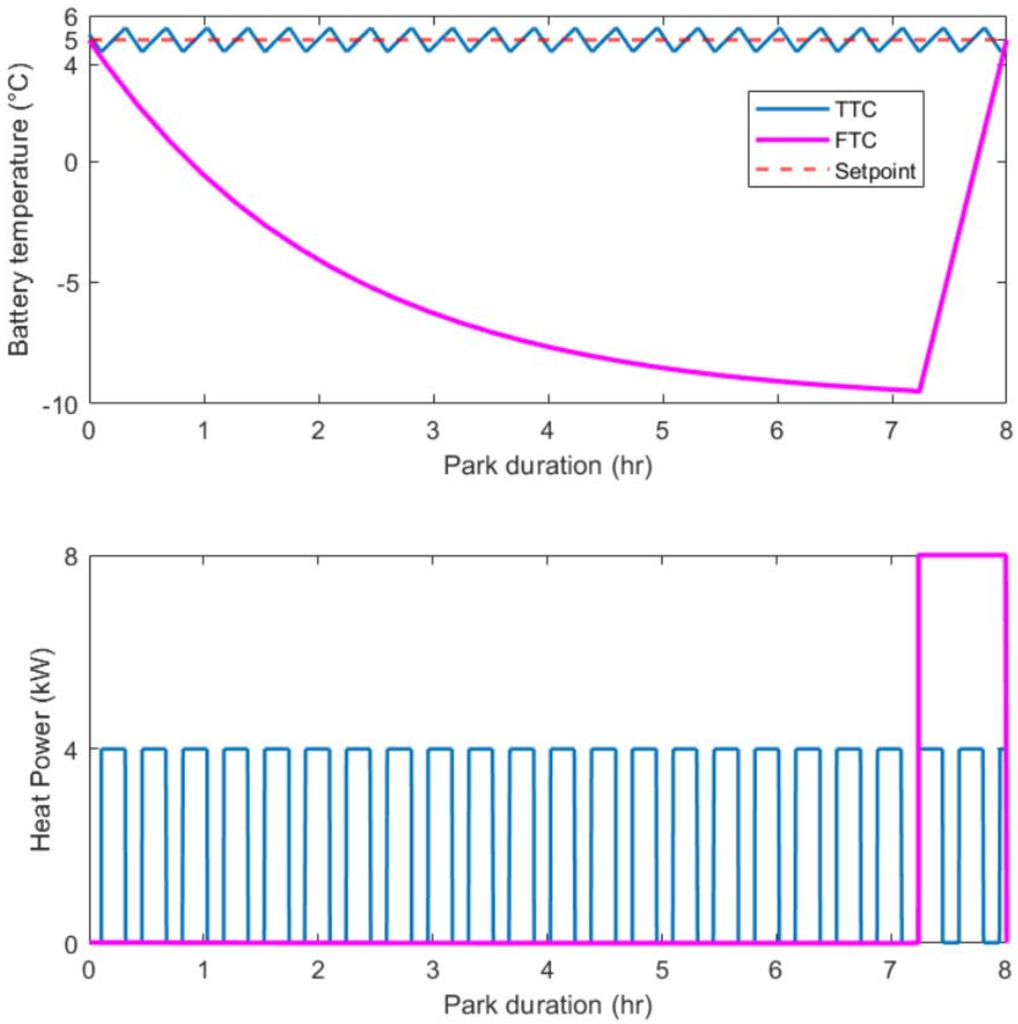
Thermal Conditioning (TC)

- External heat — Heat generated out of the battery
- Internal heat — Heat generated inside the battery




Schematics of Air and Liquid preheating

# Detailed Working Rule between TTC and FTC




- TTC:
  - Maintained the temperature at setpoint
  - Whole parking time
- FTC:
  - Cool down at first
  - Quickly warm up to setpoint
  - < one hour before operation

TTC: Trickle thermal conditioning
FTC: Fast thermal conditioning