AVL

Webinar starting soon:

The Toyota Mirai II

A serious competitor to state-of-the-art BEV´s?

Today’s Presenter

Wolfgang Fritz
Project Manager

Background:

- >25 years experience in the automotive industry at
- AVL (since 2014)
- Magna Steyr
- Volkswagen

AVL COMPANY PRESENTATION

AVL

Clean Affordable Mobility

AVL is the world’s largest independent technology partner for the development, simulation and testing of powertrain systems as well as innovative automotive solution concepts. For today and for the future.

Facts and Figures

Global Footprint

Represented in 26 countries

45 Affiliates divided over 93 locations

45 Global Tech and Engineering Centers (including Resident Offices)

1948
Founded

11,000
Employees Worldwide

12%
Of Turnover Invested in Inhouse R&D

70+
Years of Experience

65%
Engineers and Scientists

1,500
Granted Patents in Force

97%
Export Quota

Three Disciplines Under One Roof

ENGINEERING SERVICES

- Design and development services for all elements of ICE, HEV, BEV and FCEV powertrain systems
- System integration into vehicle, stationary or marine applications
- Supporting future technologies in areas such as ADAS and Autonomous Driving
- Technical and engineering centers around the globe

INSTRUMENTATION AND TEST SYSTEMS

- Advanced and accurate simulation and testing solutions for every aspect of the powertrain development process
- Seamless integration of the latest simulation, automation and testing technologies
- Pushing key tasks to the start of development

ADVANCED SIMULATION TECHNOLOGIES

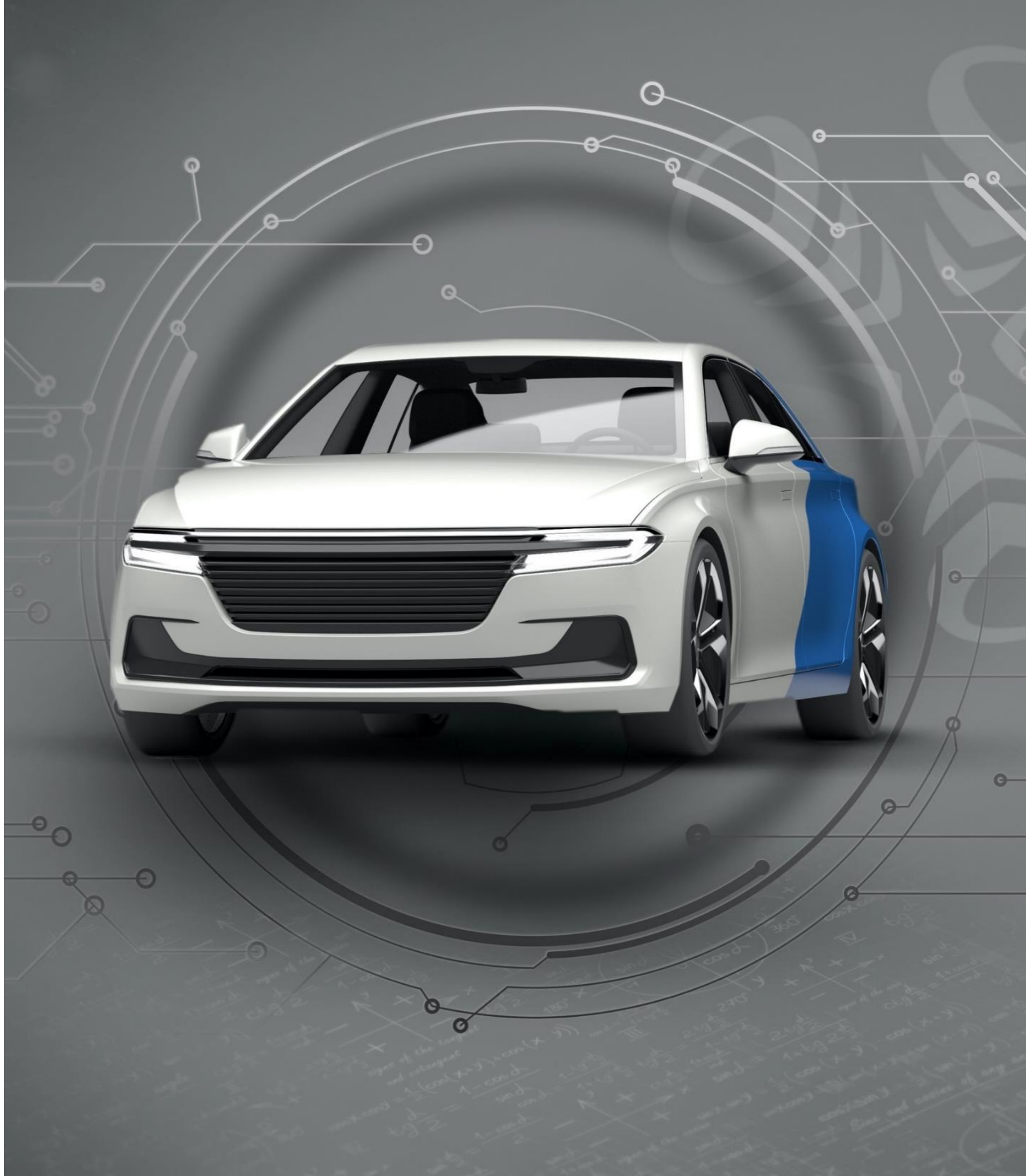
- We are a proven partner in delivering efficiency gains with the help of virtualization
- Simulation solutions for all phases of the powertrain and vehicle development process
- High-definition insights into the behavior and interactions of components, systems and entire vehicles

AVL VEHICLE ENGINEERING

Complete Development Solutions

With our comprehensive technological know-how in all vehicle systems and functions, and our many years of experience in the implementation and use of virtual development methods, we can help you manage complexity and find certainty in challenging times.

- Development, engineering, services and products
- Vehicle and vehicle systems
- Vehicle functions
- Vehicle development targets and attributes



Today’s Agenda

1. **AVL´s FC Benchmarking Program and Competence**
2. **Fuel Cell Basics**
3. **About the Vehicle**
4. **Insights into the benchmark study**
5. **The benchmark report**

Introduction

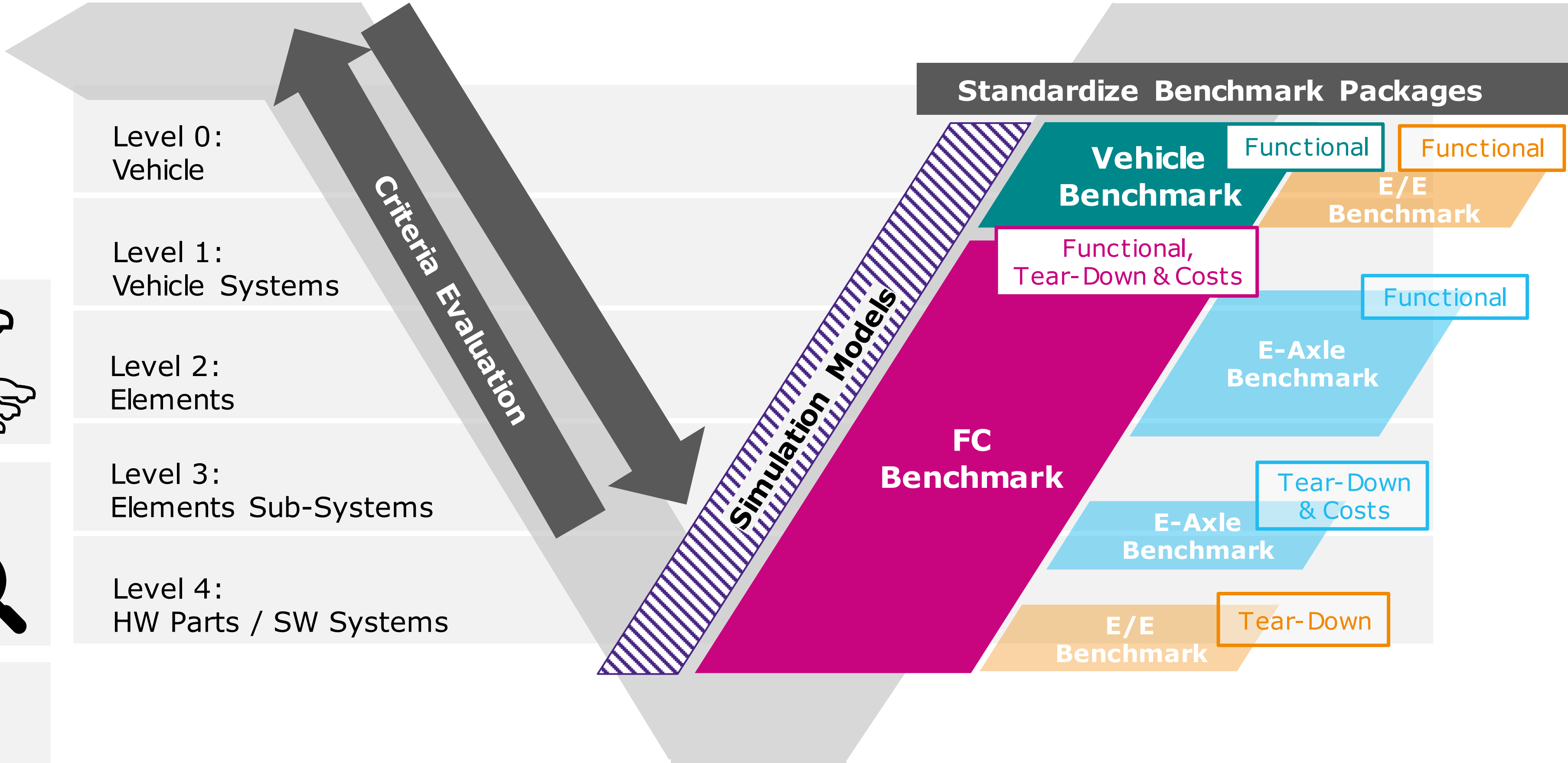
AVLs Vehicle, System & Component Benchmarking Program

Why Benchmarking ?

Standing in competitive landscape — vs.

Deriving relevant information for own development

Direct comparison to competitors — vs.



From vehicle to subcomponent analysis involving all expert fields of AVL

AVL Vehicle, System and Component Benchmarking Facilities

HQ Graz, **AUT**

Regensburg, **GER**

Tianjin & Shanghai, **CHN**

Vancouver, **Canada**

Zalaegerszeg & Kecskemet, **Hungary**

	HQ Graz, **AUT**	Regensburg, **GER**	Tianjin & Shanghai, **CHN**	Vancouver, **Canada**	Zalaegerszeg & Kecskemet, **Hungary**
Vehicle Benchmark	In place		In place		Vehicle Test-Track
E-Drive Benchmark		In place	In place		
FC Benchmark	In place			In place	In place
E/E Benchmark	In place	In place			

- In place
- Vehicle Test-Track

Vehicle, System and Component Benchmarking Program

Reports available:

- Chevrolet Bolt
- Tesla Model X P100DL
- Tesla Model 3 LR
- Nio ES8
- Hyundai Kona EV
- Jaguar I-PACE
- Hyundai Nexo (FC & Battery)
- Audi e-tron quattro 55
- Porsche Taycan Turbo S
- VW ID.3
- Tesla Model Y
- Polestar 2
- Mercedes EQC
- Hyundai Sonata

Currently in Progress:

- Hyundai Ioniq 5 AWD
- VW ID.4 GTX
- Audi e-tron S
- BMW iX xDrive50

Planned:
(start depending on vehicle launch)

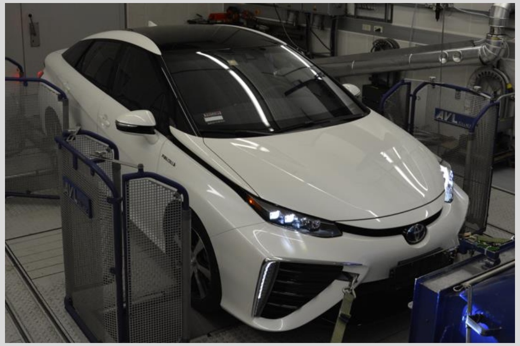
- Mercedes EQS
- Tesla Model S Plaid
- Lucid Air Dream Edition
- NIO ET7

Benchmark of **3-4** xEV **/ year** on system and comp. level

Benchmark of **>30 vehicles/ year** on vehicle level

AVL Fuel Cell Vehicle Benchmarking History

2016/17
Toyota Mirai 1



- 339 pages report
- >2.300 pictures
- Bottom up cost calculations

2019
Hyundai Nexo

- 584 pages report
- >4.200 pictures
- Bottom up cost calculations

2021
Toyota Mirai 2

- >400 pages report (estimated)
- >1.800 pictures
- Bottom up cost calculations

AVL Fuel Cell Global Footprint

- H_2 & fuel cell development since 2002
- About 500 engineers in engineering, testing & simulation
- Three H_2 & Fuel Cell Tech-Centers
  - Graz, AT
  - Vancouver, CA
  - Kecskemet, HU
- Local fuel cell support in UK, JP, CN, US & BR

Hydrogen & Fuel Cell Test & Development Center – Graz / Austria

AVL Fuel Cell Canada – Vancouver / Canada

Stack Test and Prototype Lab - Vancouver / Canada

AVL Fuel Cell Competence Highlights

Improving Durability and Reliability

AVL is the industry leader in the development and validation of PEMFC, SOFC and SOEC systems. Thanks to our technical expertise – from stacks to the complete FC system – and our leading test solutions, we are the preferred partner for OEMs and suppliers when it comes to future CO_2 neutral propulsion and power generation.

Development and Integration

- Cell and stack design for PEMFC
- Modular fuel cell system development and integration for PEM and SOC technology
- Functional safety management
- FCCU software development
- From concept to SOP

Testing and Validation

- Modular and flexible solution, easy scalability and upgradability
- Suitable for many infrastructures, from container to building
- Highest and most precise measuring performance
- Large SW portfolio applicable for fuel cell testing

Simulation Tools and Services

- Fuel cell system layout
- 3D cell and stack models
- BoP component sizing
- Fuel cell system virtual calibration

NIKOLA MOTOR COMPANY
TECO 2030
NISSAN
YUCHAI
玉柴机器 YC DIESEL
WIVA P&G Energy Model Region
HYTRUCK
KeyTech4EV
ceres

Today’s Agenda

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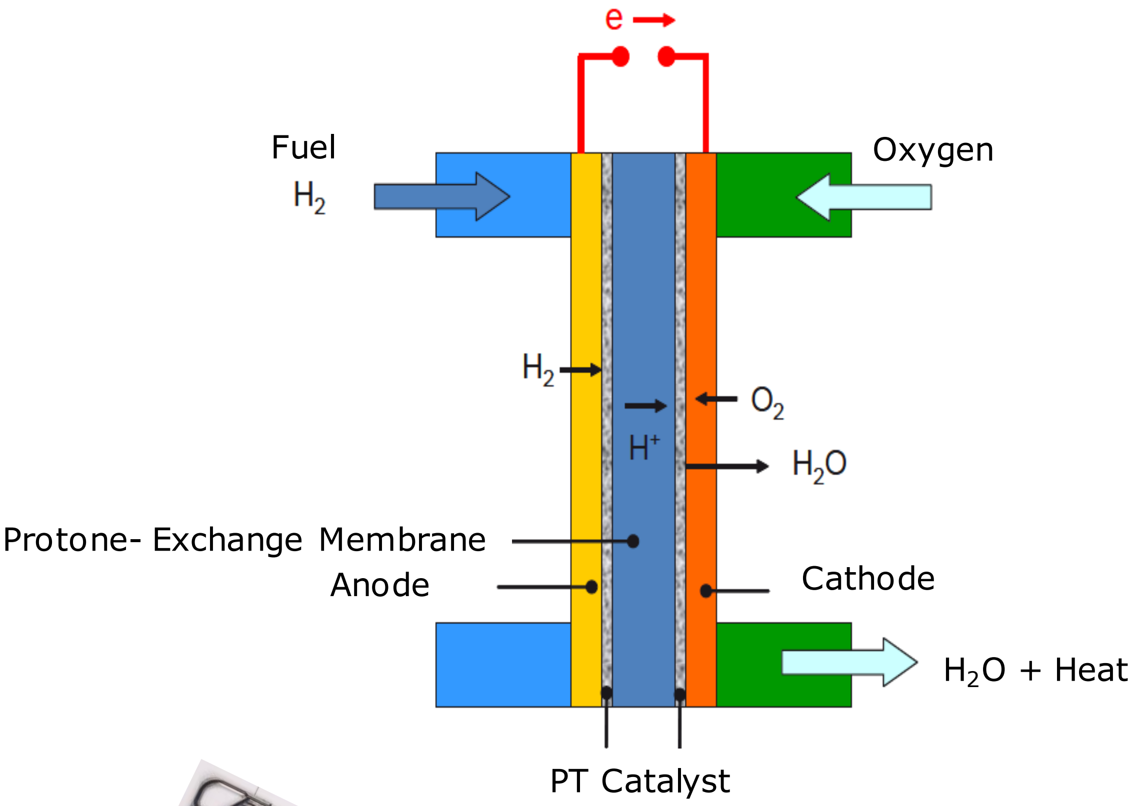
2 **Fuel Cell Basics**

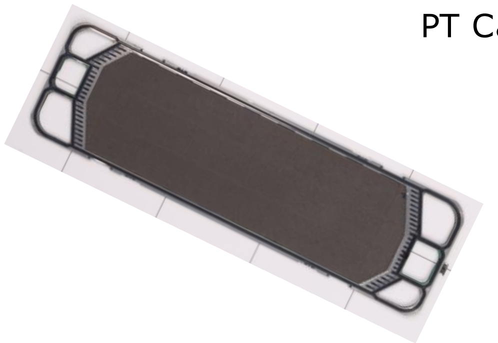
3 About the Vehicle

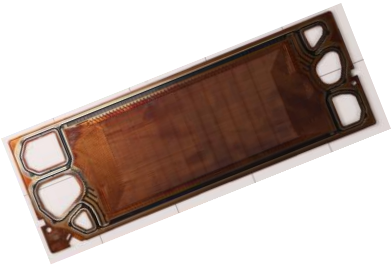
4 Insights into the benchmark study

5 The benchmark report

Fuel cell Basics – the PEM fuel cell







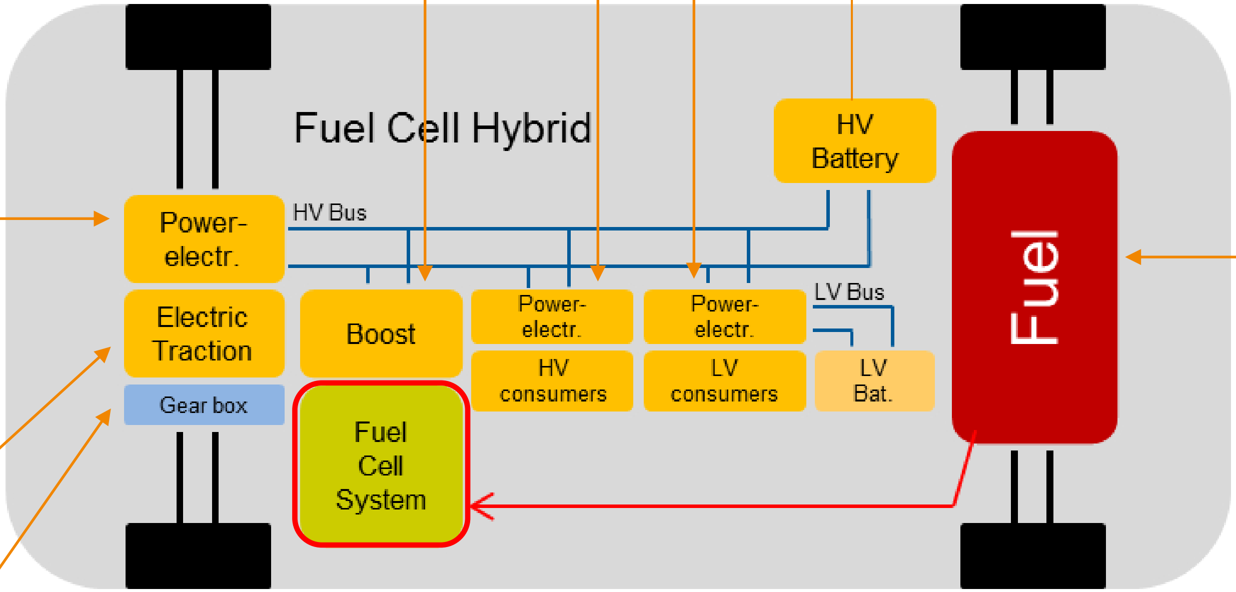
- 60–120 °C
- Proton transmitting membrane as electrolyte
- Fuel: H_2
- $H_2 + ½\ O_2 \rightarrow H_2O$
- Up to 500kW
- Humidification on the anode
  - Backdiffusion of water
  - External humidification
- Very good dynamic response
- CO-tolerance: ≤ 100ppm

Fuel Cell Basics – the vehicle components

Boost Converter & Power electronics:
- Balance voltage of FC system and HV battery
- Supply for HV and LV consumers

HV Battery:
- Rekuparation
- Boost Function
- Start up phase

Power electronics:
- Supply for e-machine



H2 Storage:

E- machine

Gear Box

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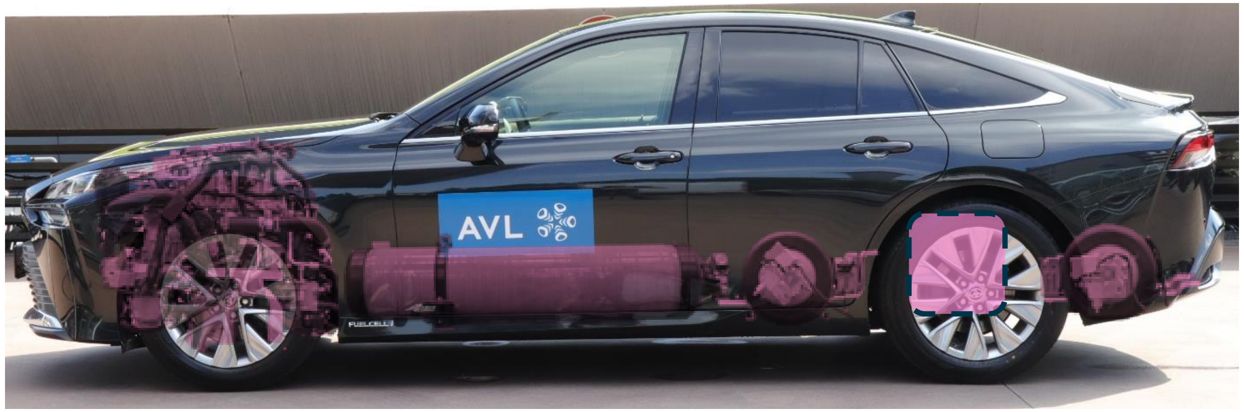
Official data
Vehicle data Toyota Mirai II Fuel Cell 134kW 2021

		Official
Vehicle Data	Total system output	134 kW
	Max. power (E-Motor)	128 kW
	Max. torque	300 Nm
	Motor type	Permanent magnet synchronous motor
	Acceleration	9.0 s
	Top Speed	175 km/h
	Driving range	650 km
	CO_2 combined (g/km)	0
	Drag coefficient	0.29
	Curb Weight	1900-1950 kg
	Overall Fuel tank capacity	142,2l (5.6kg H_2 @ 70MPa)
Battery		
	Power output battery (V)	310,8 V
	Battery type	Lithium-ion
	Cooling battery	air
	Battery Capacity	1.24 kWh



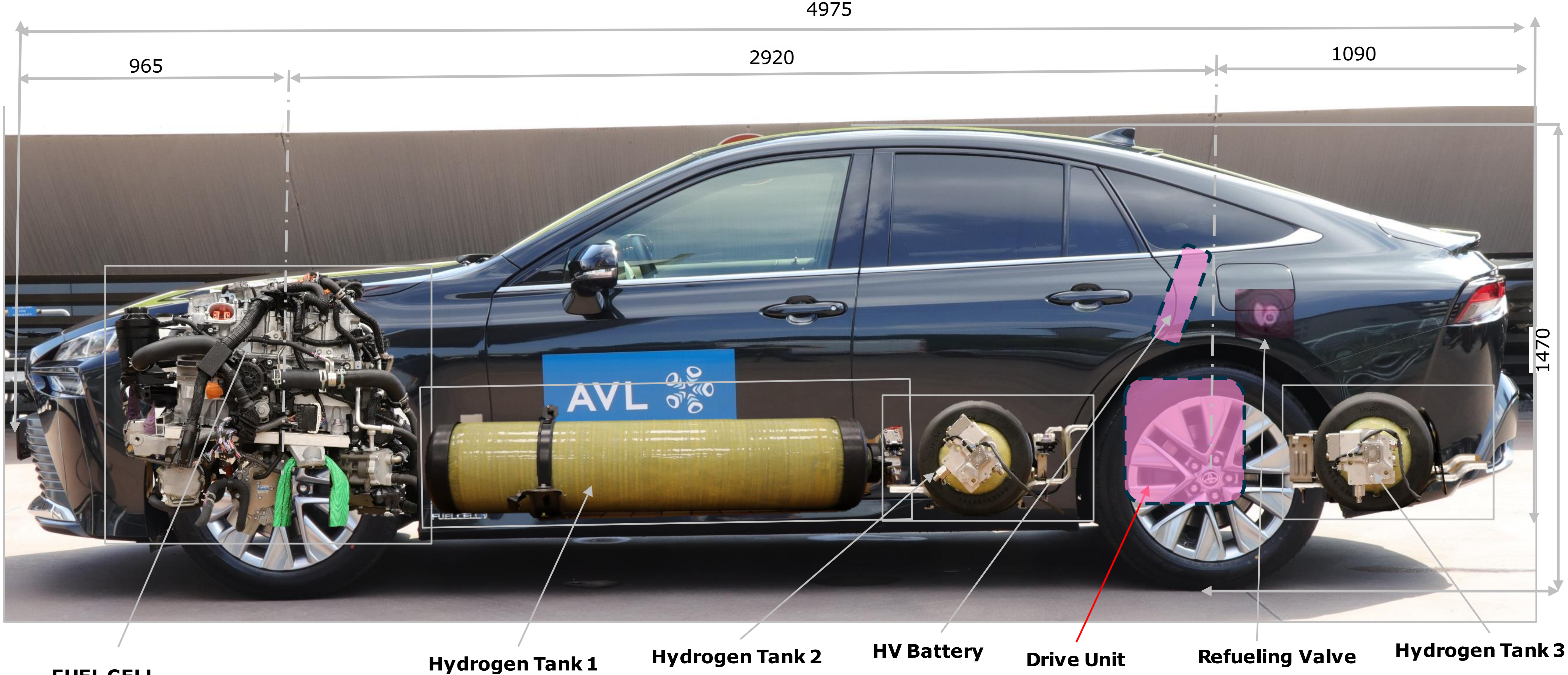
Pic 18-1: Toyota Mirai II

		Official
Fuel Cell	Power output fuel cell stack	128 kW
	Efficiency fuel cell (%)	XX
	Stack density (kW/l)	5,4
	Number of cells	334
	Fuel Cell type	Polymer electrolyte
	Cooling fuel cell stack	liquid

Source: mirai_ebrochure.pdf (toyota.com).pdf

About the Vehicle

Vehicle Dimensions, Space & Roominess



Pic 19-1: Toyota Mirai II

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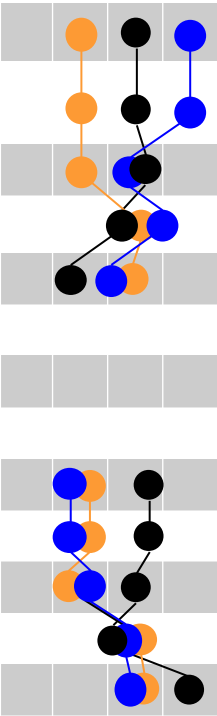
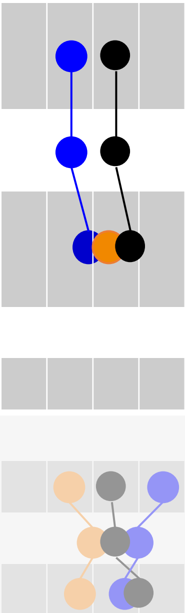
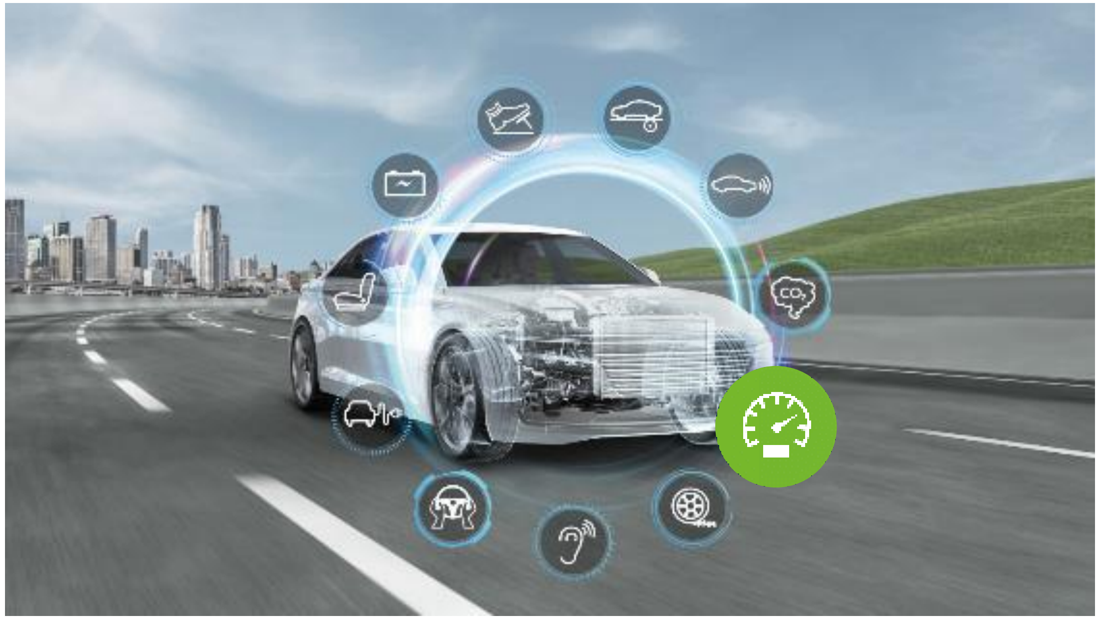
Global Vehicle Benchmarking

Executive Results and standing of 2020 Toyota Mirai 2

	 Mirai 2	 Mirai 1	 Hyundai Nexo	Standing: Below average / Average / Competitive / Leading
Performance				
0 to 100kph [s]	**9.2**	9.6	8.7	
Elasticities: 40 – 70 [kph] 60 – 100 [kph]	**2.5** **4.7**	2.98 5.98	2.4 4.8	
max. Acceleration level [m/s²]	**4.4**	4.1	4.25	
Top speed [kph]	**175**	178	179	
Curb weight [kg]	**1900**	1850	1874	
Driveability — DR … AVL-DRIVE Rating				
Drive away [DR]	**8.3**	7.6	7.3	
Acceleration [DR]	**7.9**	7.2	6.9	
Deceleration [DR]	**7.5**	6.3	6.6	
Tip in [DR]	**8.0**	8.2	8.1	
Tip out [DR]	**9.0**	8.3	8.3	

	 Mirai 2	 Mirai 1	 Hyundai Nexo	Standing: Below average / Average / Competitive / Leading
Energy consumption & Range				
Fuel consumption WLTC [kg/100km]	0.63	NN NEDC: 0.8	0.99	
Fuel consumption RDE [kg/100km]	0.85 (moderate driving)	NN	1.02 (moderate driving)	
Road load: A_0 [N] B_0 [N/kph] C_0 [N/kph²]	170 0.73 0.026	133.3 0 0.03	151.7 0.32 0.033	
Interior Sound Quality				
Interior sound quality at Full load acceleration				
Interior sound quality at Part load acceleration				
Interior sound quality at steady state conditions				

Performance



Testing conditions on test track:

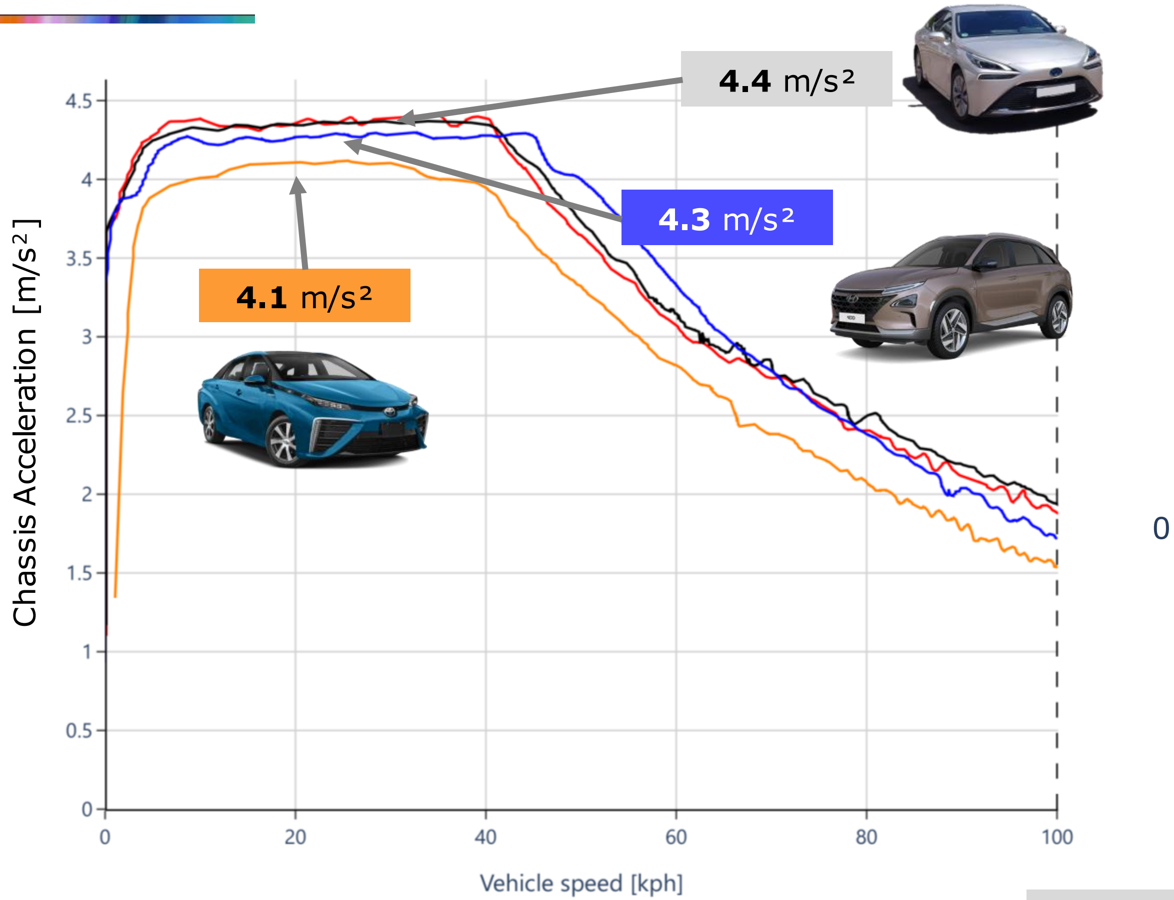
- Test weight (curb weight plus instrumentation and driver)
- Dry surface
- Fully warmed-up vehicle
- Driving mode: most sporty mode: with and without brake torque start

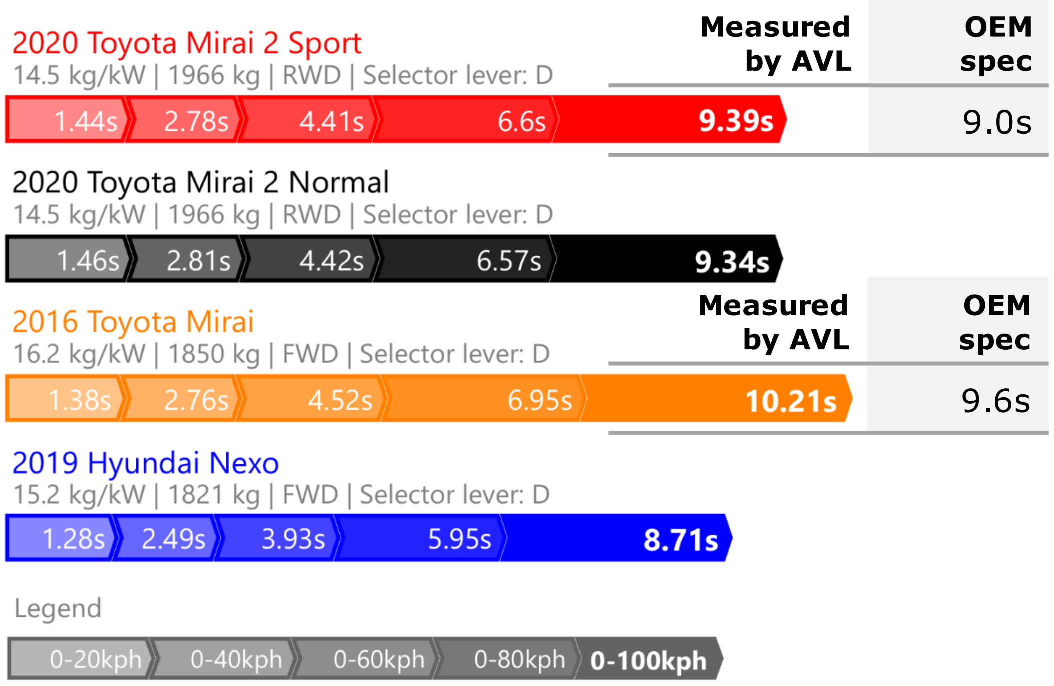
Test items:

- Acceleration performance from standstill in different SOC levels
  - 0 - 20 kph
  - 0 - 40 kph
  - 0 - 80 kph
  - 0 - 100 kph
- Elasticities:
  - 40 - 70 kph
  - 60 - 100 kph
  - 80 - 120 kph
- Max. initial acceleration level [m/s²]
- Acceleration characteristic over speed

Performance - Full load from standstill

0 to 100 kph – Mode comparison





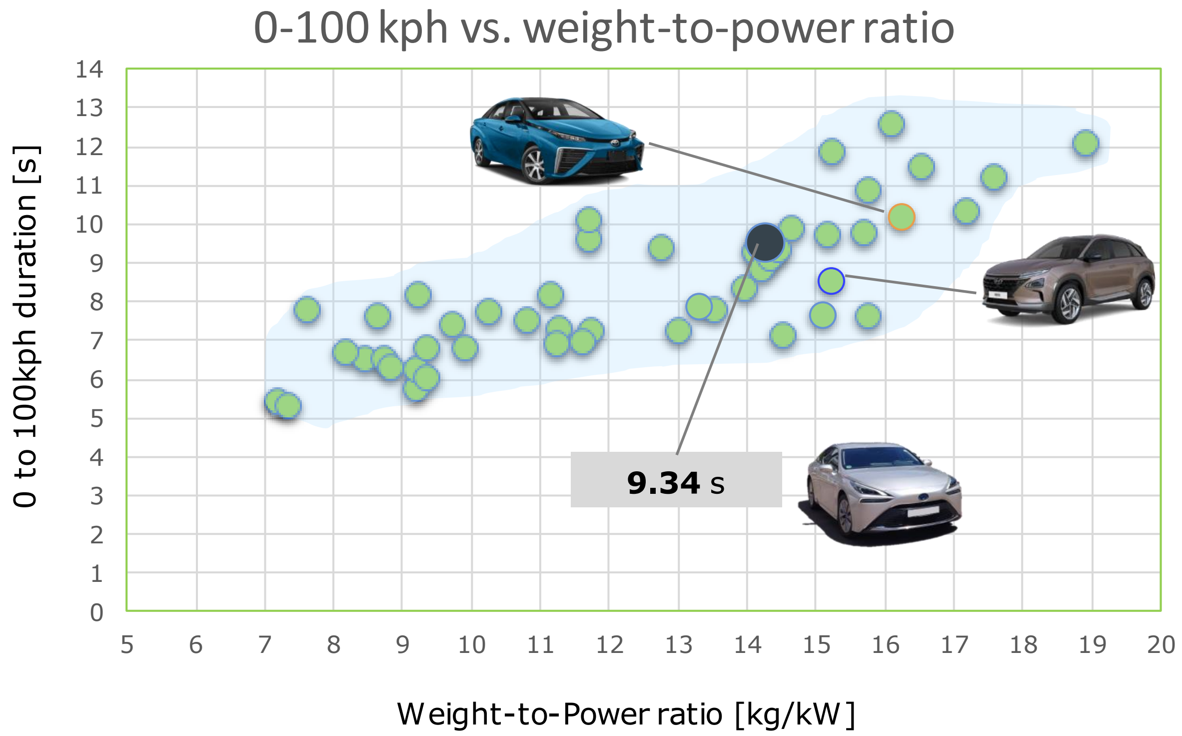
AVL results	E-motor max. torque / power	Fuel Cell	Battery	OEM specs
Normal	312Nm / 135kW	584A / 128kW	19kW	300Nm / 134kW
Sport	308Nm / 135kW	591A / 128kW	19kW	

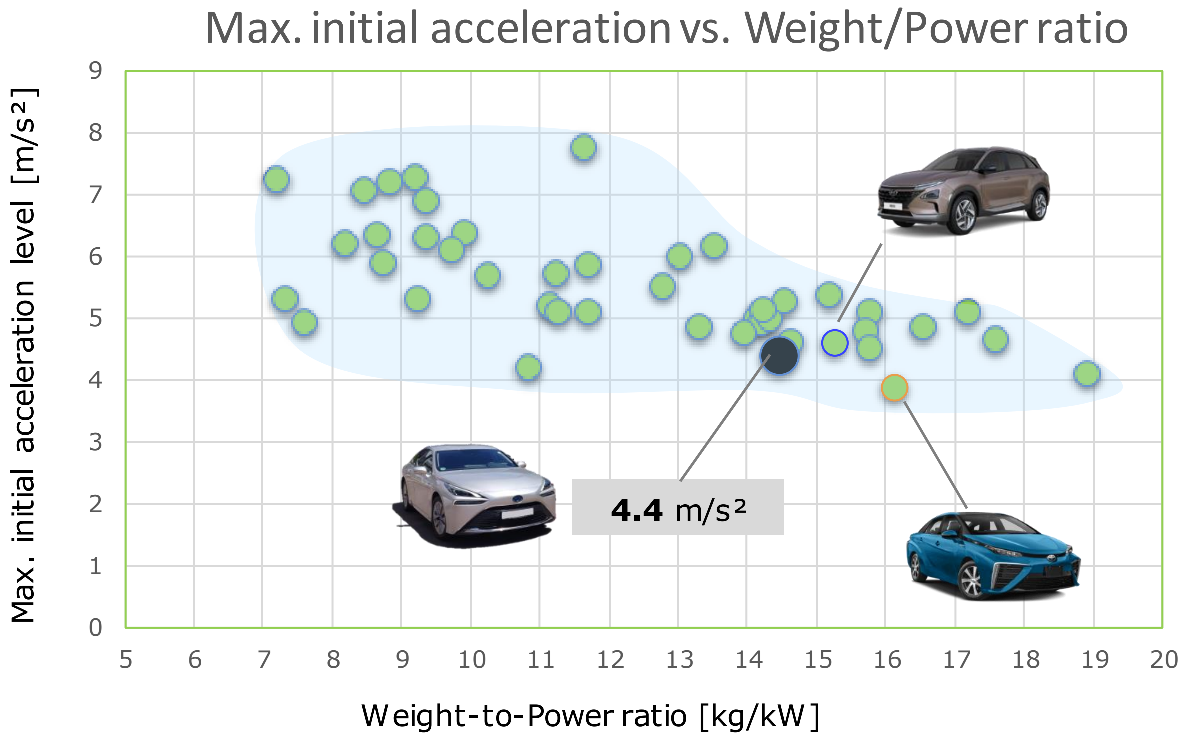
Normal & Sport: low acceleration performance compared to vehicle class and OEM expectation

Slow acceleration build up during fuel cell startup due to low capacity HV battery (1.2kWh) supplying insufficient power to achieve maximum motor performance

Performance - Full load from standstill

0 to 100 kph and max. initial acceleration

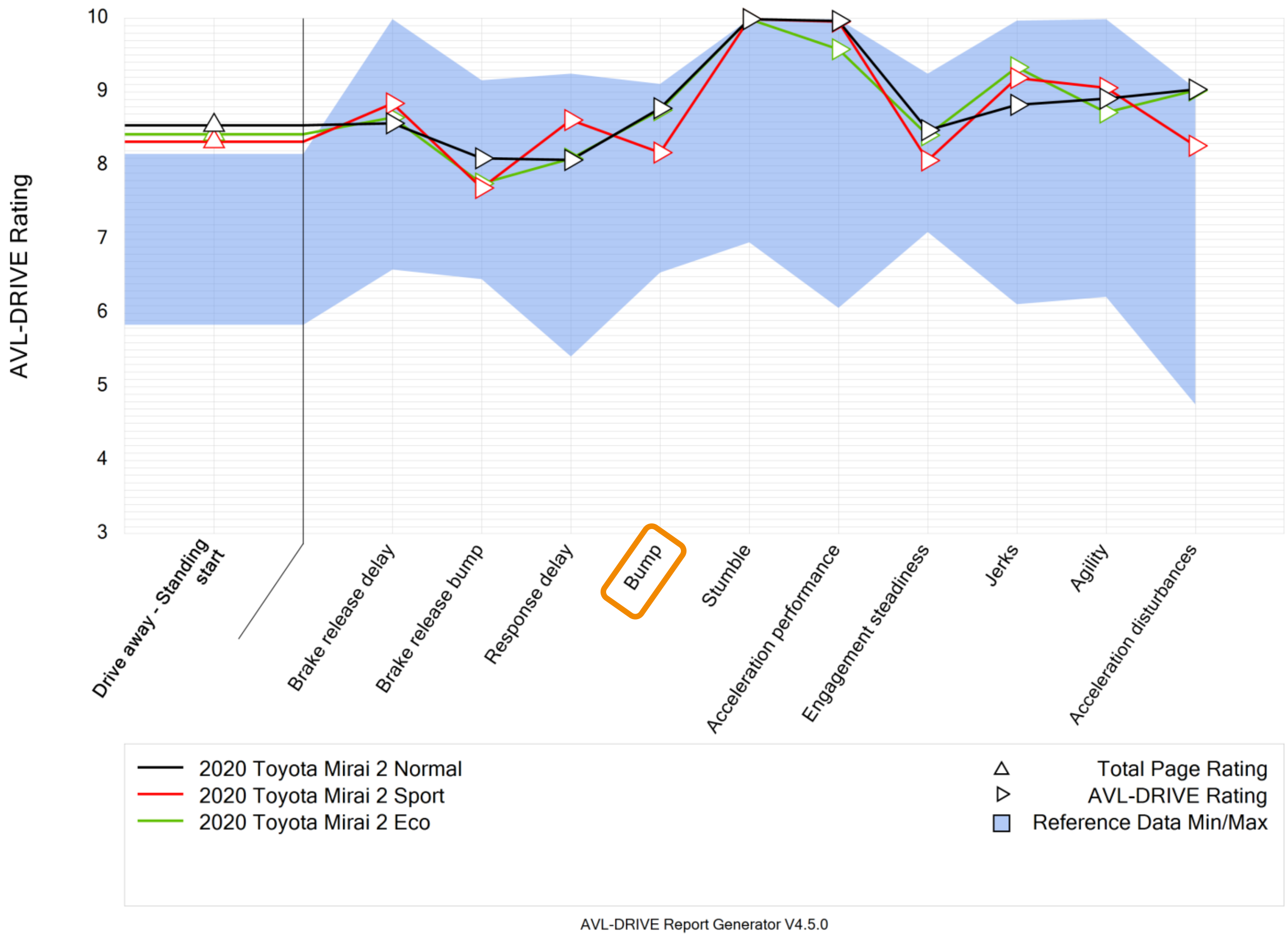


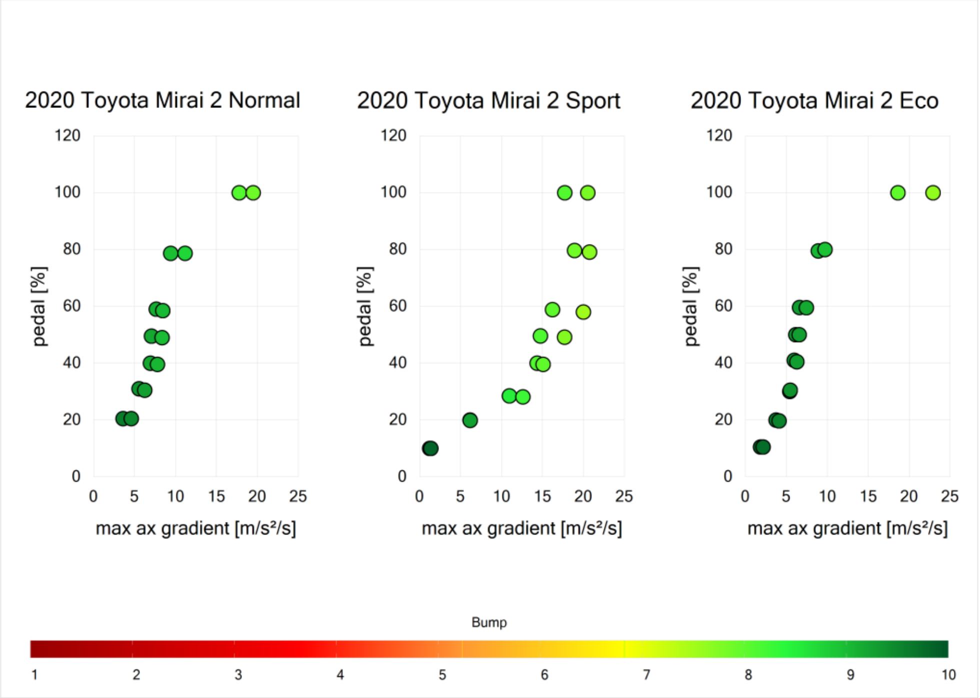


The full load acceleration is improved from Mirai 1 to Mirai 2 but significantly behind what luxury BEV vehicles can provide

Drive Away – Standing start

Detail – Pedal vs. ax-gradient and ax. bump



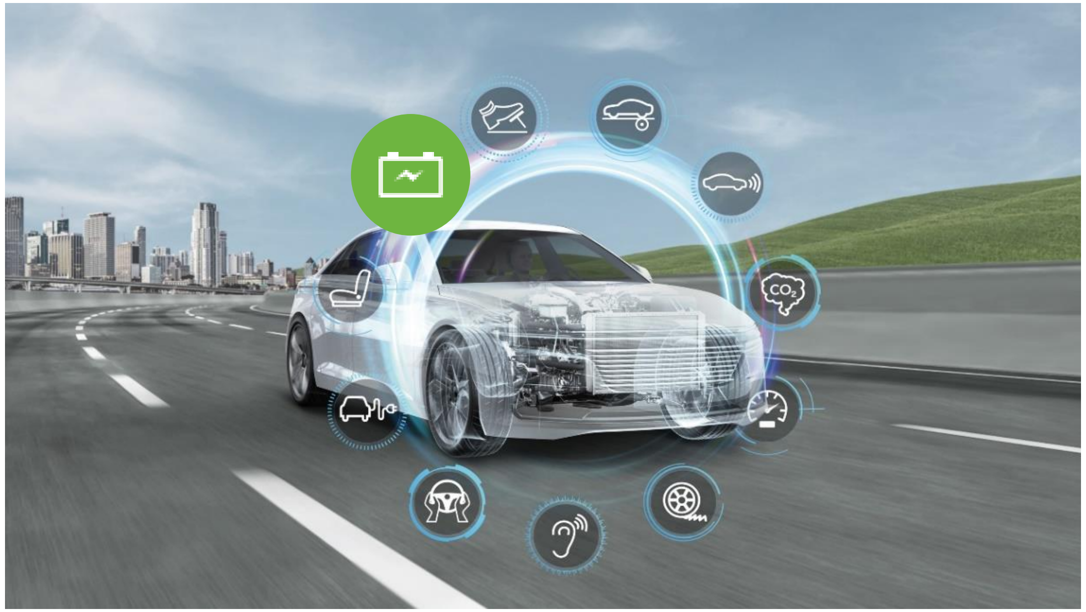


Steady acceleration build for driving in normal and eco mode, with very similar hesitating but comfortable drive away behavior.

Noticeable higher responsiveness driving in sport mode with still acceptable acceleration bumps.

The driving comfort is excellent

Vehicle Energy Efficiency & Consumption



Test	Environment
Real-world driving	Public road
WLTC	Chassis dyno
Constant Speed	Test track

Test items:

Analysis of vehicles energy efficiency in standardized cycles (e.g. WLTC) and Real-World Driving cycle (Standard AVL RDE cycle in Graz)

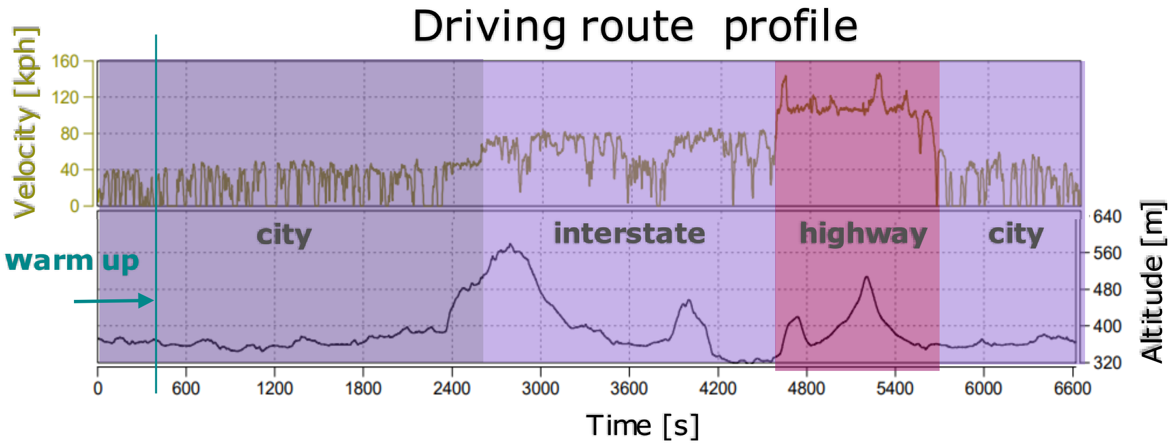
- Electric energy management
- Energy flow and loss analysis
- Electric Energy consumption of auxiliaries
- Regenerative braking and recuperation capabilities
- Operating strategy: Power output vs. vehicle speed and HV battery SOC

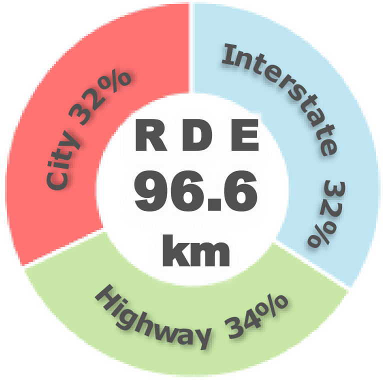
Testing conditions:

- Test weight (curb weight plus instrumentation and driver)
- Driving mode: start-up mode (Normal or Comfort)
- 23°C at test start

Energy Management, Efficiency & Consumption

Real-World driving cycle AVL Graz



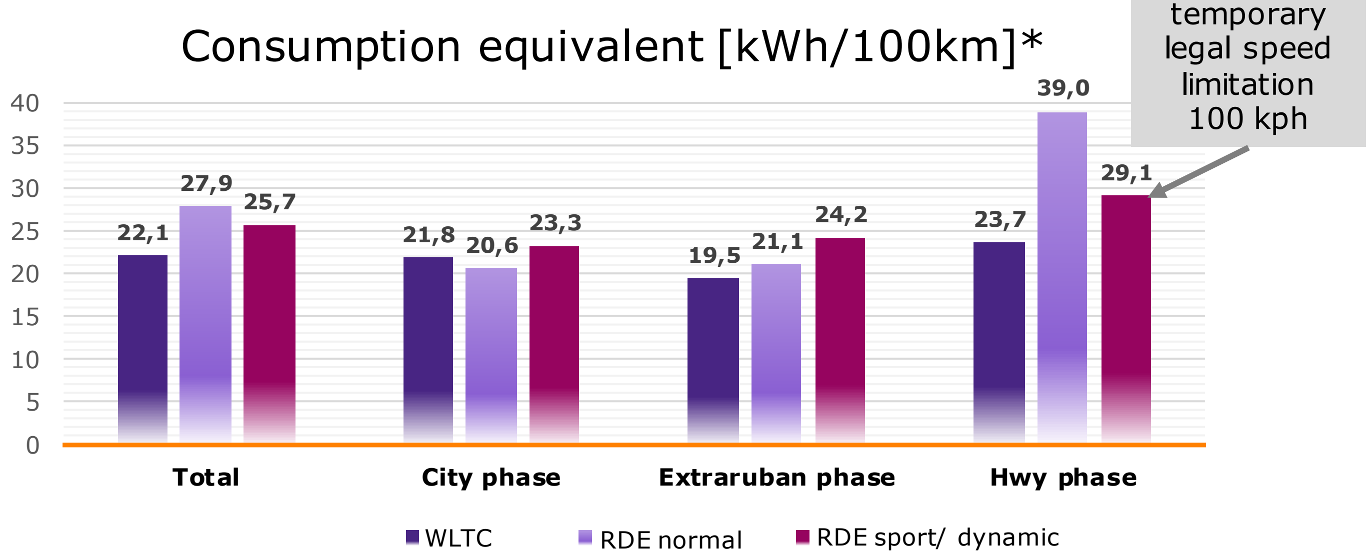


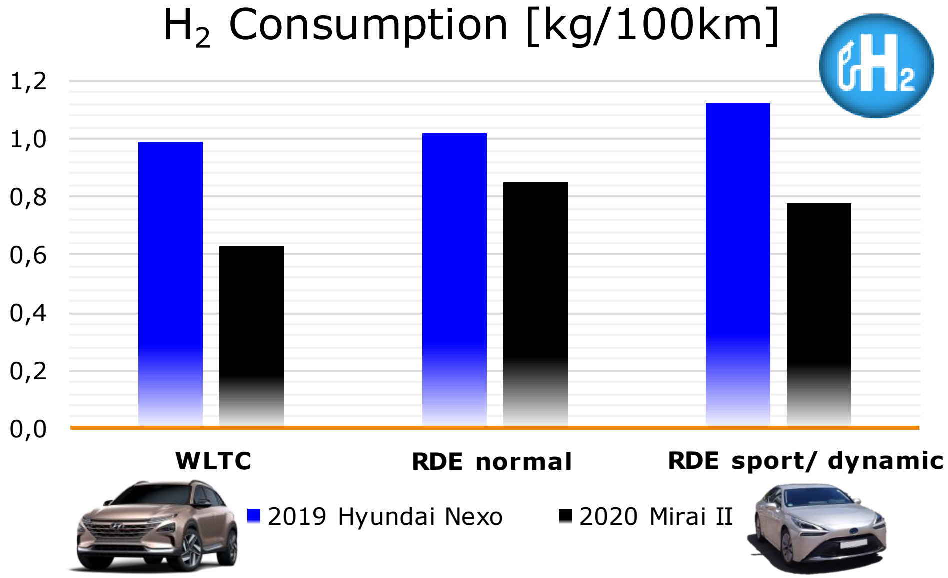
Conditions	
Ambient temp.	21 - 23[°C]
Settings	AC auto 22°, headlights on
Driving style	moderate
Driving mode	Comfort / Sport

Real world driving, referring to Real Driving Emissions (RDE) legislation with equal distance split for city, interstate and highway drive. Consumption determined by subsequent re-charge. The H_2 consumption of the fuel cell stack is calculated by followed equation, based on the stack current.

Energy Management/Efficiency/Consumption

Range & Consumption





The equivalent energy consumption (in kWh/100km) of FCEV, compared to BEV's, results in generally higher consumption values. This is caused by the hydrogen - electric power conversion.

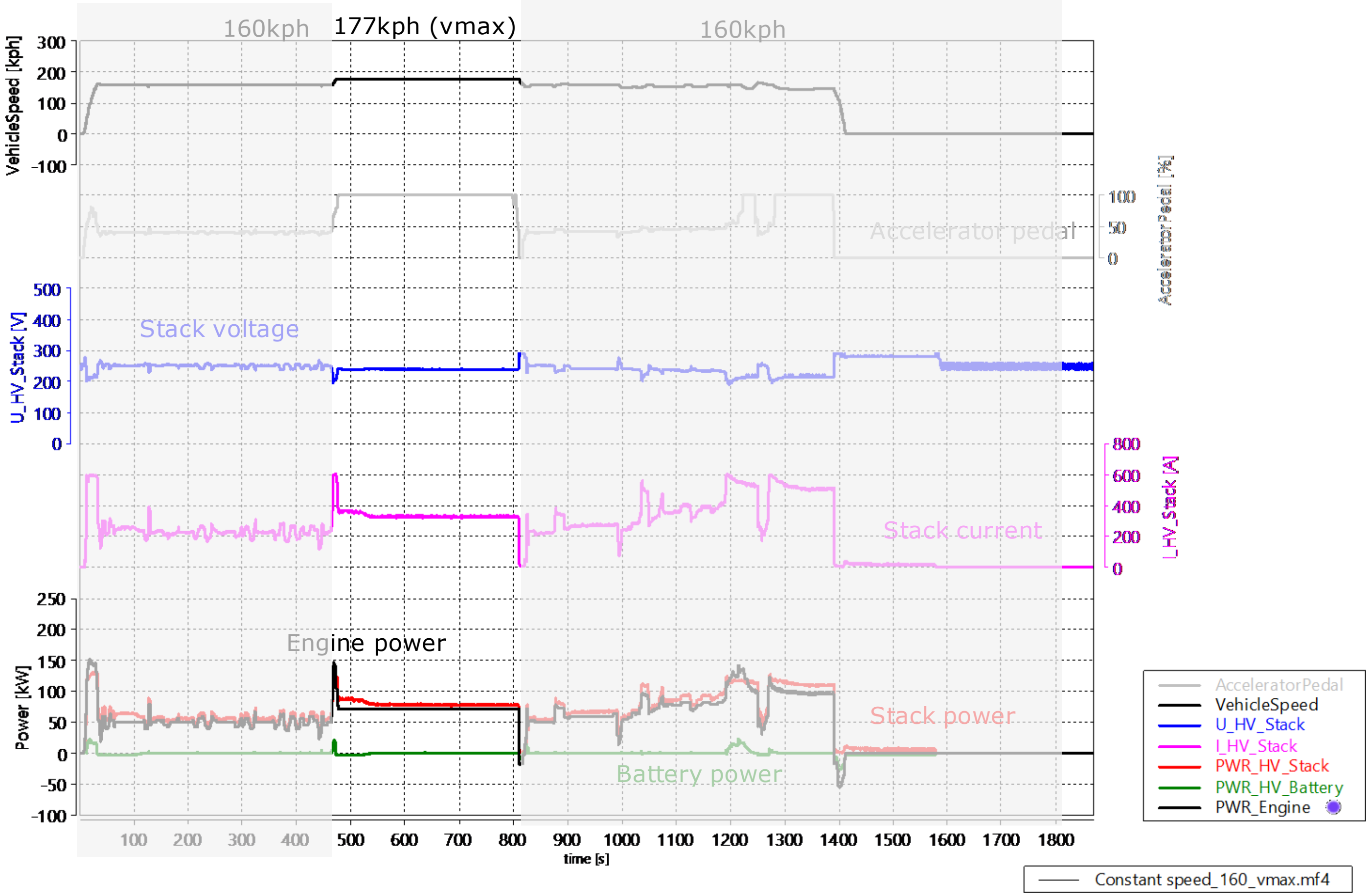
Cycle Overview	H_2 consumption [kg/100km]				Range Estimation** [km]		
	WLTC OEM	WLTC	RDE normal	RDE sport/ dynamic	WLTC	RDE normal	RDE sport/ dynamic
Toyota Mirai II	0.8	0.63	0.85	0.78	871	646	704
Hyundai Nexo	1.0	0.99	1.02	1.12	626	608	554

*** For FCEV: calculated H2 energy → Hu=33.33 kW/kg (Source "www.Linde-gas.at")**
**** For FCEV: The WLTC range estimation is based on full H_2-tank capacity of 6.33kg (full) with remaining 2% H_2- level.**

Insights into the benchmarking study

Cooling and derating

Heat rejection at different vehicle speeds



Test Description:
Constant speed driving (road grade 0%)
- 160kph
- 177kph (vmax)

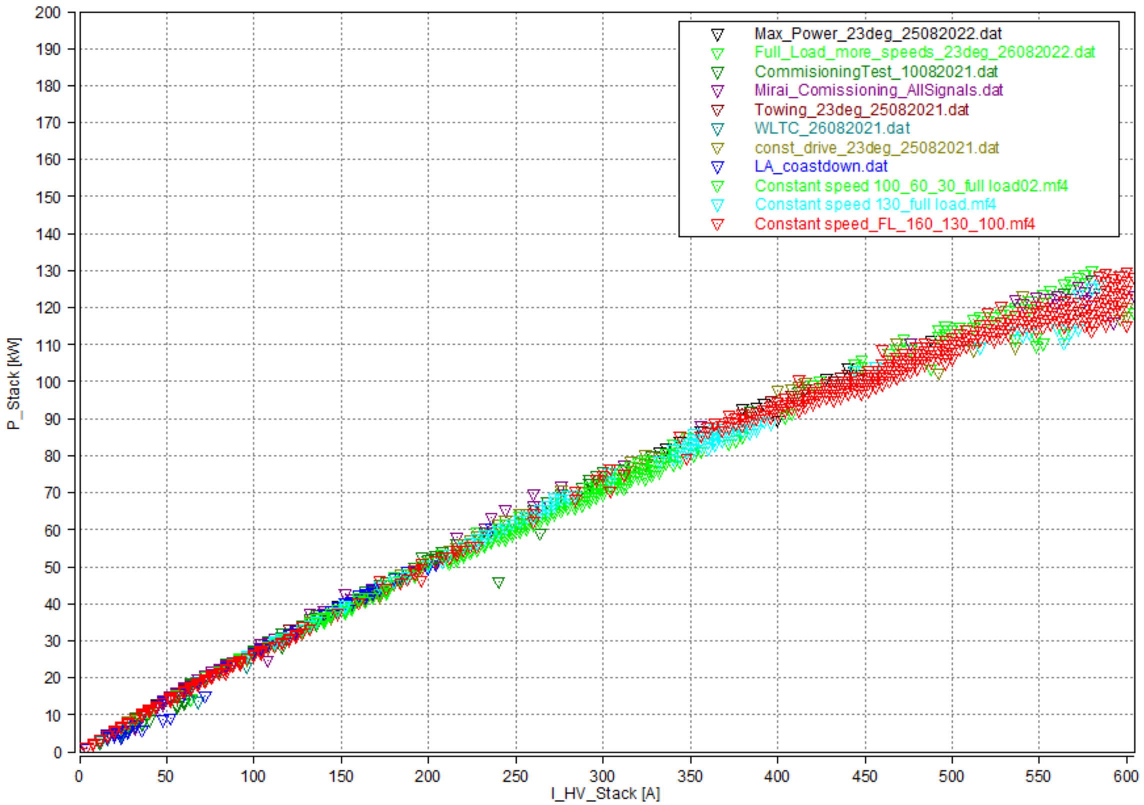
Ambient temperature: 23°C

- Verhicle speed is limited to 177km/h
- Vehicle can run v_{max} continously for long time
- No reduction of speed due to heat; temperature stays in acceptable range
- Vehicle runs v_{max} without support from battery only from fuel cell power

Note: in other test case (Townes Pass at 40°C ambient temp.) we could observe derating and speed reduction and surprisingly high temperatures

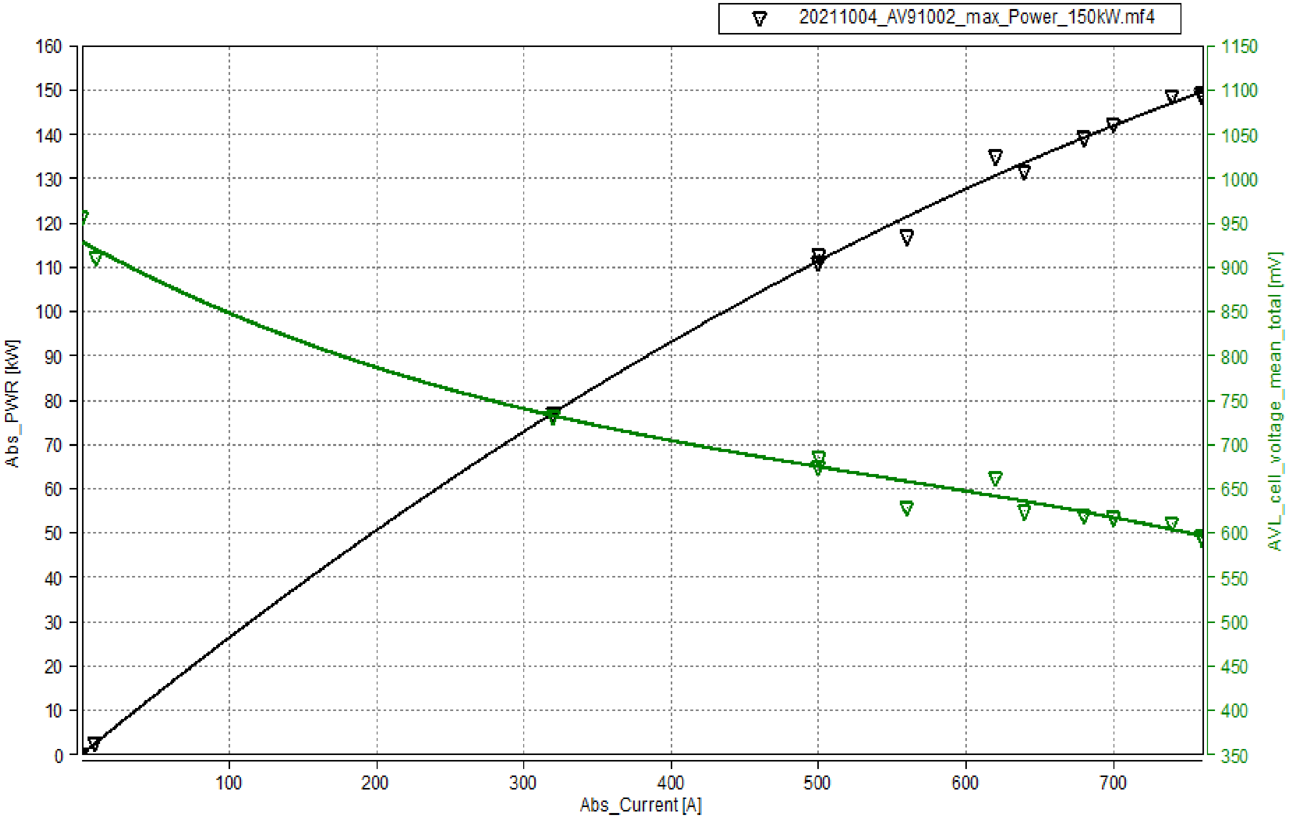
Insights into the benchmarking study
stack power

Stack Power @ vehicle



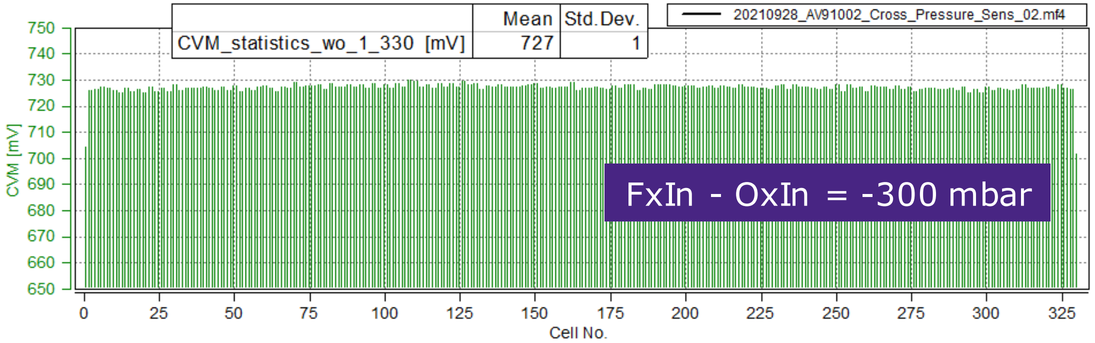
- Power of (124±6) kW reached.
- Multiple vehicle measurements included to reflect the range of reached powers during various vehicle tests.

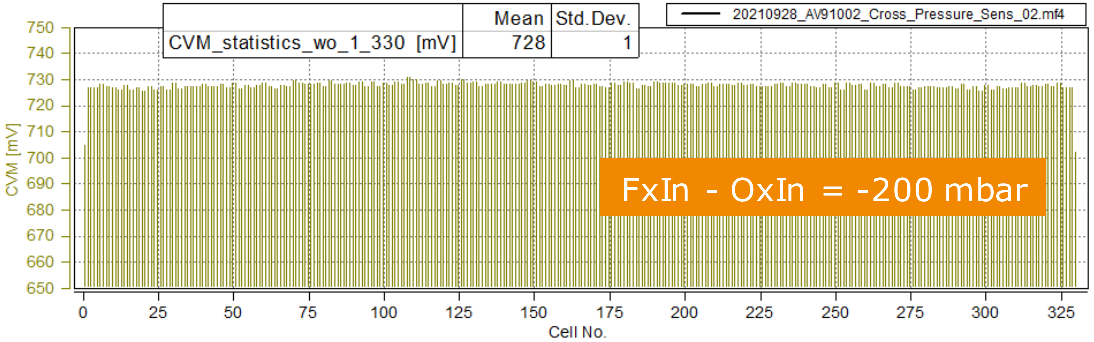
Stack Power @ testbed

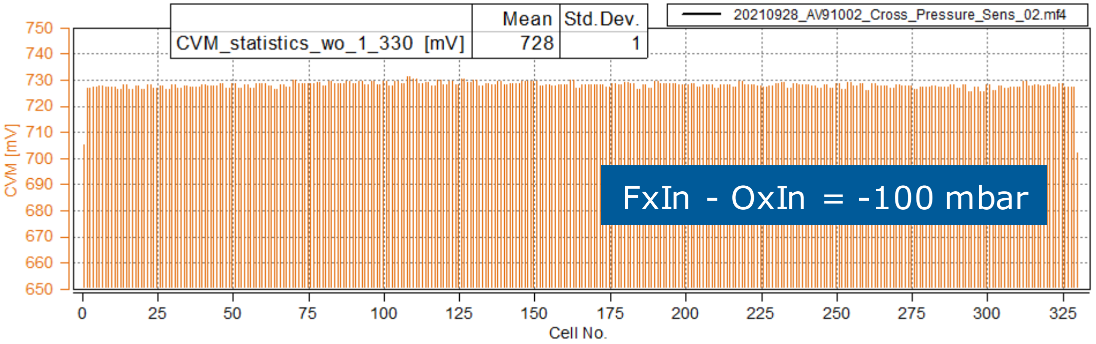


- Maximum reached stack power: 150 kW
- To reach 150 kW in the vehicle, 26% higher air mass flow and 30% higher air pressure needed.

Fx-Ox Cross Pressure Sensitivity – Negative Cross Pressure FxIn - OxIn







Observation and Interpretation:

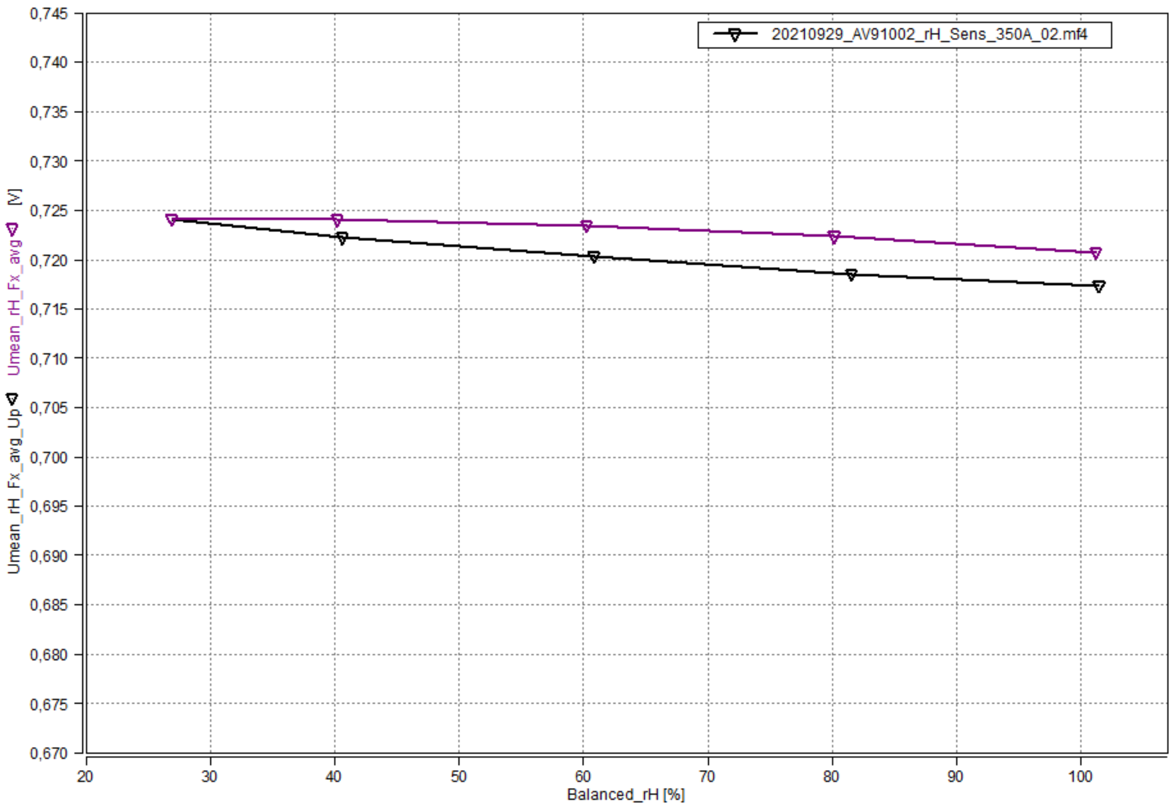
- Very low cell-to-cell voltage variation (standard deviation of 1 mV; **Note: measurement accuracy ±1 mV**)

- Excellent production quality
- Very good distribution of the gases
- Very good quality of coating

Insights into the benchmarking study

Effect of Relative Humidity at 350 A:

Balanced RH_{Fx} = RH_{Ox} , 3 mins/pt, dT = 10 °C, T_coolt_in= 55°C



Observation and Interpretation:

- The cell row is very insensitive to relative humidity at 55°C
- The cell row is able to maintain similar performance even at low relative humidity (i.e. 25 %RH at 55 ° C)
- Slightly negative trend in ACV with increasing relative humidity
- Hysteresis is shown between decreasing (violet) and increasing (black) relative humidity, with better performance for the former.

=> <u>This insensitivity to %RH is a very impressive result!</u>

Unit cell - general observations and plate coating analysis

- The unit cell is comprised of a MEFA and two plates
- Seal is present only on the coolant side of the cathode plate

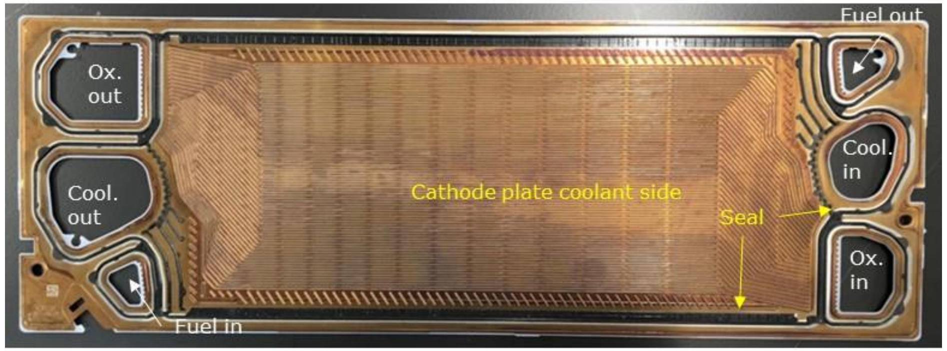
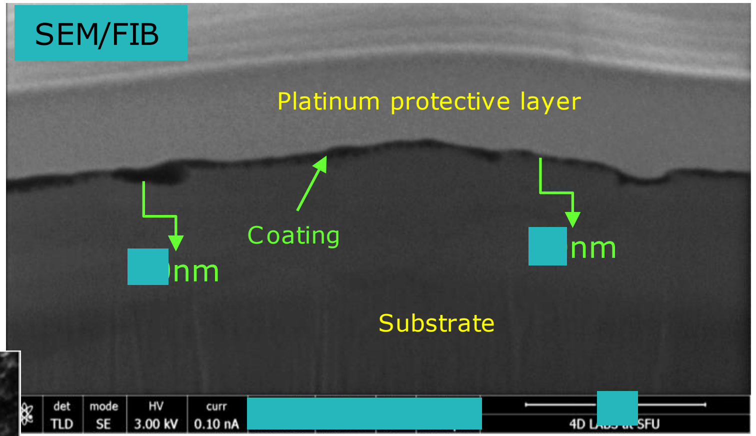
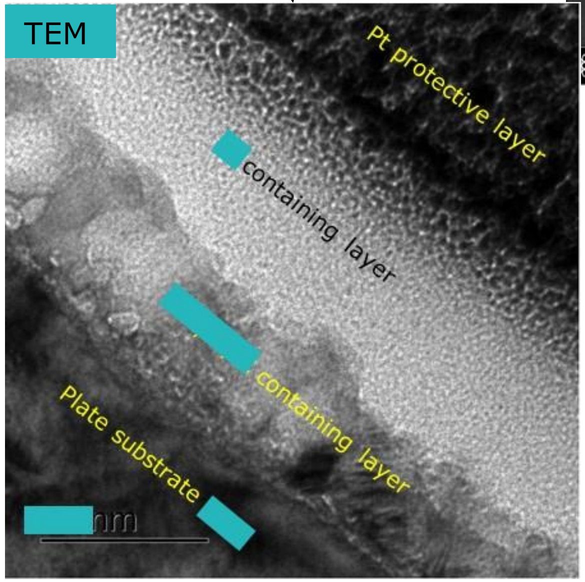


Plate coating analysis

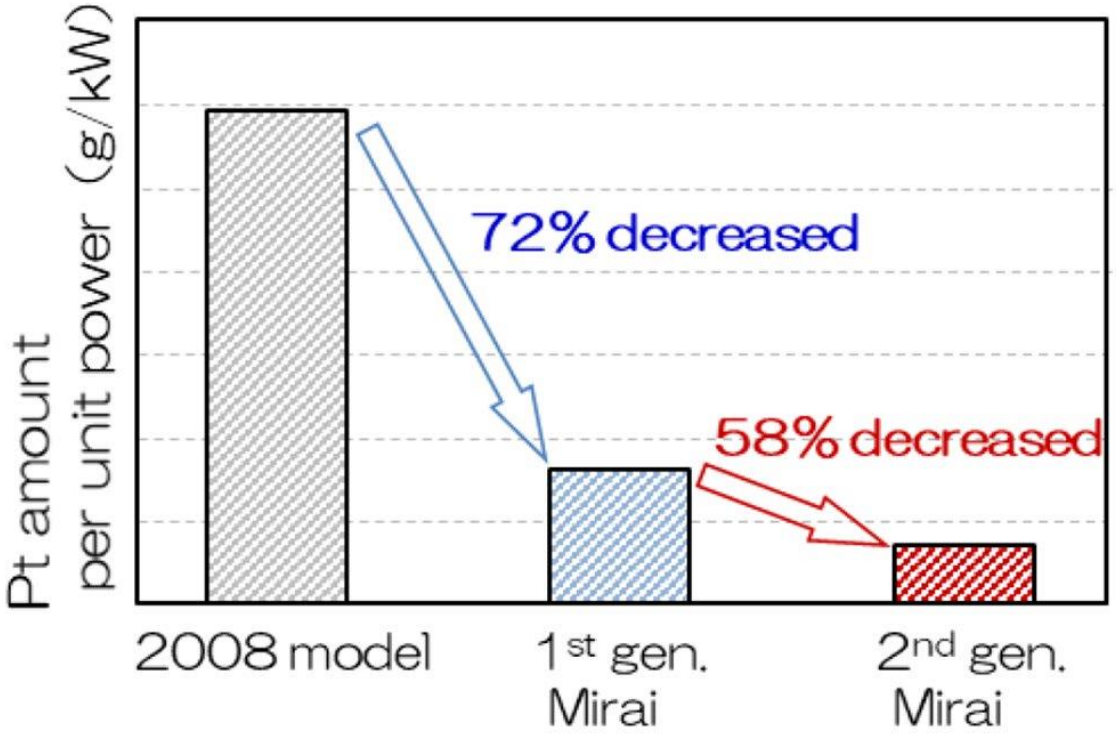




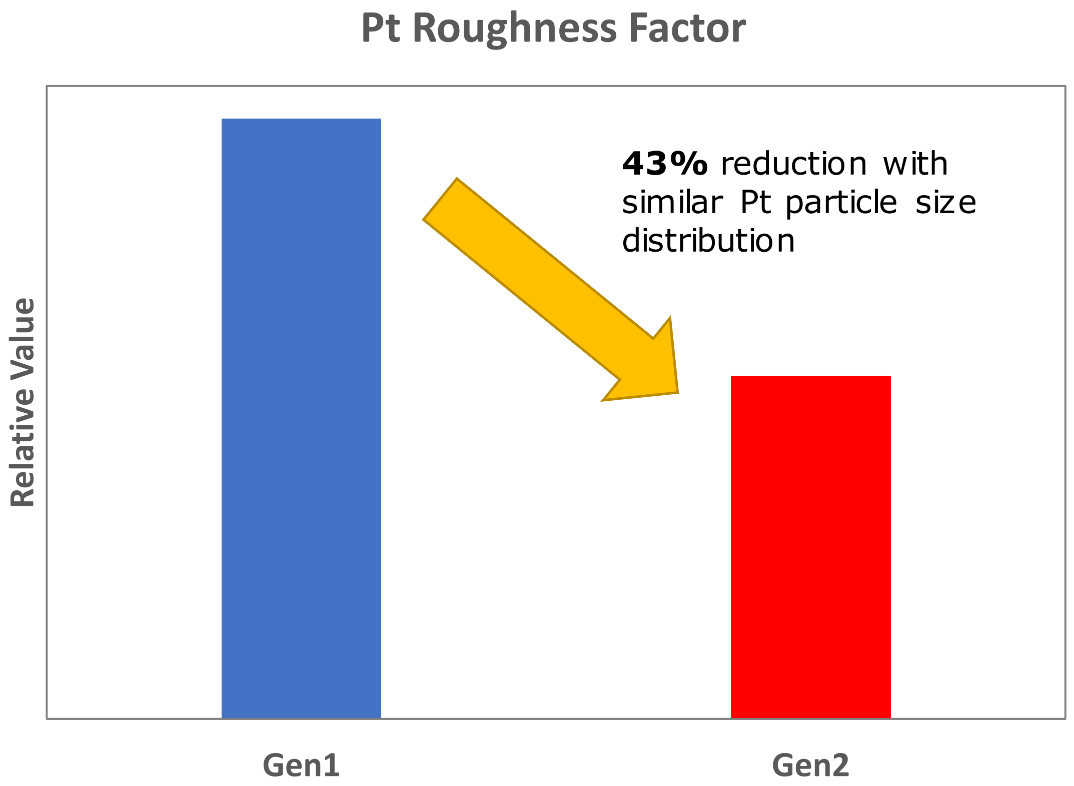
Titanium in the plates substrate can cause degradation of the fuel cell membrane therefore a coating is applied to the plates.

Legend:
MEFA – Membrane Electrode Frame Assembly
SEM – Scanning Electron Microscope
FIB – Focused Ion Beam

Reduction in Electrode Pt Loading



Yoshizumi, T., Kubo, H., and Okumura, M., "Development of High-Performance FC Stack for the New MIRAI," SAE Technical Paper 2021-01-0740, 2021, doi:10.4271/2021-01-0740.



Summary vehicle performance

pro

- 650 km range even in real world driving
- Refuelling time ~ 5 min
- Driving comfort
- Competetive price

contra

- Full load acceleration
- Space and seating comfort

Due to a lot of improvements in every detail Toyota succeeded in creating a competetive electric car with a driving range of 650km which can be bought for ~60.000 Euro

Today’s Agenda

Outlook on AVLs full benchmark study of the Mirai 2

Vehicle Benchmarking

Off the shelf benchmark attributes for vehicle benchmarking the Mirai 2

- Performance
- Chassis Dyno Testing
- Cold Starts
- Driveability
- Real-World Driving
- Thermal Perf. & Eff.
- Vehicle Acoustics
- Vehicle Efficiency & Consumption
- Driving Resistance

On request

- Handling
- Ride Comfort
- ADAS/AD Quality

2-3 times more costs attractive than performing benchmarking by themselves due to pre-financing by AVL

Highlighting a vehicles **standing against the competition** within AVLs competitor scatterband.

Instant availability of benchmark data as no time-consuming benchmarking is required

Objective assessment of **driving excitement** and evaluation of vehicle **energy efficiency**.

Outlook on AVLs full benchmark study of the Mirai 2

FC Benchmarking

Off the shelf benchmark attributes for Fuel Cell (& Stack) benchmarking

Powertrain Testing

Stack Teardown

Cell Testing

Stack Interface

Stack Cost Analysis

Cell Abuse Testing

Stack and cell benchmark database

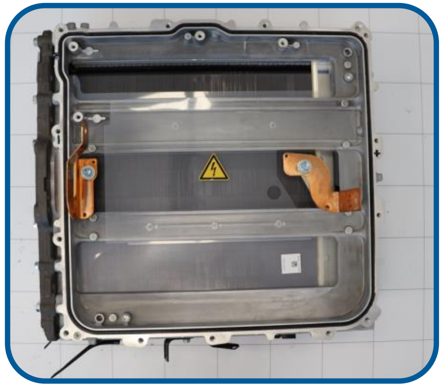
Stack tear-down and engineering judgement by FC development experts to highlight **strengths and potentials for improvements**.

Linking functional requirements to design and production costs.

Report Structure

WP 1 Vehicle

~70 Slides

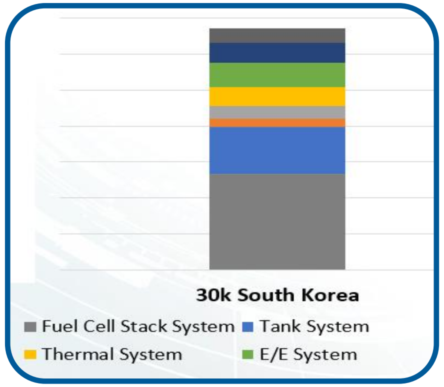


WP 2 Tear Down

~1.800 pictures

WP 3 Fuel Cell

~250 slides



WP 4 Cost

~100 slides

WP 5 Comparison with Mirai1 and Hyundai Nexo

~100 slides

Next vehicles in the program:
Mercedes EQS
Tesla Model S Plaid
Lucid Air
NIO ET7

Benchmark online platform:
https://app.avl.com/benchmarking-program

To find out more:
Visit us at our AVL Benchmark Centers!

AVL

Toyota Mirai 2

Q&A

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Thank you

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