Sensitivity of Lithium-Ion Battery SOx Estimates to Sensor Measurement Error and Latency

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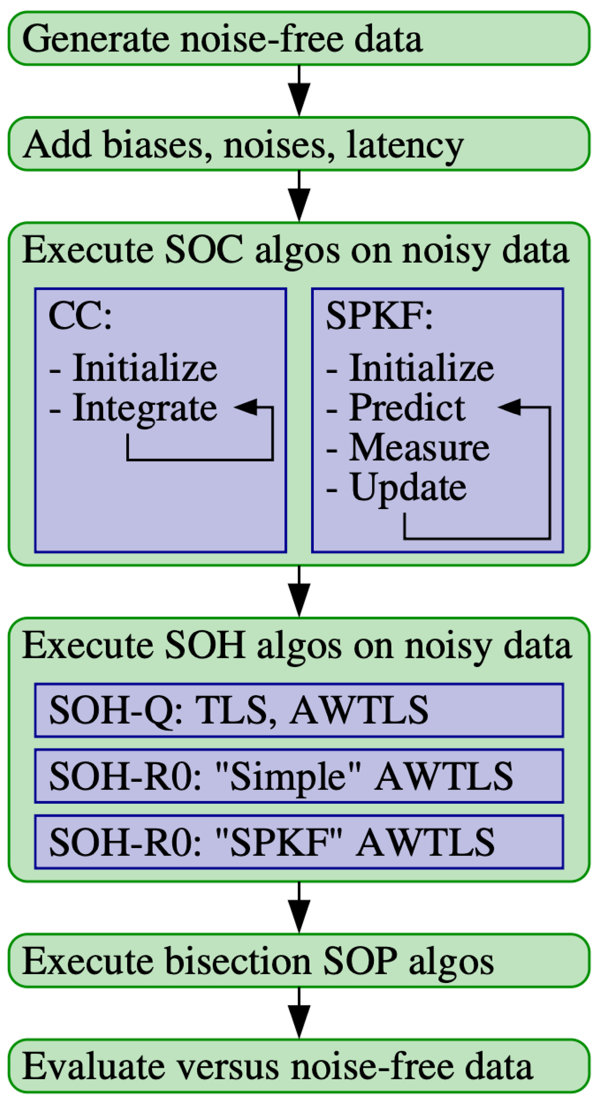
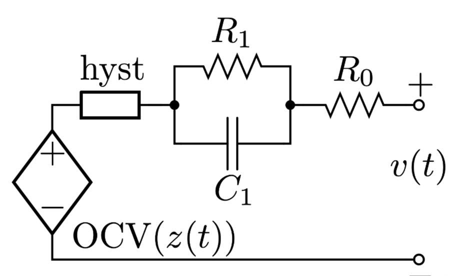
Introduction[1–3]

- A battery-management system (BMS) for a lithium-ion battery pack must compute estimates of all cell SOCs, SOHs, and SOPs, which cannot be measured directly.
- These estimates must be based on measurements of voltage, current, and temperature.
- Sensors measuring these values are characterized by their precision, accuracy, and synchronicity.
- The research question that we address in this poster is: ***How does the quality of SOC, SOH, and SOP estimates depend on sensor total measurement error (TME) and synchronization error when using coulomb counting or SPKF to make the SOC estimates, total-least-squares methods to make the SOH estimates, and bisection to make the SOP estimates?***
- We use a simulation-based approach:
  - Generate synthetic "truth" dataset based on an ECM.
  - Add measurement and synchronization errors to outputs from the truth dataset.
  - Use this modified dataset with coulomb-counting and SPKF SOC-estimation methods.
  - Apply SOH-Q and SOH-R0 estimation methods.
  - Execute bisection to compute SOP.
  - Evaluate estimates by comparing them to the true SOC, SOH, and SOP from the original truth dataset.

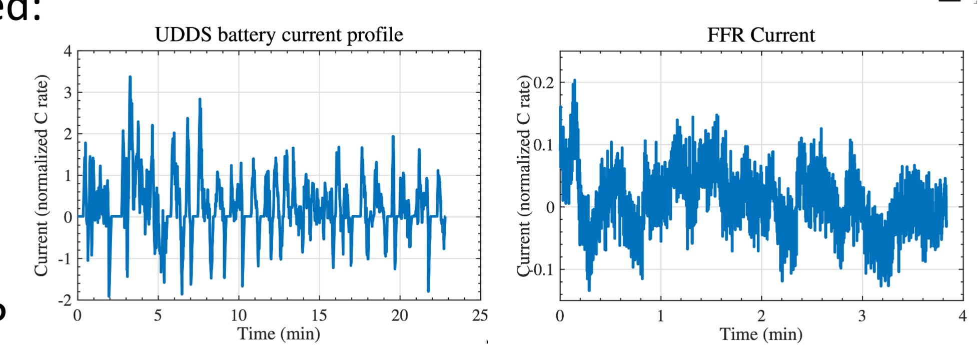


Generating the Datasets

- The synthetic "truth" dataset was generated by simulating an equivalent-circuit model (ECM) of a lithium-ion battery cell.
- The models used to generate the truth dataset incorporated three R–C pairs and were fit to data from two actual LFP and NMC cells.



- Two battery usage profiles were simulated:
  - Urban dynamometer driving schedule (UDDS, for automotive);
  - Fast frequency response (FFR, for energy storage).
- The UDDS profile was used with both LFP and NMC cells; the FFR profile was used only with LFP cells, as we believe to be typical.



- Combinations of *good* (state-of-the-art), *medium*, and *best* sensors were simulated in making the "noisy" datasets.

Sensor	Label	Parameter	Vehicle setting	ESS setting	
Voltage	SV1	dc bias noise 1σ	0.35 mV 142 μV	0.35 mV 142 μV	*Best*
	SV2	dc bias noise 1σ	3.5 mV 1.5 mV	3.5 mV 1.5 mV	*Good*
Current (C-rate)	SI1	dc bias noise 1σ	0.284×10^{-3} 0.130×10^{-3}	0.071×10^{-3} 0.0325×10^{-3}	*Best*
	SI2	dc bias noise 1σ	4.2×10^{-3} 0.07×10^{-3}	1.05×10^{-3} 0.0175×10^{-3}	*Medium*
	SI3	dc bias noise 1σ	18×10^{-3} 24×10^{-3}	4.5×10^{-3} 6×10^{-3}	*Good*
Temp.	ST1	dc bias noise 1σ	0.4 °C 0.013 °C	0.4 °C 0.013 °C	*Best*
	ST2	dc bias noise 1σ	5 °C 0.013 °C	5 °C 0.013 °C	*Good*

- Eight algorithm cases were considered, having different random typical-magnitude ECM parameter errors

Test parameter	Parameter settings
Scenarios	{UDDS for NMC and LFP; FFR for LFP}
Temperature	{25 °C (ambient)}
Cases	{z_0 initialization error of ±1 %}, {Q initialization error of ±1 %}, {truth data simulated using model having 3 R–C pairs and SPKF SOC estimates made based using model having 2 R–C pairs}
Sensor models	dc bias and random error specified for seven sensors
Sensor latencies	{0 ms, ±100 ms} between V and I
Algorithm	{Coulomb counting, SPKF}

- Latencies of 0, ±10, and ±100 ms between current-sensor and other measurements were also considered when creating noisy datasets.

SOC, SOH, and SOP Methods

- All methods are based on ECMs having two R–C pairs to account for model/cell mismatch.

- For SOC, coulomb counting (CC) estimates cell SOC by integrating charge into/out of cell.
- The sigma-point Kalman filter (SPKF) uses voltage feedback to update the open-loop predictions made by CC, and if properly implemented will always be more robust than CC.

- SOH-Q ("WLS"/"AWTLS"): The difference in cell SOC between two time points is:

$$\underbrace{-\int_{t_1}^{t_2} i(\tau)d\tau}_{y} = Q\underbrace{(z(t_2)-z(t_1))}_{x}$$

  - Data can be regressed to the linear form $y=Qx$ to estimate Q; must use TLS (not LS).
- SOH-R0 ("simple"): Change in voltage between timesteps can be approximated as:

$$\underbrace{v_k - v_{k-1}}_{y} \approx R_0\underbrace{(i_{k-1}-i_k)}_{x}$$

- SOH-R0 ("SPKF"): Using a full cell model, voltages at different timesteps can be written as:

$$\underbrace{-\left(\hat{v}_k - \mathrm{OCV}(\hat{z}_k) - M\hat{h}_k + \sum_i \hat{v}_{c_i,k}\right)}_{y} = R_0\,\underbrace{i_k^{\text{meas}}}_{x}$$

  - For both, data can be regressed to the linear form $y=R_0x$ to estimate R_0; must use TLS.

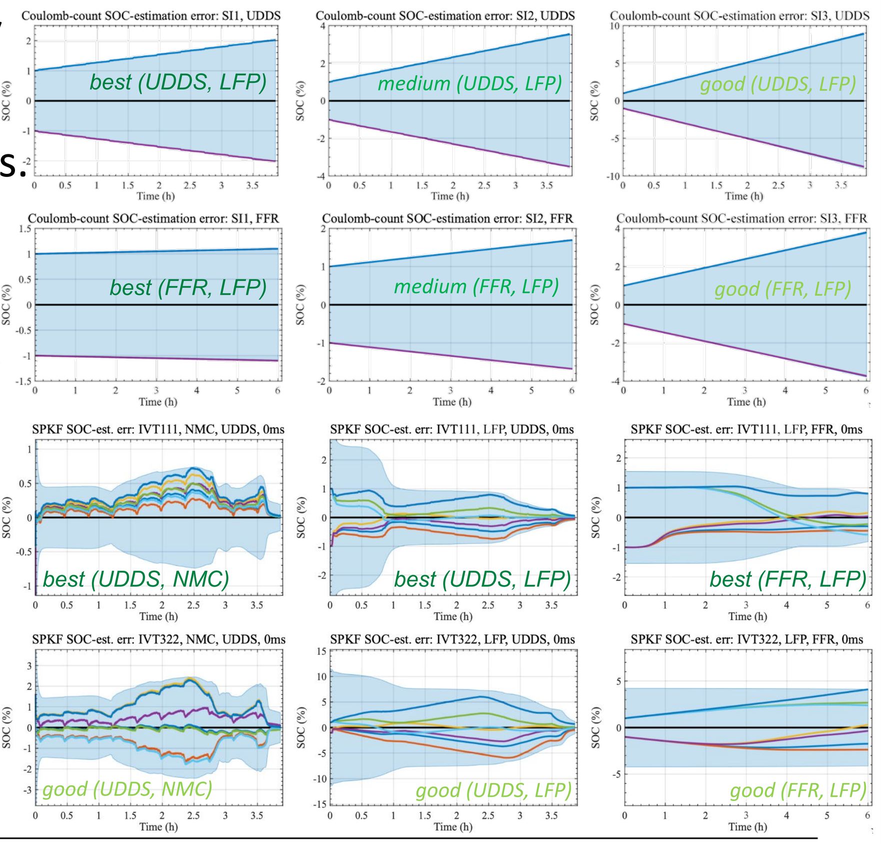
- For SOP, the cell model computes future voltage $v(t+T)$ using $R_0=\hat{R}_0+3\sigma_{R_0}$ from the SOH-R0 estimator ("simple" or "SPKF") for candidate levels of dis/charge current.
- Maximum current is found by bisecting until $v(t+T)=v_{\min}$ or $v(t+T)=v_{\max}$.
- Maximum dis/charge power is computed based on this current and future voltage.

References

[1] G.L. Plett and G. McVeigh, "Sensitivity of lithium-ion battery SOC estimates to sensor measurement error and latency," in *2024 International Conference on Electrical, Computer and Energy Technologies (ICECET)*, 2024.
[2] —, "Sensitivity of lithium-ion battery SOH estimates to sensor measurement error and latency," in *2024 International Conference on Electrical, Computer and Energy Technologies (ICECET)*, 2024.
[3] —, "Sensitivity of lithium-ion battery SOP estimates to sensor measurement error and latency," in *Proc. Modeling, Estimation, and Control Conference (submitted; under review)*, 2025.

SOC-Estimation Results

- Blue shaded areas show uncertainty boundary
- Sample CC results are shown in rows 1 & 2
  - Results exhibit near-worst-case uncertainties.
  - SOC-estimate accuracy and uncertainty depend strongly on current-sensor TME.
- SPKF results, rows 3 & 4, show more variation.
  - Voltage feedback improves estimates; error bounds are tighter as well.
- Overall, CC is always worse than SPKF, but not by much for LFP when SPKF uses poorer voltage sensor or when both methods use poorer current sensors.
- SPKF struggles with LFP as voltage contains little information value; SPKF estimates are only slightly better than CC estimates.
- Current/voltage latency has no impact on CC and remarkably little impact on SPKF.

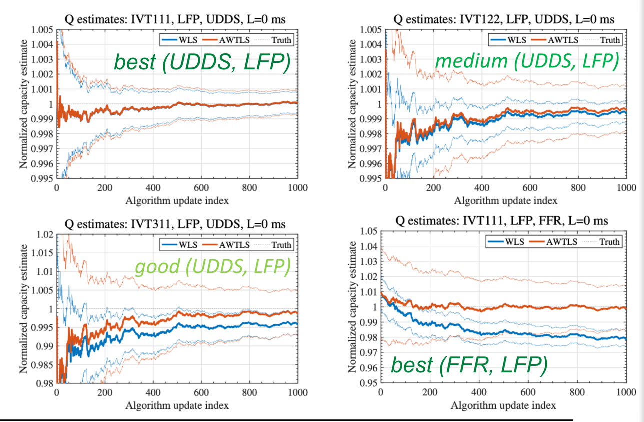


	SI	SV	ST	Profile	Cell(s)	RMSE CC (%)	Latency = −100 ms RMSE KF (%)	RMSB KF (%)	BNDX KF (%)	Latency = 0 ms RMSE KF (%)	RMSB KF (%)	BNDX KF (%)	Latency = 100 ms RMSE KF (%)	RMSB KF (%)	BNDX KF (%)
Best	1	1	1	UDDS	NMC	1.54	0.27	0.56	0.00	0.27	0.56	0.00	0.27	0.56	0.00
				UDDS	LFP	1.54	0.38	1.29	0.00	0.38	1.29	0.00	0.38	1.29	0.00
				FFR	LFP	1.05	0.65	1.06	0.00	0.65	1.06	0.00	0.65	1.06	0.00
Medium	1	2	2	UDDS	NMC	1.54	0.63	1.57	0.00	0.63	1.57	0.00	0.63	1.57	0.00
				UDDS	LFP	1.54	1.32	2.38	0.00	1.32	2.38	0.00	1.32	2.38	0.00
				FFR	LFP	1.05	1.05	1.13	0.00	1.05	1.13	0.00	1.05	1.13	0.00
	2	1	1	FFR	LFP	1.36	1.31	1.76	0.00	1.31	1.76	0.00	1.31	1.76	0.00
	2	2	2	FFR	LFP	1.36	1.33	1.85	0.00	1.33	1.85	0.00	1.33	1.85	0.00
	3	1	1	UDDS	NMC	5.43	0.28	0.57	0.00	0.28	0.57	0.00	0.28	0.57	0.00
				UDDS	LFP	5.43	4.82	8.94	0.00	4.82	8.94	0.00	4.82	8.94	0.00
Good	3	2	2	UDDS	NMC	5.43	0.77	1.78	0.00	0.77	1.78	0.00	0.77	1.78	0.00
				UDDS	LFP	5.43	2.21	7.11	0.00	2.21	7.11	0.00	2.22	7.11	0.00
				FFR	LFP	2.51	1.99	4.14	0.00	1.99	4.14	0.00	1.99	4.14	0.00

Improving performance

SOH-Estimation Results

- Sample SOH-Q results are shown; SOC-SPKF was used.
  - WLS produces biased results—if the current sensor is poor, the bias can be significant.
  - Voltage- and temperature-sensor inaccuracies have a vicarious impact through derated SOC estimates.
- AWTLS produces excellent results, with low sensitivity to sensor error and latency.

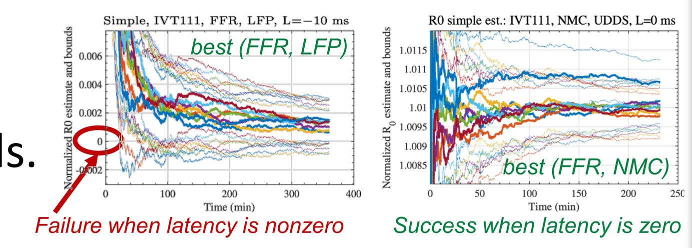


- Sensor TME caused only small variation in Q estimates when using AWTLS with SPFK-SOC since the recursive methods can overcome some sensor limitations via voltage feedback.

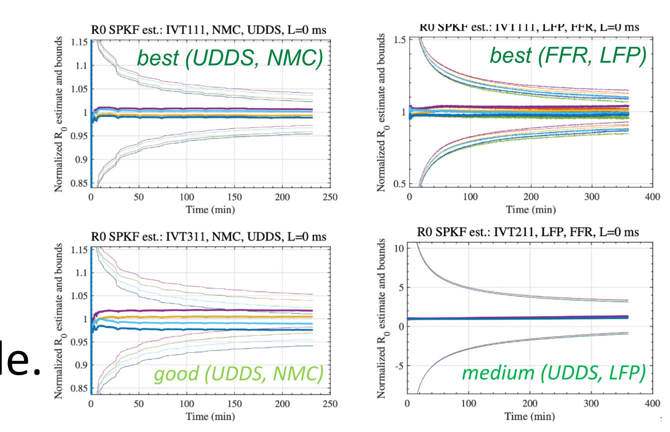
	SI	SV	ST	Profile	Cell	Latency = −100 ms (values in (%)) WLS RMSE	WLS Bounds	AWTLS RMSE	AWTLS Bounds	Latency = 0 ms (values in (%)) WLS RMSE	WLS Bounds	AWTLS RMSE	AWTLS Bounds	Latency = 100 ms (values in (%)) WLS RMSE	WLS Bounds	AWTLS RMSE	AWTLS Bounds
Best	1	1	1	UDDS	NMC	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00
				UDDS	LFP	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00
				FFR	LFP	2.02	85.80	0.11	0.00	2.02	85.90	0.11	0.00	2.02	85.70	0.11	0.00
Medium	1	2	2	UDDS	NMC	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00
				UDDS	LFP	0.06	33.30	0.04	0.00	0.06	33.30	0.04	0.00	0.06	33.30	0.04	0.00
				FFR	LFP	4.97	94.20	0.11	0.00	4.97	94.20	0.11	0.00	4.97	94.20	0.11	0.00
	2	1	1	FFR	LFP	7.69	94.50	0.46	0.00	7.69	94.50	0.46	0.00	7.69	94.50	0.46	0.00
	2	2	2	FFR	LFP	7.97	94.50	0.48	0.00	7.97	94.50	0.48	0.00	7.97	94.50	0.48	0.00
	3	1	1	UDDS	NMC	0.08	0.00	0.08	0.00	0.08	0.00	0.08	0.00	0.08	0.00	0.08	0.00
				UDDS	LFP	0.42	89.60	0.13	0.00	0.42	89.60	0.13	0.00	0.42	89.60	0.13	0.00
Good	3	2	2	UDDS	NMC	0.05	0.00	0.06	0.00	0.05	0.00	0.06	0.00	0.05	0.00	0.06	0.00
				UDDS	LFP	0.08	0.00	0.03	0.00	0.08	0.00	0.03	0.00	0.08	0.00	0.03	0.00
				FFR	LFP	16.57	96.40	1.10	0.00	16.57	96.40	1.10	0.00	16.57	96.40	1.10	0.00

Improving performance

- Two sample SOH-R0 "simple" method are shown.
  - Solid = simulation "cases," thin = confidence bounds.
  - With no latency between current and voltage, R_0 estimate is generally good, otherwise it fails.



- Four sample SOH-R0 "SPKF" are shown:
  - Estimates for the (high-voltage-variation) NMC cell are very good, and confidence bounds are reliable.
  - Estimates for (low-voltage-variation) LFP cell are less accurate, but confidence bounds are still reliable.



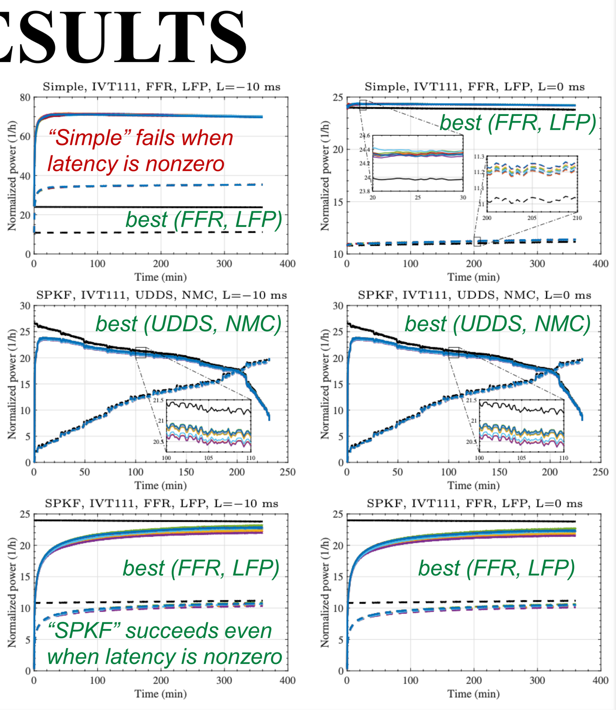
- Strong dependence between current-sensor accuracy and SOH-R0 accuracy.
- Latency also degrades estimates, but not as much as for the "simple" method.

	SI	SV	ST	Profile	Cell	Latency = −10 ms (values in (%)) Simple RMSE	Simple Bounds	SPKF RMSE	SPKF Bounds	Latency = 0 ms (values in (%)) Simple RMSE	Simple Bounds	SPKF RMSE	SPKF Bounds	Latency = 10 ms (values in (%)) Simple RMSE	Simple Bounds	SPKF RMSE	SPKF Bounds
Best	1	1	1	UDDS	NMC	99.92	100.00	1.55	0.00	0.04	0.00	1.52	0.00	100.01	100.00	1.60	0.00
				UDDS	LFP	99.87	100.00	3.40	3.17	0.06	0.00	3.43	3.72	99.97	100.00	3.30	2.82
				FFR	LFP	99.76	100.00	2.56	0.00	0.11	0.00	3.63	0.00	99.84	100.00	2.60	0.00
Medium	1	2	2	UDDS	NMC	99.77	100.00	7.34	0.00	0.39	4.43	7.35	0.00	99.96	100.00	7.33	0.00
				UDDS	LFP	99.93	100.00	8.59	0.00	0.56	0.00	8.61	0.00	99.92	100.00	8.55	0.00
				FFR	LFP	100.12	100.00	24.29	0.00	0.87	0.00	24.82	0.00	99.87	100.00	24.27	0.00
	2	1	1	FFR	LFP	99.76	100.00	12.72	0.00	0.11	0.00	15.01	0.00	99.84	100.00	12.64	0.00
	2	2	2	FFR	LFP	100.12	100.00	25.85	0.00	0.87	0.00	26.61	0.00	99.87	100.00	25.82	0.00
	3	1	1	UDDS	NMC	—	0.00	2.18	0.15	0.18	0.00	2.18	0.00	—	0.00	2.22	1.69
				UDDS	LFP	—	0.64	29.65	0.00	0.18	0.00	29.69	0.00	—	0.20	29.57	0.00
Good	3	2	2	UDDS	NMC	99.66	100.00	8.06	0.00	0.56	1.56	8.05	0.00	99.82	100.00	8.07	0.00
				UDDS	LFP	100.14	100.00	11.54	0.00	0.99	6.73	11.53	0.00	100.02	100.00	11.56	0.00
				FFR	LFP	99.91	100.00	31.62	0.00	1.02	0.02	30.86	0.00	99.66	100.00	31.65	0.00

Improving performance

SOP-Estimation Results

- Six sample SOP results are shown: Solid/dash = dis/charge.
  - Black solid/dash lines are truth power levels.
- High-accuracy synchronized sensors enable high-accuracy SOP estimates that rarely overpredict true available power.



	SI	SV	ST	Profile	Cell	Latency = −10 ms (values in (%)) Simple RMSE	Simple overest	SPKF RMSE	SPKF overest	Latency = 0 ms (values in (%)) Simple RMSE	Simple overest	SPKF RMSE	SPKF overest	Latency = 10 ms (values in (%)) Simple RMSE	Simple overest	SPKF RMSE	SPKF overest
Best	1	1	1	UDDS	NMC	232.60	99.85	6.32	0.00	1.12	2.02	6.33	0.00	233.27	99.85	6.30	0.00
				UDDS	LFP	192.17	99.96	7.79	0.24	1.71	99.35	7.81	0.22	192.69	99.96	7.75	0.25
				FFR	LFP	205.06	100.00	12.73	0.00	1.67	99.94	14.12	0.00	205.52	100.00	12.68	0.00
Medium	1	2	2	UDDS	NMC	223.89	99.84	21.08	0.00	3.51	13.75	21.10	0.00	225.18	99.84	21.05	0.00
				UDDS	LFP	185.04	99.82	36.53	0.00	2.20	78.01	36.54	0.00	184.87	99.83	36.50	0.00
				FFR	LFP	192.37	99.95	84.92	0.00	1.97	60.95	84.97	0.00	191.22	99.96	84.91	0.00
	2	1	1	FFR	LFP	204.75	100.00	69.89	0.00	1.56	99.94	70.11	0.00	205.21	100.00	69.88	0.00
	2	2	2	FFR	LFP	192.22	99.95	76.18	0.00	1.98	59.15	76.32	0.00	191.07	99.96	76.18	0.00
	3	1	1	UDDS	NMC	104.77	0.33	6.35	0.02	5.59	0.46	6.36	0.01	100.10	0.12	6.33	0.03
				UDDS	LFP	107.18	0.20	79.14	0.00	9.15	50.43	79.14	0.00	99.78	0.06	79.14	0.00
Good	3	2	2	UDDS	NMC	223.09	99.91	16.98	0.00	10.43	17.91	16.96	0.00	223.96	99.91	16.97	0.00
				UDDS	LFP	186.19	99.87	37.31	0.00	3.33	65.86	37.32	0.00	185.34	99.87	37.28	0.00
				FFR	LFP	191.05	99.94	67.42	0.00	2.14	61.00	67.67	0.00	189.92	99.96	67.41	0.00

Improving performance

Summary

- This poster presents a simulation framework for evaluating the effect of sensor total measurement error and synchronization error on SOC/SOH (Q and R_0)/SOP-estimates.
- For the scenarios that we considered, the study confirmed in a quantitative way the intuitive expectation that better sensors enable better estimates and bounds.
- Consequently, a BMS that uses better sensors does not require that the battery pack be designed with excess capacity to compensate for poor sensing, reducing overall cost, improving sustainability, and improving usable energy of the battery.
- This also implies that applications which specify maximum permitted SOx-estimation error will have referred requirements imposed on the quality of the sensing subsystem of the BMS. The proposed framework can be used to develop sensor requirements.