# Fuel and Recharging Effects on Regulated and Unregulated Emissions from a Gasoline and a Diesel Plug-in Hybrid Electric Vehicle

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Concawe
Environmental Science for European Refining

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# About Concawe

- Concawe is the scientific body of the European refining industry
- Concawe's mission is to perform scientific studies related to the refining industry, and to share the knowledge with our stakeholders and the public
    - *Our reports and papers are available in open-access on our website: www.concawe.eu*
- Concawe represents 38 Member Companies ≈ 95% of EU Refining capacity

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# Motivation

- **Plug-in hybrid vehicles (PHEVs) are regularly mentioned as a relevant option for**
  - *Low life-cyle $CO_2$ emissions*
  - *And low pollutant emissions… <u>in homologation conditions</u>*

- **PHEVs can also relieve some of the pressure**
  - *On the implementation of fast charging infrastructures for Battery Electric Vehicles (BEVs)*
  - *On the availability of raw materials to produce batteries, smaller than BEVs' ones*
  - *On the consumption of liquid fuels and the availability of low-carbon fuels*


# Motivation and objectives

- <u>Question 1</u>: Intermittent thermal/electric drive can be challenging for PHEVs aftertreatment
  - *Do they maintain low pollutant emissions <u>under real-world conditions</u>?*
- <u>Question 2</u>: PHEVs life-cycle $CO_2$ emissions are sensitive to their use cases
  - *e.g. recharging frequency, trips distance, electricity carbon intensity*
  - *Can PHEVs life-cycle CO2 emissions be predicted depending on their use case?*

- <u>Objective 1</u>: Provide data on pollutant emissions of 2 PHEVs
  - *In lab: chassis-dyno*
  - *On-road*
- <u>Objective 2</u>: By using the experimental data, set up a simulator that allows calculating PHEVs life-cycle $CO_2$ emissions depending on their use case



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# Targeted comparisons and test matrix

- Diesel vs. gasoline results
- Standard vs. renewable fuels
- Impact of recharging the battery (or not)
- PHEV vs. HEV

- 2 vehicles tested
  - *A Diesel PHEV and a gasoline PHEV;*
- Fuel matrix includes
  - *A B7 and a 100% renewable HVO*
  - *An E10 and a 100% renewable gasoline, blended with 20% v/v ethanol (E20)*
- Test matrix includes
  - *Charge depleting mode (CD) charge sustaining mode (CS))*
- Artificial variation of the weight of the vehicle on the chassis dyno



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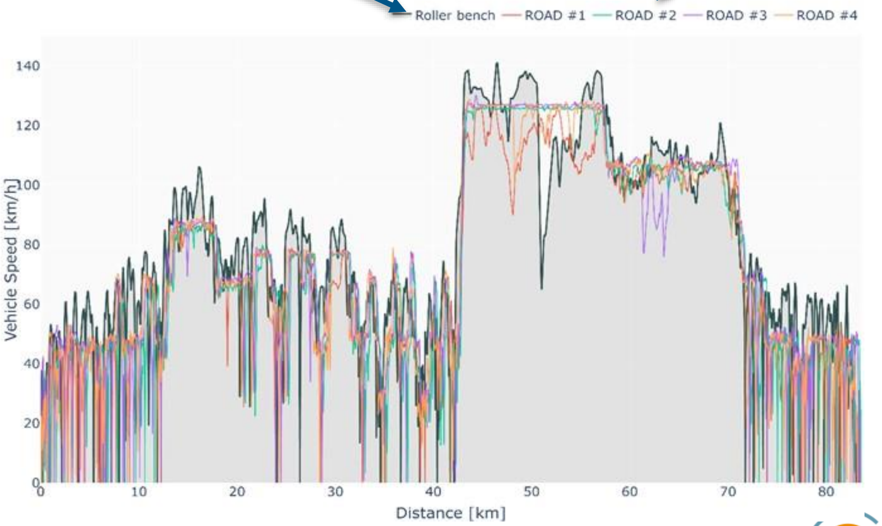
# Test vehicles


| | C300e EQ Power | C300de EQ Power |
|---|---|---|
| Regulation | Euro 6d-temp | |
| Fuel type | Gasoline | Diesel |
| Test mass [kg] | 1885 | 1970 |
| Thermal Engine | 2.0L 4cyl 155 kW turbo<br>Direct injection | 2.0L 4cyl 143 kW turbo<br>Direct injection |
| Battery | 13.5 kWh 365V | |
| Electric motor | 90 kW | |
| Hybridization | P2 parallel hybrid architecture | |
| Aftertreatment system | 2 TWC + GPF | DOC + SCRF + SCR |

# Driving cycle

- RDE compliant
- Speed profile used on the chassis dyno from the same trip driven on-road
  - *Allowing back-to-back comparisons of lab and on-road results*




| | |
|---|---|
| Trip duration [min] | 93 |
| Total distance [km] | 83.4 |
| urban share [%] | 30.8 |
| rural share [%] | 31.9 |
| motorway share [%] | 37.2 |
| total cumulated positive altitude [m/100km] | 620 |

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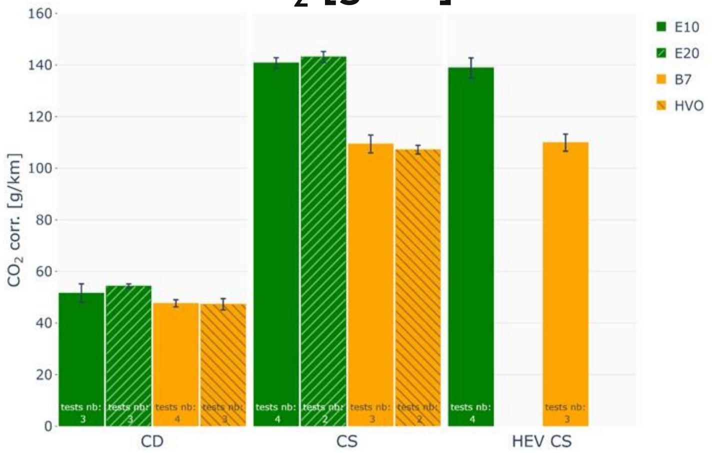
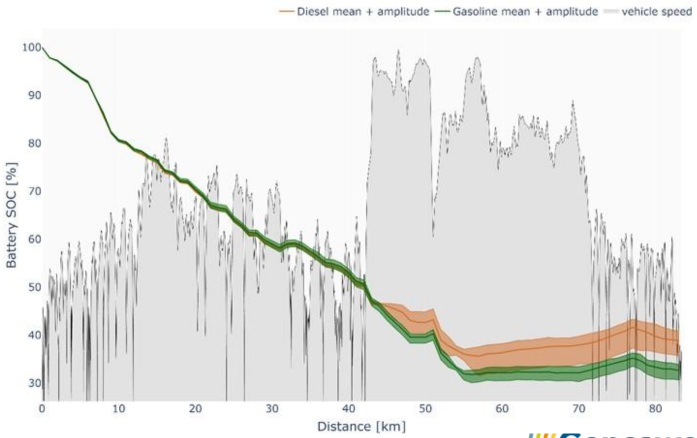
# $CO_2$ emissions

- In <u>CS mode</u>, Diesel PHEV emits 22% less $CO_2$ emissions than gasoline PHEV
  - *Mainly explained by engine efficiency difference*
- In <u>CD mode</u>, only 8% gap in $CO_2$ emissions for Diesel vs. gasoline
  - *Mainly explained by different hybrid control strategies: bigger depth of discharge in gasoline vs. Diesel*
- HVO emits 2% less $CO_2$ emissions than B7
  - *Explained by fuel properties (higher H/C ratio)*
  - *No impact on engine efficiency*
- In CS mode, PHEV has similar $CO_2$ emissions to HEV
  - *No impact of vehicle weight: more energy expended during accelerations is compensated by more energy recovered during decelerations*
- $CH_4$ and $N_2O$ contribute to an increase of 1% (gasoline) and 3% (Diesel) of GHG emissions

$CO_2$ [g/km]



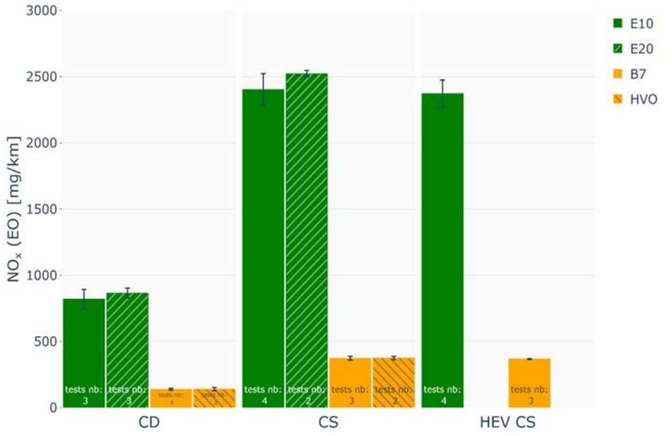

Battery SoC [%]



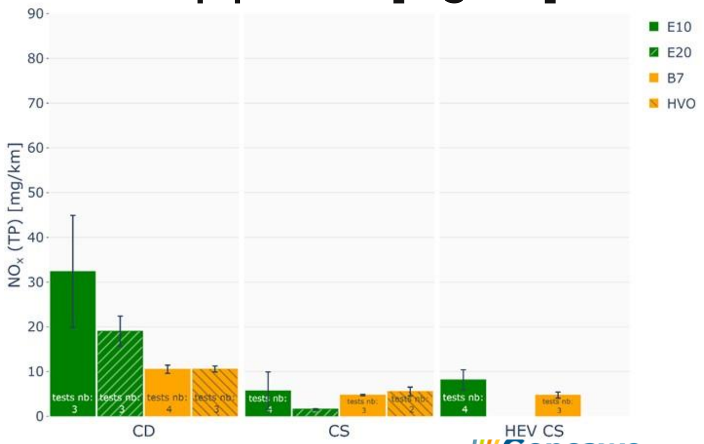
# NOx emissions

- Low tailpipe NOx emissions overall
- Lower tailpipe NOx emissions for Diesel vs. gasoline
  - *Explained by lower engine-out NOx with fairly good aftertreatment conversion efficiency*
- Higher tailpipe NOx emissions in CD mode vs. CS mode
  - *Counter-intuitive result, explained by a higher aftertreatment conversion efficiency in CS mode (see next 2 slides)*
- Lower tailpipe NOx emissions for E20 vs. E10
  - *Explained by a higher aftertreatment conversion efficiency*

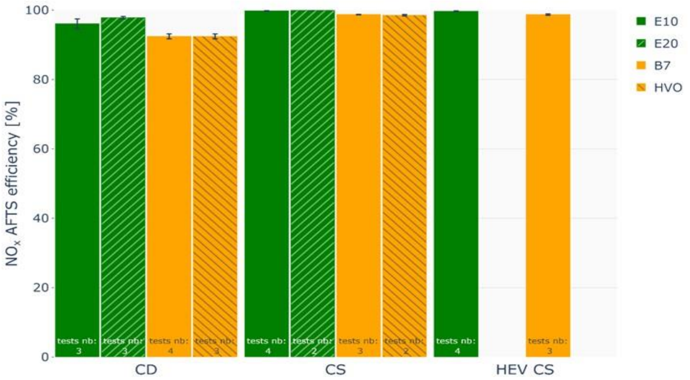
Engine-out NOx [mg/km]




Tailpipe NOx [mg/km]



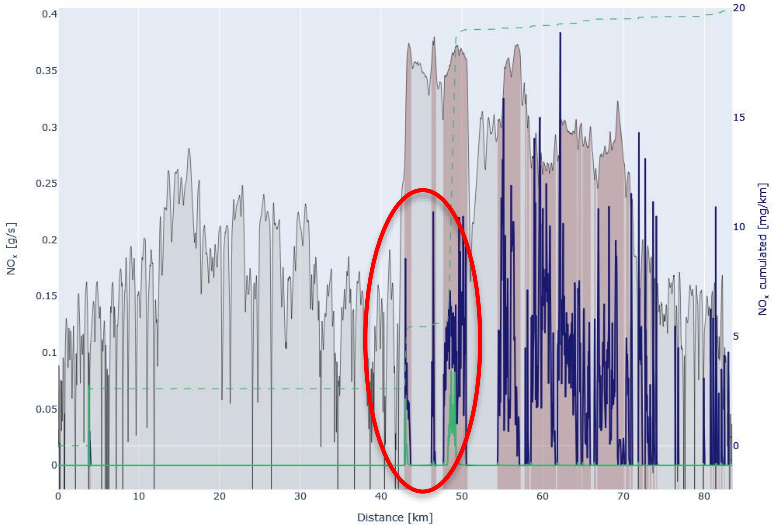

NOx conversion efficiency [%]

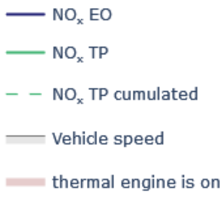


# Time-based NOx measurements (E10)

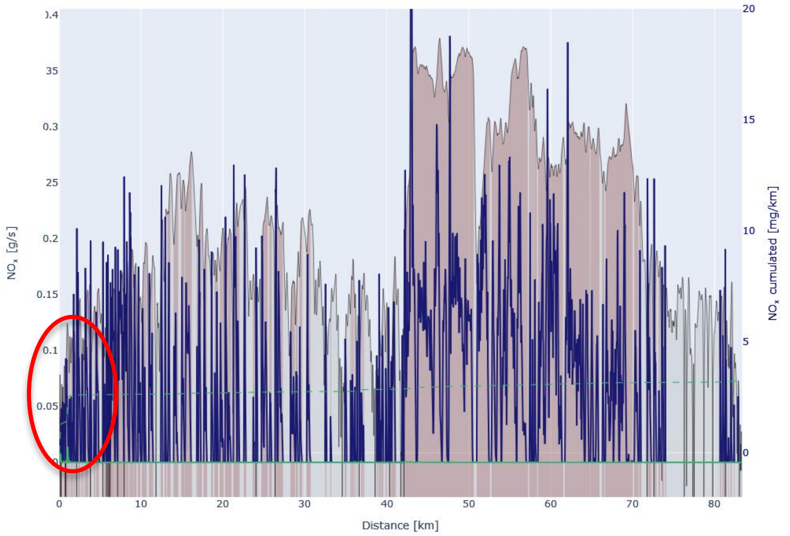
- In CD mode, cold engine start in highway conditions creates challenging conditions for NOx conversion
  - *Leading to a higher peak on NOx tailpipe emissions, although the engine is off most of time*
- In CS mode, engine start in soft driving conditions leads to a good management on NOx emissions by the TWC
  - *Leading to lower NOx tailpipe emissions, although the engine runs most of time, with higher engine-out NOx emissions*

## CD mode



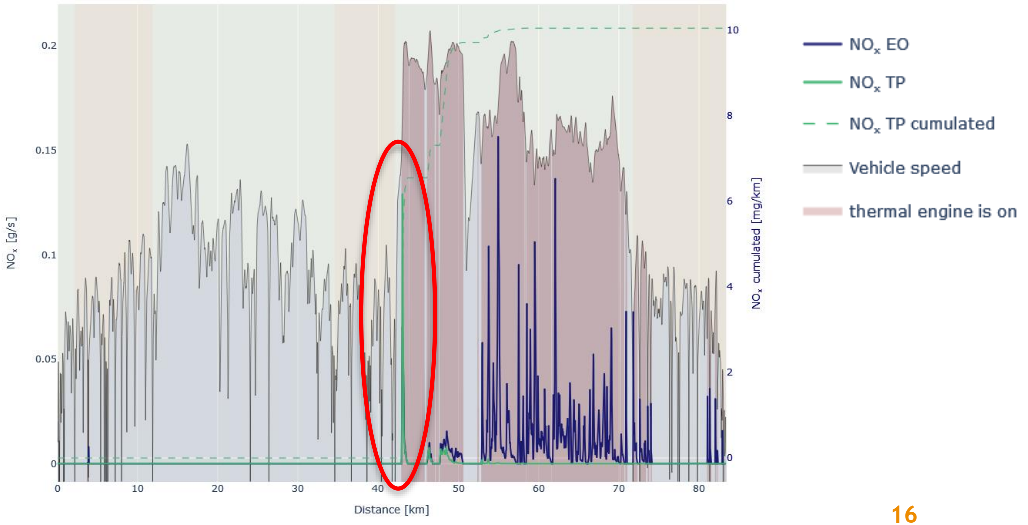

## CS mode



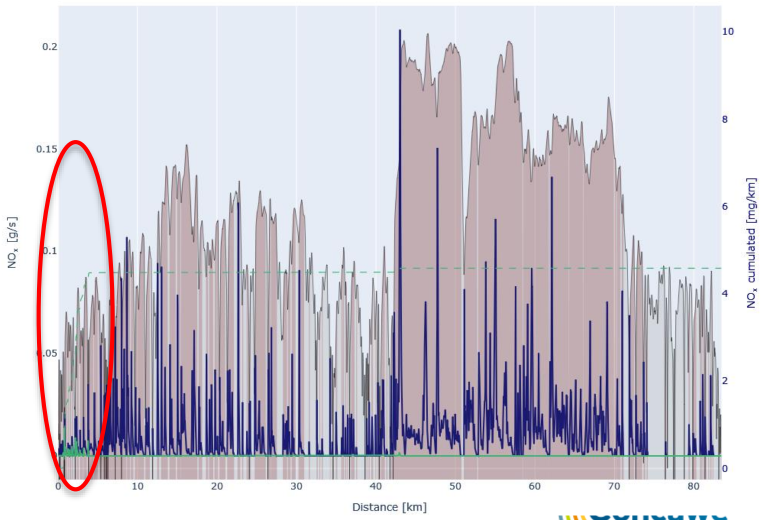
# Time-based NOx measurements (B7)

- In CD mode, cold engine start in highway conditions creates challenging conditions for NOx conversion
  - *Leading to a higher peak on NOx tailpipe emissions, although the engine is off most of time*
- In CS mode, engine start in soft driving conditions leads to low engine-out NOx emissions during SCR light-off
  - *Leading to lower NOx tailpipe emissions, although the engine runs most of time, with higher engine-out NOx emissions*

**CD mode**



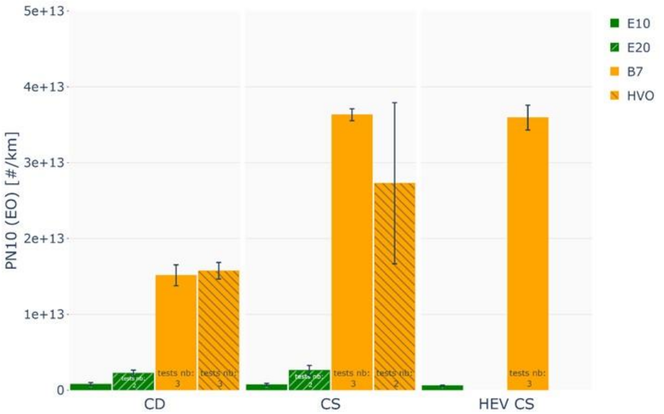

**CS mode**



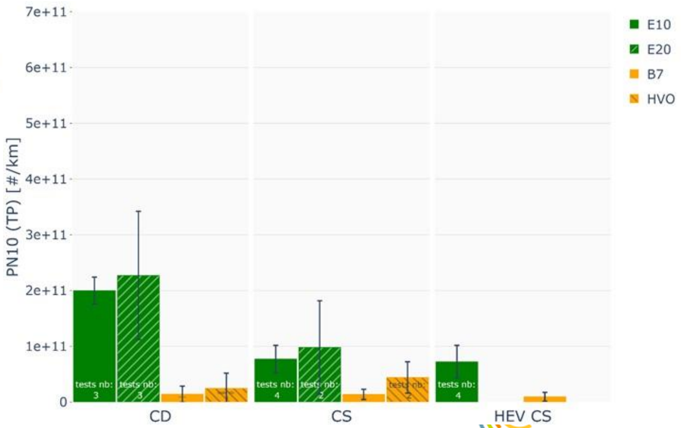
# Particulates number emissions

- **Low tailpipe PN10 emissions overall**
- **Lower tailpipe PN10 emissions for Diesel vs. gasoline**
  - *Explained by a higher filtration of the DPF vs. GPF, although Diesel engine-out PN10 emissions are higher*
- **No impact of renewable fuels on tailpipe PN10 emissions**
  - *Higher PN10 engine-out emissions from E20 vs E10 are compensated by a better filtration efficiency of the GPF*

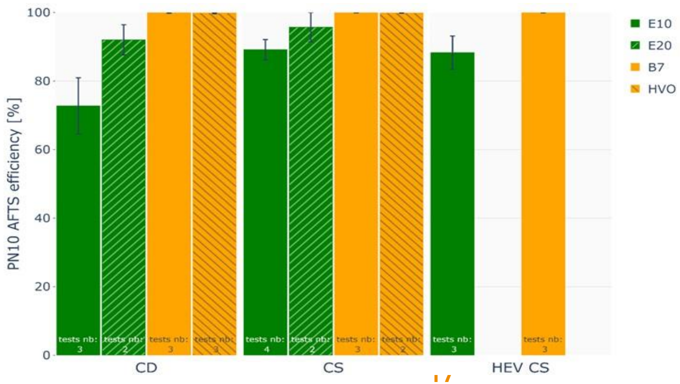
**Engine-out PN10 [#/km]**




**Tailpipe PN10 [#/km]**



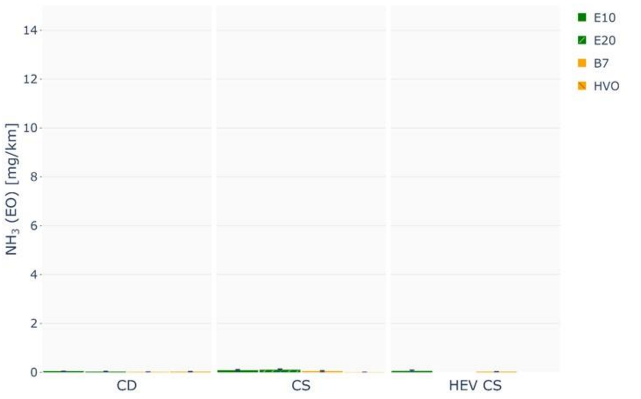

**Filtration efficiency [%]**



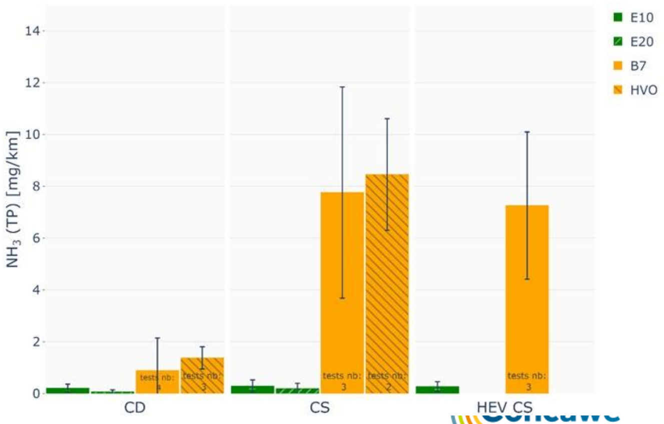
# Ammonia emissions

- **No $NH_3$ emissions engine-out**
  - *$NH_3$ is formed in the aftertreatment system*
  - *Reactions in the TWC for the gasoline PHEV*
  - *$NH_3$-slip for the Diesel PHEV*
- **Higher tailpipe $NH_3$ emissions for Diesel vs. gasoline**
- **No impact of renewable fuels on $NH_3$ tailpipe emissions**

Engine-out $NH_3$ [mg/km]

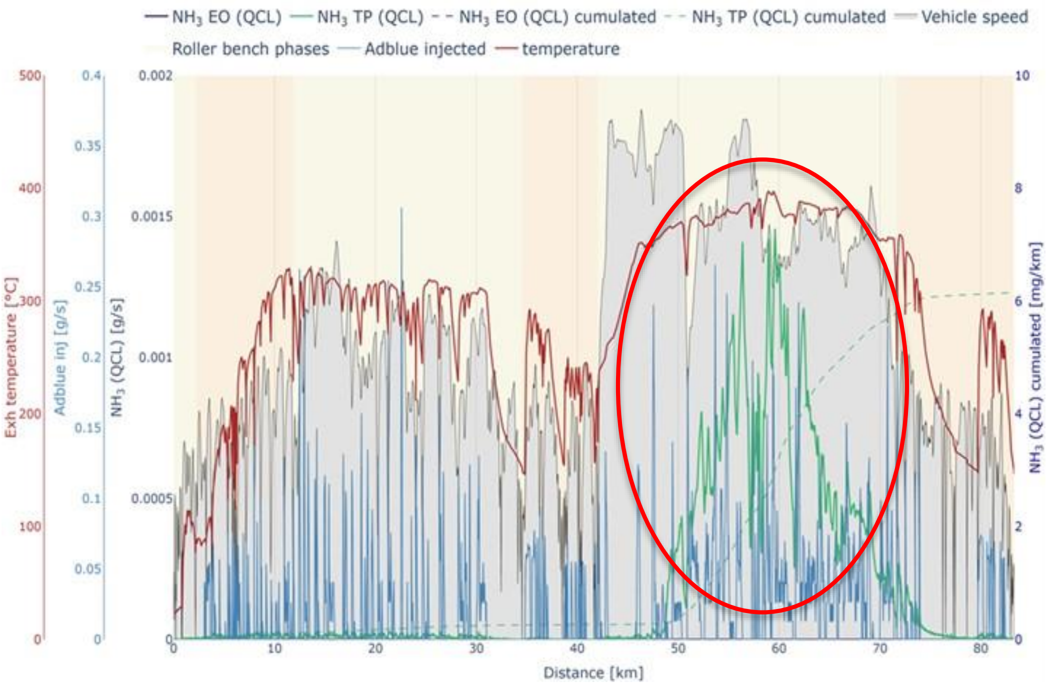



Tailpipe $NH_3$ [mg/km]



# Time-based $NH_3$ measurements (B7)

- **NH3-slip typically occurs in highway conditions**
  - *Above a level of exhaust temperature*
  - *Gas hourly space velocity is probably too high*



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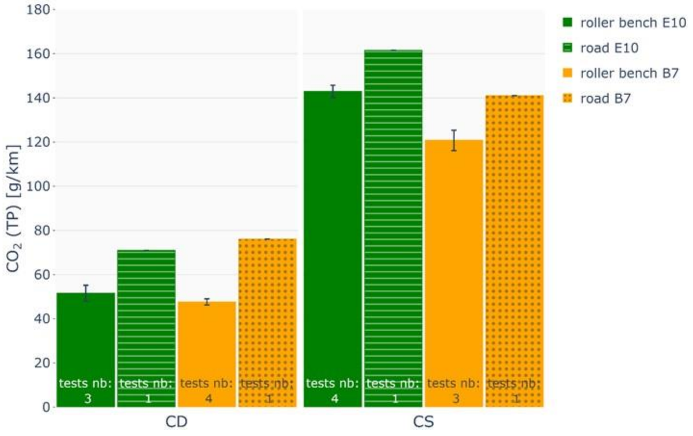
# $CO_2$ emissions: on-road vs. chassis-dyno

- $CO_2$ on-road emissions are significantly higher than measured in-lab
  - *+29% $CO_2$ emissions for Diesel PHEV*
  - *+14% $CO_2$ emissions for gasoline PHEV*
- Further analysis shows that road law used on chassis-dyno was not severe enough
  - *This aspect is corrected in the next steps of the study*
- $CO_2$ emissions from Diesel PHEV become closer/similar to gasoline PHEV

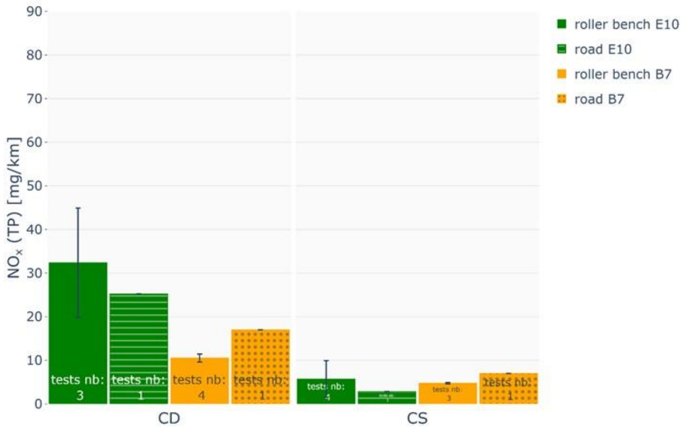
**$CO_2$ [g/km]**



# NOx emissions: on-road vs. chassis-dyno

- NOx emissions are consistent between on-road and chassis dyno measurements

**Tailpipe NOx [mg/km]**



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# Key take-away

- **Comparison of**
  - *Diesel vs. gasoline PHEVs vs. Diesel and gasoline HEVs*
  - *Charge depleting vs. charge sustaining mode*
  - *Standard (B7, E10) vs. renewable fuels (HVO, E20)*
  - *Chassis-dyno vs. on-road results*
- **Pollutant emissions**
  - *Low regulated emissions, well below Euro 6d limits*
  - *Non-regulated emissions in the range of Euro 7 proposals*
  - *Lower emissions for the Diesel PHEV, except for $NH_3$ and $N_20$*
  - *Switching from a standard (B7, E10) to renewable fuel (HVO, E20) has no significant impact on tailpipe emissions*
- **GHG emissions**
  - *Much lower $CO_2$ emissions from Diesel PHEV vs. gasoline PHEV on chassis dyno, but closer/similar on-road*
  - *$CO_2$ emissions significantly higher on-road (corrected for the next steps of the study)*
  - *$CH_4$ and $N_2O$ add 1% to 3% to GHG emissions*
  - *HVO decreases $CO_2$ emissions by 2% (TtW)*
  - *No stated impact of vehicle mass (PHEV vs. HEV)*

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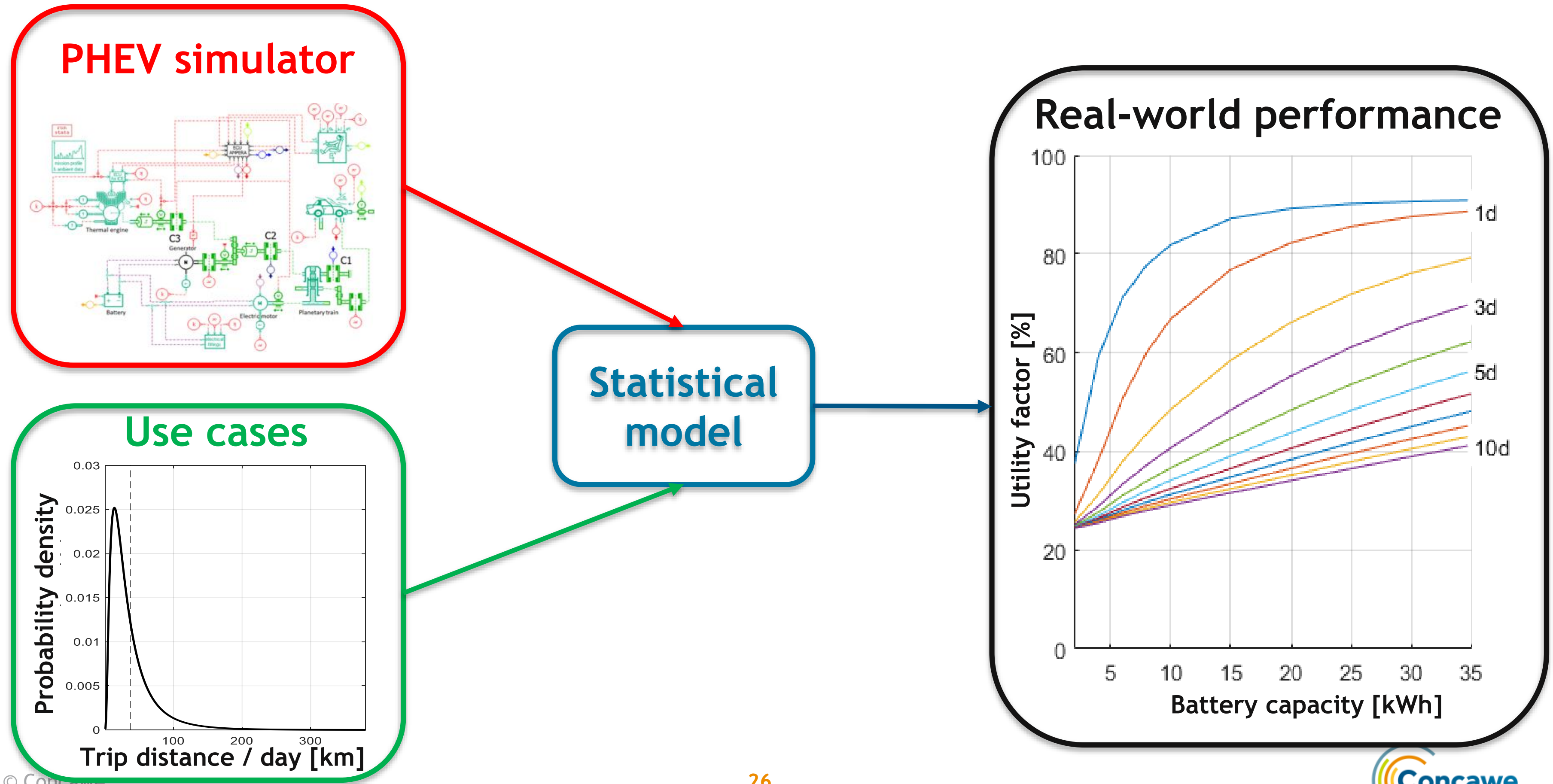
# Generating real-world use cases with a calibrated PHEV simulator





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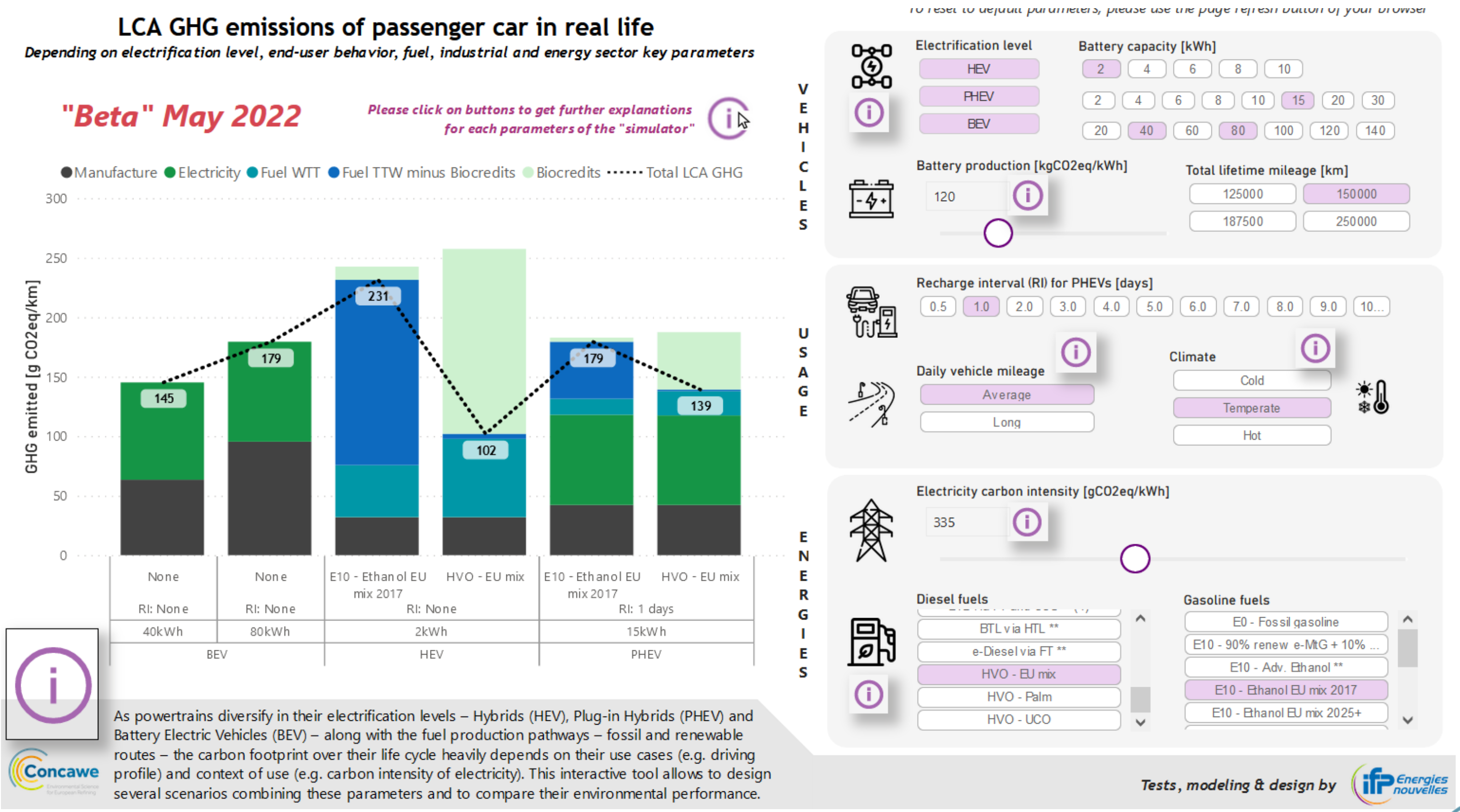
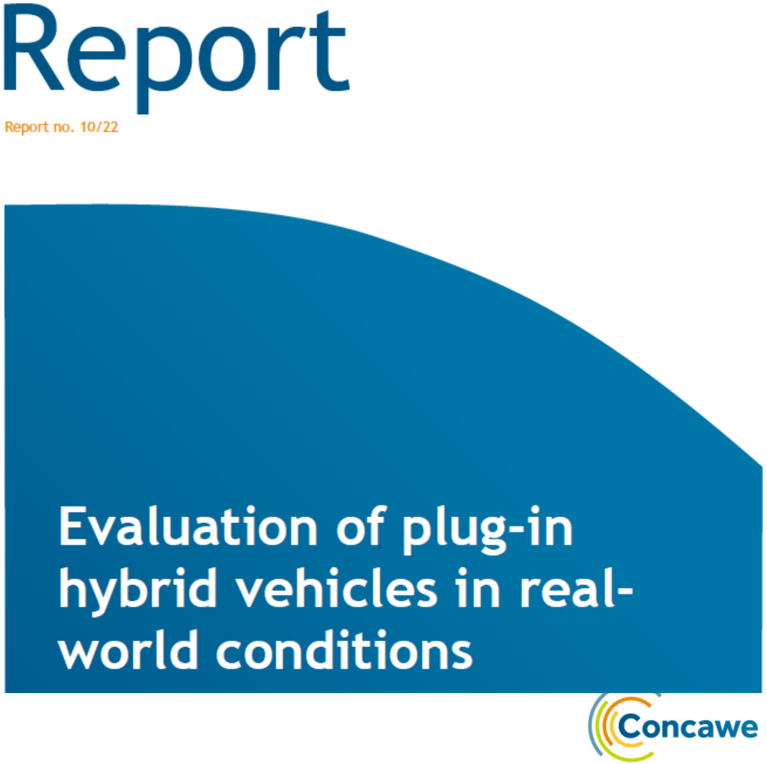
# Vehicle LCA GHG on-line simulator



# Want to know more?

- **Full Concawe report available on our website**
  - *https://www.concawe.eu/wp-content/uploads/Rpt-10-22.pdf*



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# Thank you for your attention

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