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An Electric Vehicle Battery State-of-Health Estimation System with Aging Propagation Consideration

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Background

Pure electric vehicles (EVs) become popular in current automotive markets:

TESLA

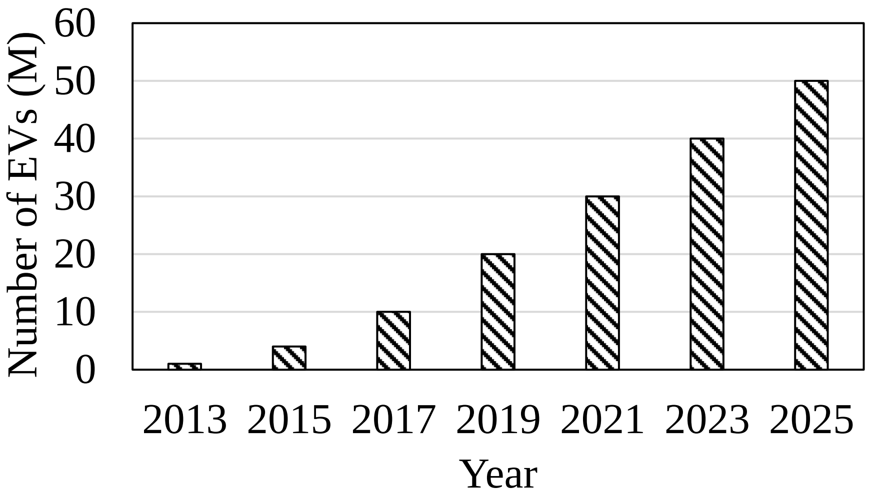
NISSAN LEAF

BMW i

BYD

Advantages of EVs

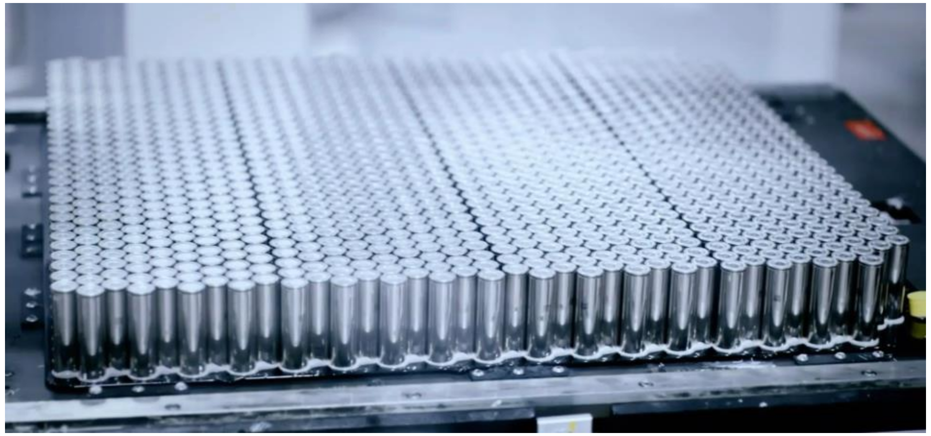
- No air pollution emission
- High energy efficiency

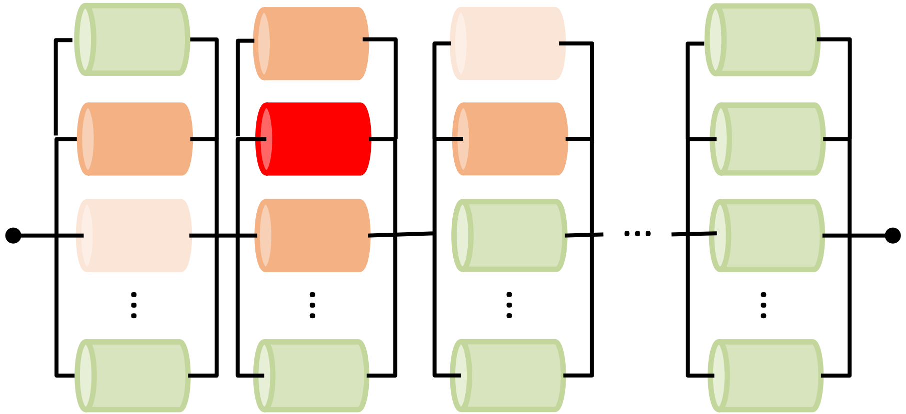


Prediction of global EV sales

Background

- Thousands of single cells in a battery pack are connected in series and parallel to drive an EV and its auxiliary functions
- Single cell ages (low electricity capacity) after several charging and discharging processes and its State-of-Health (SOH) cannot be measured





Accurately estimating SOH of each single cell becomes necessary for EVs to ensure their normal work

Related Work

- Some methods [arXiv'19, Energy'18, AE'19] tried to estimate cell SOH by modeling cell SOH dynamics under different experimental conditions

➢ Have low SOH estimation accuracy for cells working in real EV battery pack usage situations

- Some methods [TCDS'19, CDC'18, AR'17] applied machine learning technologies to estimate cell SOH based on cell relevant information (e.g., current, temperature and voltage).

➢ Fail to consider aging propagation phenomenon among individual cells in a battery pack

Challenges

Propose a battery health estimation system (BaHeS) to estimate SOH of each cell in a battery pack based on cell information (e.g., cell voltage and cell temperature)

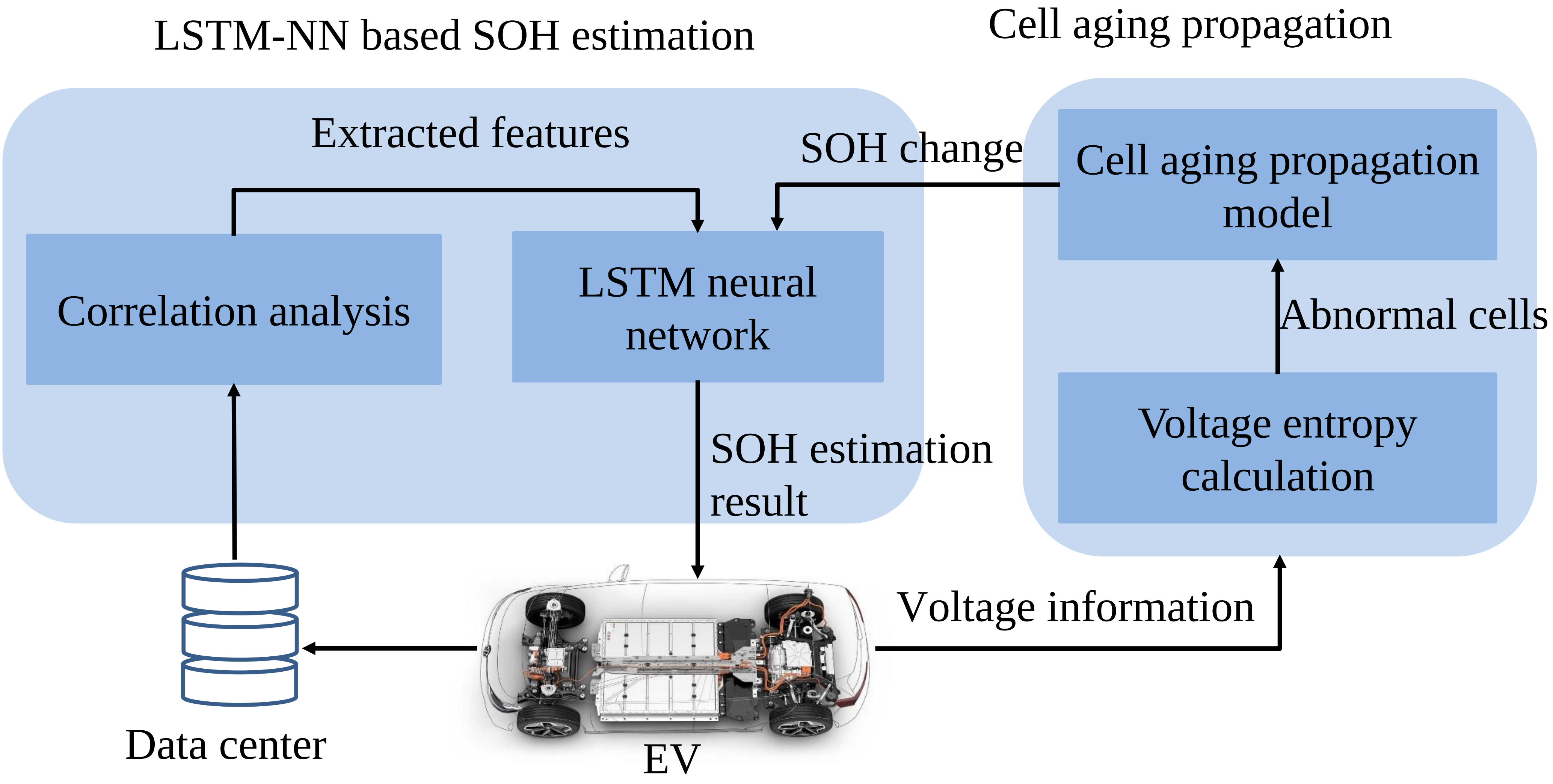
Challenge 1: How to model aging propagation phenomenon during the SOH estimation process?

- Aging propagation phenomenon exists as long as cells have different SOHs

Challenge 2: How to estimate SOH of each cell under real battery pack usage situations?

- Cells have different aging statuses when working in real battery pack usage situations

Battery Health Estimation System (BaHeS)



LSTM-NN: Long short-term memory based neural network

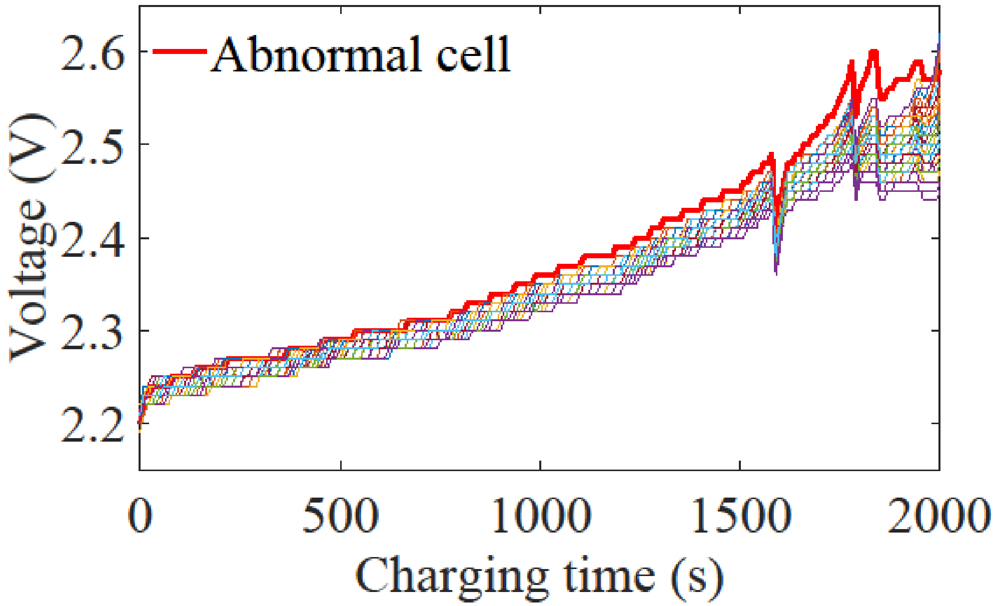
Challenge 1

How to model aging propagation phenomenon during the SOH estimation process?

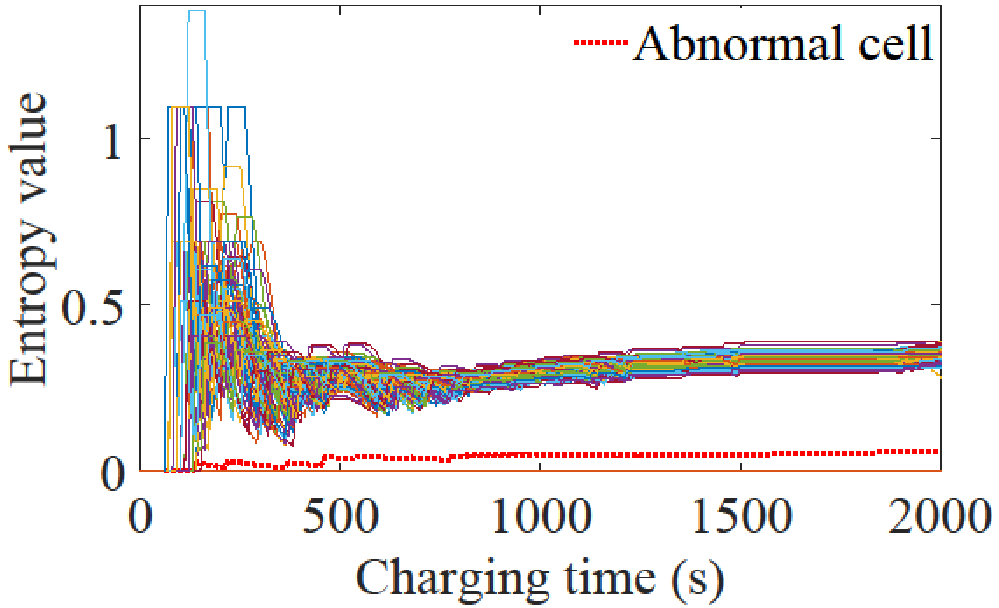
Battery Health Estimation System (BaHeS)

Voltage Entropy based Abnormal Cell Detection

- Voltages of cells can be easily measured by an EV in real time
- Aged cell has more dynamic voltage changes during a charging or discharging process



Voltages of cells after 627 discharging cycles



Voltage entropies of cells after 627 discharging cycles

Battery Health Estimation System (BaHeS)

Voltage Entropy based Abnormal Cell Detection

- Formalize the slide vector v_i with length L at each time-stamp for a cell with total N voltage samples

$$v_i = [x_i, \dots, x_{i+L-1}]$$

- Calculate vector distance between two slide vectors v_i and v_j based on each L elements

$$d(v_i, v_j) = \max_{k \in \{0,1,\dots,L-1\}} |x_{i+k} - x_{j+k}|$$

- Calculate the matching dissimilarity p_i of v_i as the percentage of slide vectors with vector distance less than λ

$$p_i = \frac{N_i}{N - L + 1}$$

Battery Health Estimation System (BaHeS)

Voltage Entropy based Abnormal Cell Detection

- Calculate the voltage entropy of the given cell with its matching dissimilarity values

$$\mathrm{E(N)} = \log\left(\frac{\sum_{i=1}^{N-L+1} p_i}{N-L+1}\right) - \log\left(\frac{\sum_{i=1}^{N-L} p_i}{N-L}\right)$$

- Detect whether such a cell belongs to the abnormal cell by calculating voltage entropy coefficient ξ

$$\xi = \frac{|E - \bar{E}|}{\sigma_E}$$

A cell will be detected as abnormal if its coefficient is more than a threshold θ

Battery Health Estimation System (BaHeS)

Cell Aging Propagation Model

Use a Gaussian Process Regression (GPR) to regress SOH change ΔSOH of the nearby cell based on the abnormal cell information q_t

- Normalize the current, voltage and temperature values of the aged cell

$$Q_t = \frac{p_t - \min_{t \in T} q_t}{\max_{t \in T} q_t - \min_{t \in T} q_t}$$

- Regress SOH change ΔSOH of a nearby cell by building the joint distribution function

$$\begin{bmatrix} \Delta SOH \\ \Delta' SOH \end{bmatrix} = \mathrm{N}(\begin{bmatrix} \bar{Q} \\ \overline{Q'} \end{bmatrix}, \begin{bmatrix} \sigma(Q,Q) & \sigma(Q,Q') \\ \sigma(Q',Q) & \sigma(Q',Q') \end{bmatrix})$$

Challenge 2

How to estimate SOH of each cell under real battery pack usage situations?

Battery Health Estimation System (BaHeS)

LSTM-NN based Cell SOH estimation method

Build a LSTM based neural network to estimate SOH of each cell in a battery pack based on ΔSOH estimation results

Step 1: Does the correlation analysis on cell information (e.g., current, voltage, temperature, derivative of current, derivative of voltage, and derivative of temperature) to select model's inputs

$$r_{x,SOH} = \frac{\sum_{i=1}^{N}(x_i - \bar{x})\,(SOH_i - \overline{SOH})}{\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2}\,\sqrt{\sum_{i=1}^{N}(SOH_i - \overline{SOH})^2}}$$

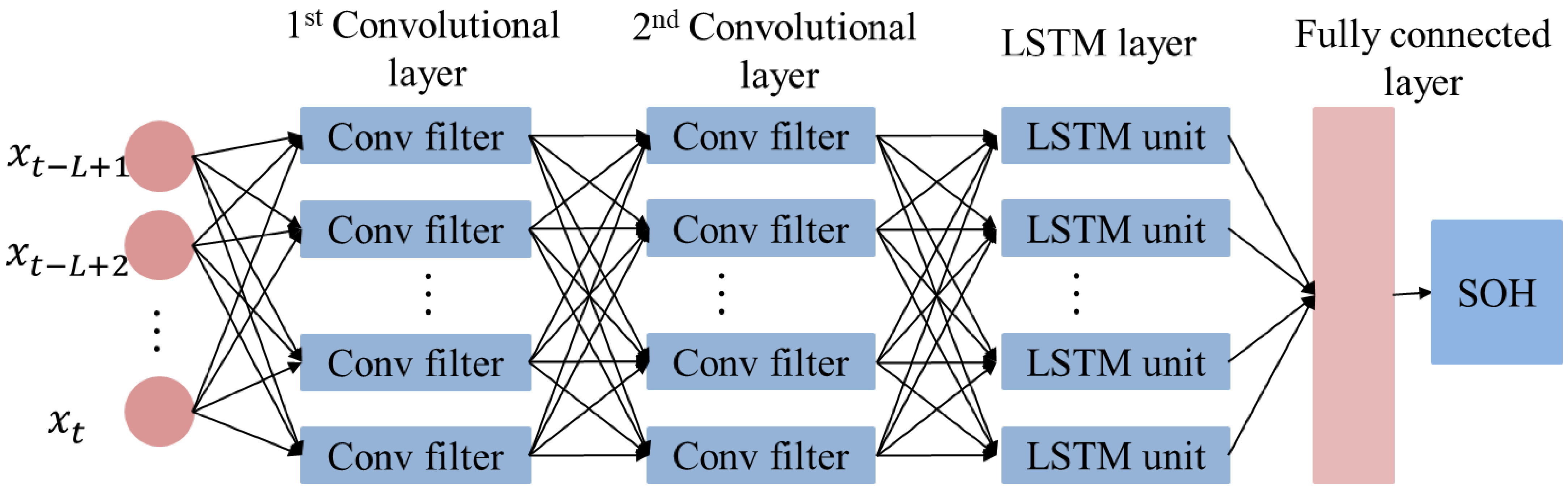
Where x and $\bar{x}$ indicate a model input type and its average value

Current, voltage, temperature, derivative of voltage have high correlation coefficients

Battery Health Estimation System (BaHeS)

LSTM-NN based Cell SOH estimation method

Step 2: input the selected cell information into the LSTM neural network to estimate SOH of each cell



Performance Evaluation

Experiment settings

- Battery pack usage data of 50 EVs [1] are recorded with the frequency of 0.1 time/second from November 1, 2019 to July 20, 2020
- Each sample includes speed, mileage, each cell information and SOH

Comparison methods

- Gaussian Process Regression based SOH estimation system (GPRS) [JPS’19] and neural network-based SOH estimation system (NNS) [ACCES’19]

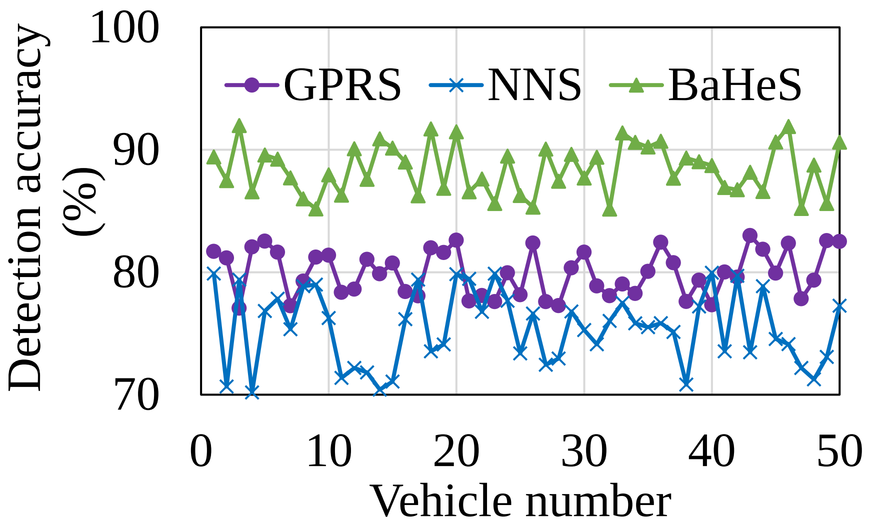
Evaluation metrics

- Abnormal cell detection accuracy
- SOH estimation accuracy

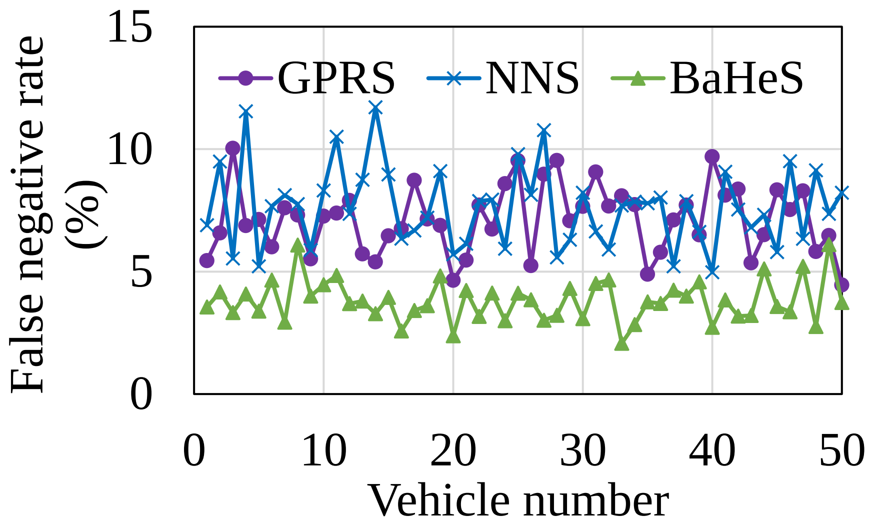
Performance Evaluation

Abnormal cell detection accuracy

- BaHeS keeps stable abnormal cell detection accuracies on different EVs
- BaHeS has higher abnormal cell detection accuracies and lower false negative detection rates



Abnormal cell detection accuracies on different EVs

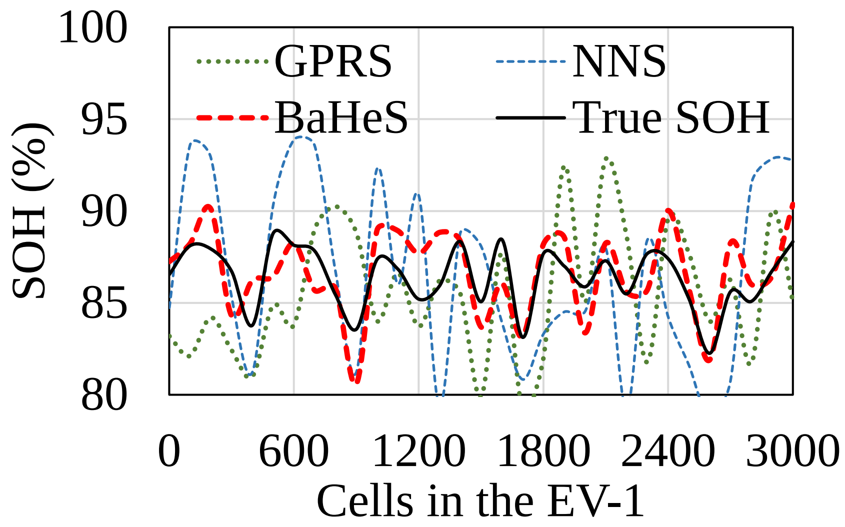


False negative detection rates on abnormal cells for different EVs

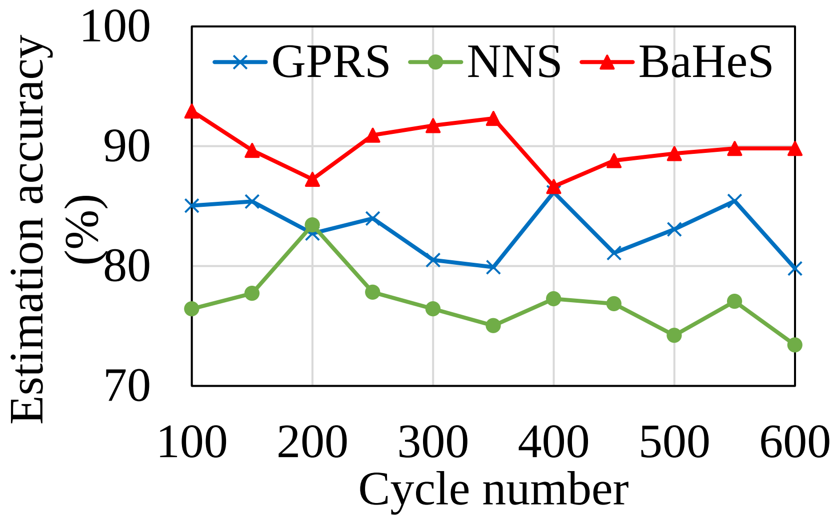
Performance Evaluation

SOH estimation accuracy

- BaHeS estimates SOH of each cell in a battery pack with higher accuracy
- BaHeS keeps high SOH estimation accuracies for different cycle numbers and its maximum value reaches 93%



SOH estimation accuracies on cells with 300 discharging cycles.

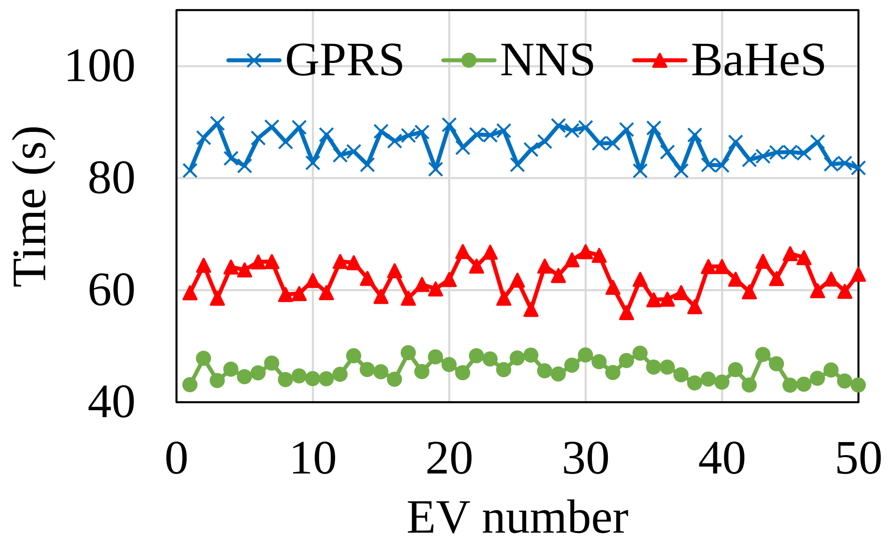


Average SOH estimation accuracies for different discharging cycles.

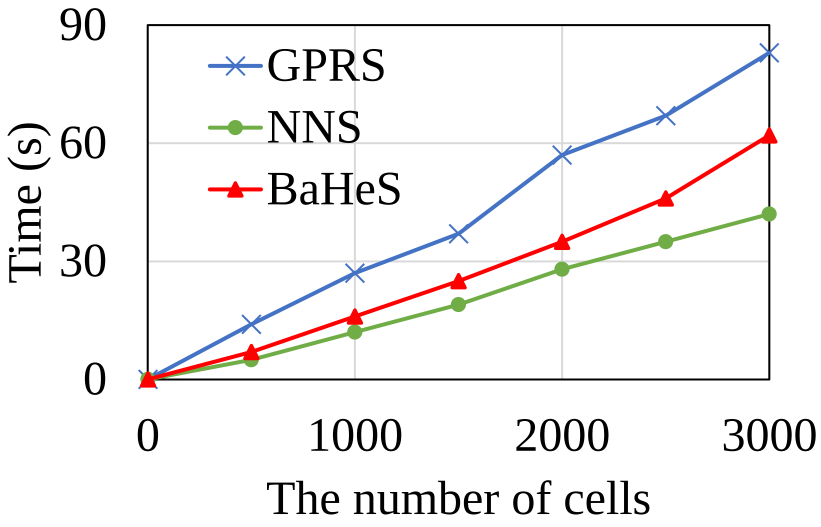
Performance Evaluation

Computation time analysis

- BaHeS needs small computation time to finish a whole SOH estimation process for different EVs
- Computation time keeps increasing as more cells are needed to estimate their SOHs



Computation time comparisons
for different EVs.



Computation time comparisons
for different cycle numbers.

Summary

Propose BaHeS to estimate SOHs of cells in a battery pack to ensure normal work of an EV

- Built an abnormal cell detection method
- Developed a SOH estimation model using a LSTM neural network
- Used real-world EV battery pack usage data to verify BaHeS

Future work

- Optimize cell charging and discharging proceses

Thank you!