CHALMERS
UNIVERSITY OF TECHNOLOGY

FAST CHARGING, THERMAL MANAGEMENT AND ECO-DRIVING OF BATTERY ELECTRIC VEHICLES

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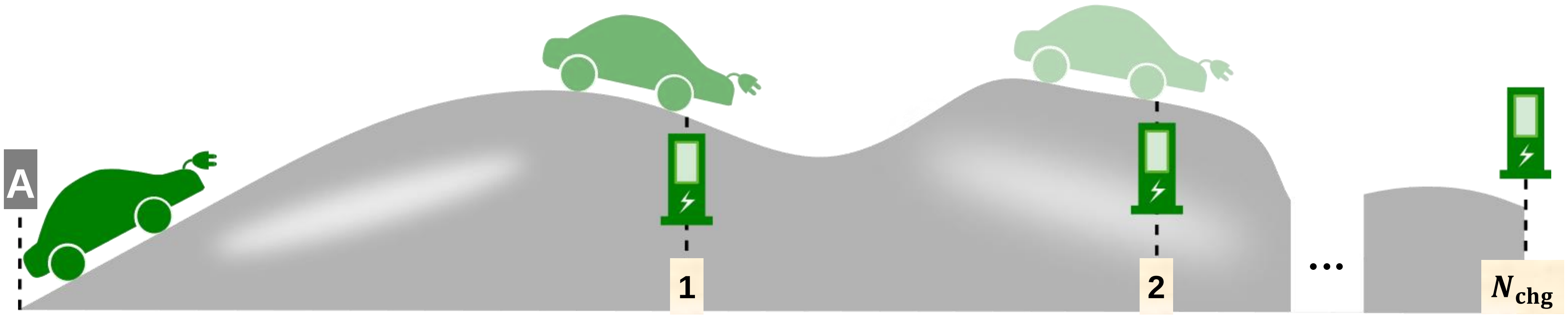
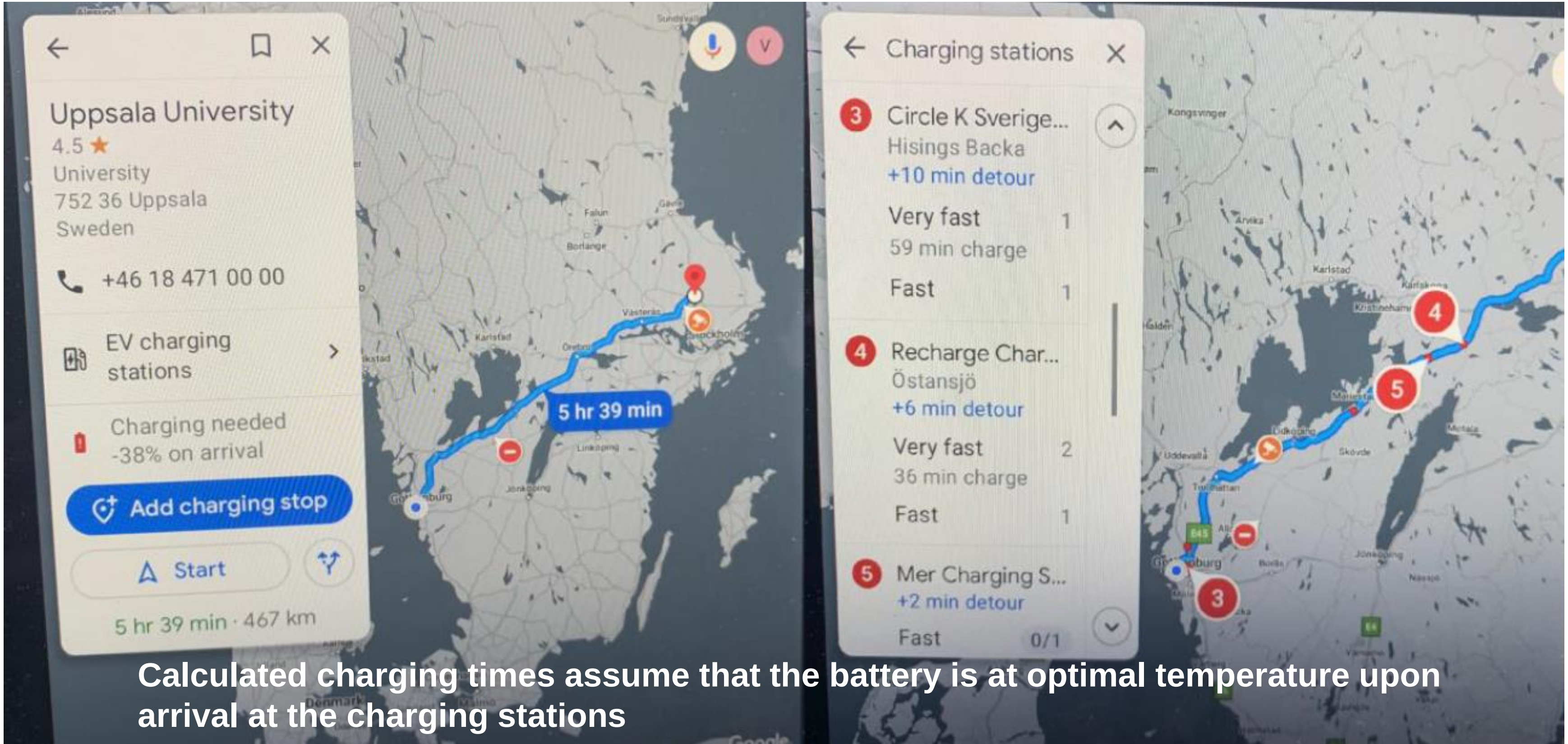
CHARGING AND TRIP PLANNING OF A BEV

- Route is longer than the BEV range.
- Charging stations allow fast charging.
- Ambient temperature could be low, e.g., -10 °C.



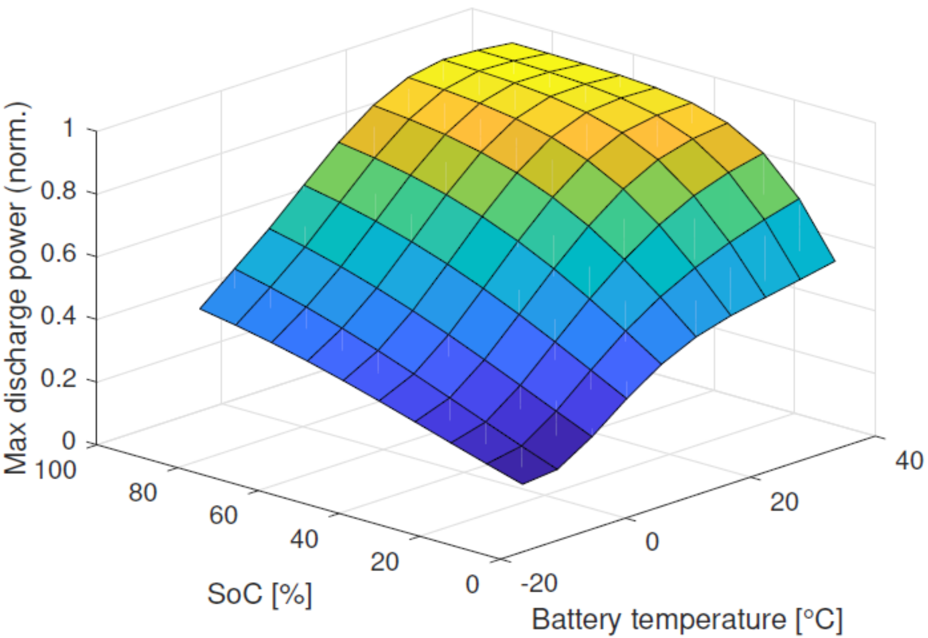
A VEHICULAR NAVIGATION SYSTEM IN A BEV



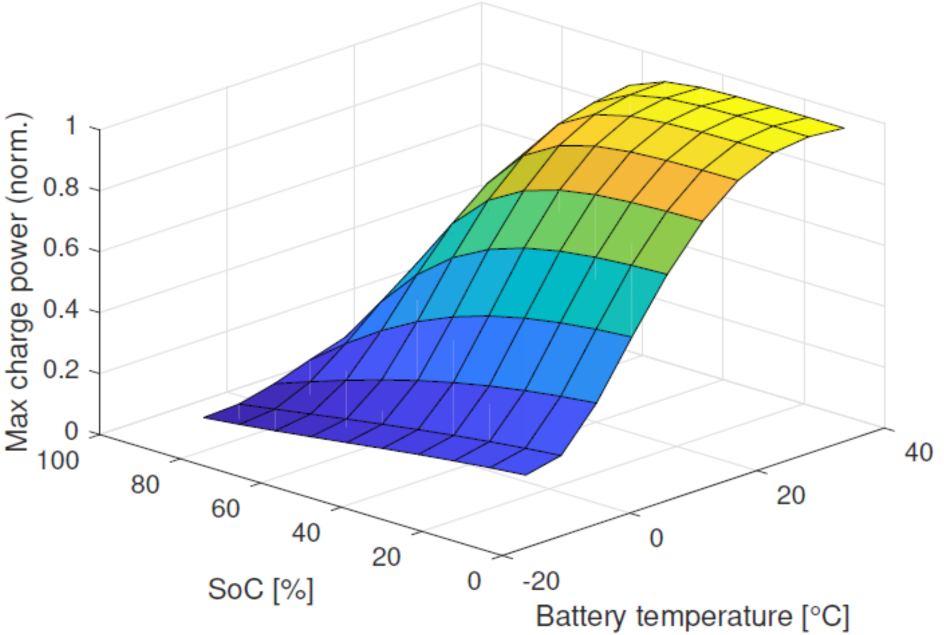
Calculated charging times assume that the battery is at optimal temperature upon arrival at the charging stations

BATTERY POWER LIMITS

- **Power limits depend on battery SoC and temperature.**



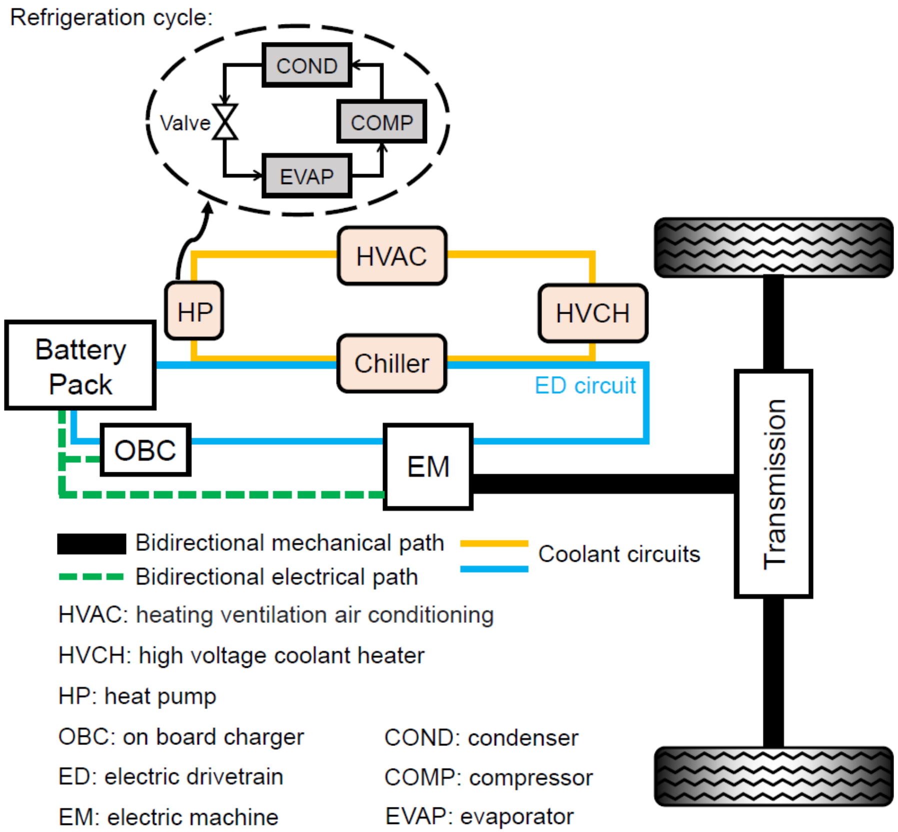
Discharge power limit



Charge power limit

BEV'S THERMAL SYSTEM

- **Passive heat is generated due to battery and electric drive losses.**
- **Active heat is generated/removed by the**
  - **HVAC**
  - **HVCH**
  - **Heat pump (HP)**
- **Heat is exchanged with the ambient air.**



RESEARCH QUESTIONS

- **Which chargers should be selected to avoid long stop-over times and high charging costs?**
- **How to pre-condition and manage the battery and the thermal system to improve energy efficiency and enable appropriate charging power in terms of**
  - **predicted thermal state of the battery,**
  - **knowledge on power capability of the charging stations,**
  - **given user preferences on cost and trip time?**
- **What are the benefits of the inclusion of a heat pump in the thermal management system?**

OPTIMIZATION OBJECTIVE

Minimize a cost function including:

- **Driving cost**
  - **Driving time**
  - **Discomfort penalties**
- **Charging cost**
  - **Charging time**
  - **Charged energy**
  - **Overstay cost**
- **Detour cost on driving time and energy to a charging location**

HYBRID DYNAMICAL SYSTEM

- **Vehicle states and dynamics differ during driving and charging modes**
  - $x_{\mathrm{drv}} = [\text{Vehicle speed, Battery SoC, Battery temperature}]^{\mathrm{T}}$
  - $x_{\mathrm{chg}} = [\text{Battery SoC, Battery temperature}]^{\mathrm{T}}$
- **Independent variables selected to reduce complexity**
  - $\frac{\mathrm{d}x_{\mathrm{drv}}(t)}{\mathrm{d}t} = f_{\mathrm{drv}}(x_{\mathrm{drv}}(t), u_{\mathrm{drv}}(t), t) \quad \Rightarrow \quad \frac{\mathrm{d}x_{\mathrm{drv}}(s)}{\mathrm{d}s} = v(s)\, f_{\mathrm{drv}}(x_{\mathrm{drv}}(s), u_{\mathrm{drv}}(s), s)$
  - $\frac{\mathrm{d}x_{\mathrm{chg},i}(t)}{\mathrm{d}t} = f_{\mathrm{chg}}\left(x_{\mathrm{chg},i}(t), u_{\mathrm{chg},i}(t), t\right) \Rightarrow \frac{\mathrm{d}x_{\mathrm{chg},i}(\tau_i)}{\mathrm{d}\tau_i} = t_{\mathrm{chg},i}\, f_{\mathrm{chg}}\left(x_{\mathrm{chg},i}(\tau_i), u_{\mathrm{chg},i}(\tau_i), \tau_i\right)$

  s **is travelled distance**

  $\tau_i \in [0, 1]$ **is normalized charging time at each charge stop** i.

A. Hamednia, N. Murgovski, J. Fredriksson, J. Forsman, M. Pourabdollah, V. Larsson. Optimal thermal management, charging, and eco-driving of battery electric vehicles. https://arxiv.org/abs/2205.01560

ENSURING CONTINUITY

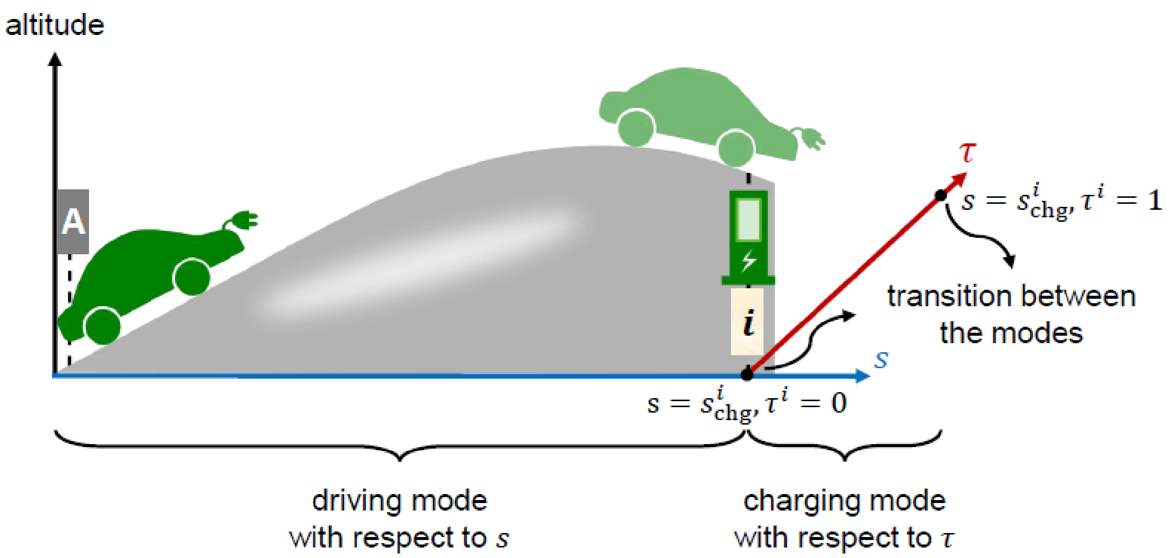
- **Define a sub-vector of overlapping states**

$$x_{\mathrm{drv,sub}} = x_{\mathrm{drv}(2:3)} = [\text{Battery SoC}, \text{Battery temperature}]^{\mathrm{T}}$$

- **Continuity ensured via constraints:**

$$x_{\mathrm{chg},i}(0) = x_{\mathrm{drv,sub}}\left(s_{\mathrm{chg},i}\right), \ \forall i$$

$$x_{\mathrm{drv,sub}}\left(s^{+}_{\mathrm{chg},i}\right) = x_{\mathrm{chg},i}(1), \ \forall i$$



OPTIMIZATION PROGRAM

The problem translates to an MINLP with:

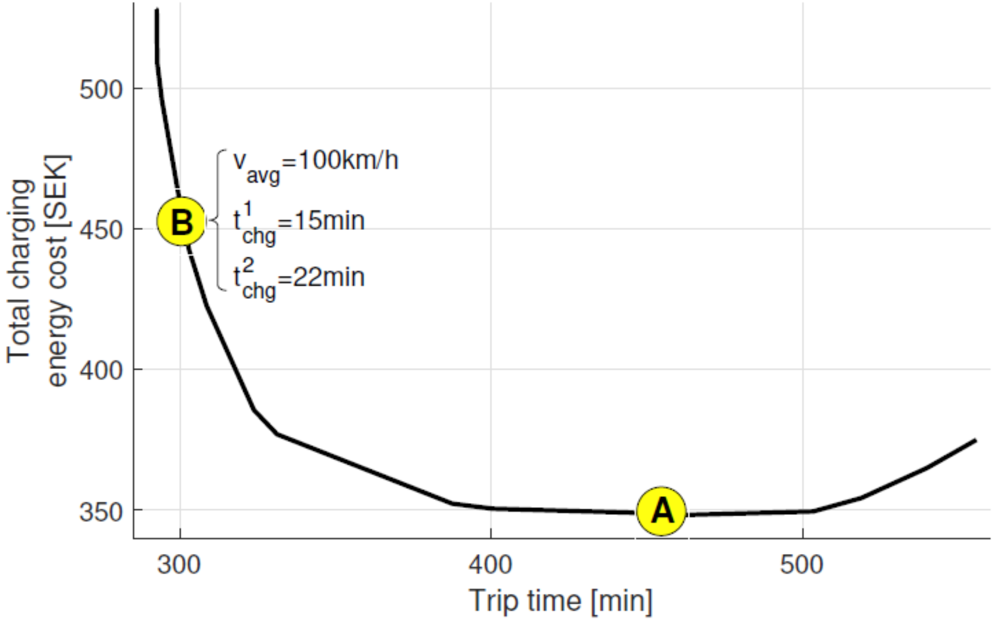
- **control inputs**
  - $u_{\mathrm{drv}} = [\text{HVCH power}, \text{HVAC power}, \text{HP power}, \text{EM torque}]^{\mathrm{T}}$
  - $u_{\mathrm{chg},i} = [\text{HVCH power}, \text{HVAC power}, \text{HP power}, \text{Grid power}]^{\mathrm{T}}$
- **binary variables**
  - $b_i = \{\text{Skip charger}, \text{Use charger}\}$
- **scalar variables**
  - $t_{\mathrm{chg},i} = \text{charging time at charger } i$

CASE STUDY 1

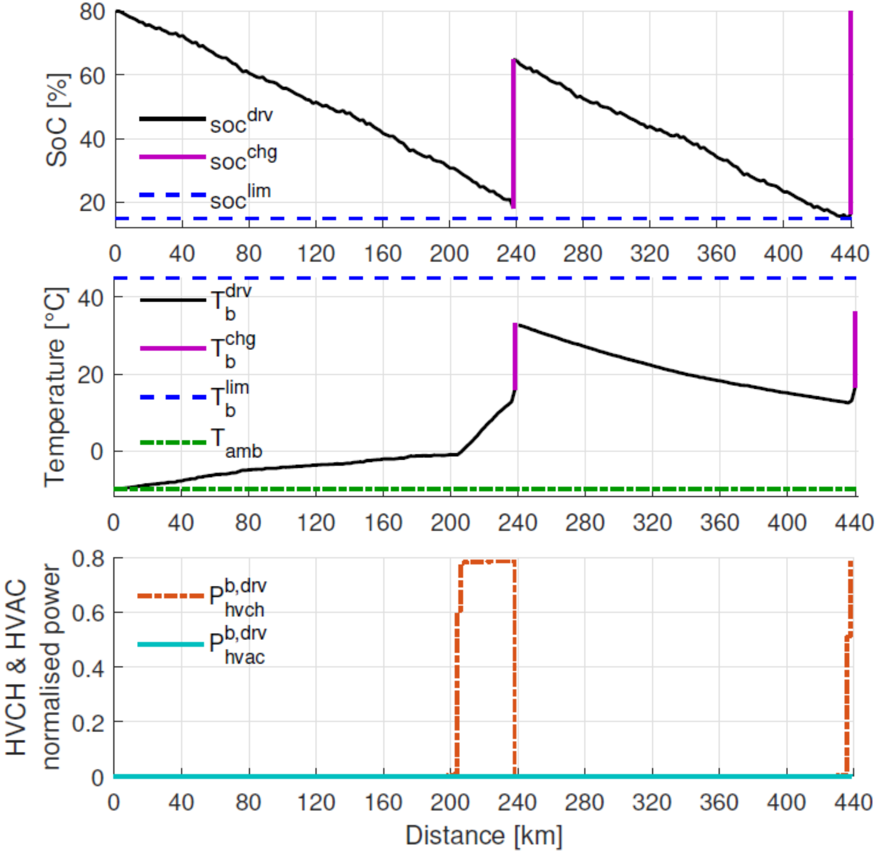
- **Heat pump disabled**
- **Eco driving enabled**
- **440 km long road with a hilly terrain**
- **Ambient temperature at -10 °C**
- **Stop at 2 fast charging stations (150 kW), one at 240 km and another at the 440 km**

THE PARETO FRONTIER

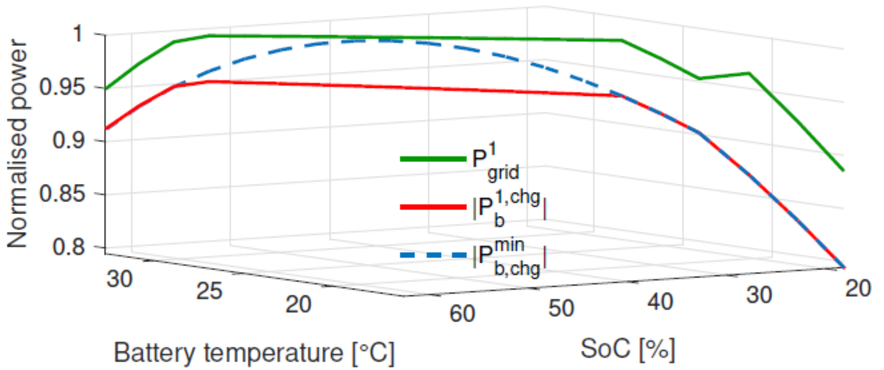
- **Point A is the most energy efficient trip**
  - **Energy is not further decreased by reducing average speed to below about 70 km/h**
- **Point B is more interesting.**
  - **Let us look into more details.**

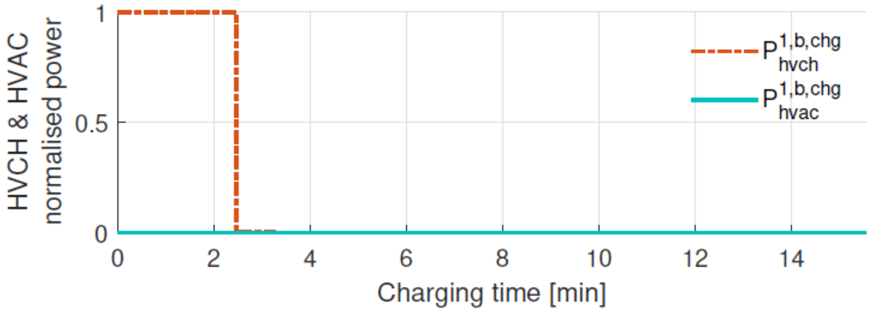


RESULTS WITH ACTIVE HEATING AND COOLING



Grid, battery and HVCH power at the 240 km charger



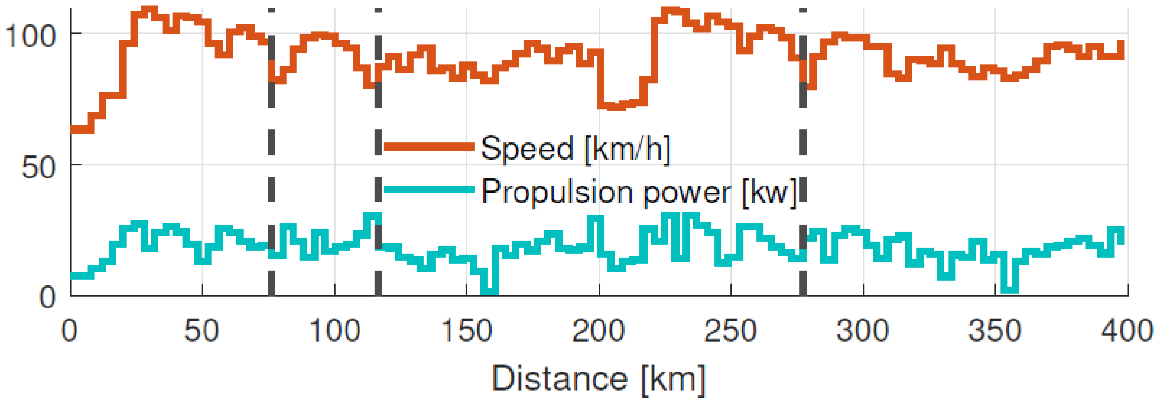


SUMMARY OF RELEVANT FINDINGS

- Active heating is turned on just before and at the beginning of the charging
  - Preconditioning the battery from start is less energy optimal
- Charged energy at the intermediate charger is just enough to reach the destination
- Charging time is reduced by more than 40% when active heating is enabled
- Driving slower may sometime save you time!
  - Eco-driving may avoid the need for stopping at a charger

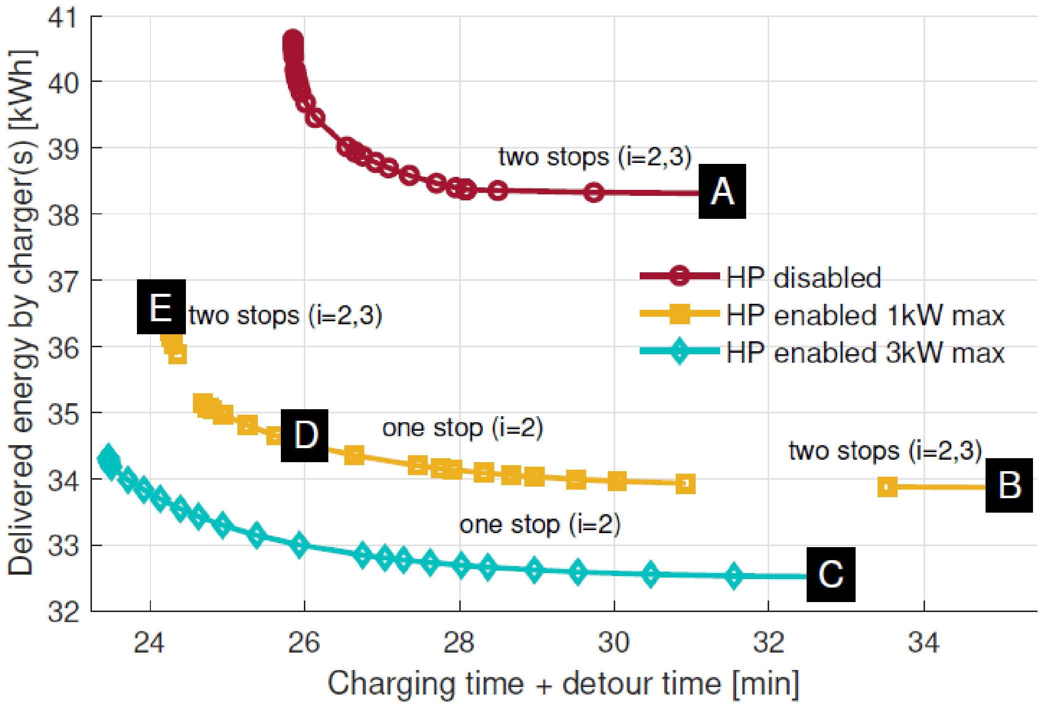
CASE STUDY 2

- **Eco driving disabled**
- **Heat pump enabled, with power limits of 1 kW or 3 kW**
- **Three charging locations, and the vehicle decides where to stop**
- **Ambient temperature varied from -15 °C to 22 °C**

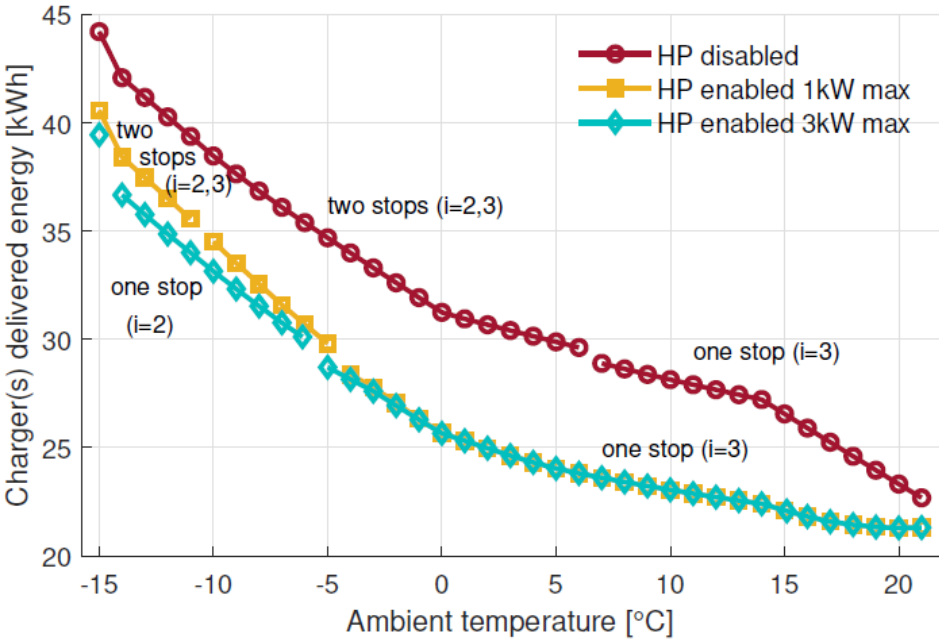


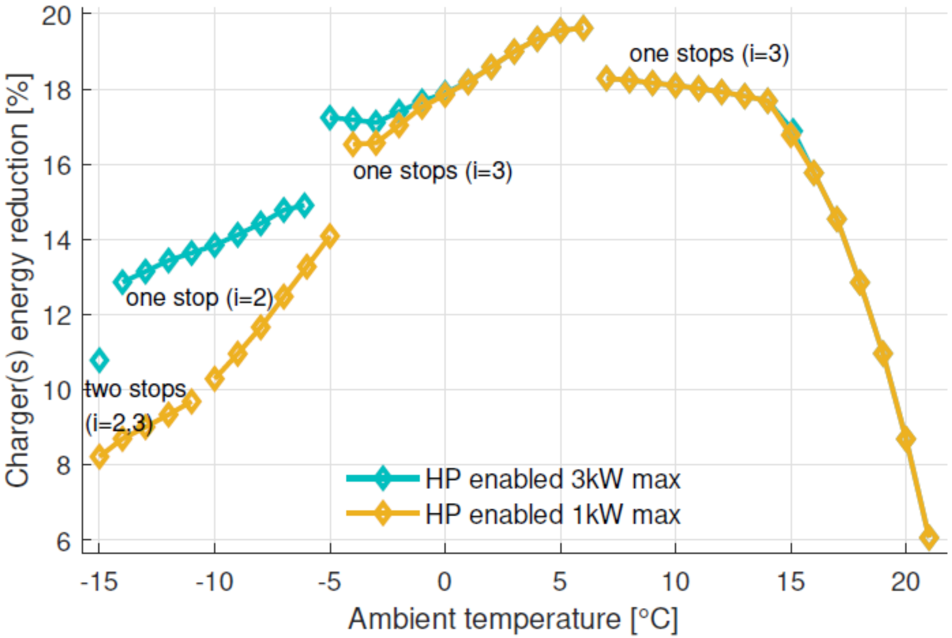
PARETO FRONTIER FOR -10 °C

- **The pareto frontier can be discontinuous.**
- **Case D: a trade off solution.**
  - **Consider the associated penalty factors on time and energy and check impact from ambient temperature**



RELATIVE ENERGY BENEFIT COMPARED TO THE CASE WHERE HEAT PUMP IS DISABLED





Relative energy benefit compared to the case where heat pump is disabled

SUMMARY OF RELEVANT FINDINGS

- A heat pump can provide more than 10% (and up to 20%) energy saving for temperatures between -5 °C to 18 °C
  - Even with a 1 kW heat pump
- Charging + detour time can be reduced by up to 30% at 0 °C compared to the case when the heat pump is disabled
- Minimum number of charging stops is favorable, regardless of user priorities on time or energy
- If charging is unavoidable, then selecting the furthest reachable charger reduces energy losses
  - Especially at low ambient temperatures

WHAT COMES NEXT

- **Development of a computationally efficient, real-time implementable solution.**
- **Development of a suitable user interface.**
- **Robust solutions when predictive information is uncertain, e.g., availability of high charging power.**
- **Distributed trip planning for a vehicle fleet.**
- **Pricing mechanisms for EV charging to minimize charging station congestion, underutilization of charging stations and optimize power-peak shaving at the charging facilities.**

THANK YOU

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