

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

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Summary

How can we analyse fuel cell stack voltage degradation with transient phenomena and are existing durability indicators as distance driven or operating hours still relevant in commercial FCEVs, used for driving and vehicle-to-grid (V2G) purposes? The mean stack voltage drop is measured over fuel cell operating time and produced electricity in 4 commercial Hyundai ix35 FCEVs. The experiments show that a durability indicator expressed solely in operating hours, distance or produced energy is not relevant for combined driving, V2G and idling load profiles. An indicator consisting of several usage parameters is recommended.

Keywords: fuel cell vehicle, hydrogen vehicle, V2G (vehicle to grid), cycle life

1 Introduction

The United States Department of Energy (DOE) increased recently the automotive fuel cell ultimate durability target to 8,000 hours at 10% voltage degradation [1], comparable to 150,000 miles on a lower average speed drive cycle [1]. Cumulative produced energy is suggested as durability indicator [2] for automotive fuel cells operating under highly variable loads affecting durability [3,4].

Variable load profiles can be categorized in transient loadings, zero-current ('idling/spinning reserve'), high and low power and number of startup/shutdowns [3,4].

Fuel Cell Electric Vehicles (FCEVs) with a 100kW fuel cell [5] can also be used for power supply to the electricity grid up to 10 kW when parked, so called 'Vehicle-to-Grid' (V2G) [6] (Figure 1). In V2G mode, durability expressed as driven distance is not relevant as the car is parked. Durability expressed as cumulative produced energy when functioning as so called 'spinning reserve', is also not relevant as no power is produced. Questionable is if the number of operating hours or distance driven still is a useful durability indicator.

Real stack voltage is measured from four commercial FCEVs used for driving and V2G purposes. Real usage data contains transient phenomena. Filtering, noise removal and fitting algorithms could help in defining voltage degradation [3]. Summarizing, how can we analyze fuel cell stack voltage degradation with transient phenomena and are existing durability indicators as distance driven or operating hours still relevant in commercial FCEVs, used for driving and vehicle-to-grid purposes?



Figure 1: Experimental Fuel Cell Electric Vehicle-to-Grid (FCEV2G) 10kW set-up at Delft University of Technology.

2 Method and Materials

2.1 Materials

Fuel Cell (FC) operating voltage, current, driving speed and other parameters in four commercial Hyundai ix35 FCEVs [5] are measured at a frequency in the range of 1 to 5 Hz by CAN bus data loggers. Three FCEVs (labelled FCEV1 to FCEV3) are used solely for driving and one FCEV (labelled FCEV2G) is used for driving and V2G purposes (Figure 1). MATLAB® was used to analyse the recorded data. It is assumed all FCEVs are built during the same period and have the same age.

2.2 Method

The data loggers were installed after a certain driven distance, therefore a linear degradation trend is assumed [7]. The voltage drop is measured over fuel cell operating time and produced electricity. The mean stack voltage drop is expressed in percentages relative to the fitted begin-of-measurement (b-o-m) voltage at measured zero operating time or zero cumulative produced electricity. This also explains that the measured voltage drop is relative to the begin-of-measurement (b-o-m) voltage, instead of the begin-of-life (b-o-l) voltage. This method is based on [7], together with filtering conditions, data exclusion and two types of linear least squares regression analysis and applied to all 4 FCEVs.

2.3 Filtering conditions and excluded data

Figure 2 to Figure 4 serve as an illustrative example for the voltage and current data filtering and exclusion for FCEV1.

The voltage measurements recorded at currents below 3 A and above 150 A are excluded (Figure 2). The lower threshold of 3 A is equal to the maximum global offset current of the fuel cell stack current sensor [8]. Voltage measurements at the upper threshold of 150 A result mainly from infrequent, irregular and transient phenomena. Fuel Cell gross electric power at 150 A is at least 40 kW. Power above 40 kW mainly occurs in harsh acceleration and lasts only several seconds. 40 kW of continuous power corresponds to cruising speeds of 130 km/h or higher on a flat road, which is allowed in the Netherlands. As the cars are primarily used on flat Dutch roads, where the speed limit is 130 km/h on a limited number of highways, often only during night time. The < 3 A and > 150 A filtering conditions results in an approximately 8.0 % data loss (Figure 3) for FCEV1.

Voltages below 250V for currents of 0-150A are excluded, as they originate from transient phenomena, specific idling and shutdown routines (Figure 2). The <250 V filtering condition together with the < 3 A and >150 A filtering condition combined result in an approximately 8.0 % data loss (Figure 3) for FCEV1. Due to overlap of both filtering conditions the data loss has not significantly increased by applying the <250V filtering condition.

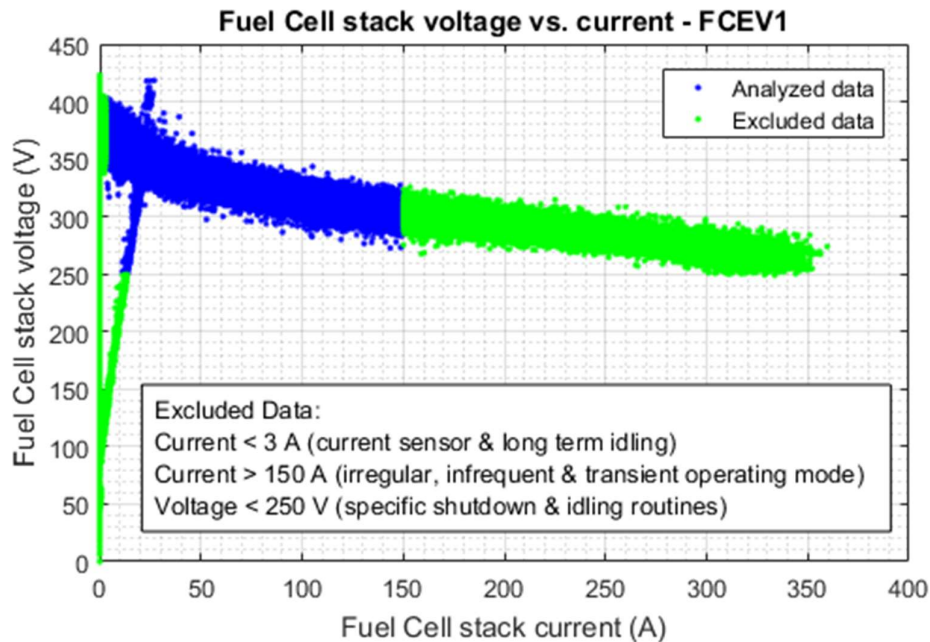


Figure 2: Fuel Cell stack voltage vs. current for FCEV1. The blue and green data points represent the analysed and excluded data respectively.

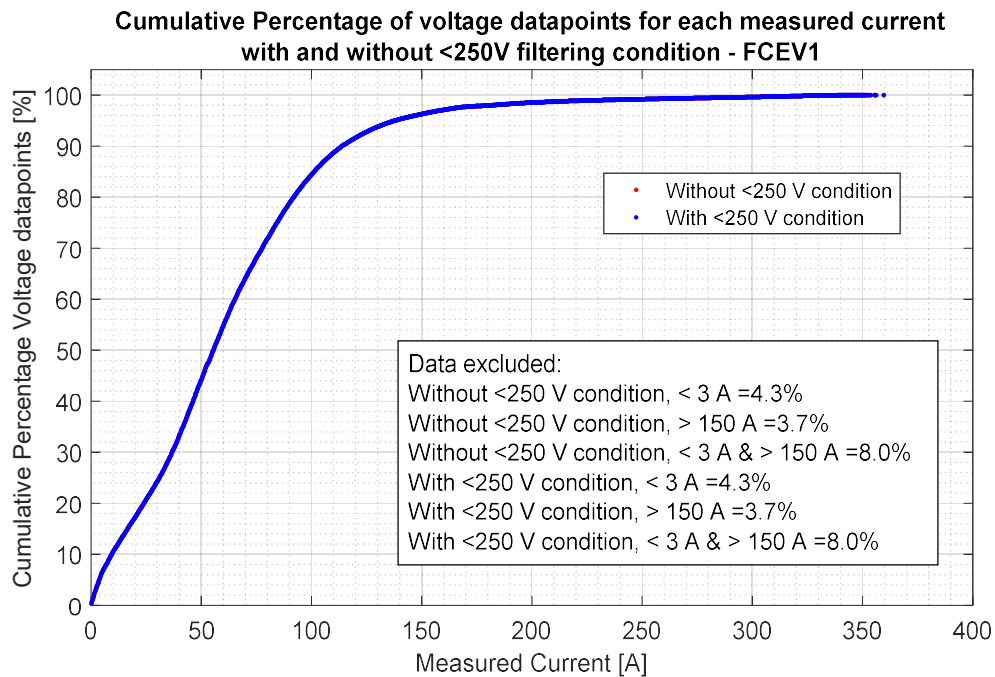


Figure 3: Cumulative percentage of voltage data points for each measured current before and after applying the <250V filtering condition for the data of FCEV1 including the approximate data loss for filtering conditions. The plotted cumulative percentage without the <250V filtering (red) condition is underneath the cumulative percentage with <250V filtering condition (blue).

Figure 4 shows the number of voltage data points for each measured current after applying the <250V filtering condition for FCEV1. Currents higher than 150A contain relatively low number of voltage data points. Figure 5 shows the Weibull distribution of the number of voltage data points for all measured currents after applying the <250V condition for FCEV1 data. All measured currents with less than 10 voltage data points are discarded from the analysis, for the FCEV1 data this is approximately 3.3 % (Figure 5). The aforementioned filtering conditions have some overlap and the total percentage excluded data for all four analysed FCEVs is listed in Table 1. The total excluded current data points is approximately 60% for all 4 FCEVs. Total excluded voltage data points for FCEV1, FCEV3 and FCEV2G is approximately 8%. Whereas for FCEV2 this is 34%. Figure 9 in the results and discussion section shows that FCEV2 has relatively more data points in the low current region than the other cars.

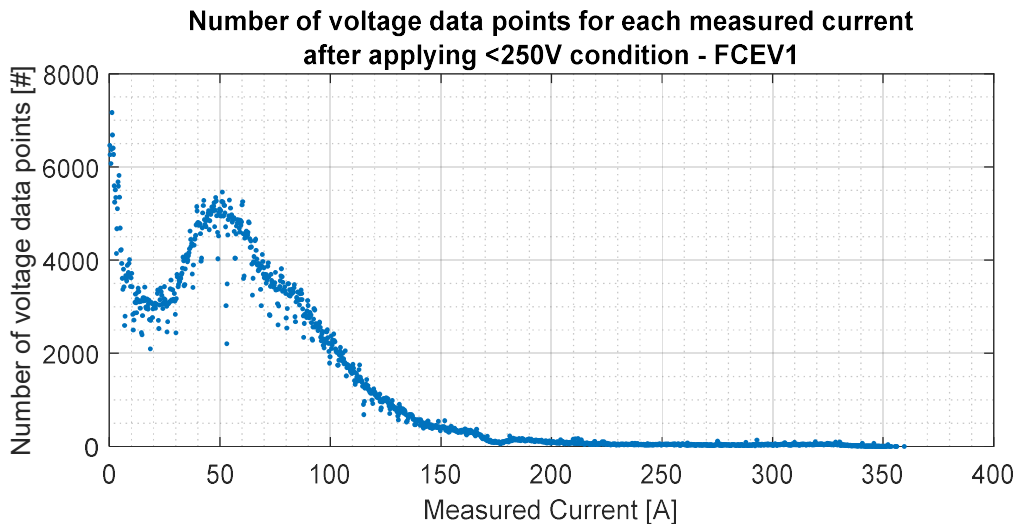


Figure 4: Number of voltage data points for each measured current after applying the <250V filtering condition for FCEV1.

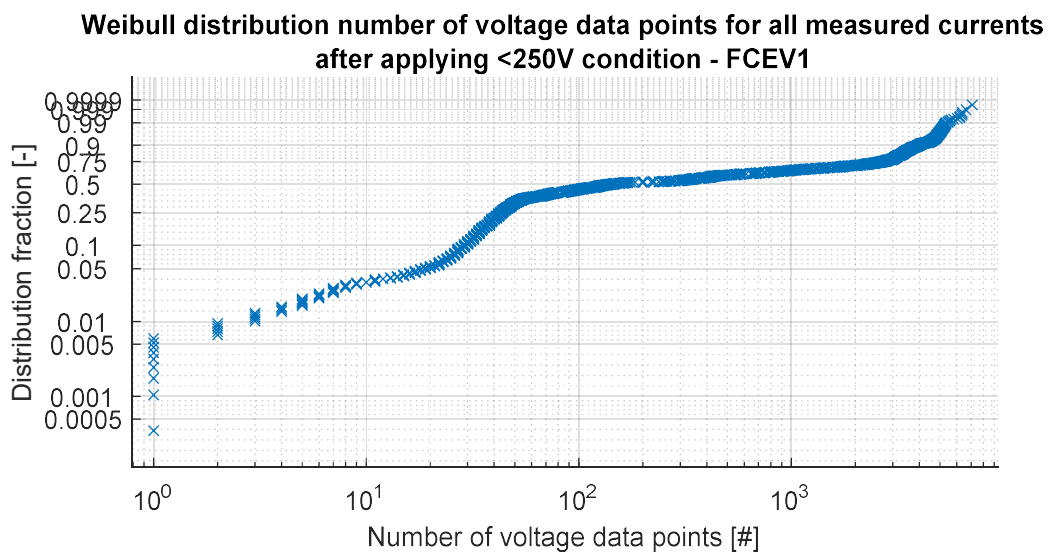


Figure 5: Weibull distribution of the number of voltage data points for all measured currents after applying the <250V filtering condition for FCEV1.

Table 1: Total excluded current and voltage data points after applying all filtering conditions

	FCEV1	FCEV2	FCEV3	FCEV2G
Total excluded current data points (%)	58	58	58	59
Total excluded voltage data points (%)	8	34	8	8

2.4 Regression analysis and mean stack voltage drop

A linear least squares (l.l.s.) and robust linear least squares (r.l.s.) regression analysis is used [9]. The latter aims to reduce the influence of outliers resulting from measurements in transient phenomena [9]. For every considered and measured current, the corresponding voltage data points (Figure 6) are plotted versus fuel cell operating time (Figure 7) and cumulative produced electricity (Figure 8). Figure 6-Figure 8 serve as an illustrative example for the voltage data regression analysis at 15 A for FCEV1. Both linear least squares regression methods are applied and a first order polynomial (Equations 1 and 2) are used to fit the data [7].

$$V_{XXA@t}(t) = V_{XXA@t=0} - a_{XXA@E} \times t(h) \quad (1)$$

Where $V_{XXA@t}(t)$ is the Fuel cell stack voltage as a function of operating time in hours, $t(h)$, at a specific current. $a_{XXA@t}$ is the fuel cell stack degradation in voltage per hour (V/h) at a specific current. $V_{XXA@t=0}$ is the fitted fuel cell stack voltage at operating time zero h at a specific current.

$$V_{XXA@E}(E) = V_{XXA@E=0} - a_{XXA@E} \times E(kWh) \quad (2)$$

Where $V_{XXA@E}(E)$ is the Fuel cell stack voltage as a function of cumulative produced electricity in kWh, $E(kWh)$, at a specific current. $a_{XXA@E}$ is the fuel cell stack degradation in millivoltage per kWh (mV/kWh) at a specific current. $V_{XXA@E=0}$ is the fitted fuel cell stack voltage at zero cumulative produced electricity at a specific current.

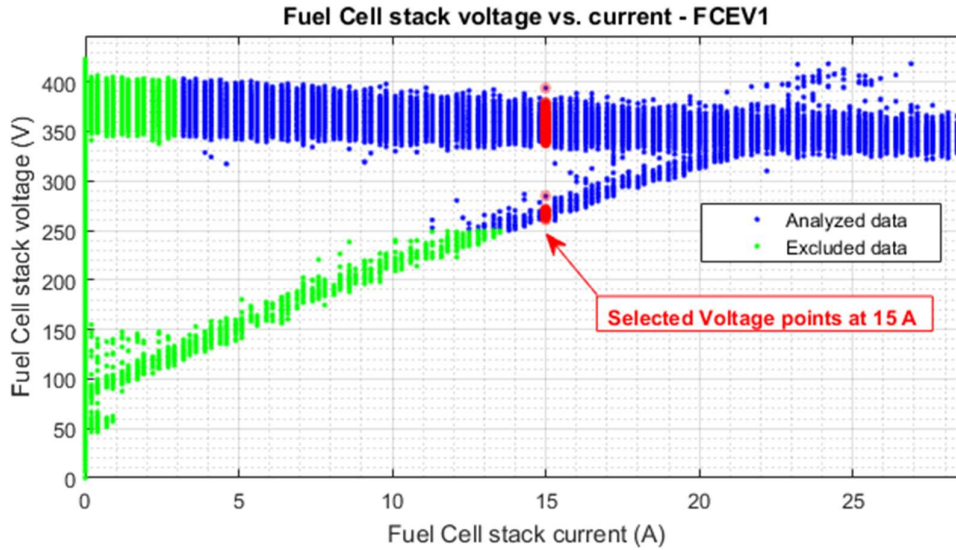


Figure 6: Fuel Cell stack voltage vs. current for FCEV1 zoomed into 0-29 A region. The blue and green data points represent the analysed and excluded data respectively. The selected voltage data points at 15 A are displayed in red.

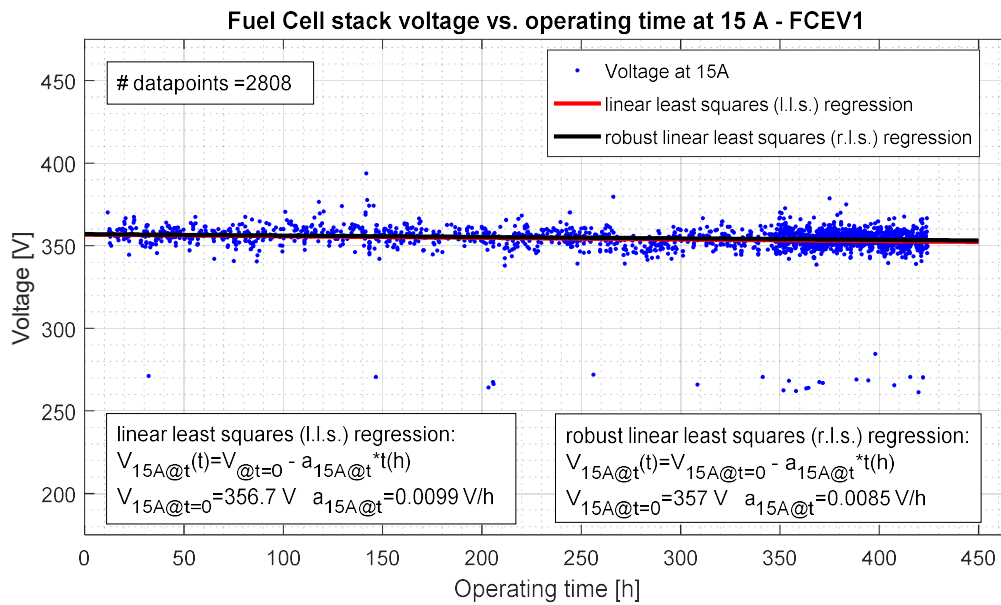


Figure 7: L.l.s. and r.l.s. regression analysis applied to Fuel Cell stack voltage vs. operating time at 15A for FCEV1.

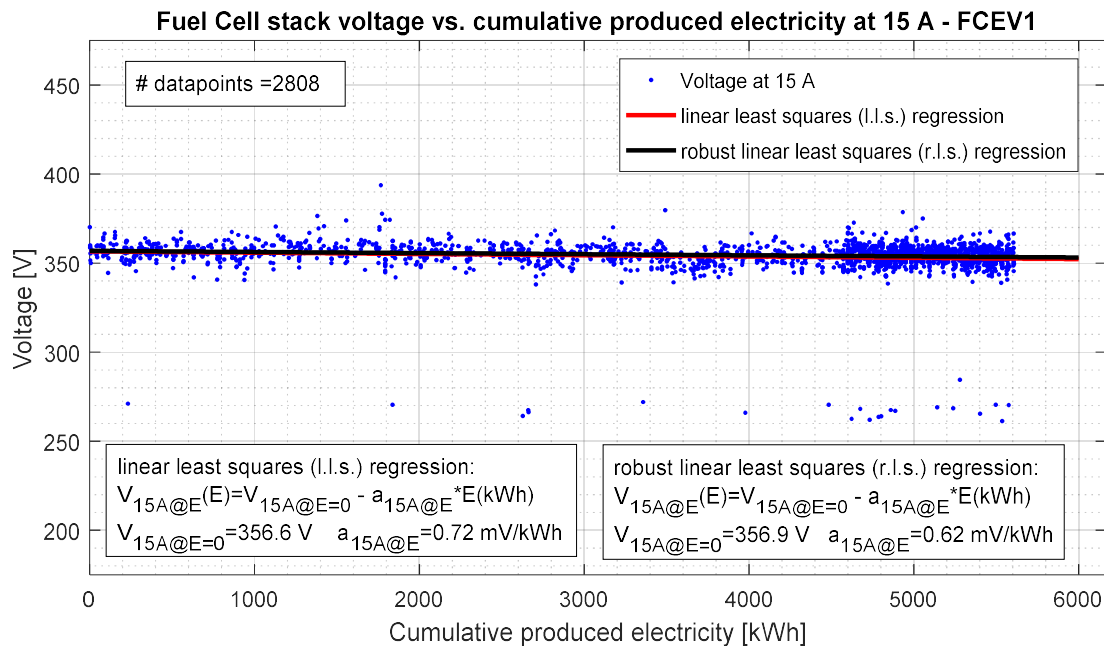


Figure 8: L.l.s. and r.l.s. regression analysis applied to Fuel Cell stack voltage vs. cumulative produced electricity at 15A for FCEV1.

The measured voltage drop is expressed in percentages relative to the fitted begin-of-measurement (b-o-m) voltage at zero operating time $\Delta V_{XAA@t}$ (equation 3) or zero cumulative produced electricity $\Delta V_{XAA@E}$ (equation 4).

$$\Delta V_{XAA@t} (\%) = \frac{a_{XAA@t} \times \max(t(h))}{V_{XAA@t=0}} \quad (3)$$

$$\Delta V_{XAA@E} (\%) = \frac{a_{XAA@E=0} \times \max(E(kWh))}{V_{XAA@E=0}} \quad (4)$$

3 Results & Discussion

Table 1 displays FCEV use indicators versus average % stack voltage drop compared to the b-o-m voltage for the considered current range using an l.l.s and r.l.s. regression analysis method based on fuel cell operating time and produced energy. The bold underlined values represent the maximum value in each row and could be an indicator for a relatively higher average % stack voltage drop. Table 1 displays results up till the 2nd quarter of 2017 for FCEV1, FCEV2 and FCEV2G, and up till 1st quarter of 2017 for FCEV3.

Table 2: Preliminary measurements and results of FCEV use indicators versus average % stack voltage drop compared to the b-o-m voltage for the considered current range using an l.l.s and r.l.s. regression analysis method.

	FCEV 1	FCEV 2	FCEV 3	FCEV2G
Distance driven before data-logger installation (km)	16276	4924	<u>22875</u>	6299
Distance driven after data-logger installation (km)	<u>27459</u>	7917	<u>18004</u>	12649
Number of Trips or number startup-shutdowns (#)	676	531	<u>1167</u>	1095
Operating time (h) (incl. zero current)	424	184	314	<u>872</u>
Total zero current time and 'idling/spinning reserve' (h)	138	28	98	<u>457</u>
Gross (Total) FC produced electricity (kWh) incl. V2G	<u>5610</u>	1970	4230	4487
Electricity delivered for V2G purposes (kWh)	0	0	0	<u>1620</u>
Average speed (km/h)	<u>65</u>	43	57	15
Standard deviation speed (km/h)	42	<u>42</u>	41	32
Average speed excluding idling time (km/h)	<u>76</u>	60	68	61
Standard deviation speed excluding idling time (km/h)	35	<u>38</u>	36	36
Average FC Power (kW)	13	11	<u>13</u>	5
Standard deviation FC Power (kW)	14	14	<u>15</u>	10
Average FC power excluding idling time (kW)	20	13	<u>20</u>	11
Standard deviation FC power excluding idling time (kW)	13	14	<u>14</u>	12
<u>% Stack voltage drop relative to b-o-m based on:</u>				
Operating time (l.l.s) - Mean	1.7%	2.0%	1.4%	<u>2.3%</u>
Operating time (l.l.s) - Standard deviation	0.5%	0.7%	0.3%	<u>0.8%</u>
Operating time (l.l.s) - Relative standard deviation	27%	<u>35%</u>	21%	34%
Operating time (r.l.s) - Mean	1.7%	2.0%	1.4%	<u>2.5%</u>
Operating time (r.l.s) - Standard deviation	0.5%	0.7%	0.3%	<u>0.8%</u>
Operating time (r.l.s) - Relative standard deviation	27%	<u>35%</u>	21%	34%
Cumulative electricity (l.l.s) - Mean	1.6%	2.1%	1.4%	<u>2.4%</u>
Cumulative electricity (l.l.s) - Standard deviation	0.4%	0.8%	0.3%	<u>0.9%</u>
Cumulative electricity (l.l.s) - Relative standard deviation	27%	37%	21%	<u>38%</u>
Cumulative electricity (r.l.s) - Mean	1.6%	2.1%	1.4%	<u>2.6%</u>
Cumulative electricity (r.l.s) - Standard deviation	0.4%	0.8%	0.3%	<u>1.0%</u>
Cumulative electricity (r.l.s) - Relative standard deviation	27%	<u>37%</u>	20%	37%

The percentage stack voltage drop relative to the begin-of-measurement is between 1.4% and 2.6% for all cars throughout all types of regression methods on a fuel cell operating time basis as well as produced electricity basis. For every FCEV the mean, standard deviation and relative standard deviation show consistent values throughout all types of regression methods on a fuel cell operating time basis as well as produced electricity basis.

Average stack voltage drop is the largest for FCEV2G and also shows the largest difference for the two regression analysis algorithms applied, 2.3% and 2.5% on an operating hour basis and 2.4% and 2.6% on a produced electricity basis. This can be an indication that a relative larger number of measurements were performed in transient phenomena [9]. FCEV2G shows low average speed and FC Power, resulting from several long term ‘spinning reserve’ tests with minimal or no power production, also highly contributing to the total zero current time. Possible reason for the highest average stack voltage drop could be the high number of operating and zero current hours [3,4]. Also FCEV2G has the 2nd highest Gross (Total) FC produced electricity and number of start-up-shutdowns. Average stack voltage drop for FCEV1 and FCEV3 is approximately 1.6% and 1.4%. The measured driven kilometres, operating hours and produced electricity is higher for FCEV1 than for FCEV3 and could be an explanation. FCEV3 has significantly more start-ups and shutdowns. FCEV2 show a relative high mean stack voltage drop when comparing the driven kilometres, operating hours, produced electricity and start-ups and shutdowns.

Both FCEV2 and FCEV2G have high standard deviations compared to FCEV1 and FCEV3. This can possibly explained by the different fuel cell use when compared to FCEV1 and FCEV3. Figure 9 shows the cumulative percentage of voltage data points for each measured current after applying the <250V filtering condition. Both FCEV1 and FCEV2G have relatively a lot more data points in the low current region. For FCEV1 65% of the voltage data points are for currents lower than 50A, for FCEV2G this is 80%. Obviously for FCEV2G this is due to the V2G electricity production, which is limited at 10kW, corresponding to currents lower than 50A. The majority of V2G test where performed at 10kW and in a lesser extent at 3 kW, this is indicated clearly by the sharp increase in the 25-40A region. FCEV2 is only used for driving and has no V2G option. The average speed of FCEV2 is lower than FCEV1 and FCEV3, which explains the high number of voltage data points below 50A region.

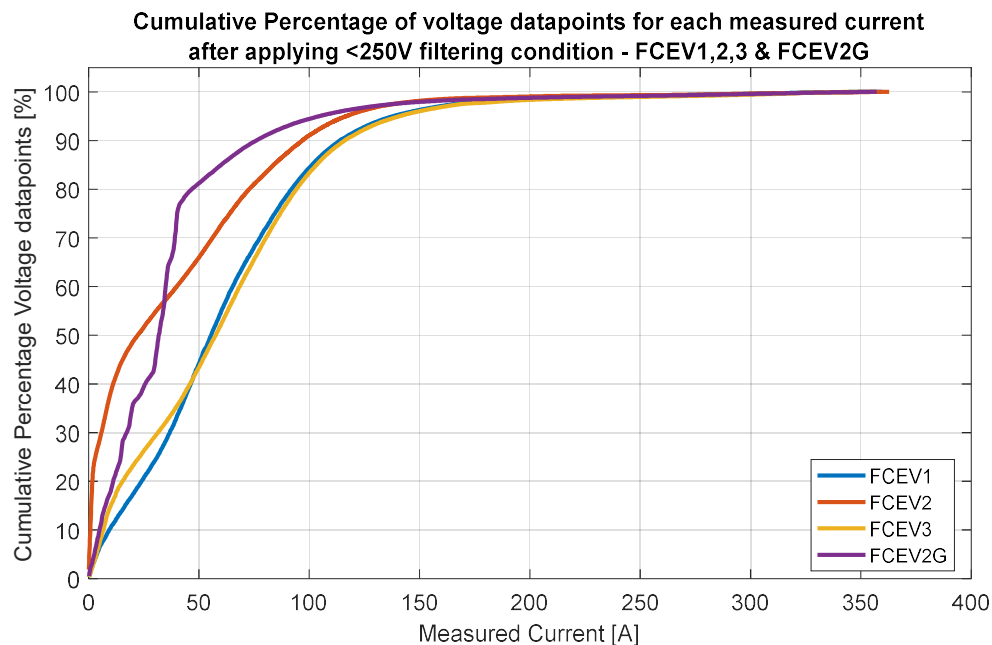


Figure 9: cumulative percentage of voltage data points for each measured current after applying the <250V filtering condition

Both FCEV2 and FCEV2G have relatively higher standard deviations, 0.7% and 0.9%, when compared to FCEV1 and FCEV3 0.4% and 0.3%. The relative standard deviation for FCEV2 and FCEV2G is between 34% and 38% whereas for FCEV1 and FCEV3 this is between 21% and 27% respectively. Aforementioned high share of data points in the low current region could be a reason for this. FCEV2 has the lowest usage compared to all cars and so has generated also the fewest data points, of which the majority is in the 0-50 current region. Further analysis at higher usage or comparing a partial dataset of FCEV1 and FCEV3 could provide more insight on the effect of the total number of data points or the effect of data points in specific current regions. Applying a weight factor to the voltage data points based on the number of data points per current could possibly reduce the standard deviation and relative standard deviation of the calculated mean voltage drop. Also increasing the minimum voltage data points of 10 or changing the upper current threshold of 150 A could have an effect on the standard and relative standard deviation.

Using the mean stack voltage drops from the time based l.l.s. regression analysis and assuming a linear degradation trend at a maximum allowable mean voltage drop of 10% [1], the durabilities expressed in kilometers, hours and electricity produced can be estimated (Table 3). This would result in estimated durabilities of 2550h, 920h, 2250h and 3710h for respectively FCEV 1-3 and FCEV2G (Table 3), of which FCEV 1, FCEV2 and FCEV2G are comparable with DOE results when compared on a fuel cell operating time basis [1]. For FCEV1 the estimated durability of 920 is very low, but is also based on the mean stack voltage drop with high standard and relative standard deviation. The durability indicator driven distance, only makes sense for driving only cars. Also the durability indicator fuel cell produced electricity seems relatively consistent for FCEV1 and FCEV3, but is approximately 50% lower for FCEV2G due to the high total zero current time and ‘idling/spinning reserve’ where the fuel cell system is operating but not producing any electricity. A durability indicator expressed solely in operating hours, distance or produced energy is not relevant for combined driving and V2G load profiles. An indicator consisting of several usage parameters is recommended, but could require extensive and long term testing under real circumstances or other measurement techniques. Some suggested combination of parameters, but not limited to, are the operating and ‘idling’ hours, produced energy, driven distance, number of start-ups and shutdowns.

Table 3 Estimated durabilities expressed in hours, distance driven and electricity produced. Using the average voltage drops from the time based l.l.s. regression analysis and assuming a linear degradation trend at a maximum allowable mean voltage drop of 10% [1].

Estimated durability in:	FCEV 1	FCEV 2	FCEV 3	FCEV2G
Fuel cell operating time (h)	2550	920	2250	3710
Distance driven (km)	164700	39800	129000	53900
Fuel cell produced electricity (kWh)	35000	9500	30900	18600

4 Conclusion

How can we analyse fuel cell stack voltage degradation with transient phenomena and are existing durability indicators as distance driven or operating hours still relevant in commercial FCEVs, used for driving and vehicle-to-grid (V2G) purposes? The mean stack voltage drop is measured over fuel cell operating time and produced electricity in 4 commercial Hyundai ix35 FCEVs. Using only voltage data in the 3-150 A current range at voltages above 250V and with a minimum of 10 datapoints per analysed current. Both a linear and robust linear least squares regression analysis are applied to the voltage data.

Fuel cell stack current and voltage are recorded in three FCEVs used for driving only and one FCEV used in both driving as well as V2G mode. Between 7900 and 27500 kilometers, 184 and 872 fuel cell operating hours, 1970 and 5610 kWh fuel cell produced electricity and 530 and 1170 startup and shutdowns are recorded in all 4 FCEVs during the analysed period.

For every FCEV the mean, standard deviation and relative standard deviation show consistent values throughout all types of regression methods on a fuel cell operating time basis as well as produced electricity basis. The percentage stack voltage drop relative to the begin-of-measurement is 1.4% and 2.6% for all FCEVs for all types of regression methods, both on a fuel cell operating time basis as well as produced electricity basis. For two FCEVs driven 18000 and 27500 km (314 and 424 operating hours), the mean stack voltage drop is 1.4% and 1.7% with a standard deviation of 0.3% and 0.4%. The relative standard

deviation is 21% and 27%. For the less driven FCEV, 7900km (184 operating hours), the mean stack voltage drop with 2.0% is relatively high compared to the other driven only FCEVs. The same FCEV also has a relative high standard deviation of 0.7% and relative standard deviation of 38%, which could be attributed to the relative low usage. Also the relative high usage in the low fuel cell current range (0-50A) compared to the high current range (150-350A) could have an impact on the higher standard deviations. A similar trend is seen for the FCEV used for both driving and vehicle-to-grid purposes.

Applying a weight factor to the voltage data points based on the number of data points per current could possibly reduce the standard deviation and relative standard deviation of the calculated mean voltage drop. Also increasing the minimum threshold of number of voltage data points per analysed current (now 10) or changing the upper current threshold of 150 A could have an effect on the standard and relative standard deviation.

For two driving only FCEVs and the FCEV used for both driving and vehicle-to-grid purposes the average voltage drops compared to the operating hours are comparable with the DOE measured durability in hours. The durability indicator driven distance, only makes sense for driving only cars. The durability indicator produced electricity is very sensitive to the number of 'idling' or fuel cell zero current operating hours, as there is no electricity production during these operating hours.

A durability indicator expressed solely in operating hours, distance or produced energy is not relevant for combined driving and V2G load profiles. As for neither operating hours, driven distance nor produced energy, no clear correlation with average voltage drop is seen amongst all four FCEVs. An indicator consisting of several usage parameters is recommended, but could require extensive and long term testing under real circumstances or other measurement techniques. Some suggested combination of parameters, but not limited to, are the operating and 'idling' hours, produced energy, driven distance, number of start-ups and shutdowns.

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