A Study of Energy Consumption Differences Between Heavy-Duty Battery Electric and Conventional Transit Buses

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Motivation

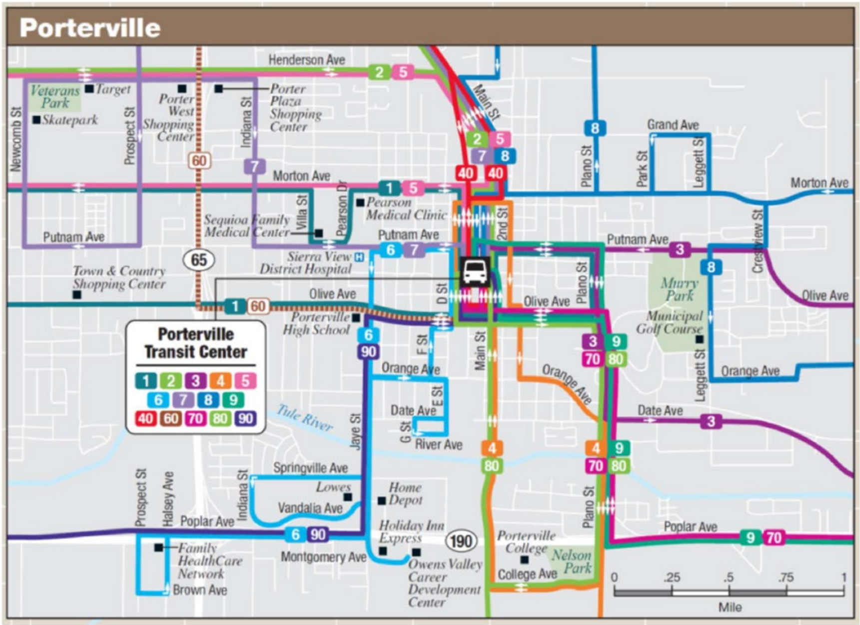
- HD ZEV population to increase significantly due to clean transportation programs
- ICT requires all public transit agencies to gradually reduce fleet vehicle tailpipe emissions
- Transit buses operate in densely populated areas → we expect significant health benefits from deploying BEVs
- Understanding real-world energy consumption of BEVs compared to ICEVs will help better characterize their benefits

Research objective

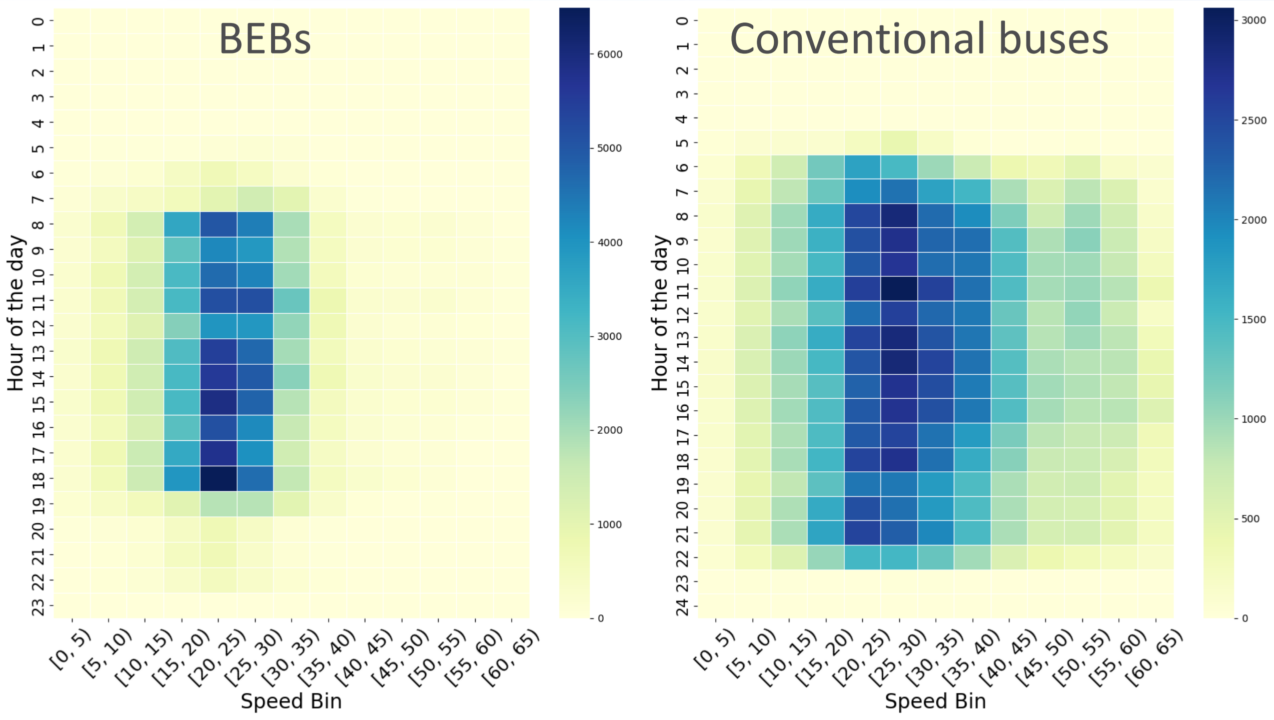
Characterize differences in real-world energy consumption (motive & regenerative braking energy, idle energy, energy efficiency ratio) between battery electric buses (BEBs) and conventional buses

Data source

- Data were collected over 28 months from 10 battery electric buses (BEBs) and 3 conventional buses
- More than 116 and 55 million 1Hz data points were collected for BEBs and conventional buses, respectively
- Collected vehicle parameters include speed, motor/engine speed, fuel rate, battery and motor I & V, SOC
- BEBs were deployed on all routes but later removed from route 9 due to battery capacity restrictions



Differences VMT profiles between BEBs and conventional buses



- CNG bus data includes pre-COVID periods. But BEB operating hr. were reduced due to lower ridership during COVID
- BEBs meet the requirements of urban routes. However, battery capacity limited operations to all but the longest route with significant elevation changes

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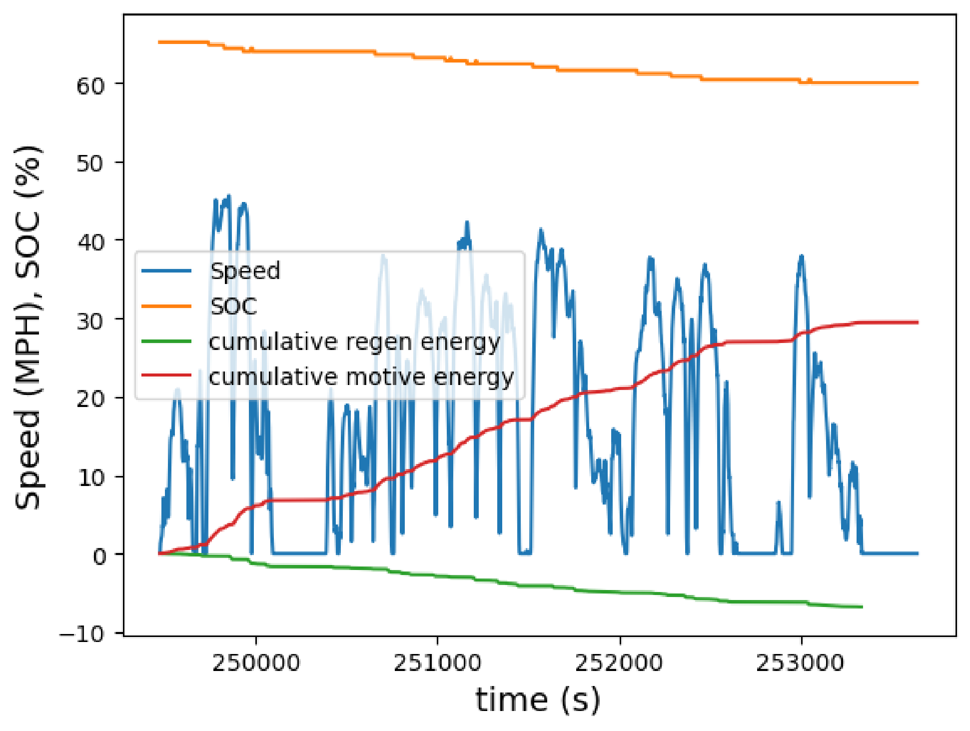
Timeserie example for BEBs



- $\text{VMT} = \frac{\sum v[mph]}{3600}$
- Energy efficiency
  - $\frac{\text{kWh}}{\text{mi}} = \frac{\left(\frac{10^{-3} * \sum I.V}{3600}\right)}{VMT}$
  - $\frac{\text{mi}}{\text{DGE}} = \frac{1}{\frac{kWh}{mi}} * 37.04 \frac{kWh}{DGE}$
- Regenerative braking energy efficiency
  - $\frac{kWh}{mi} = \frac{10^{-3} * \sum_{I<0} I.V}{3600\,.\,VMT}$

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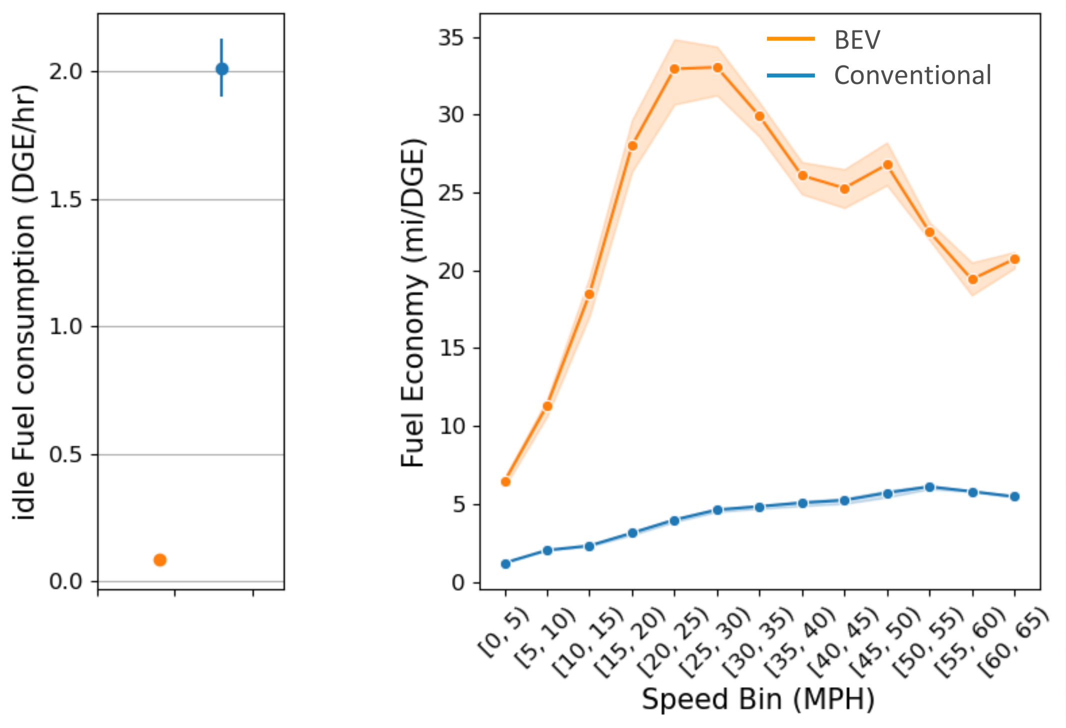
BEBs have significantly higher fuel economy compared to conventional buses

- At idle, energy consumption of conventional buses was 22 times higher than BEBs (2 DGE/hr vs. 0.09 DGE/hr)
- Vehicle fuel economy for conventional buses was ~4 mi/DGE vs. 26 – 31 mi/DGE for BEBs
- We observed large changes in BEB fuel economy with vehicle speed



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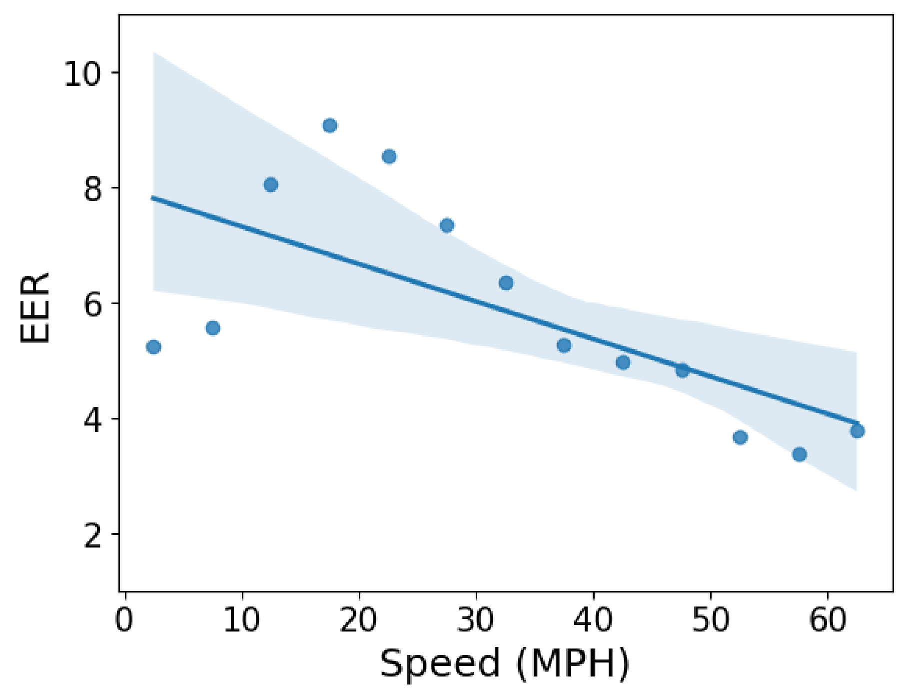
Energy Efficiency Ratio (EER)

- Why? EER is used to adjust the carbon intensity (CI) of alternative fuels in LCFS
- Overall, BEBs were **7 times** more energy efficient compared to conventional buses
- But EER varied strongly with vehicle speed, approaching a value of 3.5 at HWY speeds



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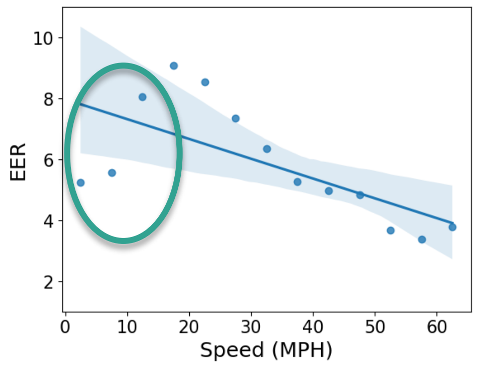
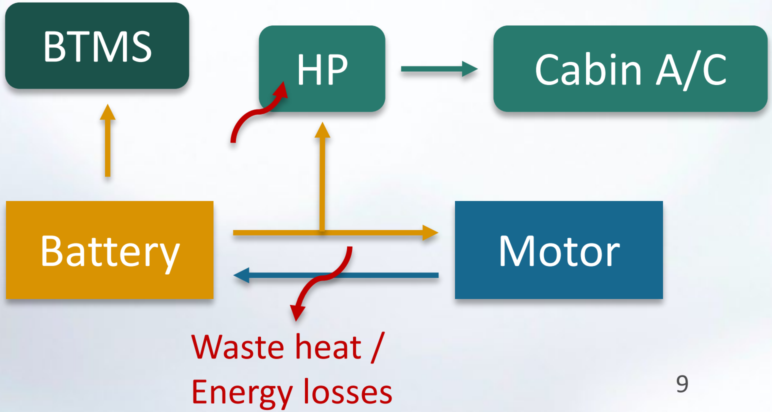
Opportunities to increase EER

- There are opportunities to increase EER – especially at low speeds where some of the battery power is consumed by aux. systems – especially reducing cabin A/C load and battery thermal management system (BTMS) power
- Some state-of-the-art technologies include:
  - Window tint (10% increase in driving range)
  - Thermal pre-conditioning (19% increase in driving range)
  - Cabin insulation (9% reduction in energy use)
  - Dual source heat pumps (6 – 22% improvement in driving range)
  - AI-based BTMS (7% reduction in energy consumption)
  - BTMS flow pattern optimization (20% increase in driving range)





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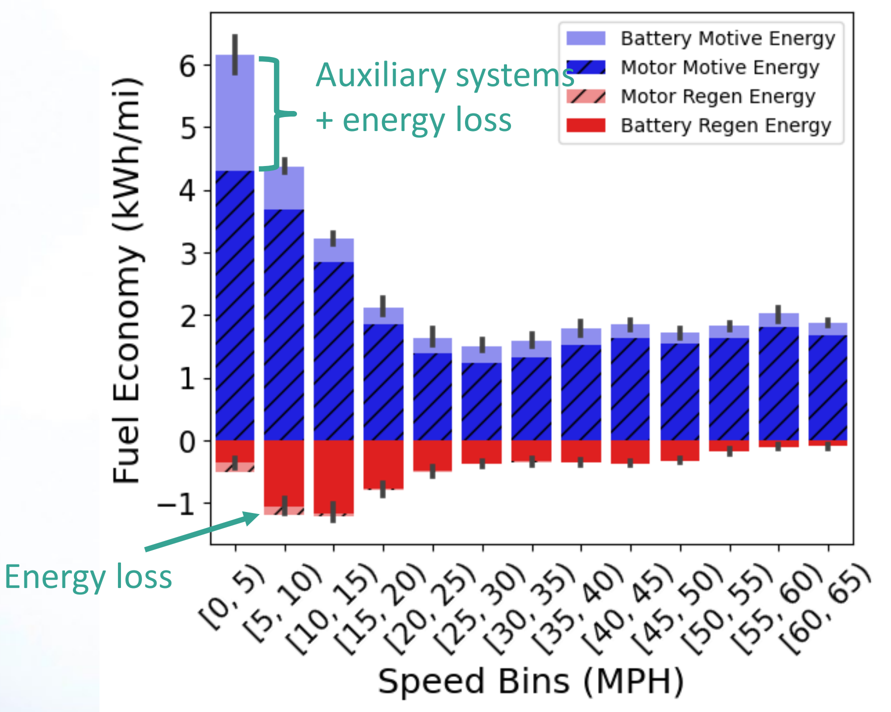
Opportunities to increase EER (cont'd)



- Auxiliary system consumed 30% of battery energy at low speeds
- 10 – 30% of energy recuperated at low speed by the motor did not reach the battery
- At higher speeds, Battery ↔ motor energy losses accounted for 5% of battery power

Summary and Conclusions

- Real-world activity and energy usage of BEBs and conventional buses were recorded for over two years
- Overall, BEBs were 7 times more energy efficient compared to conventional buses, although the efficiency varied significantly with vehicle speed
    - At idle, conventional buses consume 22 more times energy than BEBs
- BEBs recuperated between 23% and 39% of energy through regenerative braking applications
- There are opportunities to increase EER of BEB, especially at low speeds where auxiliary systems consume about 30% of battery power
- We expect significant NOx and PM reductions from deploying BEBs

Supplemental Slides

Energy accounting on BEBs

We observed consistency in BEB energy accounting at speeds >5 MPH:

- Motor receives ~85% of battery energy
- Auxiliary system consume ~10% of battery energy
- Battery ↔ motor transmission loss are ~5%