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Comparing Assessment of Passenger Cars with Batteries and Fuel Cells

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IEA Annex 26

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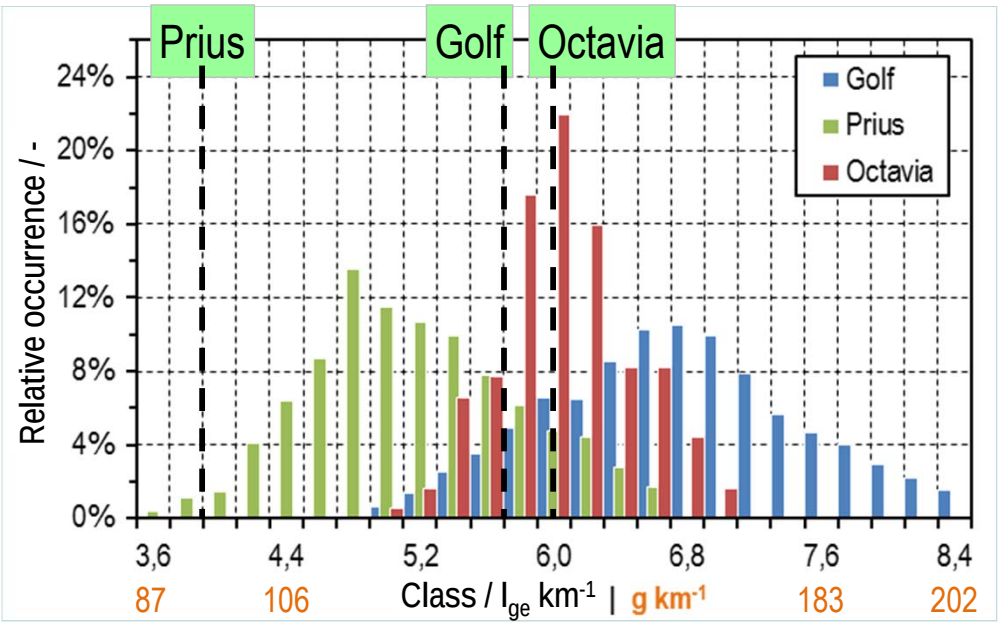
Motivation



Are fuel consumption values realistic?

Coefficient of variation:
14 % (Golf 1.2 TSI), 15 % (Prius III) und 9 % (Octavia 1.9 TDI)

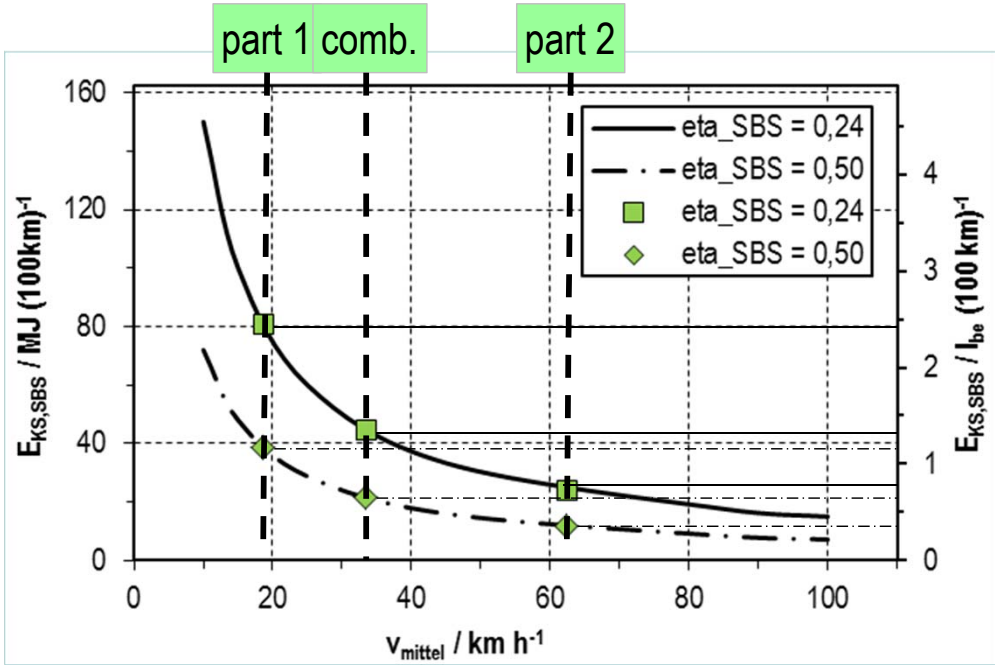
VW Golf VI, 1.2 TSI, 77 kW, MY 2010-2012, statistical population: 2120 values, 78 *users*, source: www.spritmonitor.de; Toyota Prius III, 100 kW, MY 2011, statistical population: 2511 values, 49 *users*, source: www.spritmonitor.de; Skoda Octavia Kombi, 1.9 TDI, 77 kW, MY 2006, source: own calculations, statistical population: 182 values; 2σ ranges of histograms, conversion factors: gasoline: 32,5 MJ l^{-1}, 74,0 g_{CO2} MJ^{-1}; diesel: 35,5 MJ l^{-1}, 73,3 g_{CO2} MJ^{-1}

What is the effect of auxiliary electric power?

- 1 kW_e additional power
- 0,7 – 2,5 l_{ge} (100km)$^{-1}$ at $\eta_{diff,m}$ = 0,4; η_G = 0,6 → η_e = 0,24
- 0,4 – 1,2 l_{ge} (100km)$^{-1}$ at η_e = 0,5

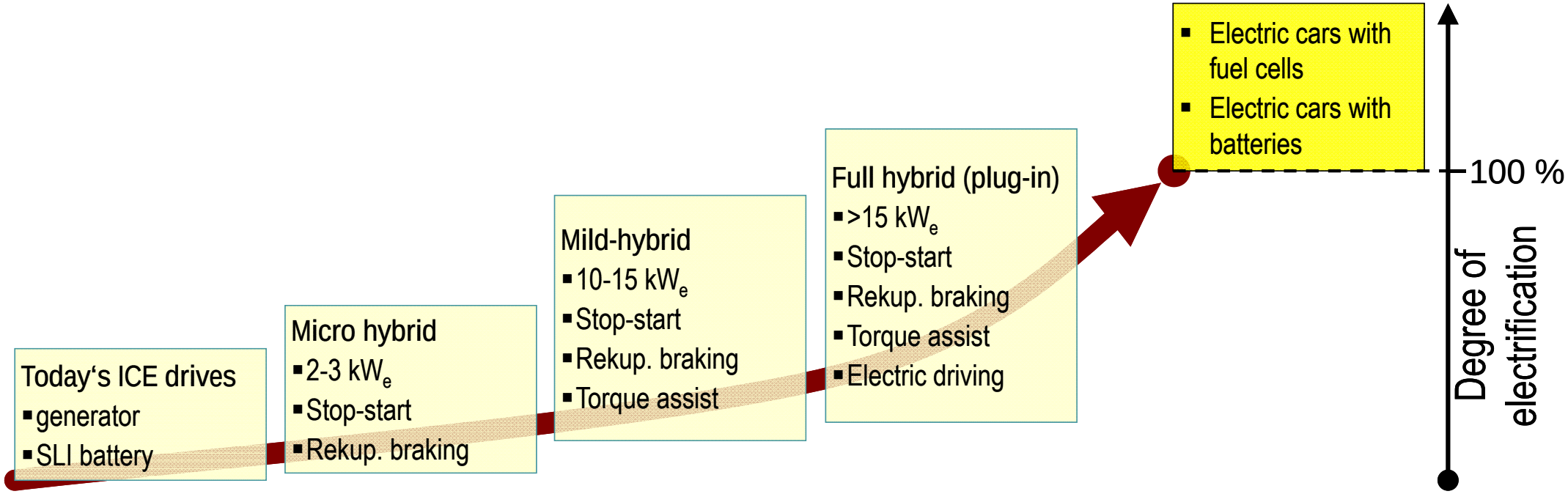
Values refer to legal rule 80/1268/EWG,
part 1: city; part 2: extra-urban; comb.: combined

Indices: diff: differential; e: electric; G: generator
m: mechanical; SBS: electricity provision system; l_{ge}: liters of gasoline equivalent; KS: fuel



Introduction

- Energy strategic targets import dependency, environmental impact, economic competitiveness
- Mobility: new fuels and powertrains for road traffic:
  - *Advanced, increasingly hybridized powertrains with ICEs*
  - *Plug-in hybrids with ICEs*
  - *Zero emission powertrains with batteries*
  - *Zero emission powertrains with fuel cells*



Assessment Task

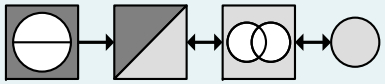
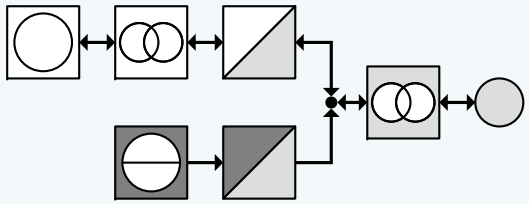
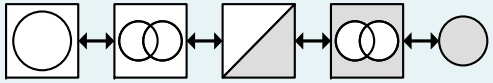
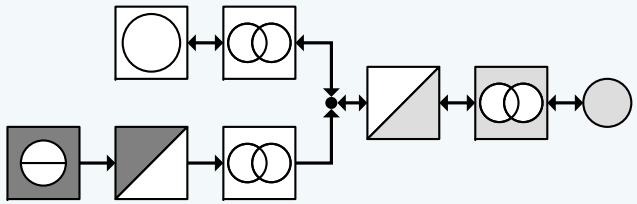
Assessment and evaluation of potentials for fuel consumption reduction by utilizing electric power:

- Passenger car concepts with different levels of electricity use ICV, PAH, BEV und FCV
- **Systematic assessment framework:**
  - *Vehicle parameters: cross-sectional area, drag coefficient, vehicle mass determination*
  - *Performance: top speed, acceleration, gradability*
  - *Load profiles: mechanical, electric, thermal*
- Car segments (EU classification): A (small) and C (compact)
- Development progress regarding component performance, vehicle mass
  → Definition of scenarios „Standard“ und „Future“
- Photovoltaic modules and thermoelectric generators

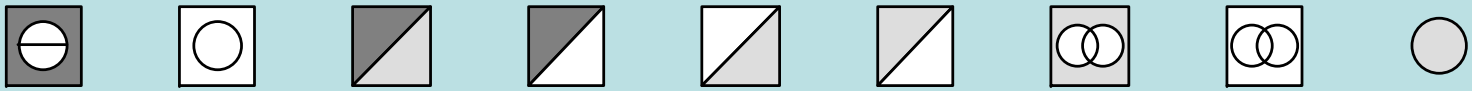
Methodology: Fuel consumption analysis with dynamic powertrain simulations

BEV: Alectric car with batteries; FCV: Electric car with fuel cells; ICV: cars with ICEs; PAH: parallel hybrid with ICEs

Passenger car concepts

ICV	Passenger car with Otto- or Diesel engines (*Internal combustion engine vehicle*)	
PAH	Parallel hybrid with Otto- or Diesel engines, electric motor/generator and Battery	
BEV	Electric car with battery (*Battery electric vehicle*)	
FCV	Electric car with fuel cells (direct hydrogen) and batteries (*Fuel cell electric vehicle*)	

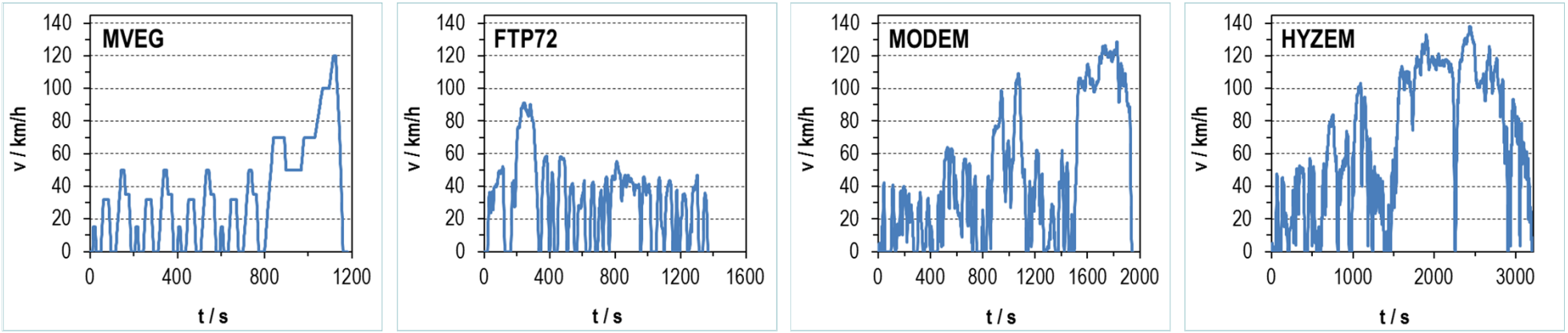
Legende



Graphic representation: after Isermann (2010), Elektronisches Management motorischer Fahrzeugantriebe, Vieweg+Teubner 2010

Fuel Consumption Analysis with Dynamic Powertrain Simulation

- Computational on the basis of simulation models:
  - *Quasi-static or dynamic models with physical or performance maps based component modelling*
  - *Examples: AVL CRUISE, ADVISOR, PSAT Engine/Autonomie*
  - *In this work: own model development on the basis of Matlab/Simulink®*
- Load profiles:
  - *mechanic: drive cycles for a large variety of user profiles e.g.*



  - *electric: base load and additional loads in the 14 V vehicle grid*
  - *thermal: cabin heating/cooling*

Model Parts and Vehicle Performance

- Longitudinal passenger car simulation:
  time-dependent velocity (25 cycles), Vehicle parameters (A- and C-Segment)
- Efficiency map based models of ICEs and und electric machines:
  M over n, consumption or efficiency tables, specific power
- Battery model as equivalent circuit model:
  internal resistance and RC-circuits, specific power and energy
- Fuel cell system: u-i curve of fuel cell, energy and molar balance, auxiliary consumers, specific power of fuel cell system, specific energy of pressure tank
- 14 V and high-voltage consumers:
  On/off cycles (14 V) or time-dependent power (cabin heating and cooling)
- Optimizing operational strategy and brake energy recovers:
  Optimization of system efficiency and maximization of rekuperative power
- Iterative determination of power class and vehicle mass:
  Performance: top-speed, acceleration, gradability, operational range

Parameter	Dimension	A-segment	C-segment
Top speed, v_{max}	$km\ h^{-1}$	160 (BEV: 130)	180 (BEV: 160)
Acceleration, $t_{0/100}$	s	12	11
Max. gradient angle, $\beta_{St,max}$	°	16,7	16,7
Operational range of BEV	km	150	150

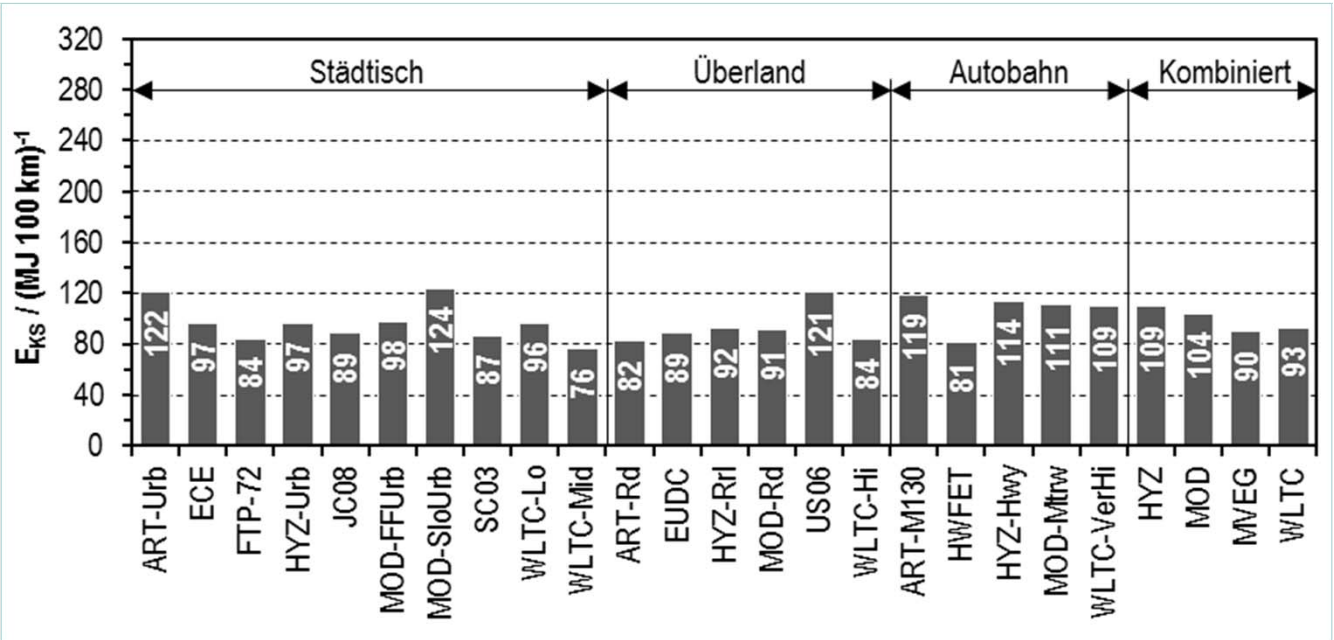
Simulations per Concept and Car Segment

- Two scenarios: „Standard“ und „Future“: Different assumptions for c_W, $f_{roll}(v)$, m_{veh}, specific power and energy, performance maps and power demand of A/C

- Four load cases:

Load cases	Grundlast	Weitere 14 V-Verbraucher	Klimatisierung
GRL: „Base load“	■	□	□
KKL: „No A/C“	■	■	□
SOT: „Summer day“	■	■	■ (A/C)
FRT: „Frost day“	■	■	■ (HE)

- 25 drive cycles, repeated simulations for balanced SOC

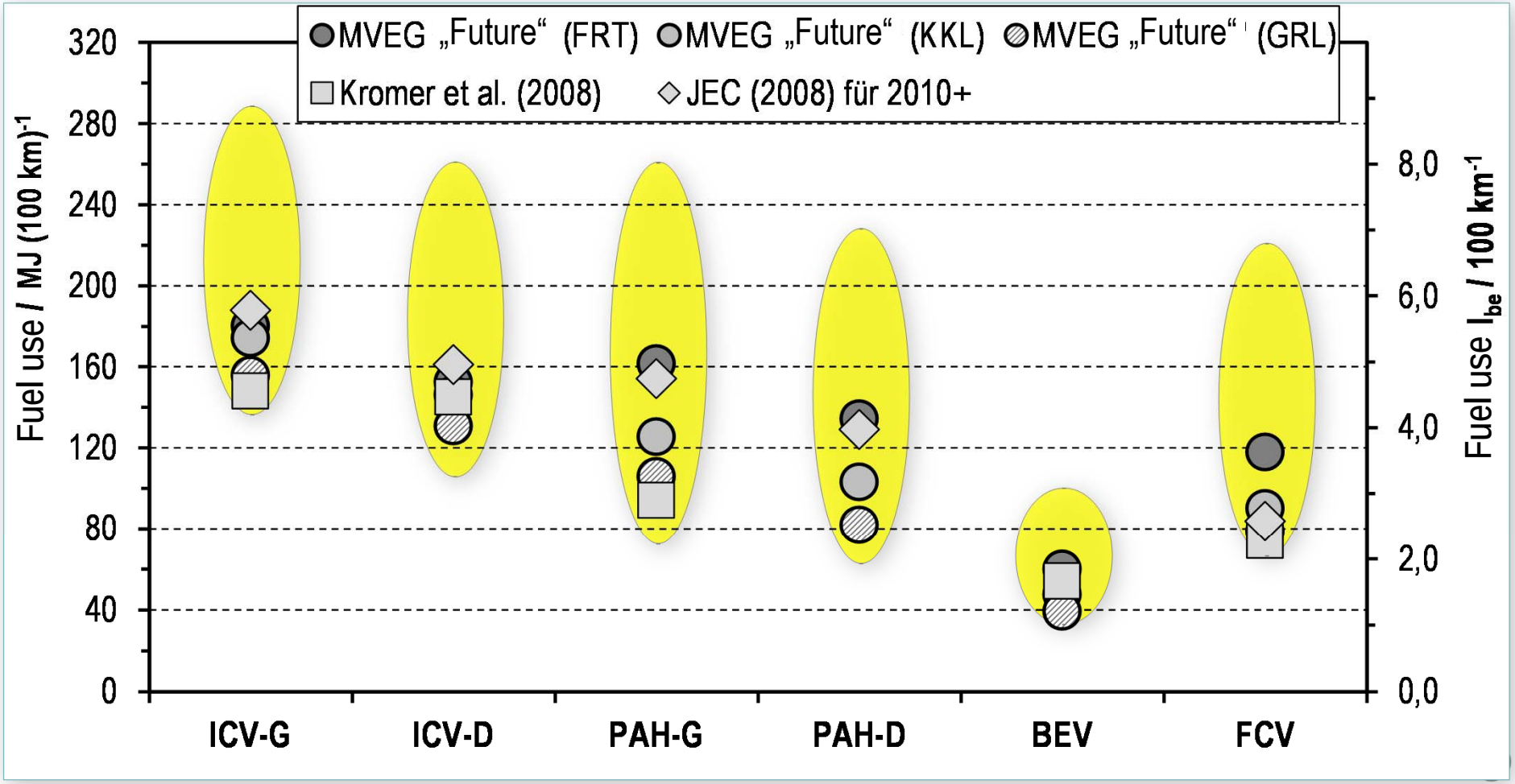


Example for C-Segments FCV:
Scenario: „Zukunft“,
Load case: „No A/C“

Results

Comparison of consumption values „Future “ with data from literature

- Comparable to Kromer et al. (2008) and JEC (2008): MVEG „Future“ (GRL)
- Differences in performance maps and operational strategies are decisive



MVEG: European Drive Cylce(kombiniert); FRT: „Frost day“; GRL: „Base load“; KKL: „No A/C“

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Comparison of Studies

Thomas Grube and Bernd Höhlein

Relevant Concepts After JEC 2014 (TTW Report 4a)

- **Internal combustion engine** (DISI, SI and DICI)
- **HEV** (Parallel or series hybrid, high voltage battery for few km)
- **PHEV20-DISI/CI*** (2020+: series hybrid, external HV battery charging for 20 km; cf. p.61)
- **BEV** (HV battery with 22 kWh determines operational range and vehicle weight; cf. p.74)
- **FCEV** (2020+: fuel cell drive with 4 kg_{H2} for 500 km at the least, 1 kWh HV battery; cf. p.74)
- **REEV80-DISI/CI*** (2020+: ICE as Range extender, external HV battery charging for 80 km; cf. p.61ff)
- **REEV80 FC** (2020+: Fuel cell drive according to **FCEV,** HV battery with 11 kWh for 80 km; cf. p.74)

BEV: Battery car; CI: Diesel engine; DICI: Diesel engine with direct injection; DISI: Otto Engine with direct injection; EM: Electric machine; ge: gasoline equivalent; HV: high voltage; FC: fuel cell; FCV/FCEV: fuel cell vehicle (H_2, hybrid); HEV: Hybrid (ICE basis); PHEV: Plug-in HEV (ICE basis); REEV: battery car with Range extender; TTW: Tank-to-wheel; ICE: internal combustion engine

Fuel Consumption and Emissions of REEV and PHEV

After ECE-Norm R 101 (August 2011) with MVEG drive cycle (ca. 11km)

$$C = \frac{D_e \cdot C_1 + D_{av} \cdot C_2}{D_e + D_{av}}$$

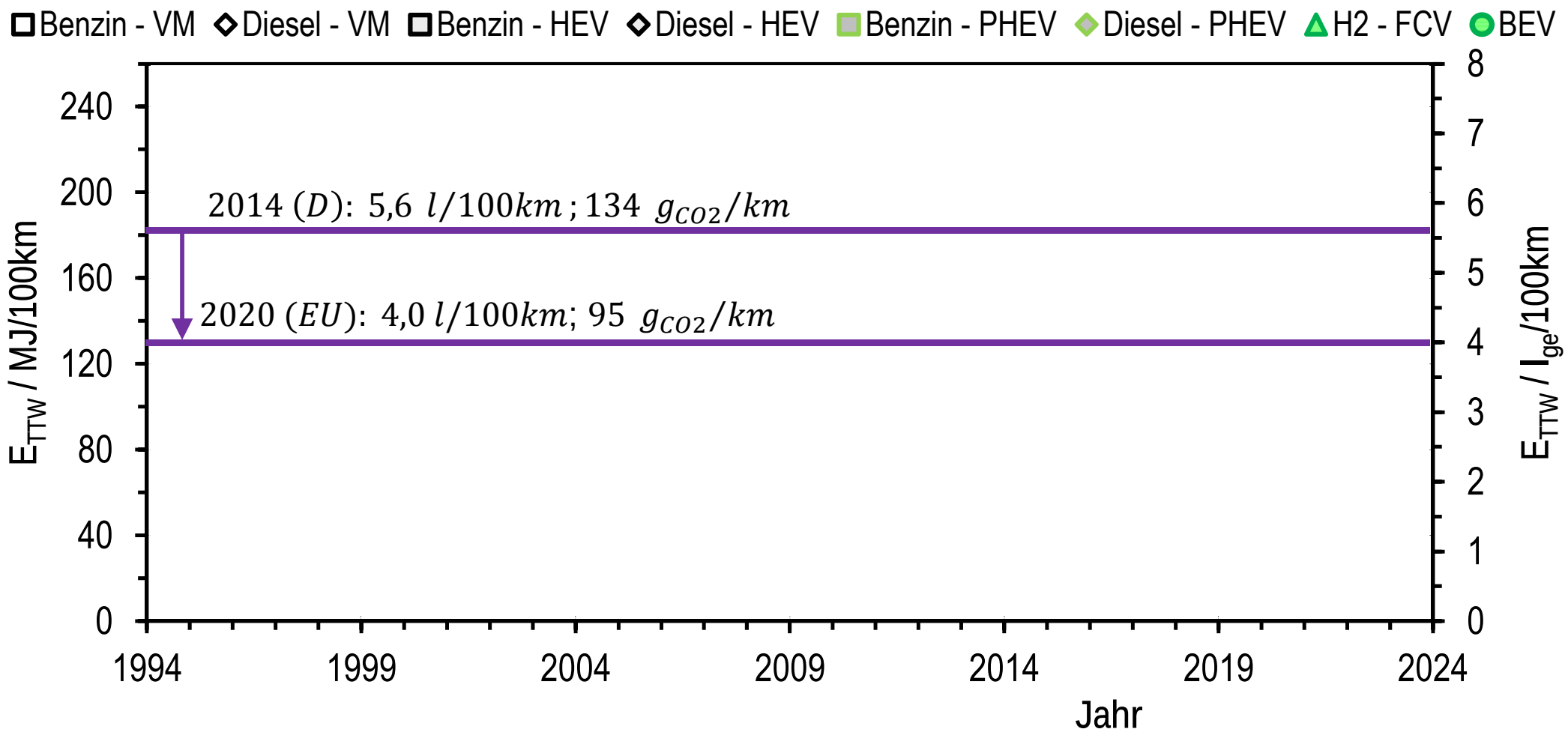
D_e:	pure electric range	50 km
D_{av}:	assumed average distance between charging	25 km
C:	Total consumption in l/100 km or MJ/100 km	
C_1:	Fuel (electricity) use with fully charged battery	60 MJ/100 km
C_2:	Fuel use with empty battery	160 MJ/100 km

Example:

$$C = \frac{50 \cdot 60 + 25 \cdot 160}{50 + 25} = 93\ MJ/100km$$

MVEG: Motor Vehicle Emissions Group

Average Fuel Consumption (D) and CO_2 Target (EU)



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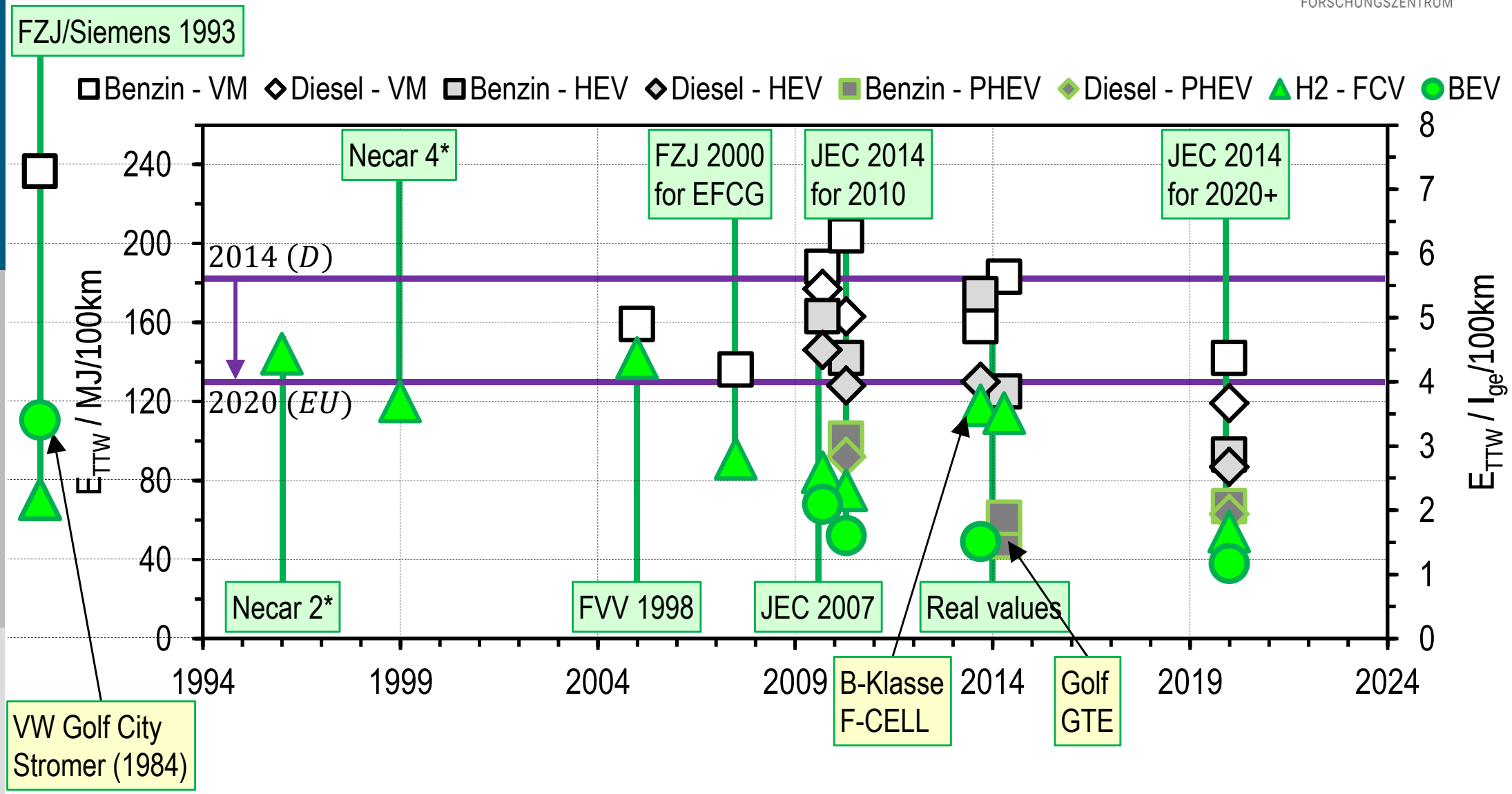
Fuel Consumption of Passenger Car Concepts (MVEG drive cycle)



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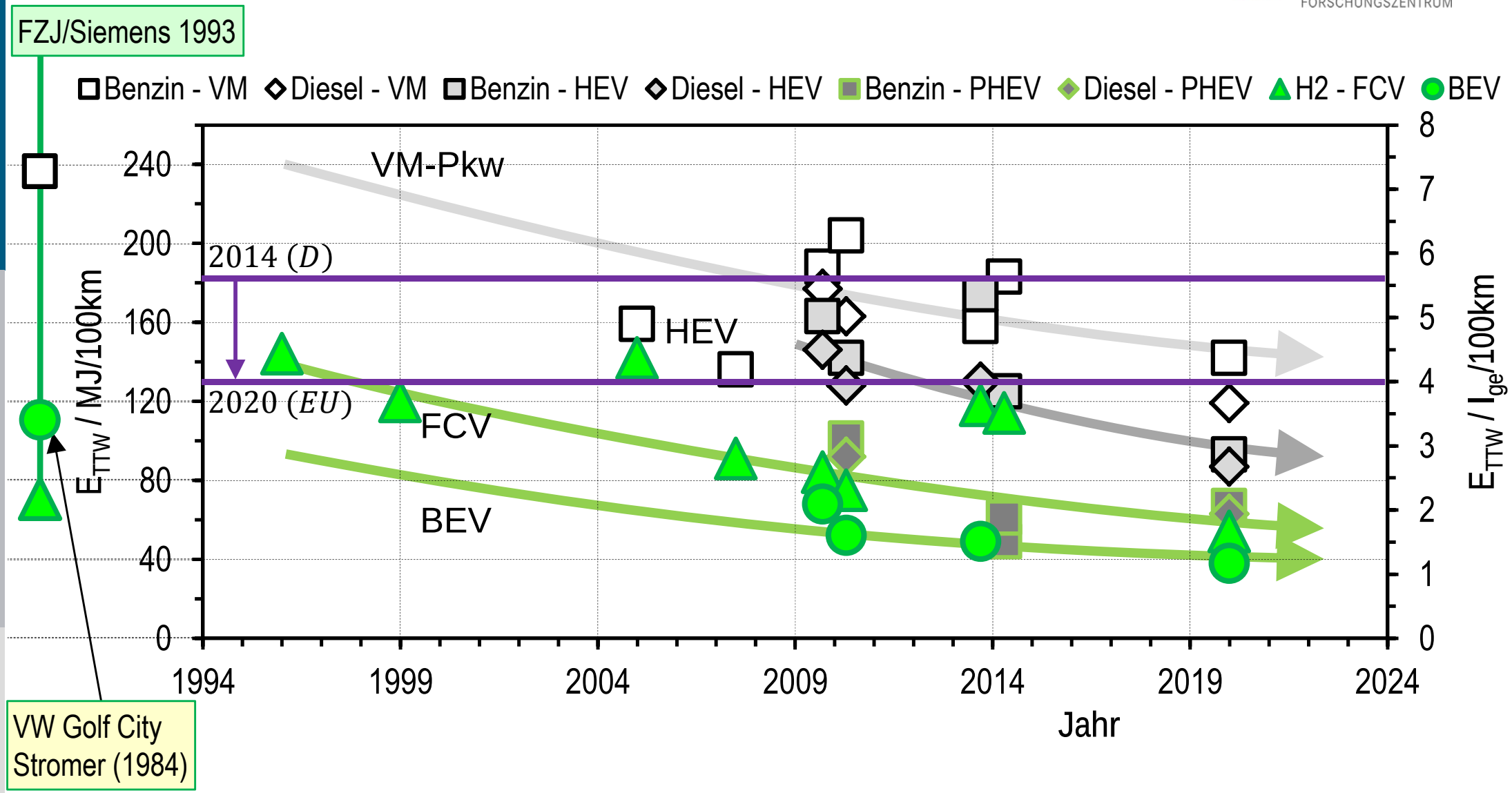
Fuel Consumption Trends of Passenger Car Concepts



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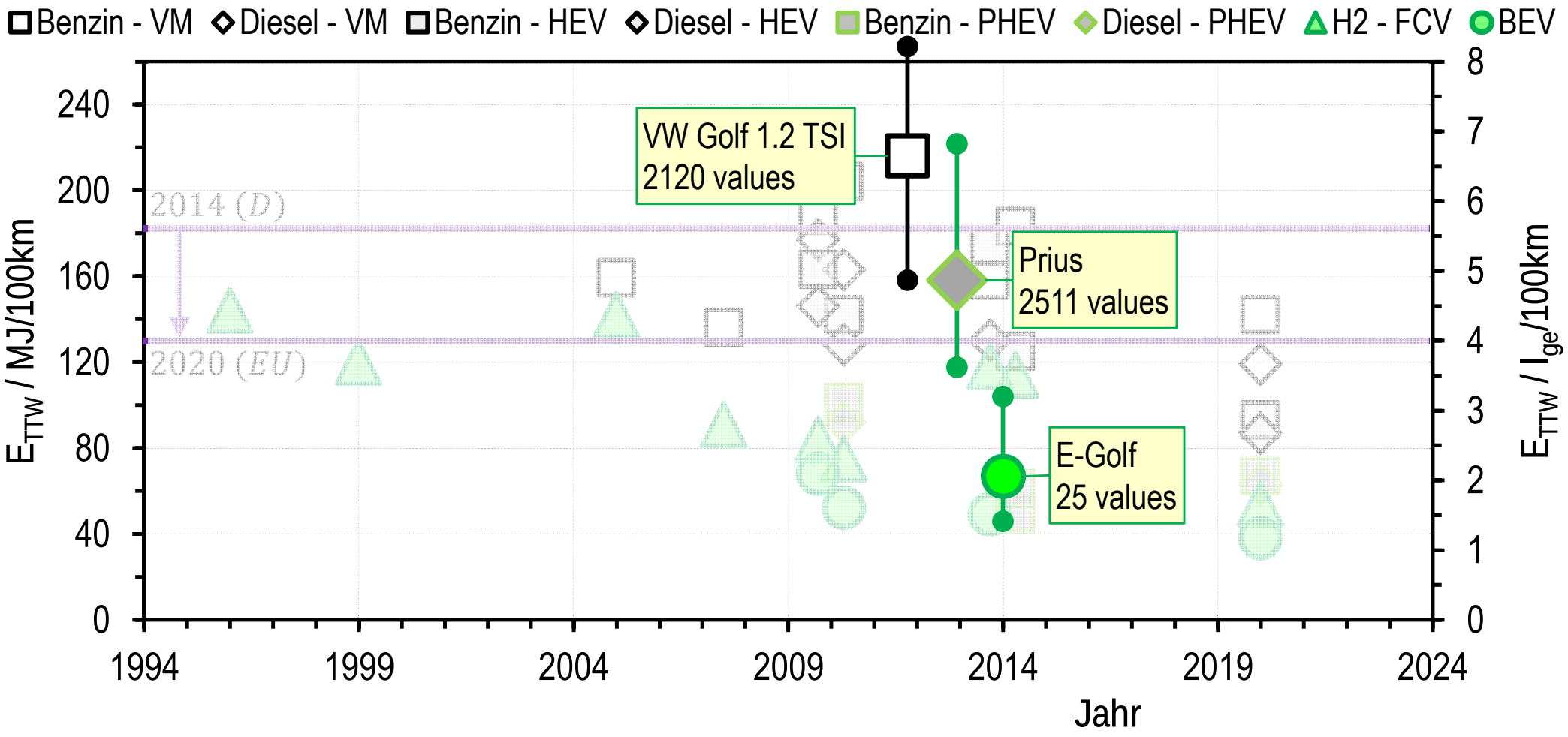
Back to Where We Started From: Real-World Data



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Summary

- Based on a simulation-based tank-to-wheel assessment fuel consumption figures of cars have been presented for different powertrain topologies and for different mechanical, thermal and electric load profiles.
- The assessment showed fuel economy improvements in comparison to present ICVs with Otto engines of:
  - 30 % - 60 % *for PAH with Otto engine,*
  - 76 % - 86 % *for BEV and*
  - 50 % - 67 % *for FCV.*
- Auxiliary power causes in particular at low average drive cycle speeds substantial fuel consumption increase
- Fuel consumption values from standard test procedures substantially deviate from measured values of real world driving, this is particularly true for (plug-in) hybrids

BEV: battery-electric car; FCV: fuel cell electric car; ICV: ICE car; PAH: parallel hybrid with ICE

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Thank you for your attention!