POLISH CONFERENCE ON HYDROGEN ENERGY AND TECHNOLOGY (PCHET 2020)

KLASTER WODOROWY

PCHET 2020

# GLOBAL TRENDS IN ELECTRIFIED POWERTRAINS – CHALLENGES IN TESTING METHODS

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# 1. INTRODUCTION

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**History &**
**Main drivers of**
**powertrain development trends**

# Early light-duty vehicle development

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- Electric vehicles appeared in late 1860s - **earlier than internal combustion engines** (ICE 1876).
- The popularity was **boosted** by **low maintenance** as it **does not require complicated start procedure** or preheating, and has no emissions.
- 1888 - first four wheeled electric car is developed by A. Flocken.
- 1899 - the "La Jamais Contente" FR first electric vehicle which **exceeded 100 km/h**.
- 1900 - electric vehicles **top selling** road vehicles in US with **28%** of the market.

**Detroit Electric Brougham: Early electric urban mobile**

**<u>Specifications</u>**

***1918 Detroit Electric Brougham*** Price, new: $ 2940; Wheelbase: 100 in
**Engine:** Electric, DC current; **Suspension:** Front - semi-elliptic leaf springs
Rear - semi-elliptic leaf springs; **Brakes:** Drums, mechanically operated on rear wheels

# Early light-duty vehicle development

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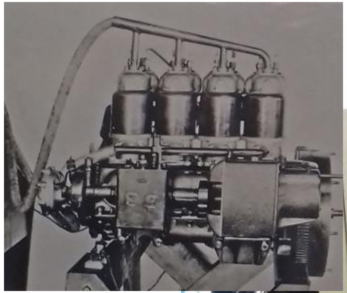


**Source**: SAE Congress 2018

**1912 Cadillac Model 30**

## Specifications

***1912 Cadillac Model 30***

Price, new: $ 1800

Wheelbase: 116 in

**Engine**

V-8 CID, L-head

Power 40HP, Bore&Stroke: 4,5X4,5in

Splash lubrication

Transmission – 3 speed manual, no synchronizers

…and from that point, the **EV era ended**,

*do you know why??*

# Main drivers of powertrain development

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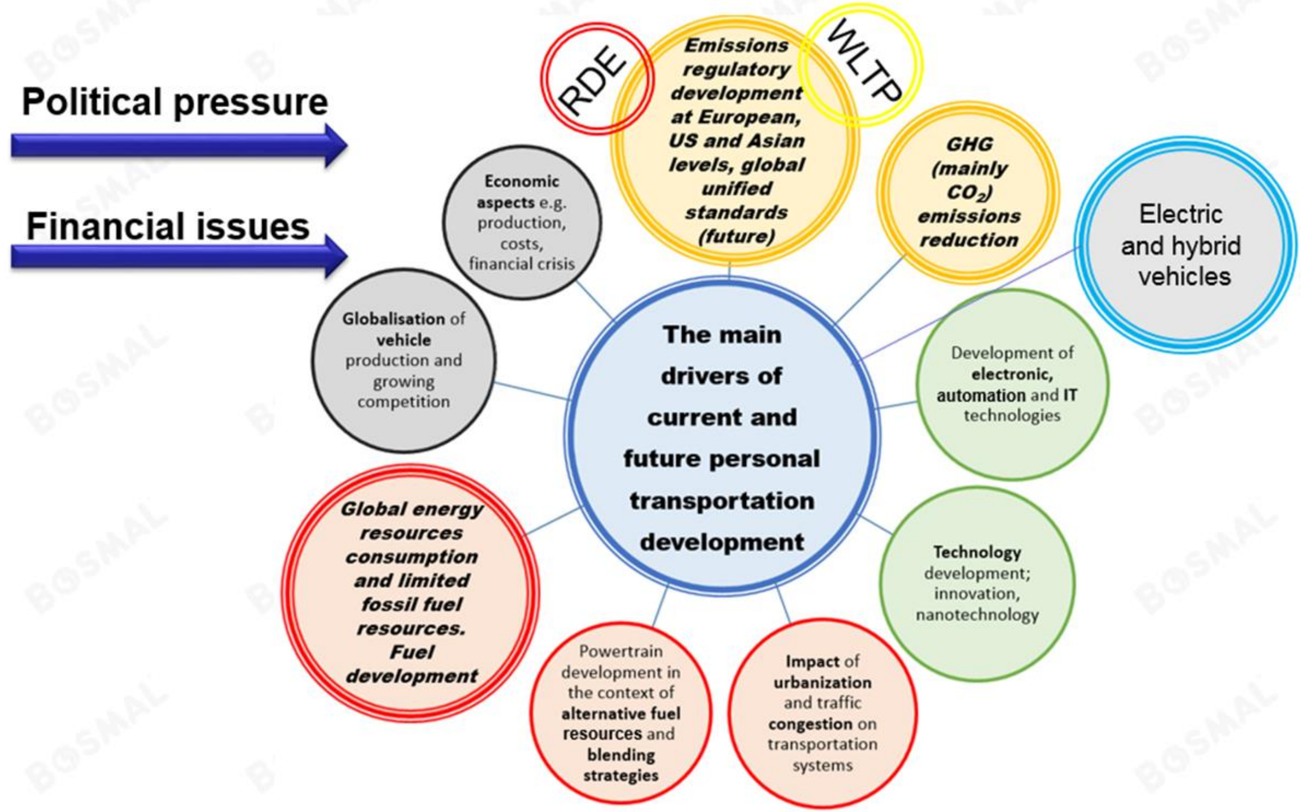
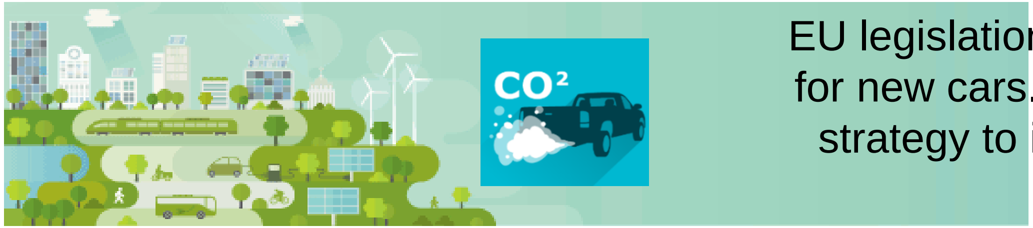
## Megatrends: Energy security & GHG



**Automotive pollutant and GHG emissions legislations in the EU, USA, China, Japan, Brazil and other areas are impacting engine technologies and development procedures**

# $CO_2$ emissions from passenger cars – EU short-term targets




EU legislation sets mandatory **emission reduction targets** for new cars. This legislation is the cornerstone of the EU's strategy to improve the fuel economy of cars sold on the European market

- Cars are responsible for around 12% of total EU emissions of carbon dioxide ($CO_2$), the main greenhouse gas
- The average emissions level of a new car sold in **2017** was **118.5 g**$CO_2$/km (g $CO_2$/km), significantly below the 2015 target of 130 g, **but for 2019: 122.4 g$CO_2$/km (NEDC)**
- **TARGET for 2021:** by 2021, phased in from 2020, the fleet average to be achieved by all new cars is 95 grams of $CO_2$ per km
- If the average $CO_2$ emissions of a manufacturer's fleet exceed its limit value in any year from 2012, the manufacturer has to pay an excess emissions premium for each car registered

# EU fleet average $CO_2$ targets for 2025 & 2030

In 2018 the EC finalized its approach concerning the proposed regulation amending Regulation (EC) No 715/2007

## Emission reduction targets

The Council agreed new targets for the CO2 emissions of cars and vans.

| | 2025 | 2030 | |
|---|---|---|---|
| Cars | **15%** | ~~35%~~ | 37.5% |
| Vans | **15%** | ~~30%~~ | 31% |

*“Today's agreement is a further step towards new legislation on $CO_2$ emissions. It sets the European automotive industry on track to build cleaner cars, invest more in innovation, and report more reliable emission data”* – Elisabeth Köstinger, Austrian federal minister of sustainability and tourism

Smaller manufacturers would be exempt (but “small” is defined as 300 thousand cars/year)

- It should be remembered that these reductions would be in addition to reductions which have been required for years
- 95 [g/km] - 15 [%] = 80.75 [g/km]; 95 [g/km] - 37.5 [%] = 59.375 [g/km] (WLTP)
- **The overall FC-emissions trade-off will become even more important**

Sources: EU press releases, EU legislation (2018, 2019, 2020)

# WLTP & RDE are truly global topics

**WLTP**

- The WLTP is already the laboratory procedure used for the majority of cars sold globally (India still to join – 2021)
- The number of large/medium markets not using WLTP (e.g. USA, Russia, Brazil) is getting smaller…
- Developing countries which do not currently have any formal emissions requirements likely to move straight to WLTP in the future

**RDE**

- UN regulation and global technical regulation (GTR) on RDE currently under development
  - Agreements made on certain items (e.g. temperature/altitude range)
  - Other technical items remain subject to scrutiny/debate (EU-Japan-S. Korea)
  - Plan to submit to GRPE session in January 2021
- The EU, India, China, South Korea and Japan either already have RDE in force, or have confirmed plans for its implementation before 2023/24
- The USA (EPA-CARB) has no formal RDE test requirement, but has RDE-like provisions for defeat device detection
- Australia and Brazil are strongly considering introducing RDE (no dates confirmed)

*"This United Nations global technical regulation (UN GTR) aims at providing a worldwide harmonised method to determine the levels of Real Driving Emissions (RDE)…"*

# Heavy-duty sector: energy/$CO_2$ challenges > emissions challenges

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**Euro VII is expected, but HD sector is quite well placed regarding emissions control**

- Potential challenges include $N_2O$ from Diesel-SCR and $NH_3$, $N_2O$ and PN10 from CNG-TWC
- Electrical heating of aftertreatment probably required for Euro VII-level in service conformity (ISC PEMS)

**EU HD $CO_2$ legislation will probably prove to be a stronger driver of development than post-Euro VI**

Short-term targets can be met using combinations of existing technology; 2030+ targets require more radical approach

*Hydrogen is attracting strong interest (see below)*

**A range of strategies are under intensive investigation:**

Aerodynamics and powertrain electrification

Powertrain ICE enhancements – universal benefits, but very complex:

waste heat recovery, air management improvements

friction/parasitic loss reduction, general fuel delivery/combustion enhancements

Meeting fleet average $CO_2$ by means of selling substantial numbers of zero-emitting vehicles:

**$H_2$ ICE/fuel cell,** as well as electric vans/urban trucks/buses

“**Hydrogen** is a key solution to cut greenhouse gas emissions in sectors that are hard to decarbonise and where electrification is difficult or impossible. This is the case [for] heavy-duty transport…”

– European Commission, A Hydrogen Strategy for a climate neutral Europe, July 2020

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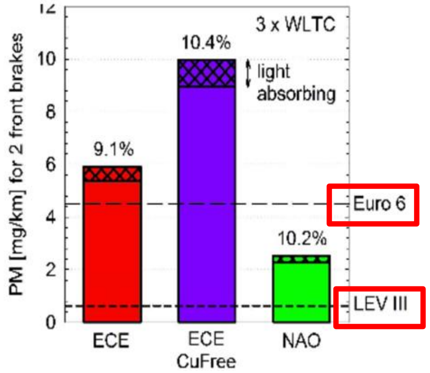
Nowadays, exhaust emissions of particulate are much lower (especially with DPF/GPF) and so non-exhaust emissions (brakes, tyres, clutch) are becoming more important than in the past

Let’s not forget about particle number emissions from vehicles which
- don’t burn carbon ($H_2$)
- don’t burn any fuel / don’t have a combustion engine of any kind




**Brake PM**
Source: Ilmenau Uni, 47th PMP meeting

**Vehicle Engines Produce Exhaust Nanoparticles Even When Not Fueled**

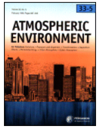
Topi Rönkkö†*, Liisa Pirjola‡, Leonidas Ntziachristos§, Juha Heikkilä†, Panu Karjalainen†, Risto Hillamo∥, and Jorma Keskinen†

Environmental Science & Technology

Particulate emissions from laser ignited and spark ignited hydrogen fueled engines

Akhilendra Pratap Singh, Anuj Pal, Neeraj Kumar Gupta, Avinash Kumar Agarwal

International Journal of Hydrogen Energy




Non-exhaust PM emissions from electric vehicles

Victor R.J.H. Timmers [a], Peter A.J. Achten [b]

**Which powertrain technologies will survive and which won’t?**

# LDV powertrain development in the EU (Euro 7)

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**LONG-TERM DEVELOPMENT →** beyond Euro 6d and to meet recently confirmed $CO_2$ requirements

- Further development of SI DI engines (lean burn?)
- Alternative fuels development (HVO, DME, Ethanol, Methanol, CNG/LNG)
- Reducing share of Diesel engines – new solution Diesel Hybrid
- CNG fuelled SI engines, GPF for all SI engines
    - GPF for PFI affects direct injection cost:benefit ratio
- Hybridization → MHEV, PHEV
- HCCI/GCI engines
- Electric powertrain → BEV
- E-fuels
- Fuel cells and hybrid fuel cells

**Not only electrification!**

# Range extenders: a question of ICE type, size, shape and location

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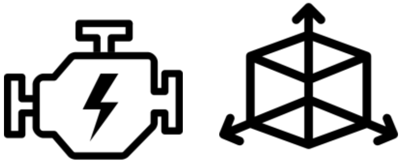
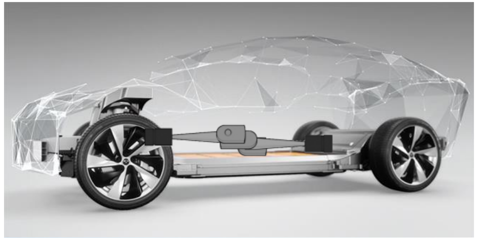
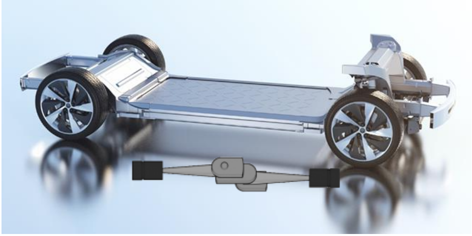
**Range extenders are a feasible way of increasing use of EVs in markets/areas with low charger density**



**Range extender ICEs are subject to different requirements and therefore different designs and concepts can be leveraged**

**Transient response is not an issue and operating point can be fully optimised**





Rotary (Wankel), opposed piston and free piston designs are all mentioned in this context – may influence general ICE development and even create new trends

Consideration of “dead weight” means that range extenders and all associated systems (aftertreatment, fuel storage/delivery, mechanical couplings) need to be light, with every kg saved offering additional pure electric range

In addition to weight, packaging is becoming ever more important:

- The so-called EV “skateboard” platform lends itself to long, flat engines – i.e. the exact opposite of current engine designs
- Space at the front of the vehicle is at a premium (excellent passive cooling)

# “High-brid” or “low-brid”? Real world performance is what counts

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Hybrid / EVs | Plug-in Hybrids

Shocking News! Plug-in Hybrid Cars Need To Be Plugged In!

September 21, 2017

Plug-in hybrid users branded ‘ridiculous’ for not charging their cars

November 12, 2018 / by Richard Aucock

**“The analysis has shown that the average $CO_2$ output is 168 g/km in day-to-day use”**

- Plug-in hybrids (PIH) can have very low tailpipe $CO_2$ emissions, but this is offset (at least partially) by $CO_2$ generated in the production of electricity (which varies significantly – from fully renewable to coal)
- **Low real-world PIH tailpipe emissions require that the battery be charged (!) *(“Who knew?”)***
- Many PIH purchased by companies to operate as fleet vehicles (high mileage, high proportion of motorway driving) because of tax incentives
- Vehicle users were unwilling to charge at home (own cost) – or physically unable to
- Employees don’t always have access to suitable charging facilities at work/while traveling on business
- **As a result, both FC and tailpipe $CO_2$ for PIH can be massively higher than advertised – significantly higher than an equivalent vehicle with a Diesel engine**
- A lack of suitable charging points / appropriate charging behaviour defeats the purpose of PIH and forces use of the combustion engine, which must deal with the dead weight of the hybrid system+battery
- Thus, the real-world $CO_2$ benefits of PIH can be zero-to-negative, even if carbon-free electricity is available

Sources: gas2.org, motoringresearch.com, themilesconsultancy.com

# EVs are still subject to the laws of physics (and finance) – nothing for free!

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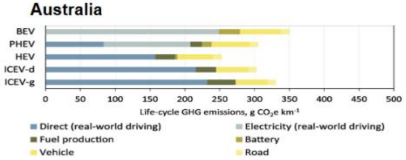
## Zero emission hype

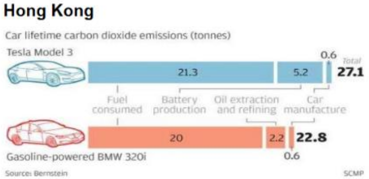

Zero emissions won't be possible until a "perpetuum mobile" is invented.

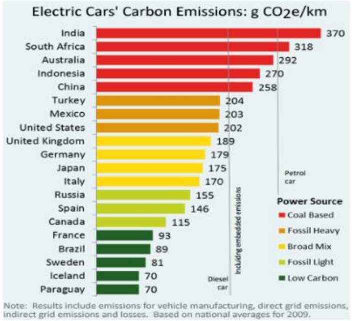

"Perpetual motion, the action of a device that, once set in motion, would continue in motion forever, with no additional energy required to maintain it. Such devices are **impossible** on grounds stated by the first and second laws of thermodynamics." *Source: Encyclopaedia Britannica*

## Zero emission? Not quite.

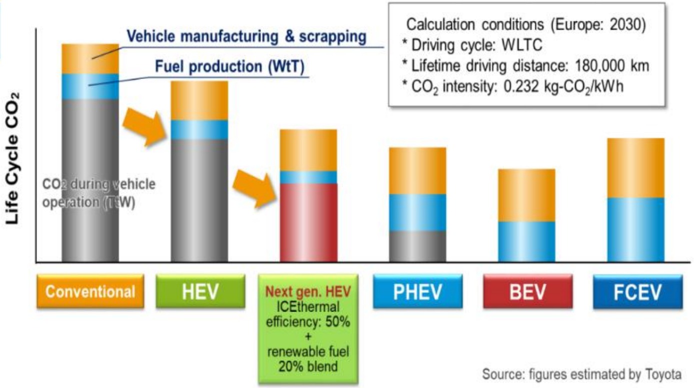



Ref.: P. Wolfram, T. Wiedmann, Applied Energy 206 (2017) 531-540.



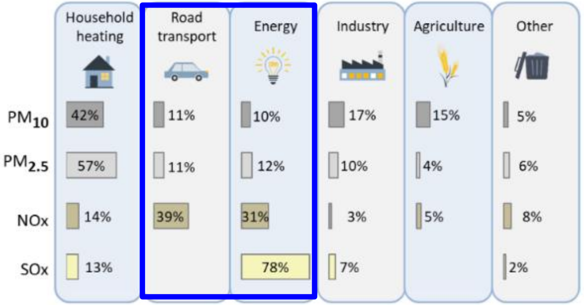




Source: Euan Mearns, Energy Matters, 2017




Source: figures estimated by Toyota

Not only $CO_2$: power generation creates PM/PN, $SO_x$, $NO_x$, CO, $NH_3$, PAH, etc (varies by fuel type)




Sources: B. Zhmud, ACI Base Oils & Lubricants Summit, Florence, Italy, 2018;
K. Keiji, "Diversified electrification" Vienna Motor Sympoiusm 2019;
European Environment Agency 2019

# Choose your poison – hydrocarbons or electrons

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| Battery system hazards | | | BMS hazards |
|---|---|---|---|
| Electrochemical hazards | Electric hazards | Mechanical hazards | Battery cooling fault |
| Emission of toxic or flamable gas | Short circuits | Crash | Battery heating fault |
| Emission of toxic or flamable liquid | Loss of electrical continuity | Liquid ingress | Communication fault |
| Electrolyte leakage | Impedance increase | Operator fault | Short circuit |
| Cell fire | | Road bump / road debris | Overcharge due to BMS fault |
| Thermal runaway | | | Overtemperature due to BMS fault |
| | | | Overdischarge due to BMS fault |

Manufacturers of EVs have provided guidance for first responders (police, fire, ambulance) – e.g. [https://aar.com/standards/pdfs/2018_LEAF-first-responders-guide.pdf](https://aar.com/standards/pdfs/2018_LEAF-first-responders-guide.pdf)

Source: Adama, B. (Samsung), 2018

# Raw materials needed to produce lithium-ion electric

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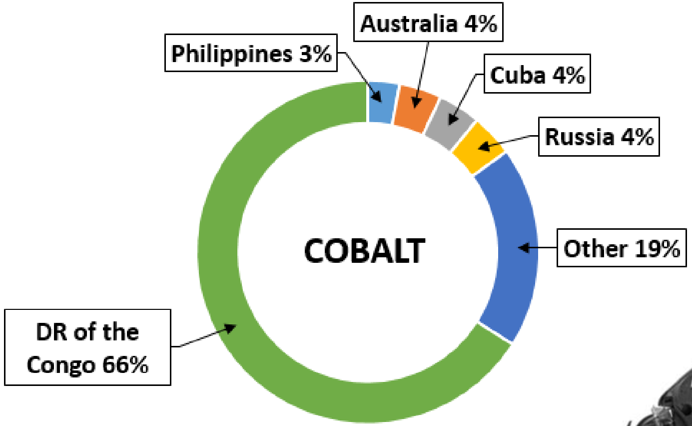


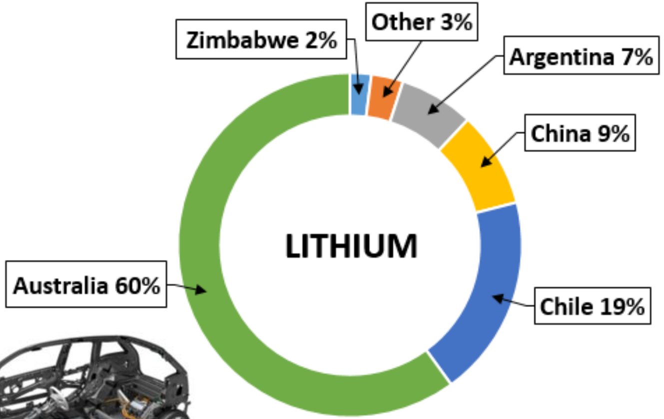


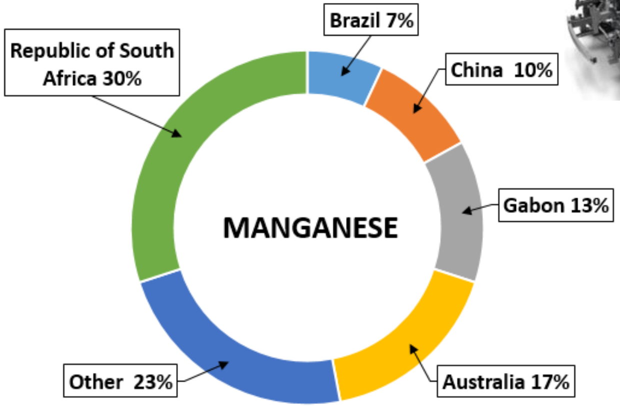


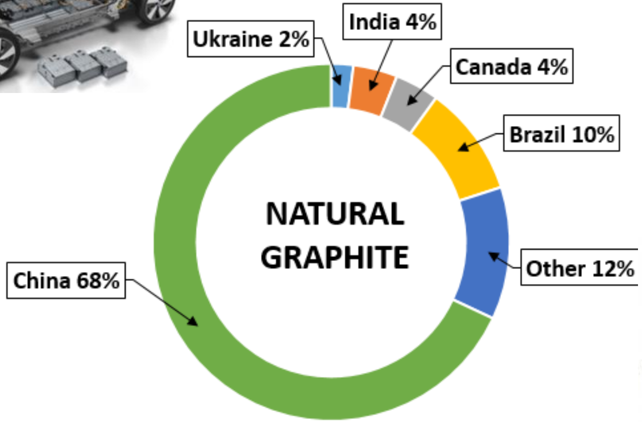


Very rapid development in alternative means of transport (especially urban): electric bicycles, scooters, electric tricycles (especially in China), **all equipped with batteries**.

This causes intense competition for key raw materials – see graphs.

# Hydrogen: lightening the load?

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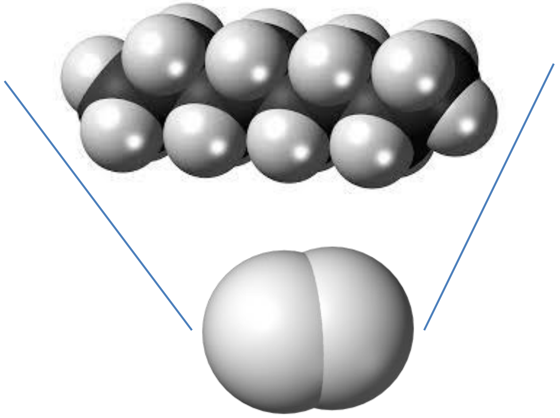
**The concept has a long history and has been abandoned several times in the past. Has the time finally come for $H_2$ in road transport? $CO_2$ legislation and concern over electrical powertrains' weak points is driving very strong interest in $H_2$**



**Usage in ICE – stepping stone from current technology:**

- dual fuel (potentially including retrofit)
- bi-fuel (potentially including retrofit) – overcome range concerns
- monofuel (dedicated designs to make use of high RON) – zero $CO_2$

**Usage in $H_2$ fuel cells:**

no combustion, no $NO_x$; FCEVs already on the market
Seen as a key route for the HD sector to reduce (even eliminate) $CO_2$ emissions

**Problems of production and storage:**

Water is stable and electrolysis is energy-intensive – ongoing research into catalysts and maximising use of renewable electricity
Locations with high solar flux and access to water could become $H_2$ hotspots
Storage and transport of gaseous fuels (also when liquified) is challenging – very low overall efficiency for small quantities
Highly uneven, mostly underdeveloped infrastructure: USA and China both have <100 $H_2$ refuelling points…but Japan has >130
General and sector-specific safety concerns remain – not clear to what extent the public accept H2 as safe

# Fuel cell electric vehicles (FCEVs)

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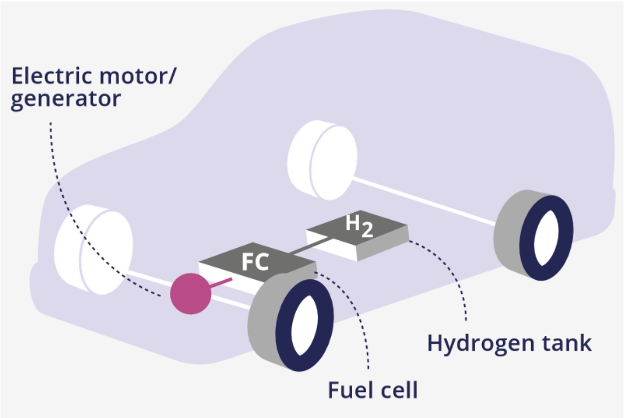
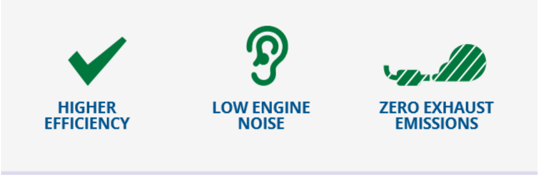
FCEVs are entirely propelled by electricity. In this case, the electrical energy is not stored in a large battery system, but is instead provided by a fuel cell 'stack' that uses hydrogen from an on-board tank combined with oxygen from the air. The main advantages of FCEVs over BEVs are their longer driving ranges and faster refuelling. Because of the current size and weight of fuel cell stacks, FCEVs are better suited for medium-sized to large HD vehicles and buses and longer distances.




**ADVANTAGES**




Source: Electric vehicles in Europe; EEA Report | No 20/2016

**DISADVANTAGES**


Fuel cell electric vehicles use a fuel cell to create on-board electricity, generally using compressed hydrogen and oxygen from the air.

Further technological development is needed for FCEVs to improve their durability, lower the costs and establish a hydrogen fuelling infrastructure, including standalone stations or pumps for hydrogen. **Indicative electric driving range: 160– 500 km.**

# Hybrid Fuel Cell Powertrain

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- Electric vehicles combined with batteries and equipped with fuel cell technology – an **innovative** and **favorable** solution
- Concept offers zero emission from tank-to-wheel
- So far, the automotive industry has **focused mostly on pure battery versus pure fuel cell approaches**
- This powertrain concept is a combination of battery and fuel cell technologies in a single dedicated hybridized powertrain architecture, benefitting from all possible synergies available
- **High range can be achieved (>> 600km)**
- Effective hydrogen storage still a **challenge**

- This approach toward a hybridized fuel cell vehicle **overcomes** the current barriers of electromobility as the driveability performance, but **there is still much to do in term of optimization**
- **Heavy duty sector could act as an incubator for fuel cell technology, later passing to light duty**

**Source**: Hybrid Fuel cell Powertrain. Electric & Hybrid Technology International. January 2018.

# Hybrid Fuel Cell Challenges

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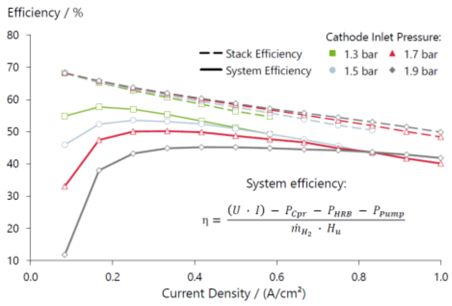
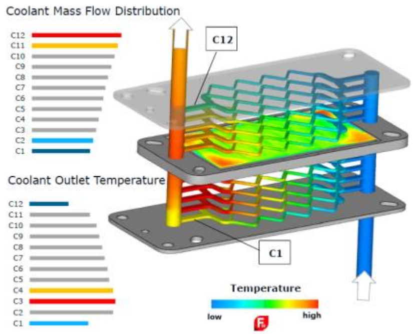
- **Efficiency:** achieving efficiency high at high current densities, with implications for FC size and weight and the possibility of using smaller cells

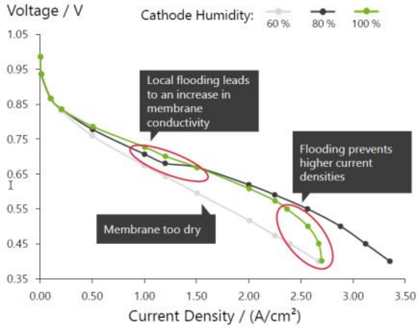
- **Thermal management:** generally moderate temeperatures, but no exhaust flow to carry away heat, other design requirements complicate cooling

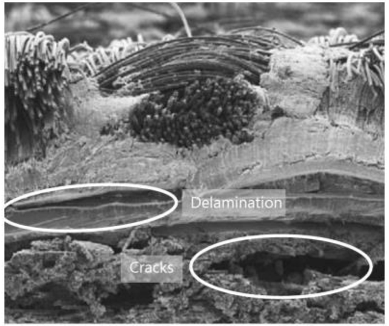
- **Durability/reliability/long-term performance:** mitigation of cold start effects (i.e. damaging impact of water and ice), general humidity management and avoidance of blockages

- **Hydrogen fuel:** general considerations and concerns (storage, dosing, safety, legal considerations, etc)




**Main sources, image sources:** S. Pischinger (FEV), SAE PF&L keynote, 22.09.2020; AVL Virtual Fuel Cell Development Webinar, 29.06.2020 – mobex.io
**Additional sources:** FEV, Ricardo (2020) – mobex.io

# Beyond carbon: ammonia as fuel and/or hydrogen carrier

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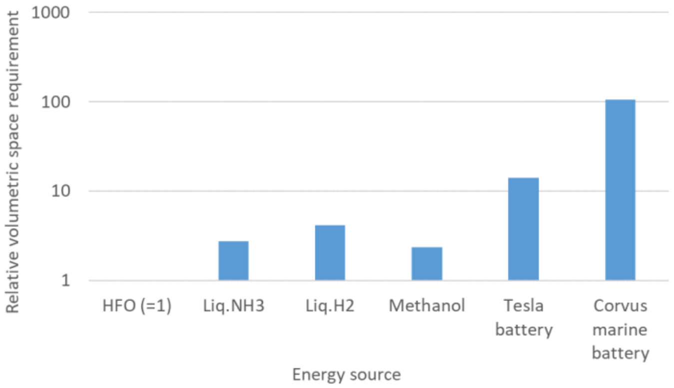
Ammonia is flammable and was first proposed as a fuel decades ago
Usage has been very limited, but it can be burned in practical combustion engines (RON=130). Emissions of concern are high levels of $NO_x$ and $NH_3$, which can be remediated by suitable aftertreatment (SCR)
$NH_3$ is much discussed for marine applications, but seems highly unsuitable for road vehicles and especially for passenger cars.

However:
Formation of $NH_3$ via innovative methods (e.g. reverse fuel cells) can create a carbon-free energy carrier of high density (liquid ammonia). The energy intensity of the process can be aided by improved catalysis and processes can be powered by a high share of renewable energy.
Liquid $NH_3$ can be transported to its destination market and decomposed to $H_2 + N_2$, again aided by advanced catalysts. $NH_3$ boiling point -33°C (compare $H_2$ -253°C)

Sources: MAN (2019), ammoniaenergy.org (2020)




**"Ammonia—a renewable fuel made from sun, air, and water—could power the globe without carbon" – *Science*, 2018**


# e-fuels: the promised fuel from water and air, via green electrons

E-fuels are synthetic fuels created using hydrogen produced using sustainable electricity
Carbon input options are $CO_2$ obtained from biogenic/industrial processes, or even capture of $CO_2$ from the atmosphere

Why?
E-fuels: pathway to use renewable electricity, avoid heavy batteries and improve the sustainability of the current fleet – can be burned in a wide range of ICE
$CO_2$ capture from the atmosphere closes the circle

Technology readiness levels (TRLs) of the various sub-processes are higher than often assumed
Difficulties with scale-up and attracting funding; traditional business models not always suitable
High costs have proven extremely problematic, but situation may change by 2050
Incremental improvements in catalysis, photovoltaics, etc all play a part

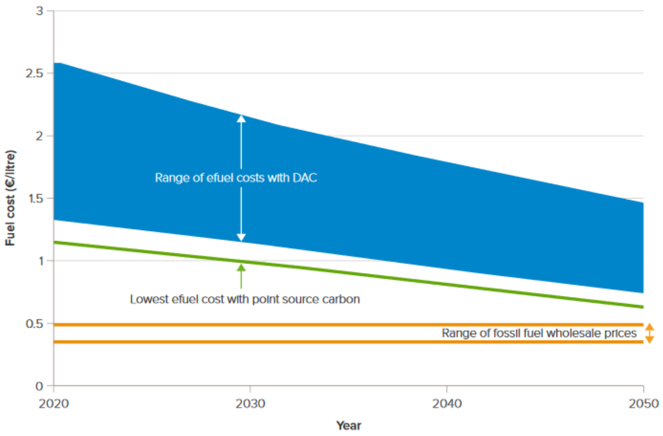
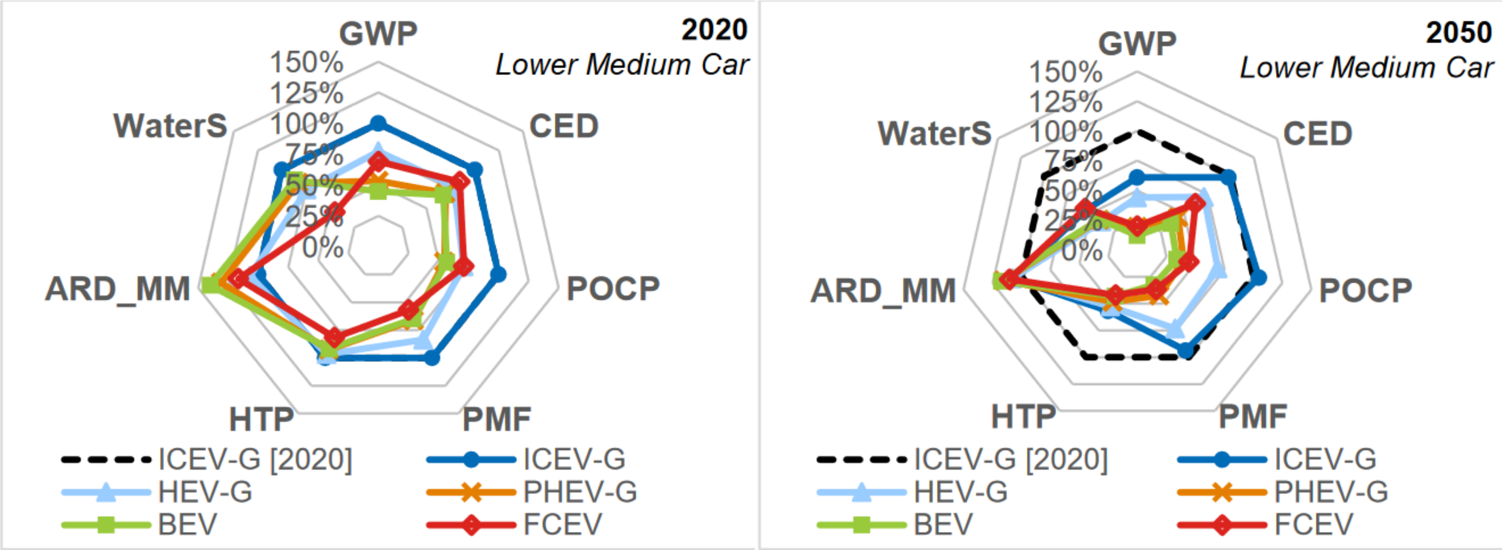



Image source: UK Royal Society Briefing DES6164 (2019); other sources: CONCAWE Report no. 14/19 (2019), Hanggi et al. A review of synthetic fuels for passenger vehicles (2019)

# Full LCA comparison: various powertrains vs 2020 ICE

**Figure ES4: Summary of the relative impacts for Lower Medium Cars for the most significant mid-point impacts for road transport, by powertrain for 2020 and 2050 (Tech1.5 Scenario)**




*Notes*: Total emissions are presented relative to a 2020 conventional gasoline ICEV = 100%.
**Powertrain types**: G- = Gasoline; ICEV = conventional Internal Combustion Engine Vehicle; HEV = Hybrid Electric Vehicle; PHEV = Plug-in Hybrid Electric Vehicle; BEV = Battery Electric Vehicle; FCEV = Fuel Cell Electric Vehicle.
**LCA impacts**: GWP = Global Warming Potential, CED = Cumulative Energy Demand, POCP = Photochemical Ozone Creation Potential, PMF = Particulate Matter Formation, HTP = Human Toxicity Potential, ARD_MM = Abiotic Resource Depletion, minerals and metals, WaterS = Water Scarcity.

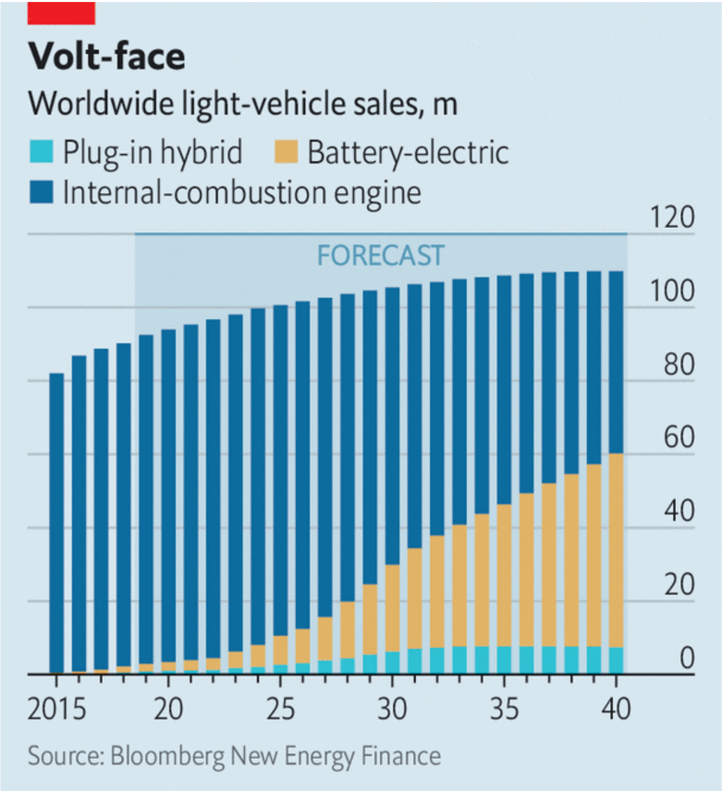
**Source:** https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/2020_study_main_report_en.pdf

~~Tank to wheel~~→life cycle

~~Only $CO_2$/electricity~~→ 7 impact categories over full life cycle

# Forecast for worldwide light vehicle sales

BOSMAL




The Economist

Worldwide light-vehicle sales for 2019-2040, as forecast by *Bloomberg* & *The Economist*.

The number of battery-electric cars sold will grow 30 times and there will be a slight rise in sales of plug-in hybrid vehicles. At the same time, sales of internal-combustion engine vehicles will fall.

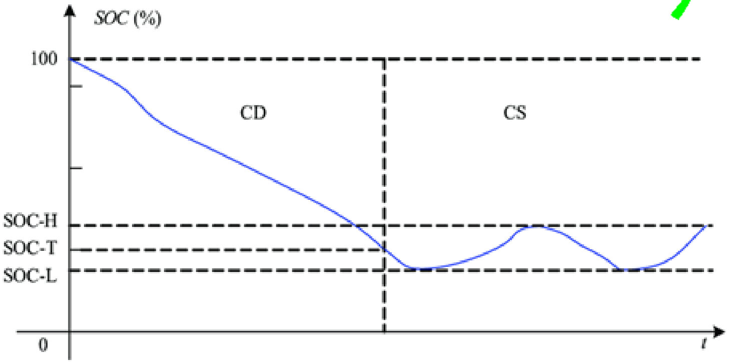
However, the ICE proportion is forecast to be ~40% even in 2040 (this includes non-plugin hybrids); plug-in hybrids (here shown separately) also have combustion engines

**Challenges in elelctrified powertrain test methods -WLTP and RDE regulations are causing a massive increase of testing procedures for R&D and TA**

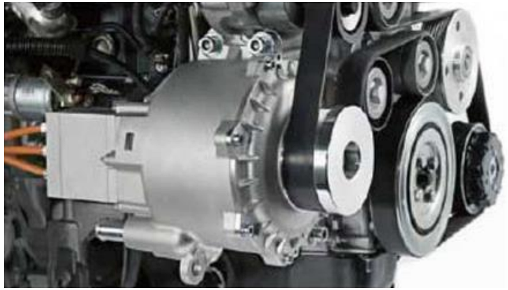
# Powertrain development- hybrid/electric vehicles/powertrains tests

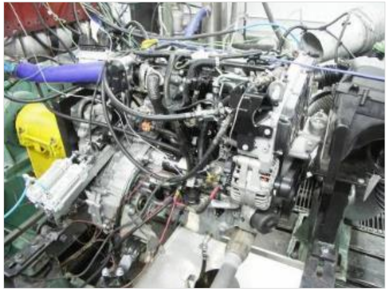
## Activities carried out on hybrid vehicles/ powertrains

**Chassis dyno:** Start-Stop system validation, full hybrid vehicle emissions testing at multiple ambient temperatures and SOC values; PER determination




**Engine dyno:** durability testing of mild hybrid/BSG systems with a low voltage battery emulator, Start-Stop system validation



# BOSMAL on POWERTRAINS: test bench approach

**Vehicle testing for all powertrain technologies (ICE, hybrid, EV, FCE):**

- 2 chassis dynos compliant to the newest emission legislation requirements
- Emission measurements of IC-engine and hybrid powered vehicles
- Chassis dyno built-in climatic chamber
- Certified technical service for Type-approval procedures
- Electric and hybrid vehicles energy consumption and range measurements
- PEMS measurements (HD & LD)
- Fleet testing / mileage accumulation / emission deterioration

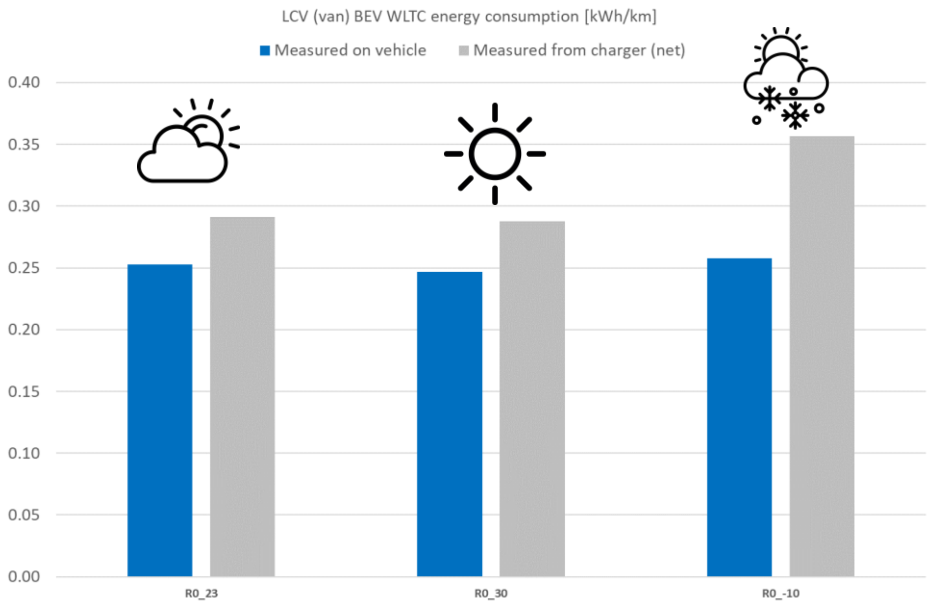
# Chassis dyno testing of heavily electrified powertrains

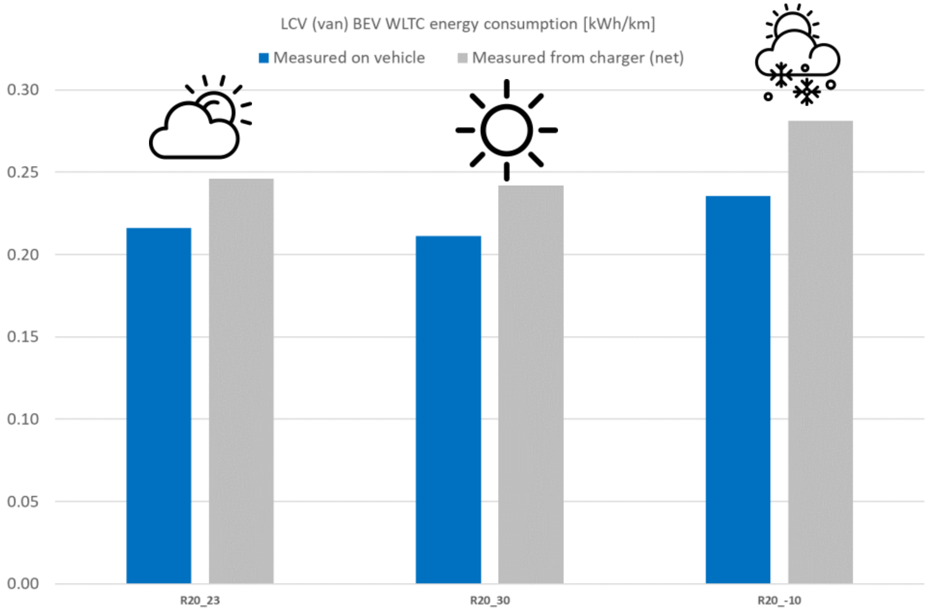
- Type approval requirements for hybrids of all types, EVs and FCEVs given in legislation – procedures are longer and somewhat more complicated than for ICE-only vehicles
- Highly electrified powertrains where the ICE rarely runs represent an emissions testing challenge
- Extensive R&D requirements which differ from those of ICE-powered vehicles
- Optimisation of control strategy (especially regenerative braking) for range, drivability, NVH, safety, etc
- Optimisation of thermal management and energy recovery following intensive deceleration
- Electrical load has a large impact on range – much scope for optimisation
    - Lack of waste heat (no ICE or ICE mainly off)
        - testing at low ambient temperatures (inc. window demisting, cabin heating)
        - testing at high ambient temperatures (inc. use of air conditioning)
    - Use of other systems and accessories at any ambient temperaturę
- Recreation of real-world scenarios (full climate control, slope simulation)

# BEV performance at various ambient temperatures

BOSMAL

**Tests of the energy consumption of an electric van at three different ambient temperatures (+30°C, +23 °C, -10 °C) and two different energy recovery strategies**




- **Energy consumption measured on this vehicle was always lower than the charge balance**
- **Small difference in energy consumed between 23°C and 30°C (when air conditioning is not used)**
- **Larger difference at -10 °C**

**Source: BOSMAL data**

# Powertrain development/ elelctric motor testing

## MD/HD/hybrid/electric dedicated test cell

**Fully Dynamic AC Dyno (DynoExact 504/5 Px):**
500kW/3000Nm – 5 000 rpm

**Test bench software functionalities:**

- iGEM
- ISAC
- InMotion
- AVL PUMA OPEN 1.5.5

**AVL e-storage DC Power Unit**:

- Nominal capacity: 160 kW
- Output voltage: 8-800 VDC
- Output current: 600 A
- Fixed on the test bench no. 19

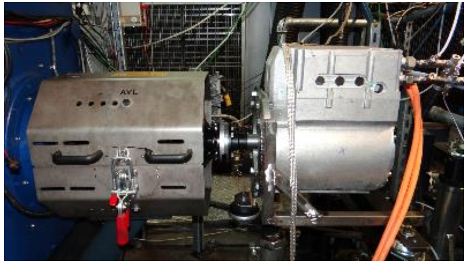
**Regatron Low Voltage Battery Emulator**:

- Nominal capacity (max): 20 kW
- Output voltage (max): 65 V
- Output current (max): 385 A
- Portable unit (mobile usage)


**Power analyzer (Yokogawa unit)**

## Automotive electric motor testing

- Measurements of motor performance: T = f(n), P = f(n),
- **NET MAX POWER OUTPUT** measurements
- **NET POWER OUTPUT in 30 MINUTES**



# Testing of hydrogen mixtures fuelled ICE engines ($H_2$, CNG+$H_2$; syngas)

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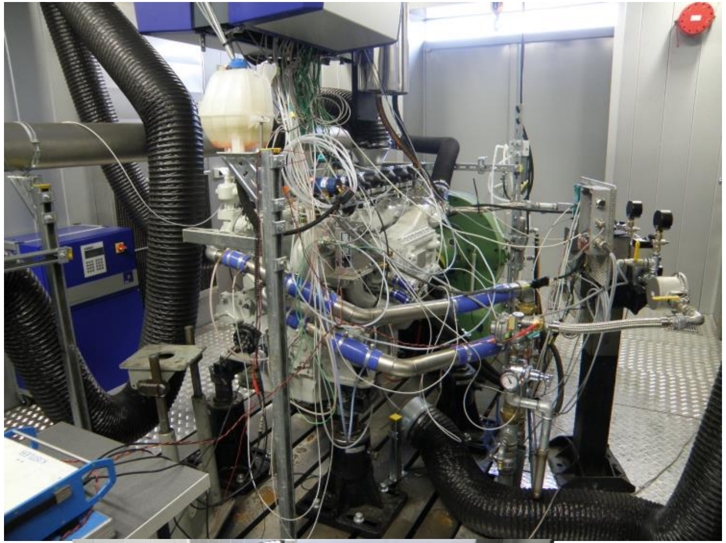
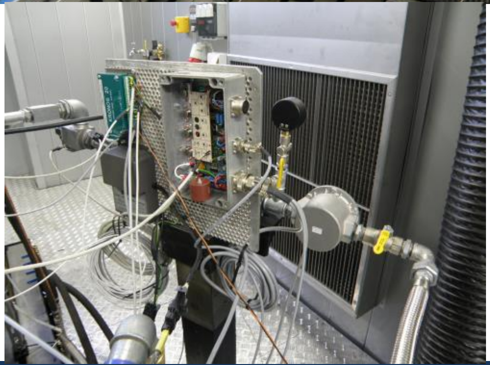




## CNG Infrastructure

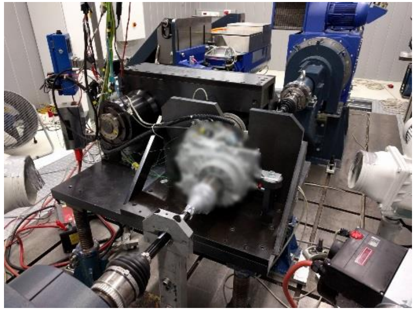

# BOSMAL on POWERTRAINS: test bench approach

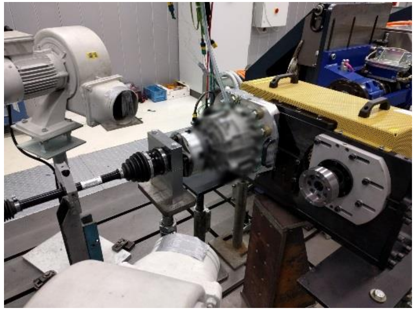
BOSMAL

## Transmission and e-axles test bench

**Key features:**

1. Wide range of powertrain components covered:
   - E-motors
   - E-axles
   - Hybrid transmissions
   - MT, CVT, AT, DCT
2. Driver/road/vehicle simulation under transient conditions
3. Constant Reilhofer deltaAnalyser and CrashPreventer monitoring





# Conclusions

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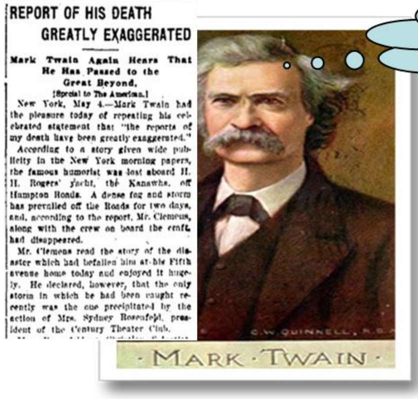
- Despite huge pressure for powertrain electrification, it would be very difficult to give up on ICEs for road transport – important ICE market share will remain (mainly in various hybrid configurations and HD vehicles )
- The IC engines used in hybrid powertrains with significant electrical range may strongly differ from those currently in use
- Demanding $CO_2$ standards are also in force and are strongly pushing hybridisation, electrification and use of low-carbon or non-carbon fuels (hydrogen)
- LCA gives a basis for PWTs comparison - in 2020 and 2050 the hybrid/battery/fuel options score well for global warming potential and human toxicity potential, with variable results for other impacts, but all alternative powertrains perform poorly for depletion of abiotic resources (minerals and metals)
- Fel cells can be a solution for the road transport sector. There are certainly advantages, but there are still significant challenges to overcome before widespread commercialization is possible
- E-fuels (carbon-based, but synthetic) could be a good compromise between electrified powertrains and ICE
- Manufacturers have very strong incentives to work on electrification (mainly light duty), fuel cell (mainly heavy duty), as well as natural gas (both sectors)



Image source: UK Royal Society Briefing DES6164 (2019); other sources: CONCAWE Report no. 14/19 (2019),

# ICE case…



REPORT OF HIS DEATH GREATLY EXAGGERATED

Mark Twain Again Hears That He Has Passed to the Great Beyond.

[Special to The American.]

New York, May 4.—Mark Twain had the pleasure today of repeating his celebrated statement that "the reports of my death have been greatly exaggerated."

According to a story given wide publicity in the New York morning papers, the famous humorist was lost aboard H. H. Rogers' yacht, the Kanawha, off Hampton Roads. A dense fog and storm has prevailed off the Roads for two days, and, according to the report, Mr. Clemens, along with the crew on board the craft, had disappeared.

Mr. Clemens read the story of the disaster which had befallen him at his Fifth avenue home today and enjoyed it hugely. He declared, however, that the only storm in which he had been caught recently was the one precipitated by the action of Mrs. Sydney Rosenfeld, president of the Century Theater Club.



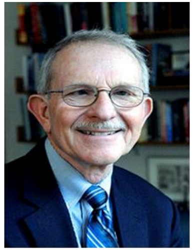
*"the reports of my death are greatly exaggerated"*

*"the reports of ICE engines' death are greatly exaggerated"*

the rumour disruptors….

*Professor John B. Heywood:*

***"there is still some life left in combustion engines…"***



Prof. Heywood predicts that in 2050, 60% of light-duty vehicles will still have combustion engines, often working with electric motors in hybrid systems and largely equipped with a turbocharger. Vehicles powered purely by batteries, he estimates, will make up 15% of sales (**PANEL DISCUSSION during 2018 SAE World Congress**)

**2018 expert opinion: "Up to to about 80% of passenger cars will be equipped with Combustion Engines as individual powertrain source or in hybrid system to 2030"** SAE 2018 International Powertrains, Fuels & Lubricants Meeting, 17-19 September 2018, Heidelberg, Germany, Expert Panel Discussion: 'The Future of Combustion Engines' – participants' overall conclusion

**2019 expert opinion: "The final propulsion solution for passenger cars will be a hybrid which can deliver the advantages of both EVs and ICEs"** SAE 2019 WCX, 9-11 April 2019, Detroit, USA, Expert Panel Discussion: 'EU/China Emissions Regulations' – participants' overall conclusion

**2020 expert opinion from various conferences: "ICEs will remain in use in road transport for decades, perhaps as hybrids and perhaps fuelled with e-fuels and hydrogen (in some cases)"**

# Thank you – Questions welcome

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Send questions/comments to

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