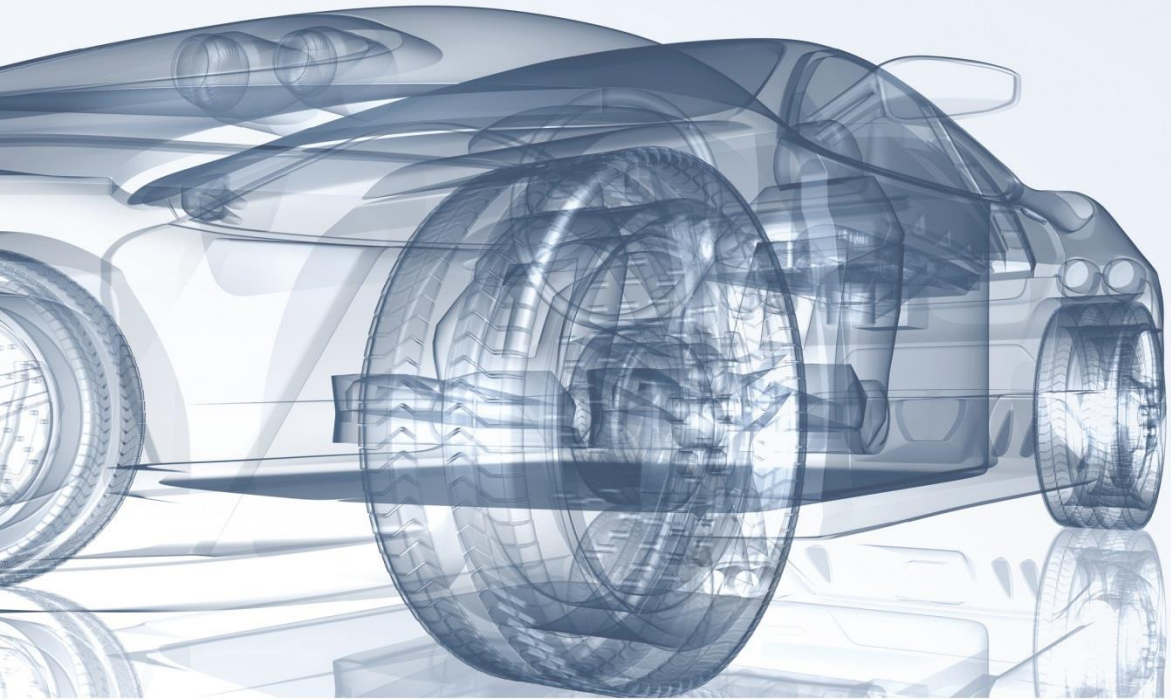
evs 30



The 30th International
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October 9–11, 2017

Messe Stuttgart, Germany

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Hyundai ix35 fuel cell electric vehicles: degradation analysis for driving and vehicle-to-grid usage

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Agenda

- Introduction
- Materials
- Method
- Results
- Conclusion

Introduction – Fuel Cell Durability

- Fuel Cell Electric Vehicle (FCEV) → **Driving mode**

- U.S. Department of Energy (DoE) automotive fuel cell **durability (to 10% voltage drop)**:
- 4,100 hours[1] → **Today**, fleet **maximum** durability, real-world driving, no simulated drive cycle.
  → fleet average ~2,000 hours

- 8,000 hours[1] → **Ultimate target,** in slow-speed driving conditions (e.g. city driving)
- ≈ 241,000 km (150,000 mi)

[1]) DOE Hydrogen and Fuel Cell Technologies Program Records #16019 - On-Road Fuel Cell Stack Durability – 2016

Introduction – Vehicle-to-Grid

- Fuel Cell Electric Vehicle (FCEV) → **Vehicle-To-Grid (V2G) mode**
- V2G → parked; produce power to electricity grid → Modification of existing Hyundai ix35 FCEV
- Future grid services: balancing intermittent renewables, converting seasonal stored hydrogen
- Fuel Cell durability in **Vehicle-To-Grid (V2G) mode?**
  - **→ pricing future grid services?**
  - Relevant for manufacturer guarantees or scheduling maintenance

Introduction - Research question

- Fuel Cell durability in **<u>Vehicle-To-Grid (V2G) mode?</u>**

- **Possible** durability parameters V2G, % Voltage drop vs.;
- *Operating Hours* → What 'Vehicle-to-Grid' Cycle?
- *Driven distance* → not relevant if car is parked but producing power
- *Produced electricity* → What if idling & not producing power? → 'spinning reserve' grid service
- … *Other*?

- **Research question:**

How can we analyze fuel cell stack voltage degradation

& are existing durability indicators still relevant in commercial FCEVs,

used for driving and vehicle-to-grid purposes?

Materials

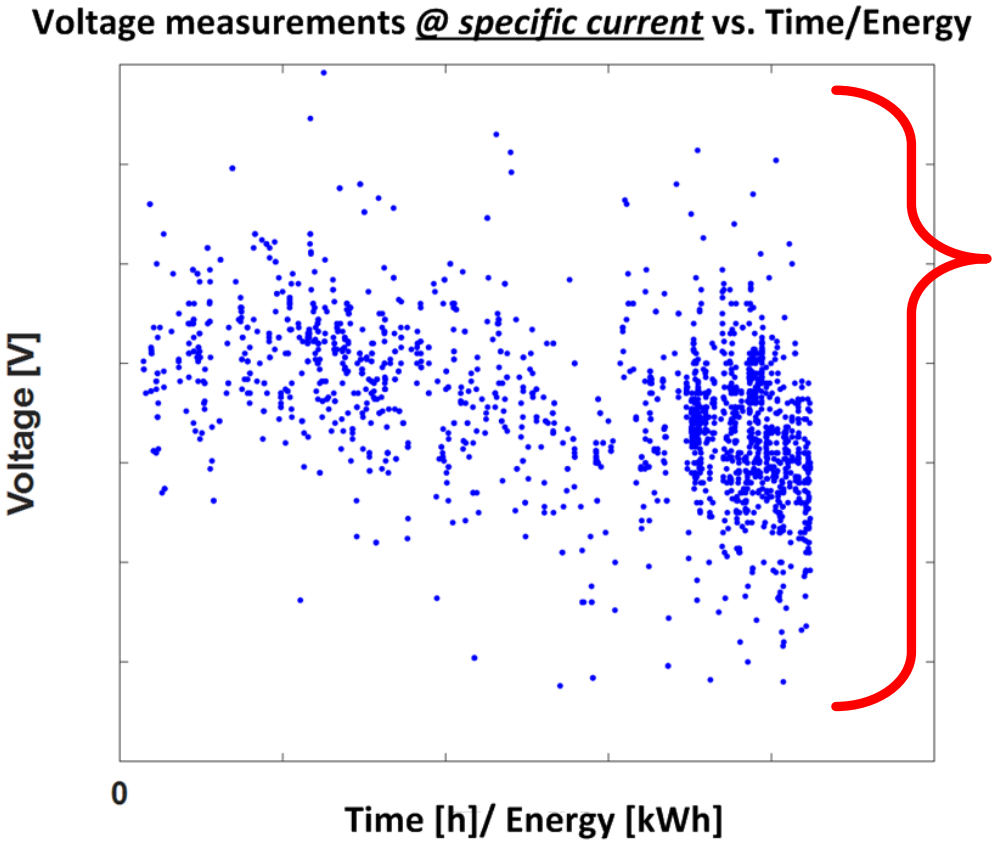
- 4 Hyundai ix35 FCEVs
  - 3x FCEVs: Driving only (‘FCEV1/2/3’)
  - 1x FCEV: Driving & Vehicle-to-Grid (‘FCEV2G’)

- Vehicle to Grid set-up[2]

- CAN bus data logging;
  - Voltage Fuel Cell stack @ 1Hz-5Hz
  - Current Fuel Cell stack @ 1Hz-5Hz
  - Driving speed
  - .. many other parameters

[2]) V. Oldenbroek et al. Fuel Cell Electric Vehicle-to-Grid : Experimental feasibility & operational performance. 6th Eur. PEFC & Electrolyser Forum 2017

Method



- Real voltage data vs.
  - Operating time[3]
  - Produced energy[4]
- **'scattering'**
  - Transient phenomena
  - Different operating conditions
  - Specific operating routines

→ **Applying;**

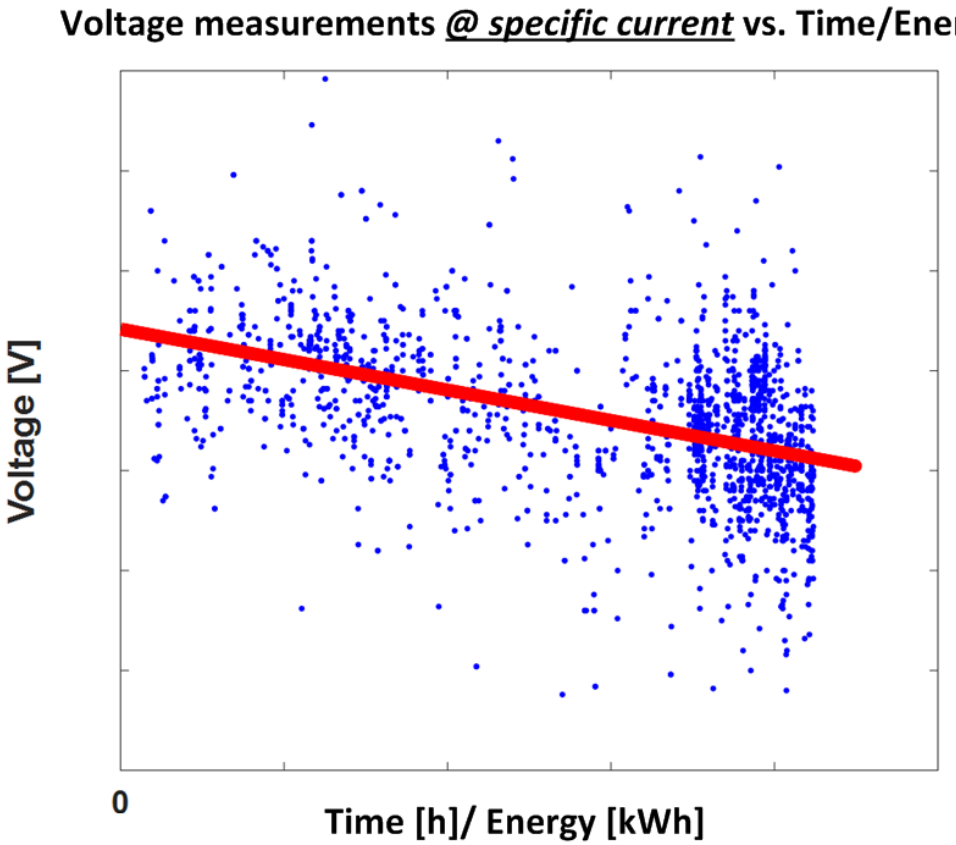
- Fitting algorithm & filtering[5]

3) DOE Hydrogen and Fuel Cell Technologies Program Records #16019 - On-Road Fuel Cell Stack Durability – 2016

4) Jouin M, et al. Estimating the end-of-life of PEM fuel cells: Guidelines and metrics. Applied Energy. 2016.

5) Fletcher T, et al. An Energy Management Strategy to concurrently optimise fuel consumption & PEM fuel cell lifetime in a hybrid vehicle. Int. J. of Hydrogen Energy. 2016.

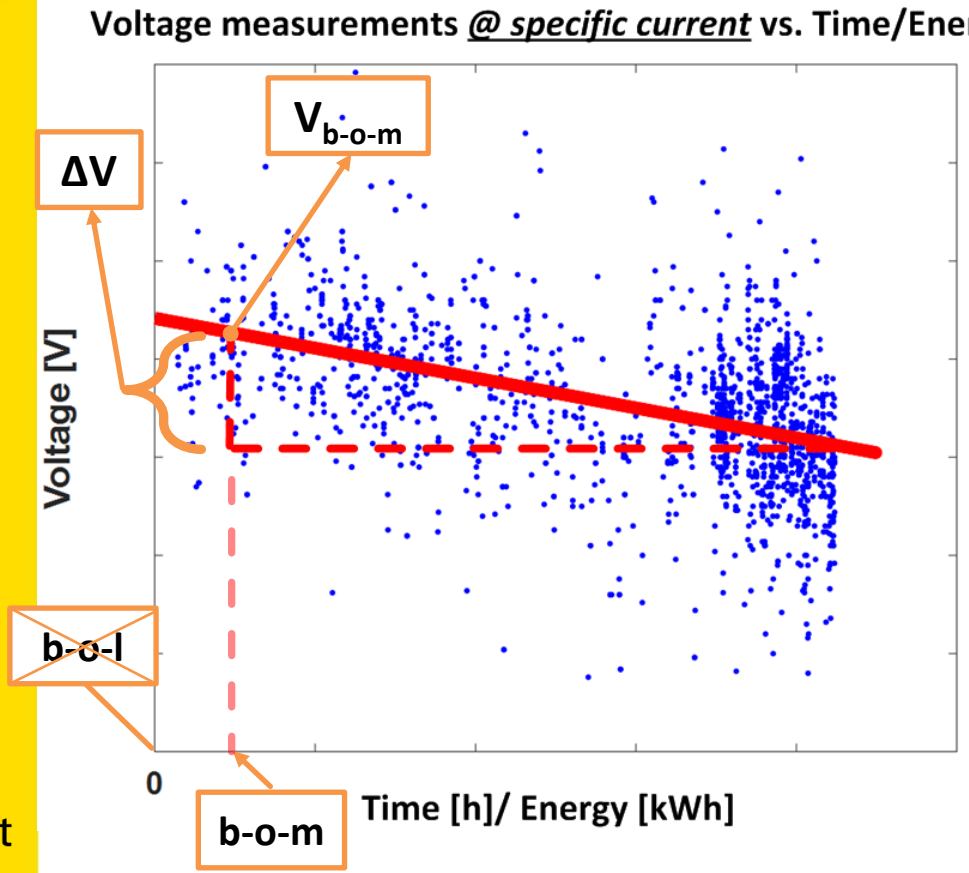
Method



- 2 least squares regression analysis methods:
  - Linear
  - Robust linear
- Robust → reduce influence outliers from transient phenomena[5]

[5]) Least-Squares Fitting - MATLAB, https://nl.mathworks.com/help/curvefit/least-squares-fitting.html

Method



- Fuel cell stack voltage drop for specific current vs. begin-of-measurement (b-o-m)
- **NOT** begin-of-life (b-o-l)

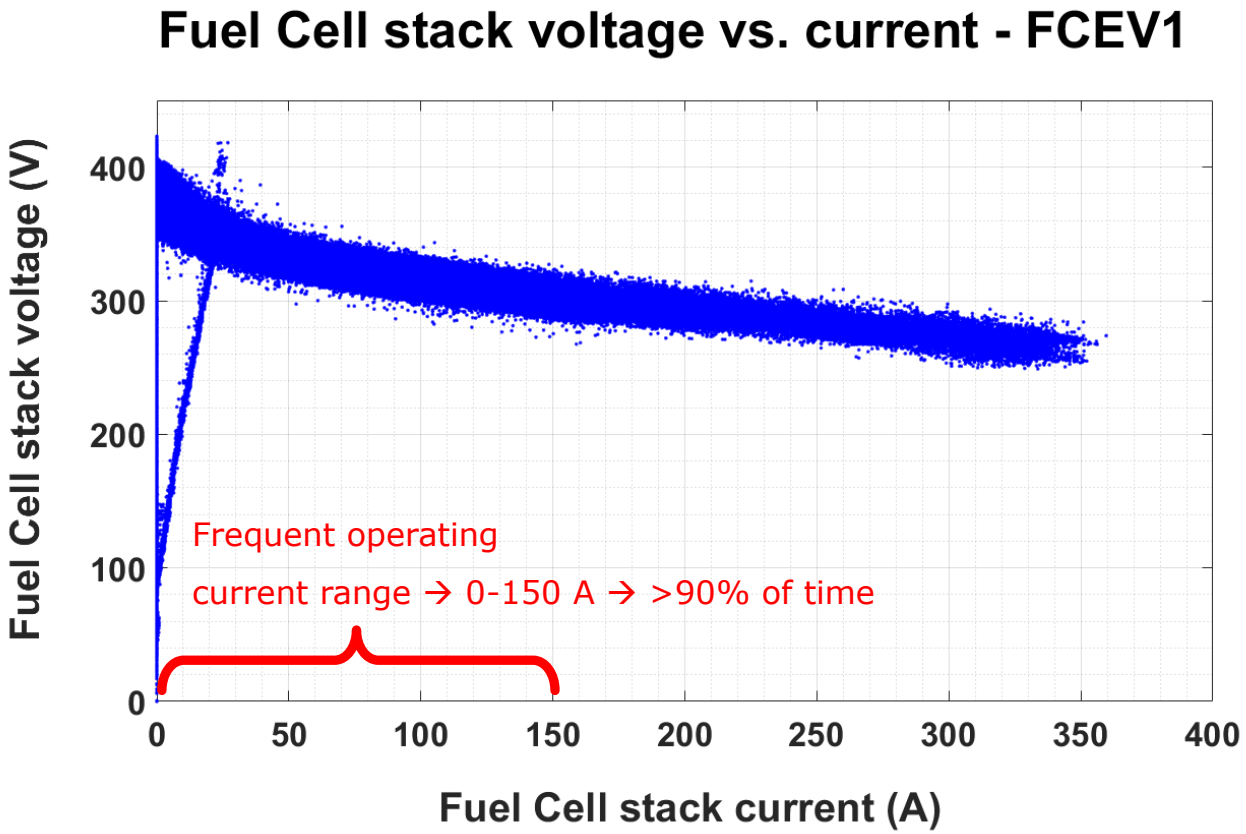
Relative Voltage drop @specific current:

- $\%V_{@current} = \Delta V / V_{b\text{-}o\text{-}m} \times 100\%$

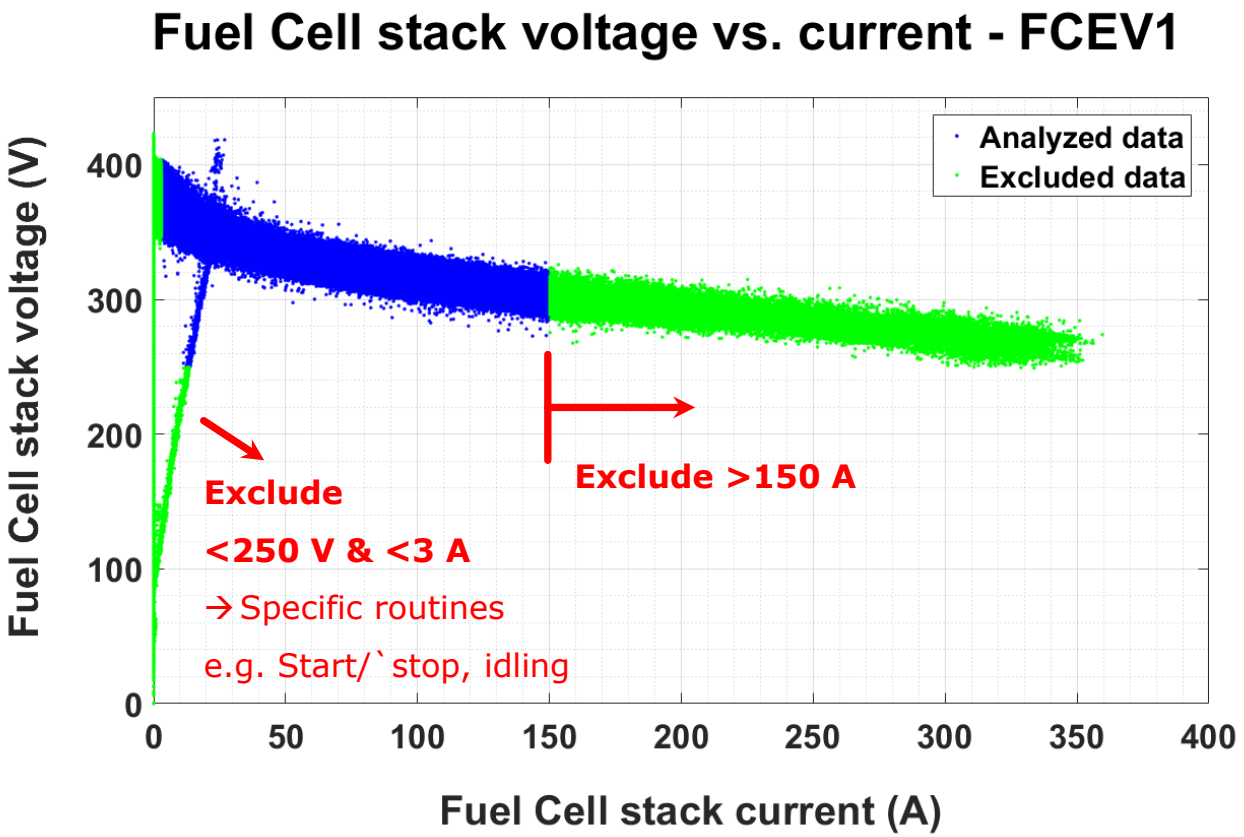
- **Mean Fuel Cell stack voltage drop:**

$$\overline{\Delta V_{\%}} = \frac{\sum_1^n \%V_{@current}}{\#\ currents}$$

Method


Fuel Cell stack voltage vs. current - FCEV1
Fuel Cell stack voltage (V)
400
300
200
100
0
Frequent operating
current range → 0-150 A → >90% of time
0
50
100
150
200
250
300
350
400
Fuel Cell stack current (A)

Method


Fuel Cell stack voltage vs. current - FCEV1
Fuel Cell stack voltage (V)
Fuel Cell stack current (A)
Analyzed data
Excluded data
Exclude
<250 V & <3 A
→ Specific routines
e.g. Start/`stop, idling
Exclude >150 A
0
100
200
300
400
0
50
100
150
200
250
300
350
400

Results

- Results of the voltage drop shows similar results for:
  - **Voltage drop vs.**
    - **Operating time**
    - Produced energy
  - **Least squares regression analysis methods:**
    - **Linear**
    - Robust linear

Results

	FCEV1	FCEV2	FCEV3	FCEV2G
FC stack voltage drop (%) - Mean	1.7%	2.0%	1.4%	**2.3%**

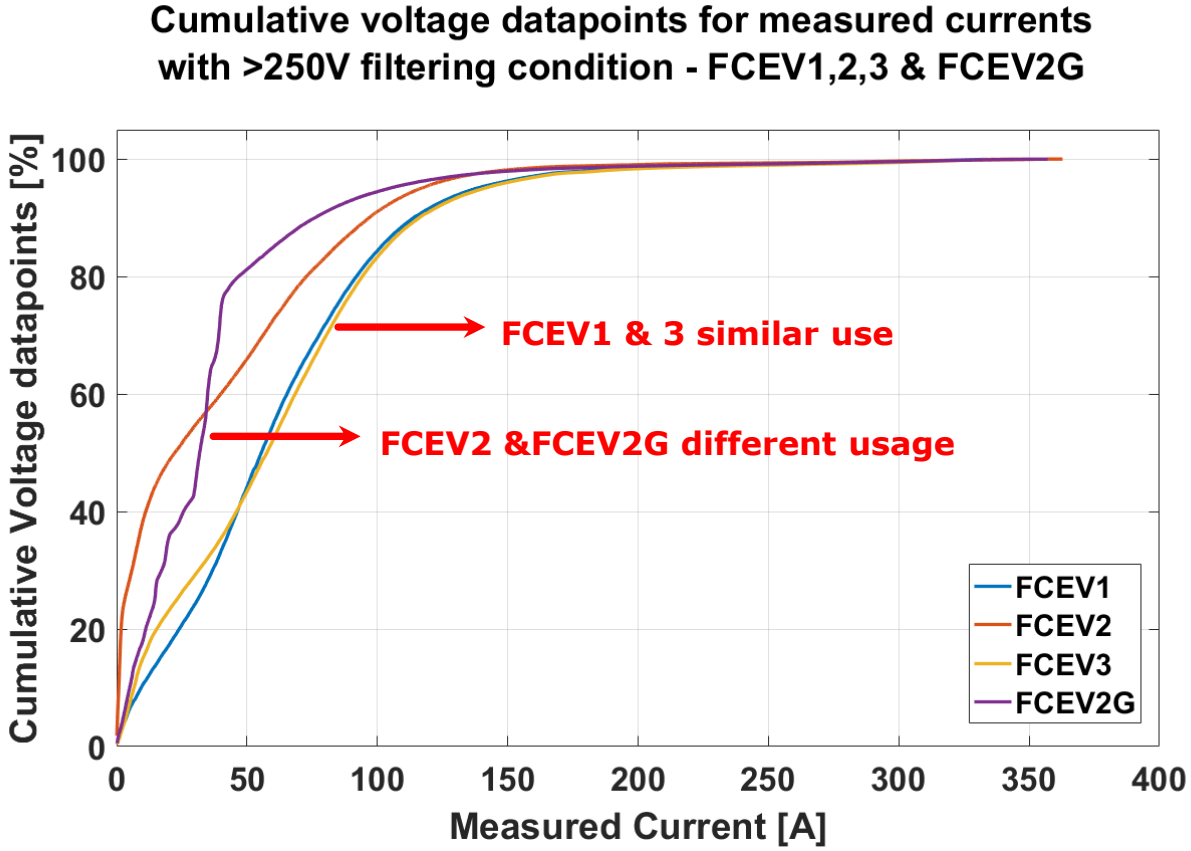
Results

Estimated durability @ 10% Mean FC Voltage drop Based on:	FCEV1	FCEV2	FCEV3	FCEV2G
FC operating time (h)	2,550	920	2,250	3,710
Distance driven (km)	164,700	39,800	129,000	53,900
Fuel cell produced electricity (kWh)	35,000	9,500	30,900	18,600

- FCEV1, FCEV3 & FCEV2G estimated durability in hours in line with U.S. DOE FC Durability study[1]
- FCEV1 estimated durability 920h very low → voltage drop with high standard deviation
- Durability indicator distance driven → relevant for driving only use.
- FC produced electricity consistent for FCEV1&3, low for FCEV2G (high zero current time)

[1]) DOE Hydrogen and Fuel Cell Technologies Program Records #16019 - On-Road Fuel Cell Stack Durability – 2016

Results


Cumulative voltage datapoints for measured currents with >250V filtering condition - FCEV1,2,3 & FCEV2G
Cumulative Voltage datapoints [%]
Measured Current [A]
0
20
40
60
80
100
0
50
100
150
200
250
300
350
400
FCEV1 & 3 similar use
FCEV2 &FCEV2G different usage
FCEV1
FCEV2
FCEV3
FCEV2G

Conclusions

- **Research question:**

How can we analyze fuel cell stack voltage degradation

& are existing durability indicators still relevant in commercial FCEVs,

used for driving and vehicle-to-grid purposes?

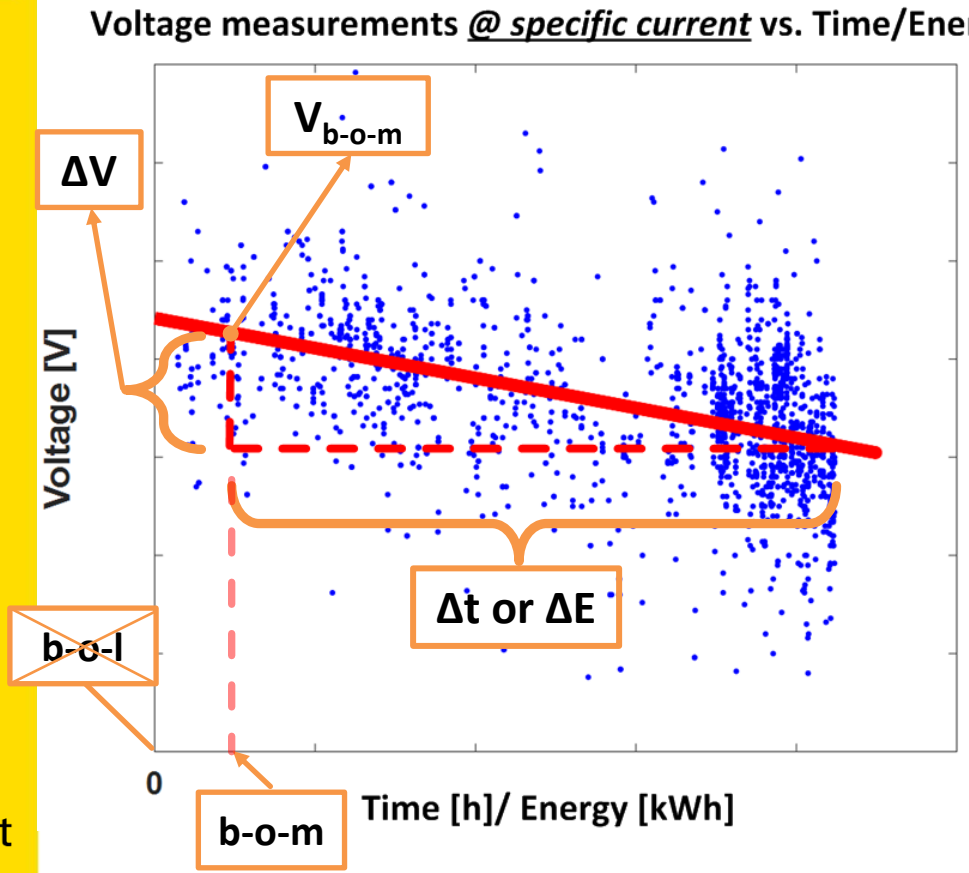
- Developed method works, but accuracy sensitive to:
- Amount of datapoints
- Non-uniform distribution of data → use of weight factor?
- Voltage drop similar for analysis based on operating time/energy or different regression methods
- Durability parameter operating hours/distance/energy not relevant for driving & V2G usage
- Suggestion; combination of operating & 'idling' hours, energy, distance, #start-ups/shutdowns.
  - Relevant for pricing V2G services, maintenance schedule
- Compare use based on detailed load pattern analysis (e.g. upward/donward ramps)

Acknowledgements

- Netherlands Organisation for Scientific Research (NWO) [Program 'Uncertainty Reduction in Smart Energy Systems (URSES)', Project number 408-13-001]
- Gasterra b.v.
- Hyundai Motor Netherlands
- Hyundai Motor Europe
- Hyundai Motor Company
- Rijkswaterstaat
- Gemeente Arnhem
- HAN University of Applied Sciences

Any questions?

Method

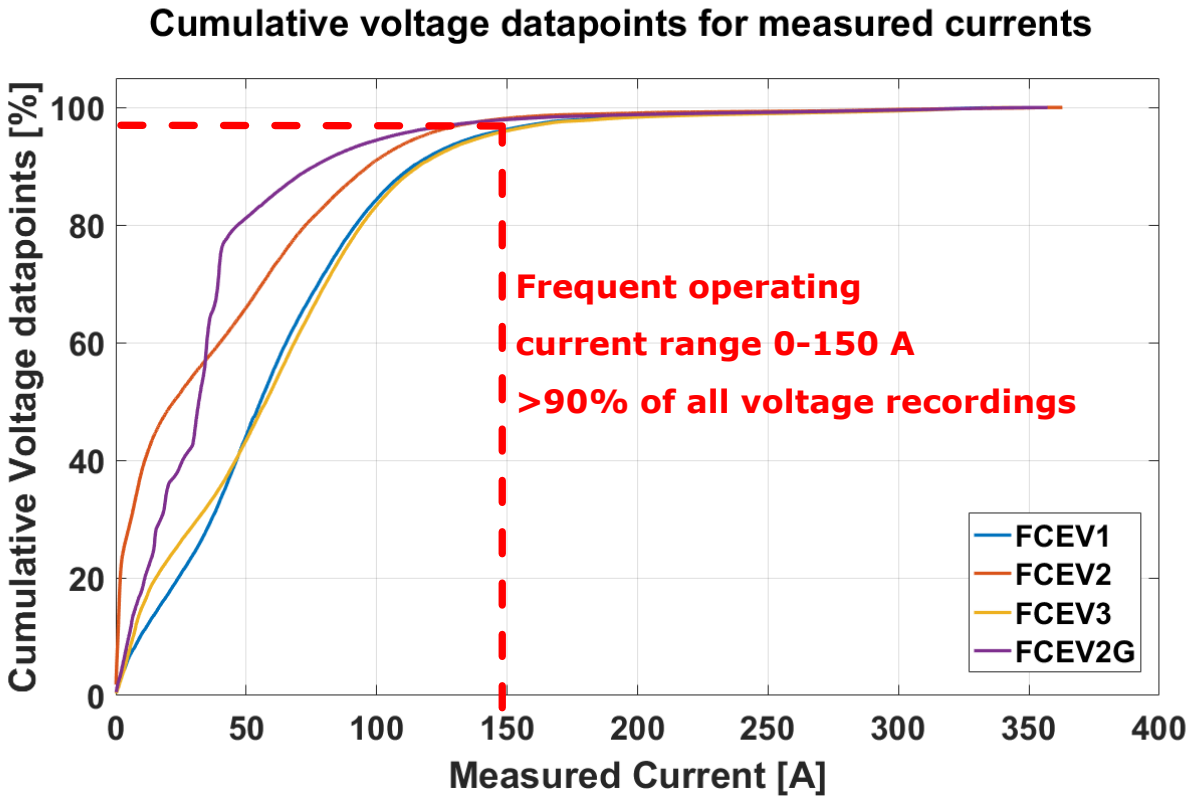


- Fuel cell stack voltage drop for specific current vs. begin-of-measurement (b-o-m)
- **NOT** begin-of-life (b-o-l)

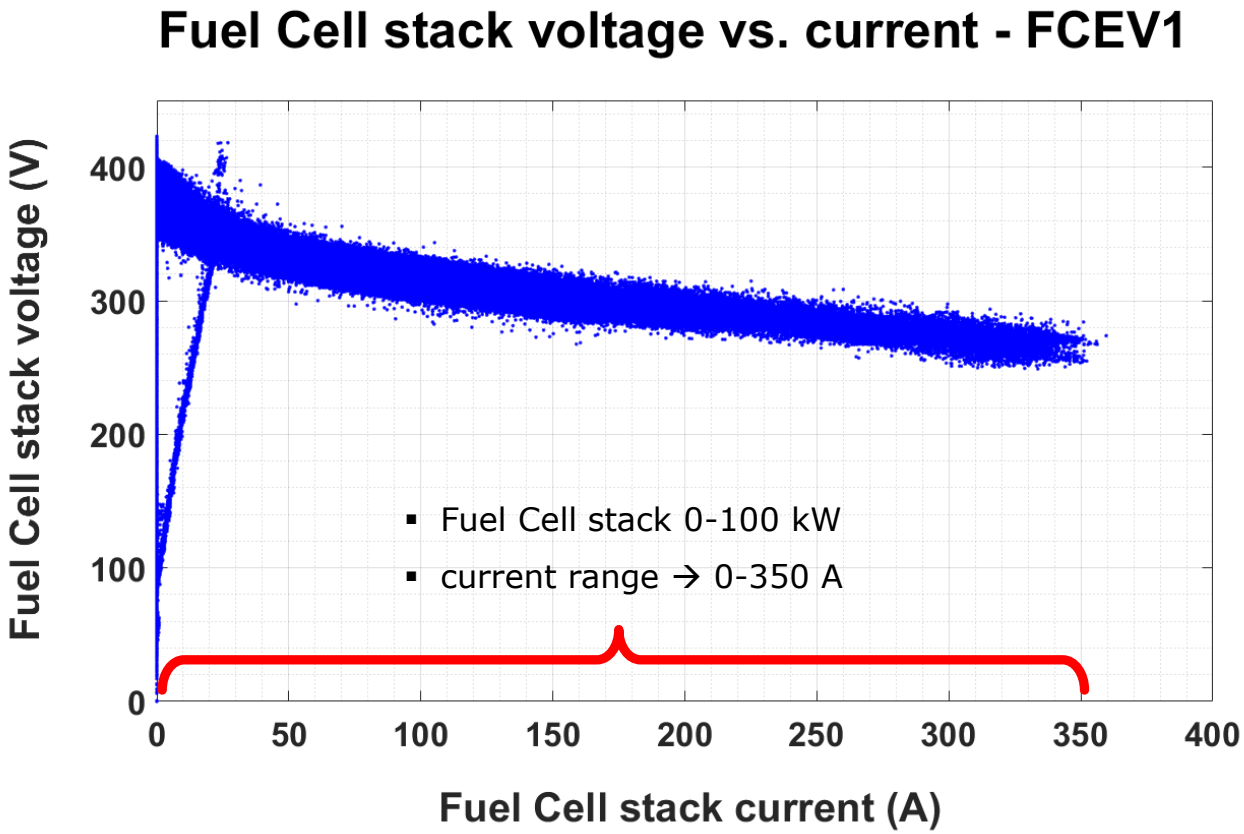
- **Voltage vs. Time @ specific current**
- $V(t)=V_{b\text{-}o\text{-}m} - \Delta V/\Delta t \times \Delta t$

- **Voltage vs. Energy @ specific current**
- $V(E)=V_{b\text{-}o\text{-}m} - \Delta V/\Delta E \times \Delta E$

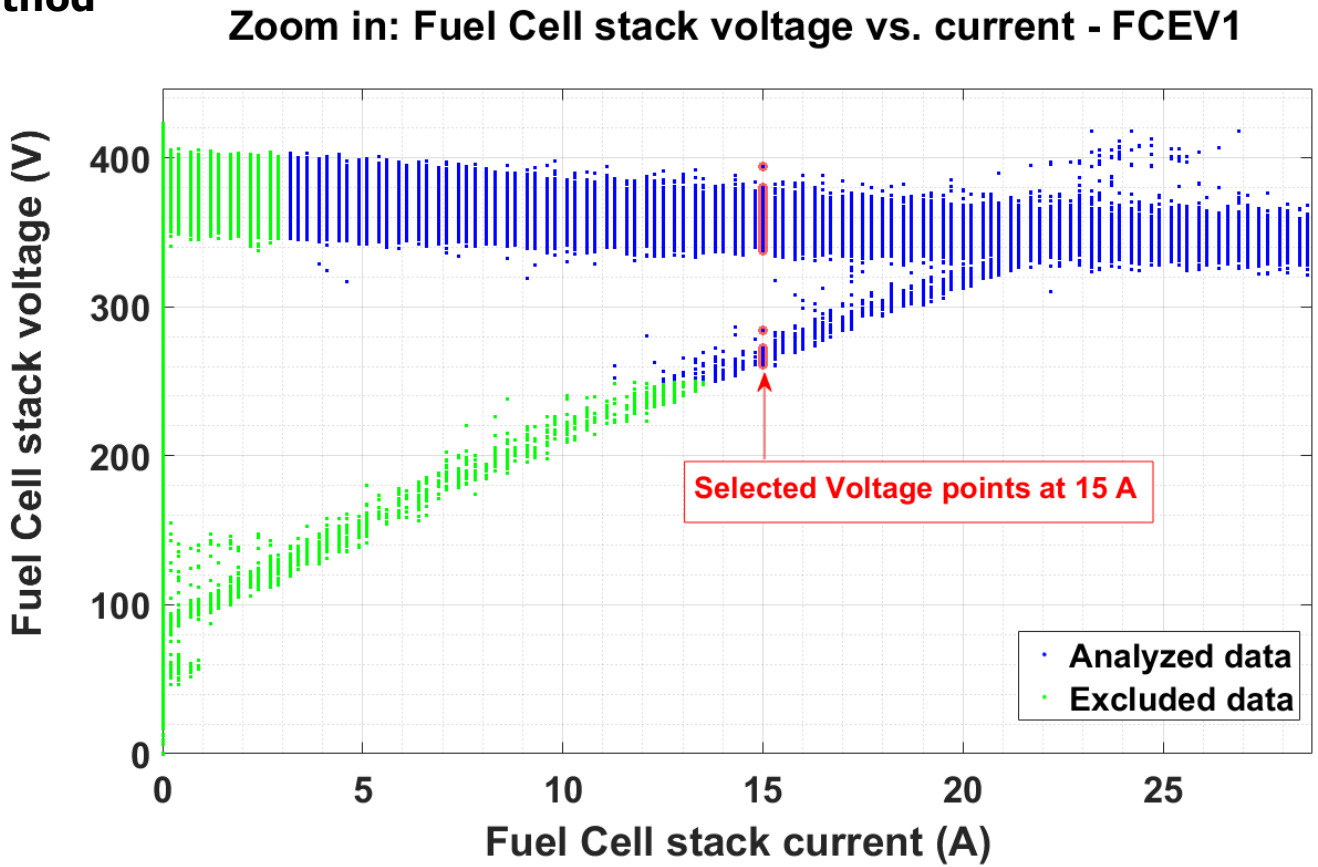
Method


Cumulative voltage datapoints for measured currents
Cumulative Voltage datapoints [%]
Measured Current [A]
0
20
40
60
80
100
0
50
100
150
200
250
300
350
400
Frequent operating
current range 0-150 A
>90% of all voltage recordings
FCEV1
FCEV2
FCEV3
FCEV2G

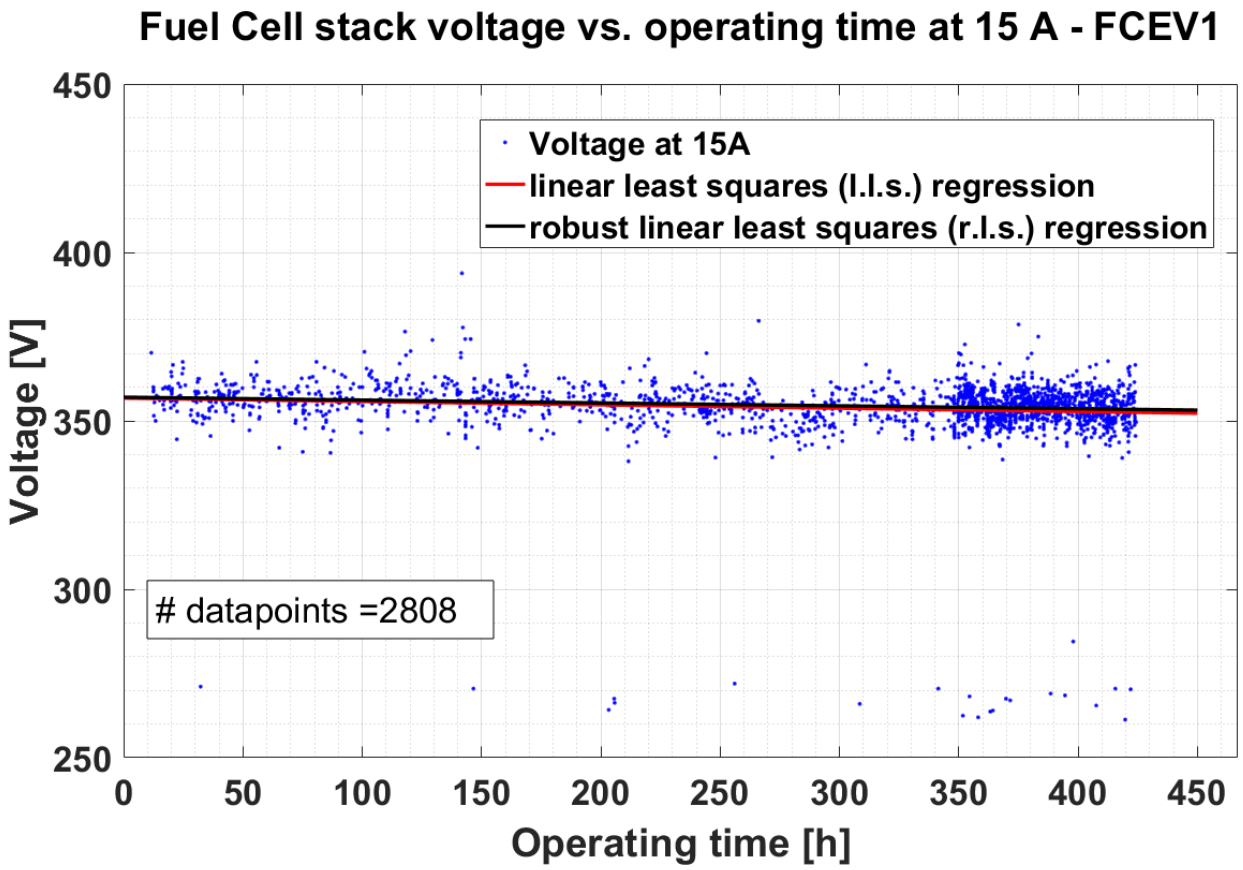
Method


Fuel Cell stack voltage vs. current - FCEV1
Fuel Cell stack voltage (V)
0
100
200
300
400
0
50
100
150
200
250
300
350
400
Fuel Cell stack current (A)
▪ Fuel Cell stack 0-100 kW
▪ current range → 0-350 A

Method


Zoom in: Fuel Cell stack voltage vs. current - FCEV1
Fuel Cell stack voltage (V)
400
300
200
100
0
0
5
10
15
20
25
Fuel Cell stack current (A)
Selected Voltage points at 15 A
Analyzed data
Excluded data

Method


Fuel Cell stack voltage vs. operating time at 15 A - FCEV1
Voltage at 15A
linear least squares (l.l.s.) regression
robust linear least squares (r.l.s.) regression
datapoints =2808
Voltage [V]
Operating time [h]
450
400
350
300
250
0
50
100
150
200
250
300
350
400
450

Results

	FCEV1	FCEV2	FCEV3	FCEV2G
FC stack voltage drop (%) - Mean	1.7%	2.0%	1.4%	2.3%
Distance (km) (before datalogger installation)	16,276	4,924	**22,875**	6,299
Distance (km) (after datalogger installation)	27,459	7,917	18,004	12,649
Analyzed FC operating time (h) (incl. zero current)	424	184	314	872
Gross FC produced electricity (kWh)	5,610	1,970	4,230	4,487
Average FC Power (kW)	**13**	11	**13**	5
Estimated durability @ 10% Mean FC Voltage drop				
FC operating time (h)	2,550	920	2250	3,710
Distance driven (km)	164,700	39,800	129,000	53,900
Fuel cell produced electricity (kWh)	35,000	9,500	30,900	18,600