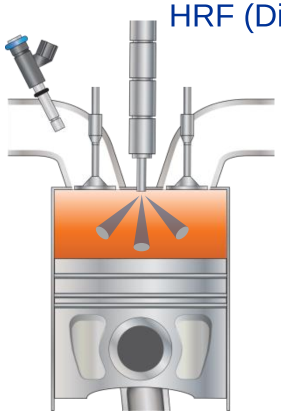
ASME ICEF 2022 Internal Combustion Engine Fall Conference

Is the RCCI *"THE"* Practical Low-temperature Combustion of the future?

Assoc. Prof. Dr. Antonio García Martínez
Universitat Politècnica de València (UPV)
Institute CMT – Motores Térmicos

22.07.2022 ASME Webinar ICEF 2022: Evolution of the Internal Combustion Engine for Ultra-High Efficiency and Near-zero Emissions: RCCI and GCI

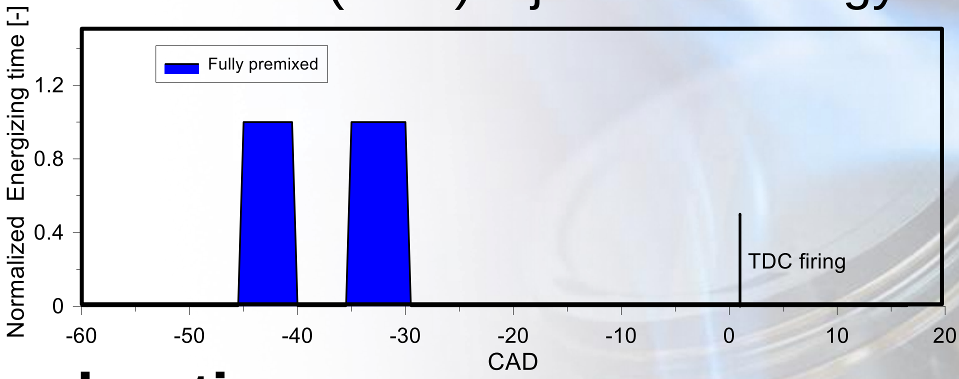
Reactivity Controlled Compression Ignition (RCCI)



Fully premixed

$$PER = \frac{\dot{m}_{LRF} \cdot LHV_{LRF}}{\dot{m}_{LRF} \cdot LHV_{LRF} + \dot{m}_{HRF} \cdot LHV_{HRF}}$$

DI (HRF) Injection Strategy

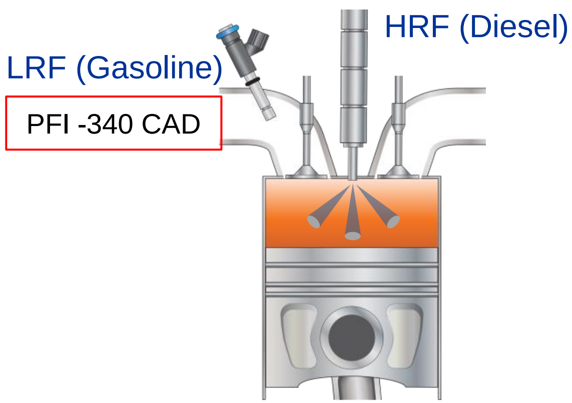


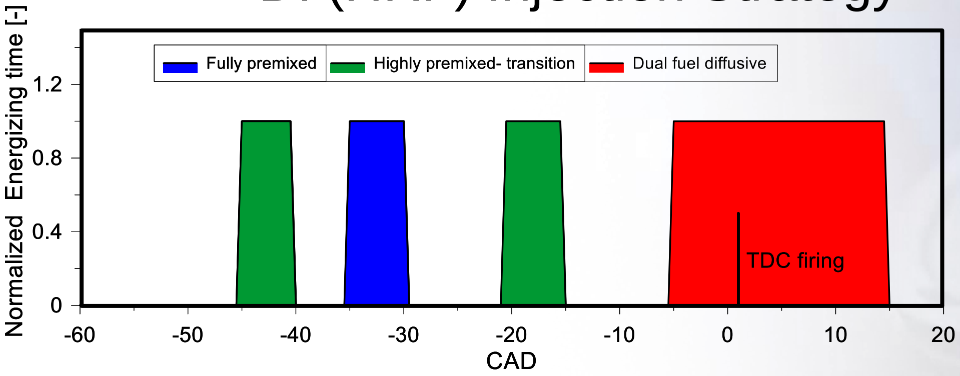
RCCI combustion:

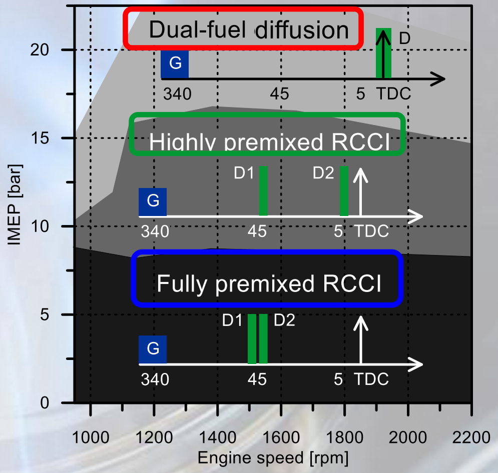
- Early high reactivity fuel injection.
  - Low local equivalence ratio stratification.
- **RON stratification** to control the reaction progress.
- High levels of EGR dilution and PER* values.
- Benefits:
  - High conversion efficiencies.
  - Low NOx and Soot emissions.
- Drawbacks:
  - Excessive HC and CO.
  - Limited to medium loads if conservative mechanical constraints are considered→ high pressure gradients.

How to enable full map operation?

Dual Mode Dual Fuel (DMDF) concept







J. Monsalve, 2016 (SCE, CFD, TRL1-2)

Fully premixed

V. Boronat, 2018 (MCE, TRL1-2)

Highly Premixed (Transition)

R. Sari, 2020 (MCE, TRL3-4)

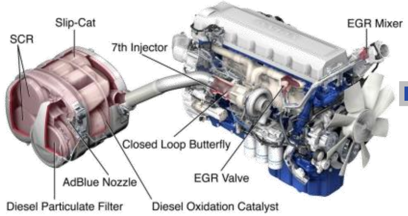
Dual Fuel diffusive

SCE= **S**ingle **C**ylinder **E**ngine   MCE= **M**ulti-**C**ylinder **E**ngine

What tools have been used?

Experimental and Numerical Tools

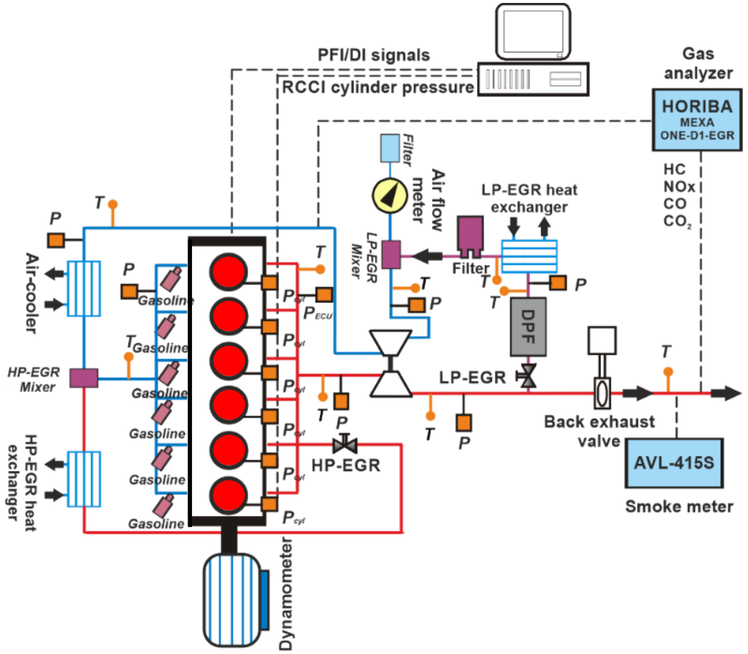
Volvo D8 K 350



- 6 PFI
- LP EGR Loop
- 6 RCCI pistons

CR 17.50:1

CR 12.75:1

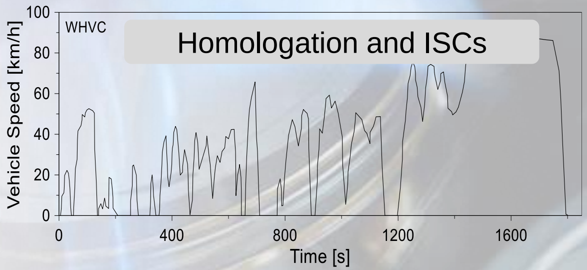


Numerical setup

- **Truck model**

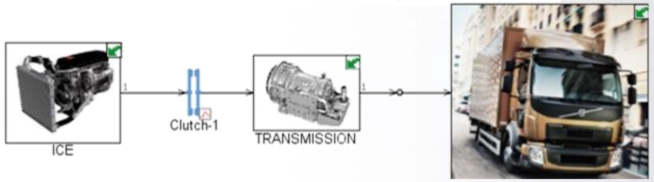
FE 350 hp
FL 280 hp

- **Driving cycles:**



- **0D-Vehicle modelling**

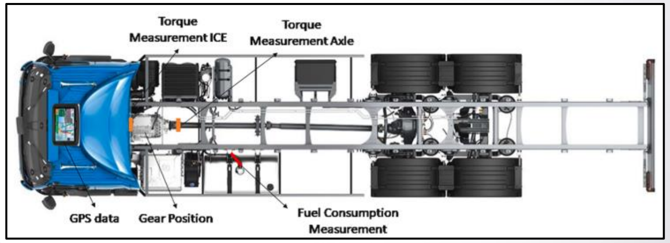
GT Gamma Technologies
GT AutoLion Lithium-ion Battery Simulation



- **Other Numerical tools**

CONVERGE CFD SOFTWARE
Cantera

- **Road Vehicle Validation**



Fuel Cons.	Exp [kg]	Simu [kg]	Diff. [%]
D8K 280 15t	29.9	30.1	0.7
D8K 350 20t	36.23	35.7	1.48

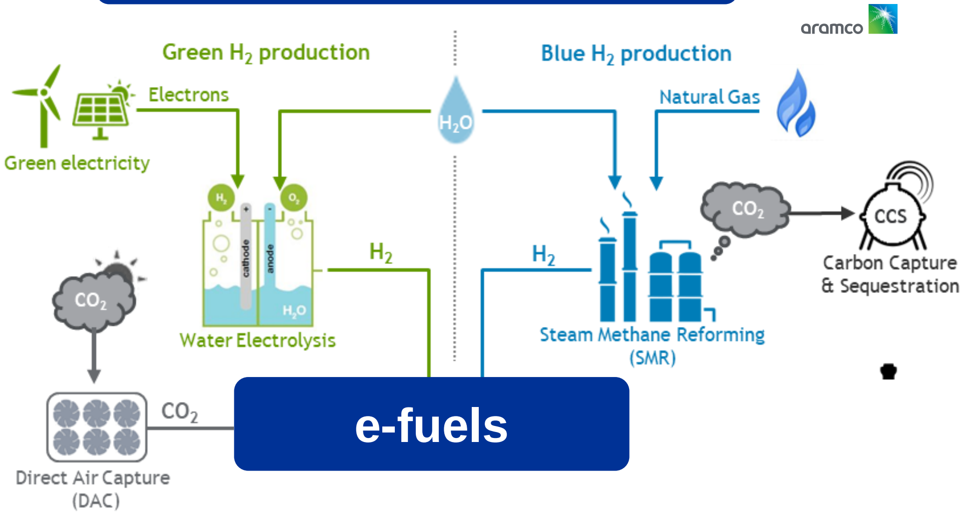
DMDF + future challenges (CO_2 + EU7?) Two Solution Pathways

Introduction of requirements on CO_2

2025 (-15%)

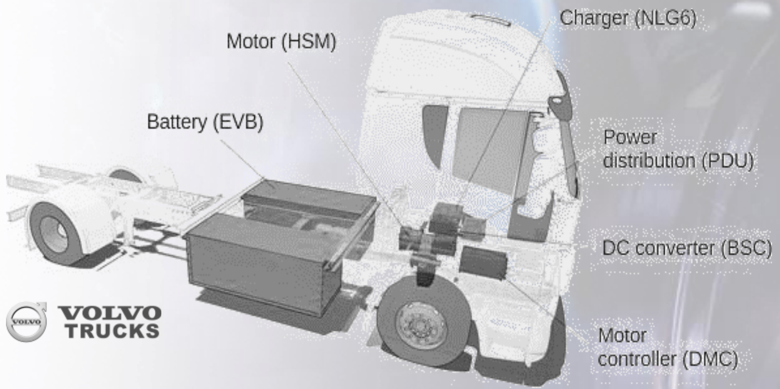
2030 (-30%)

Synthetic Fuels



e-fuels

Hybridization



Fuel's pathway

Commercial Diesel and Gasoline for reference

Drop-in Fuels

Market penetration of the concept:

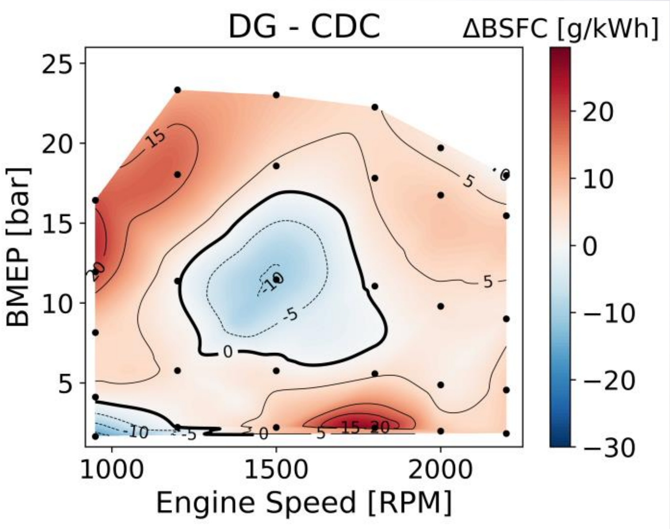
- Use of commercial fuels with well established distribution system.
- Understand the benefits and drawbacks of using them.
- Create a benchmark for next comparisons.

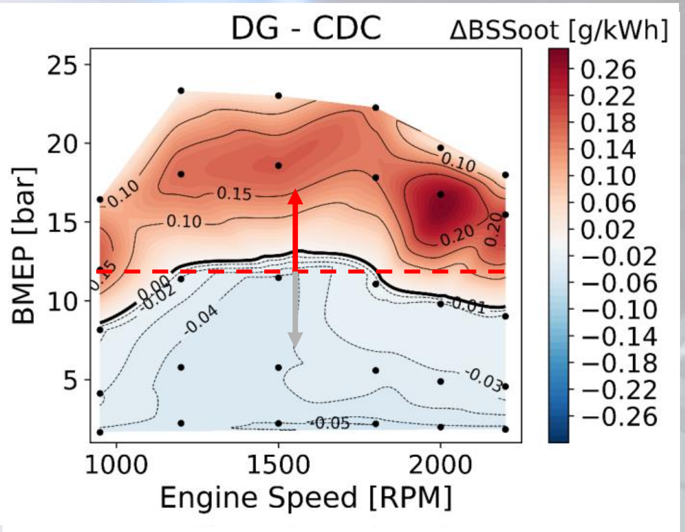
Mode	DMDF
HRF	Diesel
LRF	Gasoline
EGR	HP & LP

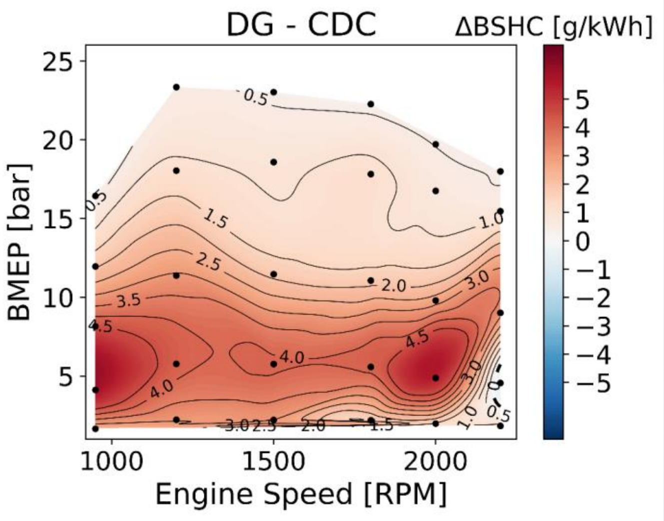
Calibration Results (steady conditions)

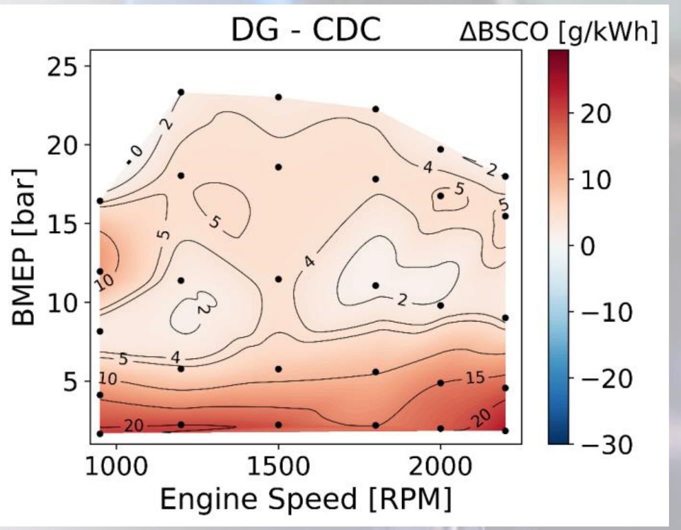
Main remarks:

- Complete engine map calibration with DMDF concept.
- Similar BSFC in most of the calibration map.
- Benefits:
  - NOx emissions reduced in the whole map.
  - Soot emissions lower than 0.01 g/kwh up to 60% of engine load.
- Drawbacks:
  - Soot emissions higher than CDC from medium to full load.
  - HC and CO one order of magnitude higher than CDC.









Fuel's pathway

Commercial Diesel and Gasoline for reference

Drop-in Fuels

Market penetration of the concept:
- Use of commercial fuels with well stablish distribution system.
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Is there a better LRF?

Why not lower RON on the LRF?

- Can we lower fuel price and keep engine efficiency?

PRF & TRF

Engine HW designed for a medium-high RON (90-95)
- Fuel blends ranging RON 80 to 100 with different sensitivities.
- CR and bowl design with low RON fuels produced excessive. pressure gradients → ↑ **EGR** → ↑ **soot**.

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Is there a better HRF?

Can synthetic diesel reduce soot?

-Lower content of aromatics.

E-Fischer Tropsch

Increase of oxygen content is the key for non soot comb.
- Paraffinic diesel allows to reduce soot formation → reduce PAHs.
- CO_2 benefits in a well to wheel basis.
- Paraffinic fuels still produce soot → **small improvements → ↑ O_2.**

Fuel's pathway

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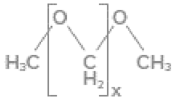


Poly-Oxymethylene dimethyl ethers

How can we get an oxygenated HRF?

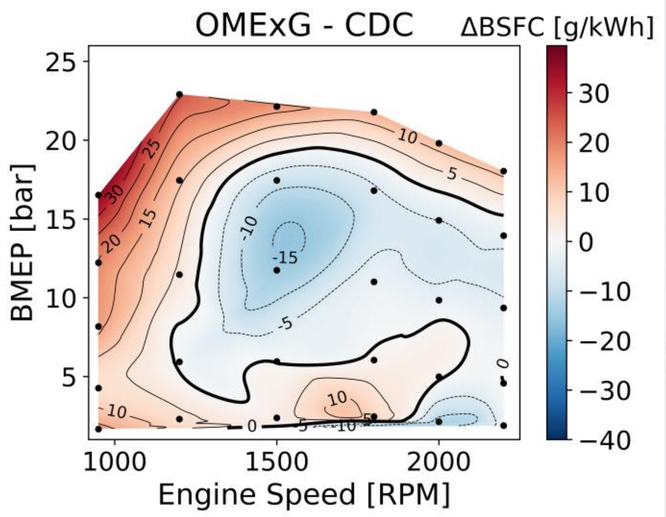
OMEx

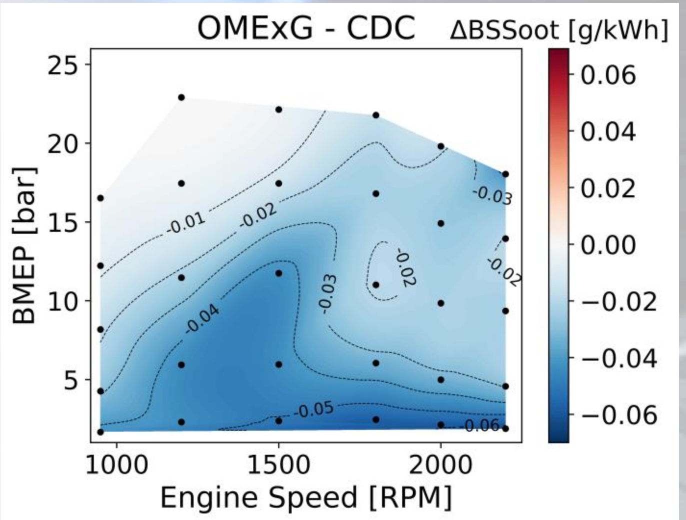
Balance between emissions and fuel consumption

- Low LHV → Higher PER → Compensation for fuel consumption.
- Oxygenated fuel with non-sooting capabilities.
- Reactivity and RON greater stratification → LTC.
- E-Fuel → Benefits in WTW CO_2.

Calibration Results (steady conditions)

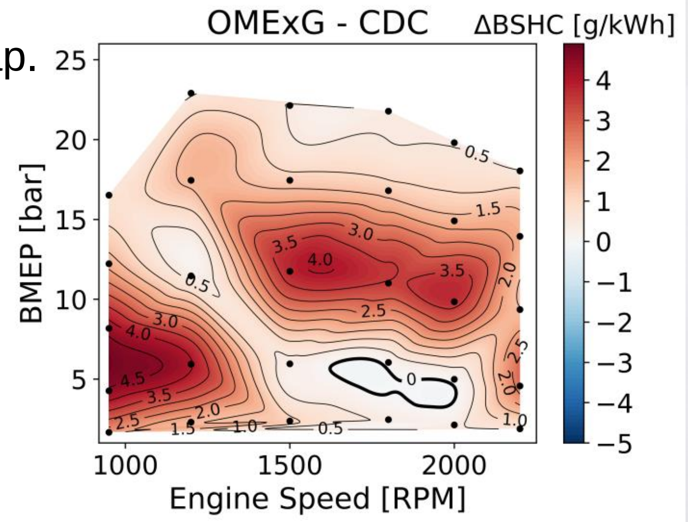
Mode	DMDF
HRF	OMEx
LRF	Gasoline
EGR	HP & LP
Target	EU VI

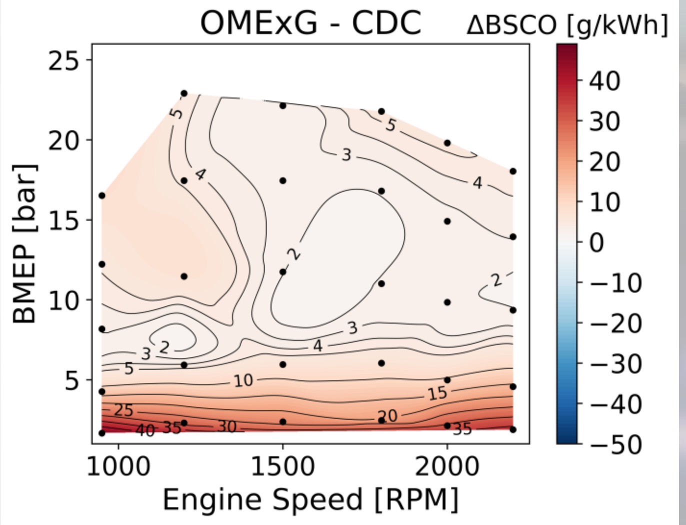




Main remarks:

- Full map calibration with OMExG.
- Benefits in BSFC for an important map zone.
- Benefits:
  - engine-out EUVI NOx in the complete map.
  - NOx emissions reduced as much as 6 g/kWh compared to the CDC calibration.
  - zero soot emissions measured by the AVL 415 S independently on the engine load.
- Drawbacks:
  - HC* and CO still higher than CDC.





*HC are under reported due to the high oxygen concentration in the molecule.

Driving Cycle results: WHVC & 50% Payload



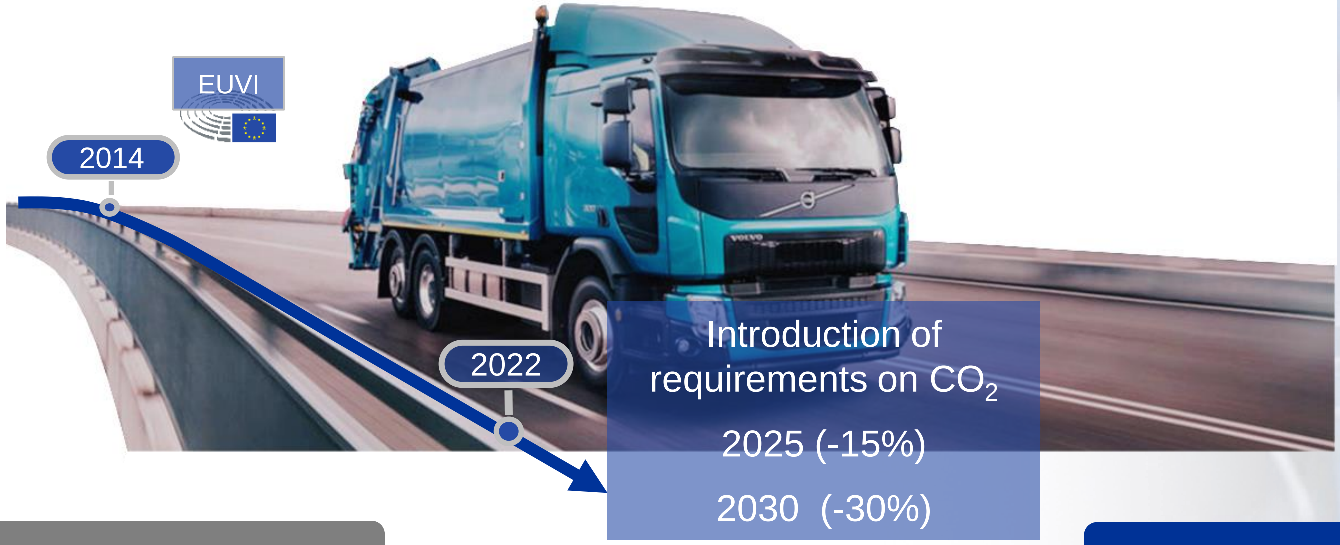
FL 280 hp 18 ton		$BSFC_{eq}$	NOx	Soot	HC	CO	TTW	WTW
	CDC	[-] g/kWh	[-] g/kWh	[-] mg/kWh	[-] g/kWh	[-] g/kWh	[-] g/tkm	[-] g/tkm
	DMDF DG EUVI	+0.9%	-91.1%	-92.7%	EUVI	EUVI	-0.23%	-0.7%
	DMDF OMExG EUVI	-4.0%	-90.1%	-100%	EUVI	EUVI	-0.16%	-56.3%

*Homologation: WHVC & 50% Payload
**g/tkm: grams per vehicle tone and travelled kilometer

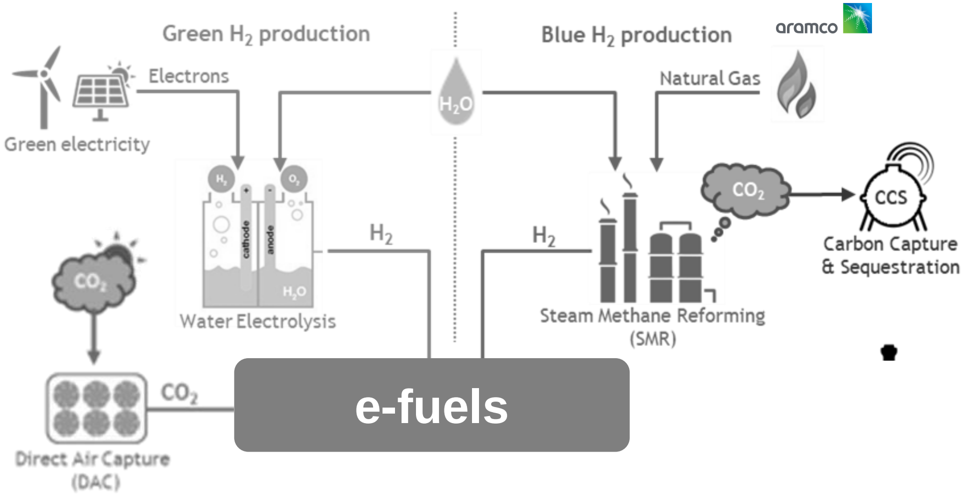
- The application of DMDF in the original MCE with a few modifications allows to attain similar/ better efficiency depending on the HRF used.
- NOx and soot are significantly reduced at homologation conditions
- Drawbacks for HC and CO (stock ATS allows to achieve EUVI tailpipe emissions)
- Benefits on WTW CO_2 are obtained if OMEx is used as HRF (15% - 35%)

EU VI limit | EU VII limit | 2025 CO_2 Targets | 2030 CO_2 Targets

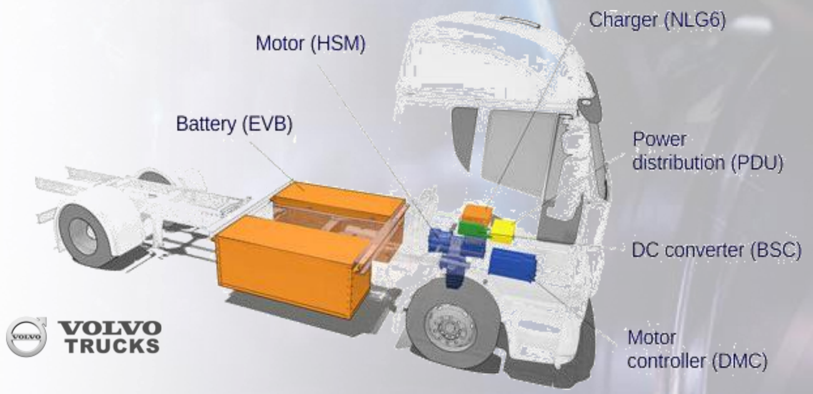
DMDF + future challenges (CO_2 + EU7?) Two Solution Pathways



Synthetic Fuels

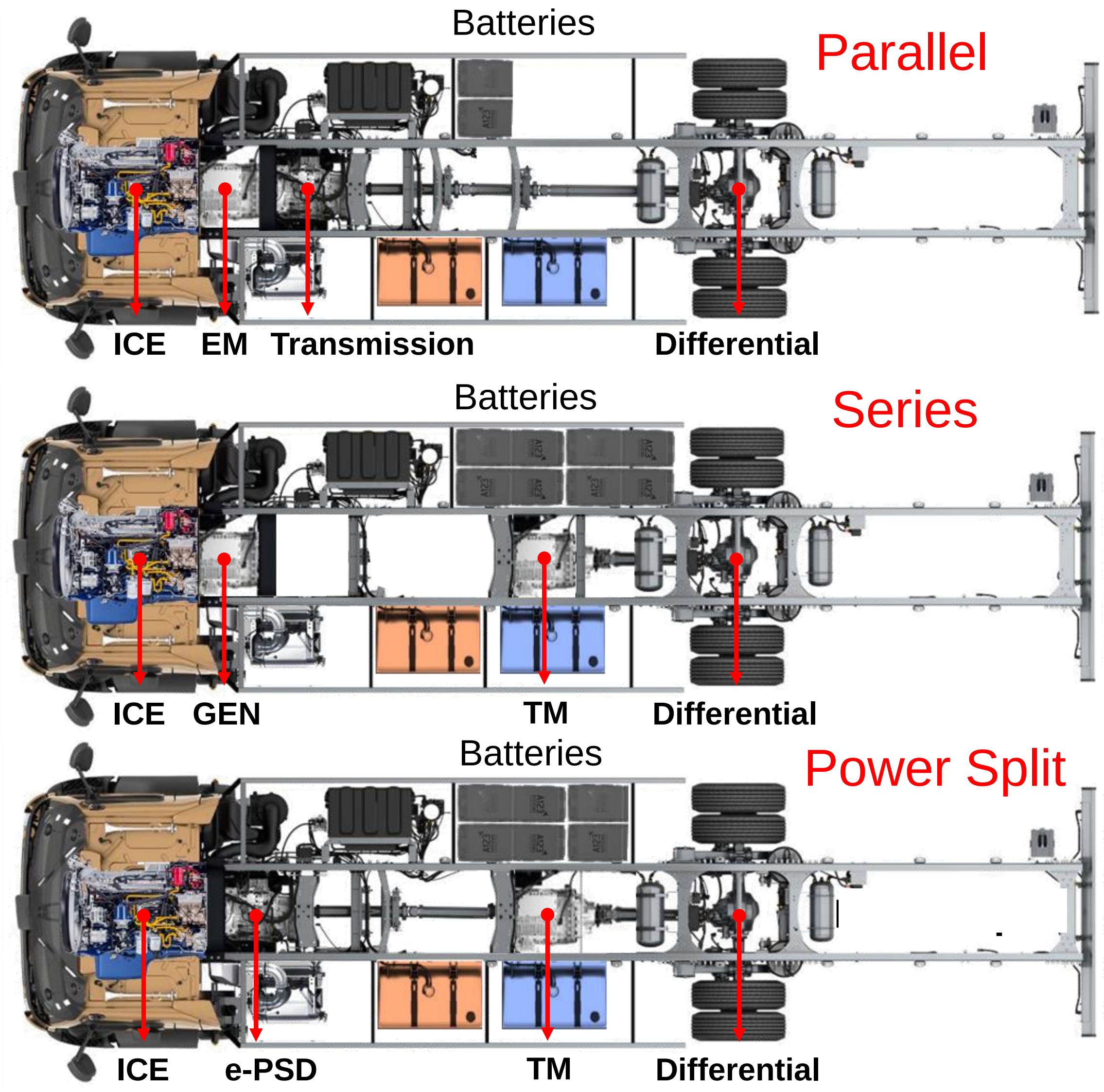


Hybridization

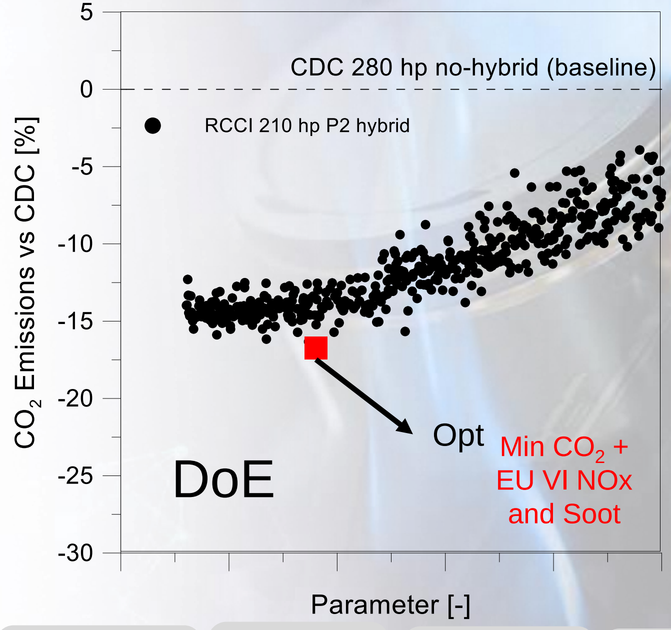


Hybridization Pathway

Three powertrain architectures for evaluating the Dual Fuel Hybrid Concept



Optimization and e-sizing strategies



Battery Capacity | Shift Strategy | EV Max Speed | Charge Strategy

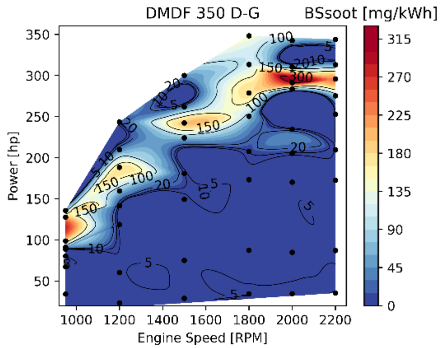
Ex.

FL 280 hp 18 ton	P2	RCCI	70 hp	8 kWh
	Series	D-G 210 hp	280 hp	22 kWh

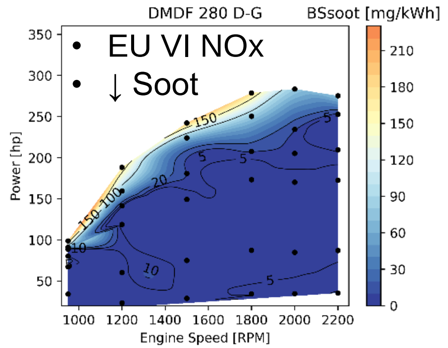
Hybridization Pathway

De-rated MD8 engine to allows low soot DMDF and full RCCI operation.

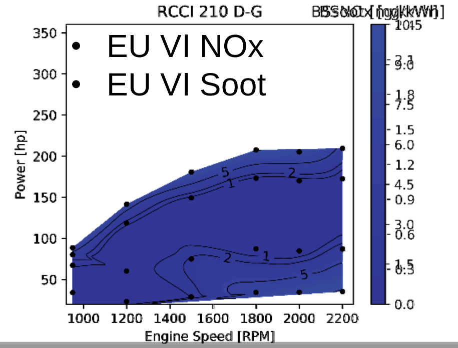
Full DMDF map 350 hp



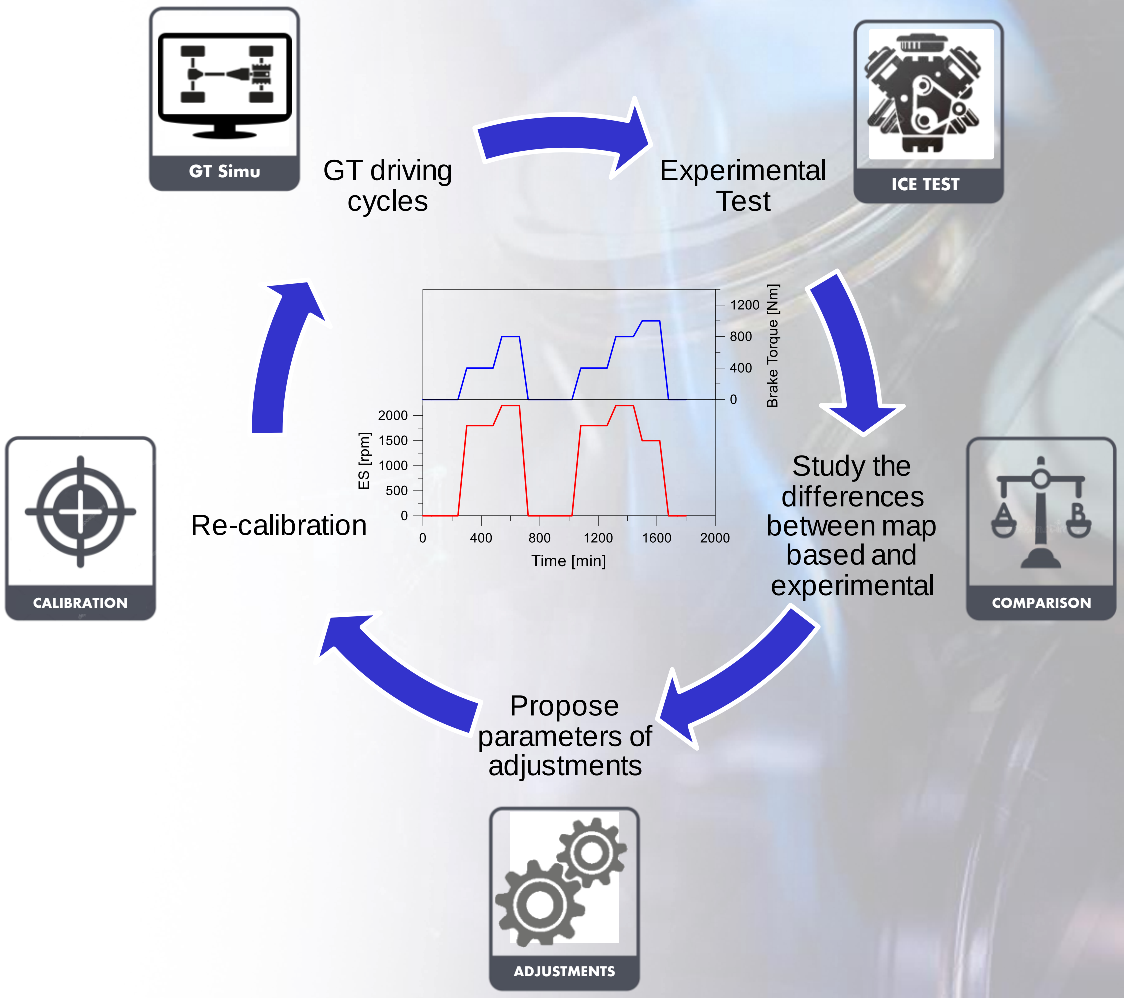
De-rated DMDF map 280 hp



Full RCCI map 210 hp



Hardware in the loop simulation

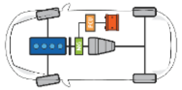


Hybrid powertrain results: WHVC & 50% Payload

Ex: Hybrid RCCI D-G:

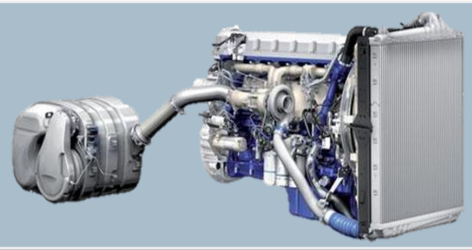
- De-rated 210 hp engine.
- Electric machine compensate the ICE power.
- Results after components and energy management control optimization.


FL 280 hp

			$BSFC_{eq}$	NOx	soot	HC	CO	TTW	WTW
FL 280 hp 18 ton	CDC	OEM	[-] g/kWh	[-] g/kWh	[-] mg/kWh	[-] g/kWh	[-] g/kWh	[-] g/tkm	[-] g/tkm
	RCCI D-G EU VI	P2	-16.2 %	-91 %	-93 %	+2807 %	+1227 %	-17.0 %	-17.5 %
		Series	-8.9 %	-92 %	-95 %	+2473 %	+749 %	-11.3 %	-11.9 %
		PSD	-8.5 %	-92 %	-92 %	+1812 %	+930 %	-9.8 %	-10.3 %
	RCCI OMEx-G EU VI	P2	-15.6 %	-90 %	-100 %	+1683 %	+1115 %	-13.9 %	-38.6 %
		Series	-11.4 %	-91 %	-100 %	+2510 %	+690 %	-12.6 %	-25.0 %
		PSD	-15.1 %	-90 %	-100 %	+2902 %	+535 %	-14.8 %	-31.3 %

EU VI limit
EU VII limit
2025 CO_2 Targets
2030 CO_2 Targets

Takeaways



Full map operation in a stock hardware engine with **DMDF combustion:**

- addition of LP-EGR.
- low pressure injection.
- compression ratio reduction.

RCCI +DF diffusive:

- **ultra-low soot & NOx concept**
- **similar efficiency of the original CDC engine with CR of 17.5:1**.

Driving cycle results shows an engine out EUVI NOx compliant engine.

DMDF is an alternative to introduce of **low carbon footprint fuels:**

- gasoline enables the operation with low LHV fuels → ↓ modification in the fuel injection system.
- the partial usage of **OMEx enables to achieve both H2025 and H2030 CO_2 targets (WtW)**

OMEx usage:

- **soot-free combustion** → non-C-C bonds and ↑ O_2.
- EGR can be tailored to attain **low NOx**.

Hybrid powertrains allow **derating of the DMDF engine** to operate in RCCI-only mode.

- **EURO VI NOx and soot emissions.**

Hybrid operation **improves fuel consumption with reduced battery sizes** (8 to 22 kWh for the 18 tons vehicle).

- Up to 17% CO_2 reduction in **TtW** basis.
- Synthetic fuels can reach more than 38% CO_2 reduction in **WtW basis.**

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Assoc. Prof. Dr.

Antonio García Martínez

angarma8@mot.upv.es

ORCID :0000-0001-5783-4936

LinkedIn :https://acortar.link/2eirGa

CMT Motores Termicos www.cmt.upv.es

Universitat Politècnica de València

Camino de Vera S/N 46022 Valencia (Spain)

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