Hybrid Powertrain Trends in Commercial Vehicle Propulsion Systems

FEV propulsion

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Prepared for

ASME ICED

Webinar Presentation

Your engineering and consulting partner – strong, competent and reliable

GLOBAL REACH –
ONE FACE TO THE CUSTOMER

>7,500
Employees globally

>800 M€
Total output (2023)

>230
Test cells for engines, T/M, e-drives, fuel cells & batteries

200
Patent applications per year

70%
Academics

>45
Years of experience

>45
Subsidiaries on six continents

>50
Different nations

CO2 emission regulations for heavy-duty trucks are being constantly tightened; Adoption of zero-tailpipe emission vehicle critical

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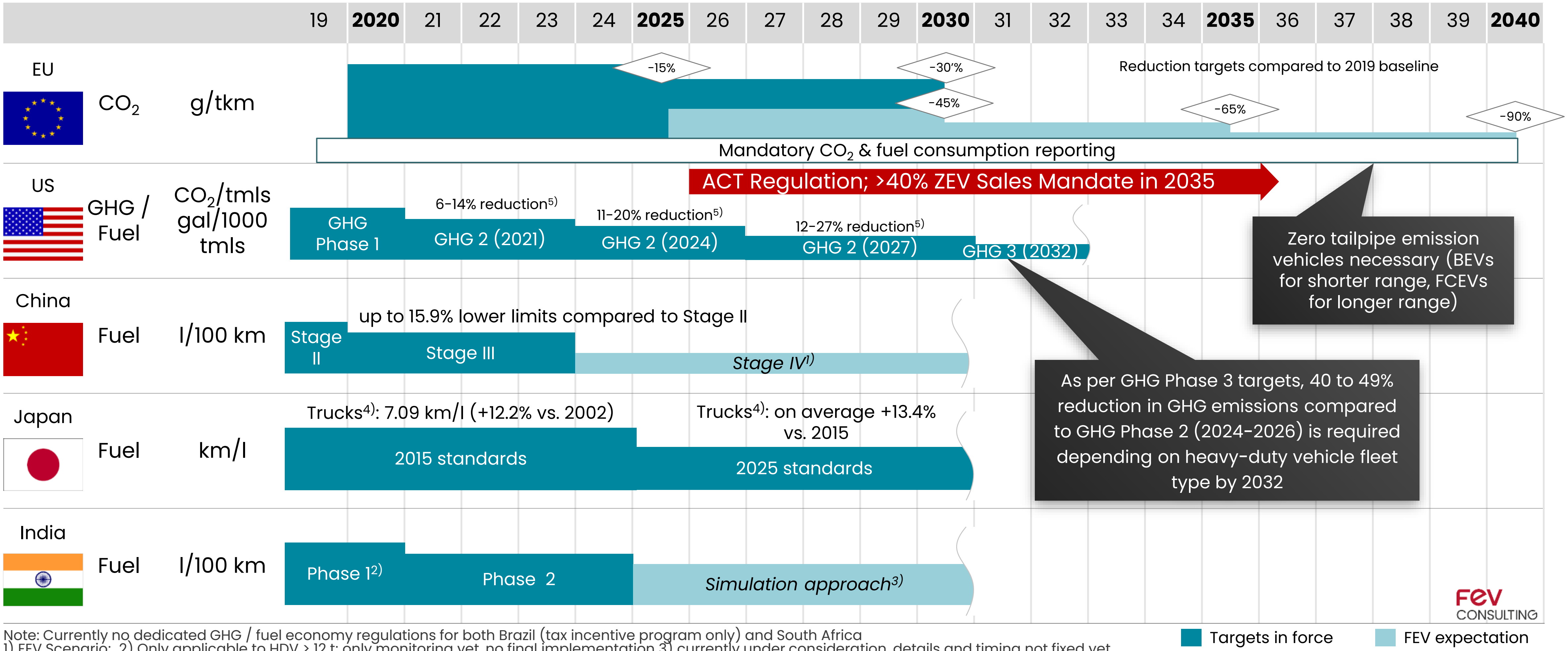
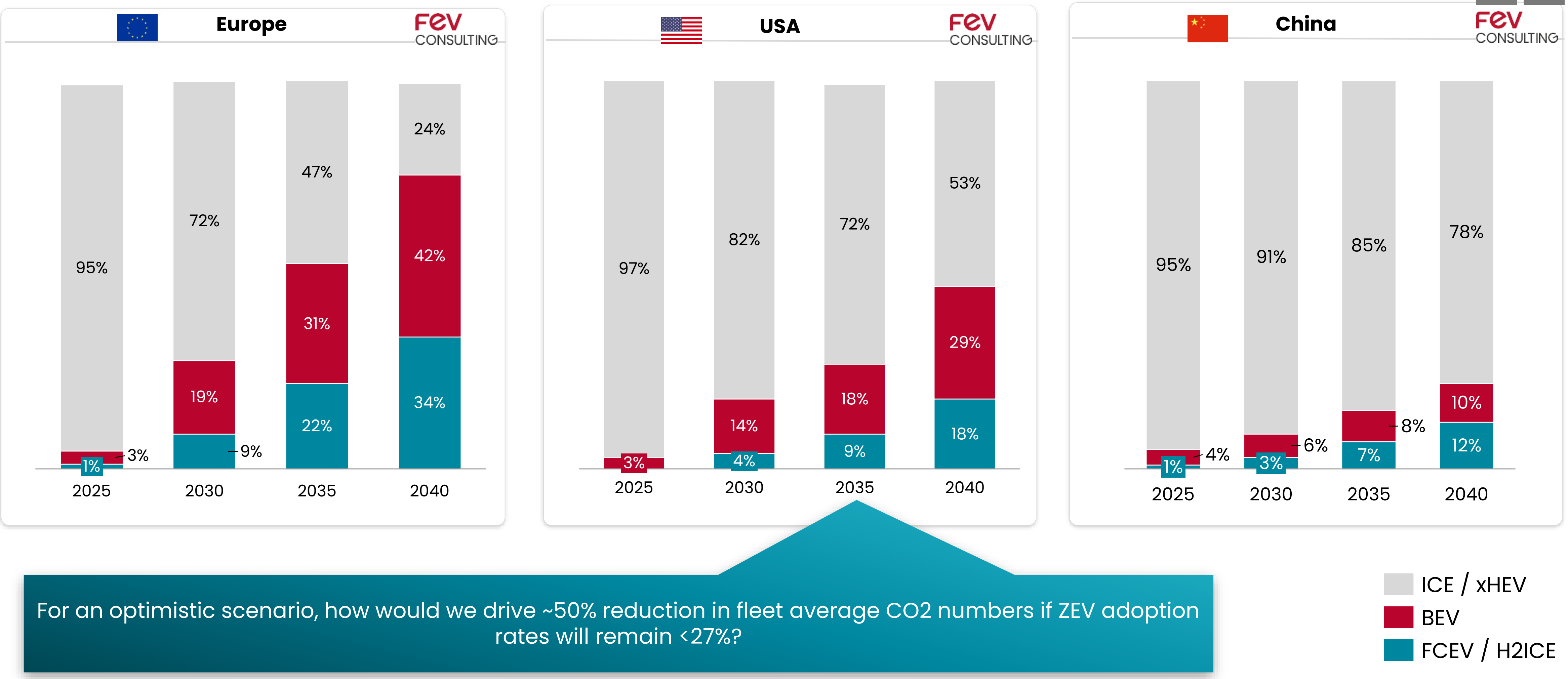
FUEL ECONOMY/CO2 EMISSION REGULATION – HEAVY COMMERCIAL VEHICLES



Note: Currently no dedicated GHG / fuel economy regulations for both Brazil (tax incentive program only) and South Africa
1) FEV Scenario; 2) Only applicable to HDV > 12 t; only monitoring yet, no final implementation 3) currently under consideration, details and timing not fixed yet
4) Fleet average fuel economy; 5) Relative to 2017 & depending on truck class

FEV's sales forecast based on multiple factors such as current regulation, policy discussions, material availability and customer acceptance

COMMERCIAL VEHICLE – POWERTRAIN FORECAST OVERVIEW BY REGION



For an optimistic scenario, how would we drive ~50% reduction in fleet average CO_2 numbers if ZEV adoption rates will remain <27%?

Expected roadmap for hybrid powertrains for commercial vehicle applications

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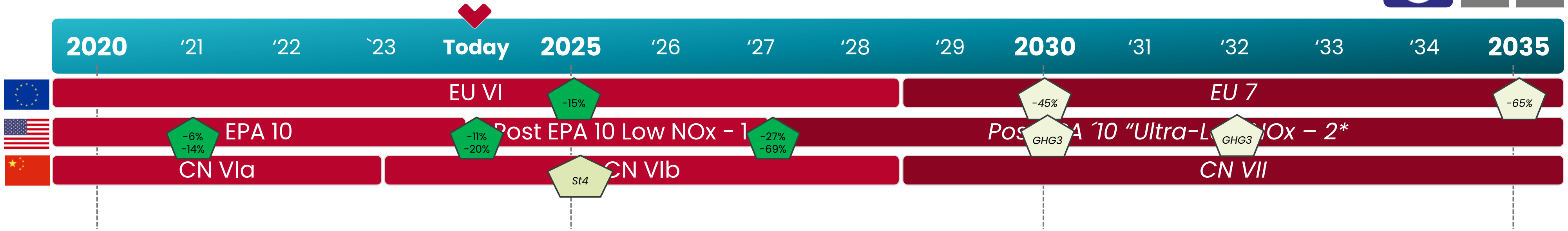
COMMERCIAL VEHICLES - LONG-HAUL APPLICATION (HYBRID POWERTRAIN)



	Current technology focus	Next generation technology focus	Future technology focus
Platform strategy	1: P0 48V Limited Hybridization	HEV/PHEV Solutions (Ex. P2, P4, P1P3)	Dedicated Hybrid Engine PHEVs
	2: Hybrid BEV / Fuel Cell EV (BEV based hybrid)	Fuel Cell EV Dominant Solutions	Fuel Cell EVs
Energy Conversion	Diesel; CNG/LNG; 2nd generation biofuels; early PFI H2-ICE market entry	PFI H2-ICE ; LP-DI H2-ICE; Dedicated SI engine parts	HP-DI H2-ICE; methanol
	H2 PEM Fuel Cell with 350/700 bar Tank; 25000hr durability	H2 PEM Fuel Cell with 700 bar Tank; 35000hr durability	H2 PEM Fuel Cell with liq. H2 tank
Electric machine	PMSM Radial Flux, speeds <8,000 rpm, power to weight ratio 1.0-2.0 kW/kg	PMSM Radial/Axial Flux, power to weight ratio 2-3 kW/kg, transmission integration for platform 1	PMSM Radial/Axial/Transverse Flux , power to weight ratio of 2-4.5 kW/kg, direct drive in at wheels for platform 2
Battery	Cathode: NMC, NCA, LFP Electrolyte: liquid Anode: graphite with low % silicon	Cathode: high-energy NMC, LMFP, LTO Electrolyte: liquid, solid-liquid-hybrid Anode: graphite with high % silicon	Cathode: LMNO, LR-LMO, LTO Electrolyte: solid-liquid-hyb., solid-state Anode: pure silicon, lithium metal
Supervisory Controls	Rule based energy management with some predictive controls capability, temperature-based feedback control for thermal systems	Model based optimal control for energy management and thermal systems; predictive controls capability	Cloud-based optimization for energy management and thermal system for a horizon
Thermal Systems	Independent cooling loops for EDU/Battery, ethylene-glycol based cooling, low voltage fan/pumps	Integrated cooling loops, heat pumps, direct oil cooling for EDU, high voltage fans/pumps	Integrated immersion cooling concepts for battery/EDU

Current technology focus | **Next generation** technology focus | **Future** technology focus

CV CHALLENGES

Near-term challenges in development of hybrid powertrains for commercial vehicles

CO2 Reduction: Technology development for 2027-2032 GHG emission regulations

Emission Reduction: Technology development for 2027-2032 ultra-low emission regulations

Durability: Robustness of solutions for emission compliance and extended vehicle life requirements

Electrification Architecture: Identifying right electrified architecture for right application and corresponding technology development

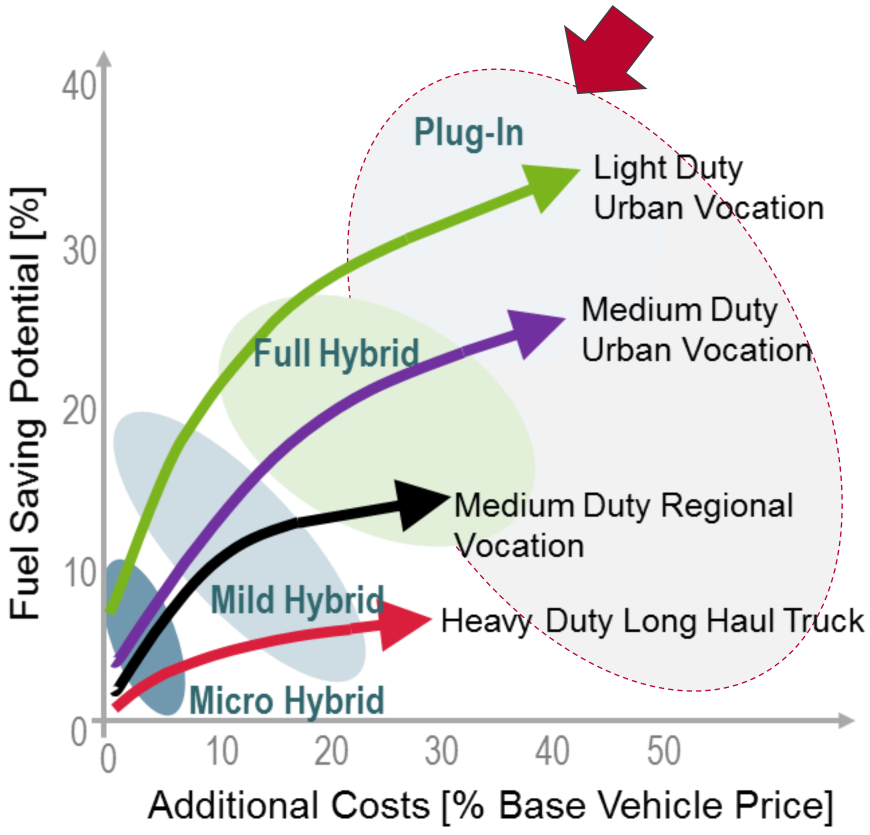
Trade-offs: Product strategy assessment e.g. package, weight, TCO, initial cost, durability, reliability, maintenance etc

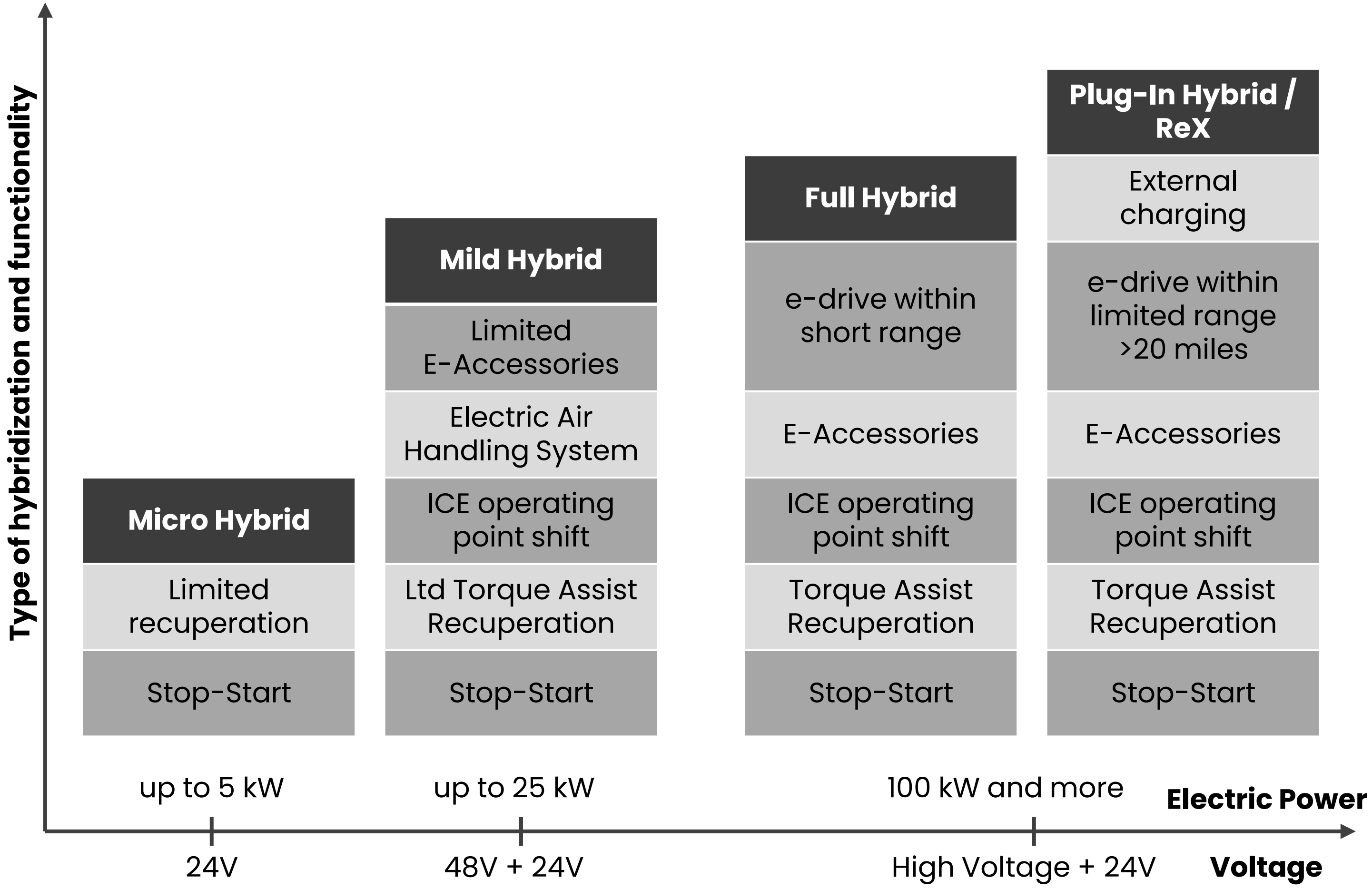
Real-World Emissions: On-road emission monitoring and compliance assessments

Development Timing: Need to accelerate product development timelines to meet regulation and business goals

Defining the hybrid powertrain architecture most significant challenge as optimum architecture varies with application type, and Regulation!

Expect more penetration of PHEVs
in not-so-attractive applications





Source: FEV

FEV's holistic design process for conventional and hybrid vehicles includes a detailed process for an optimal system layout with highest efficiency

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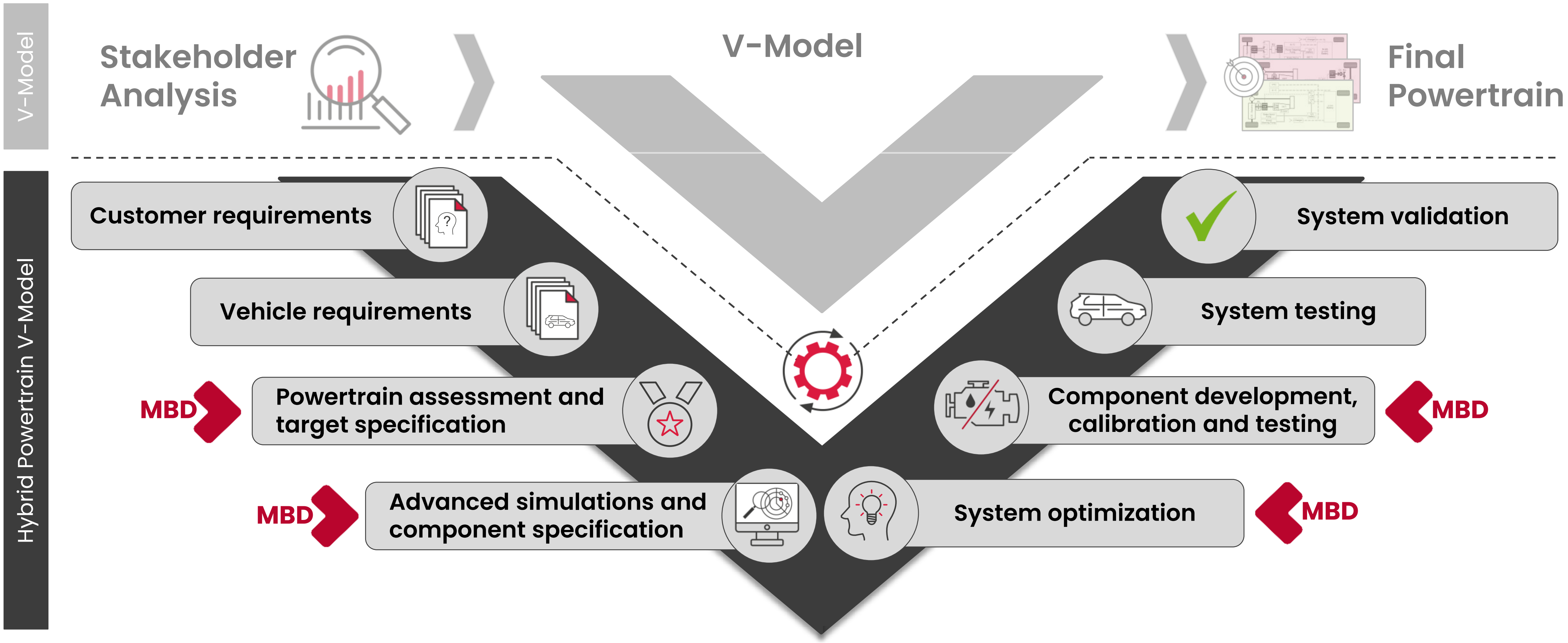
SYSTEMS ENGINEERING FOR HYBRID POWERTRAIN LAYOUT



In the first phase, FEV uses its powertrain concept tool to determine impact of various propulsion system technologies on multiple factors of interest!

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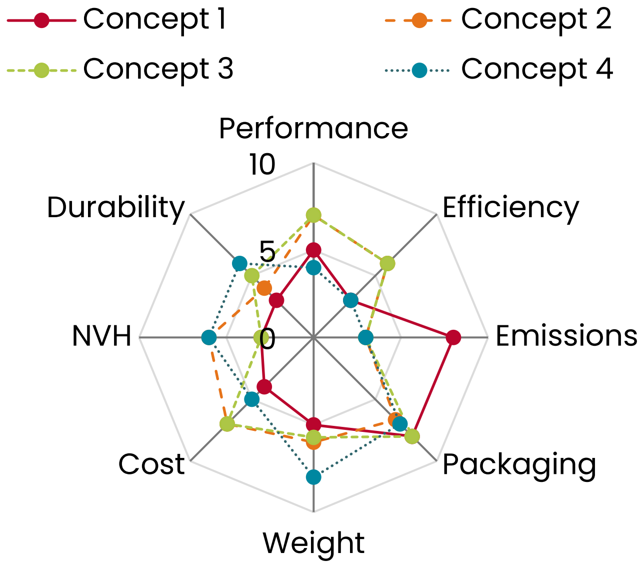
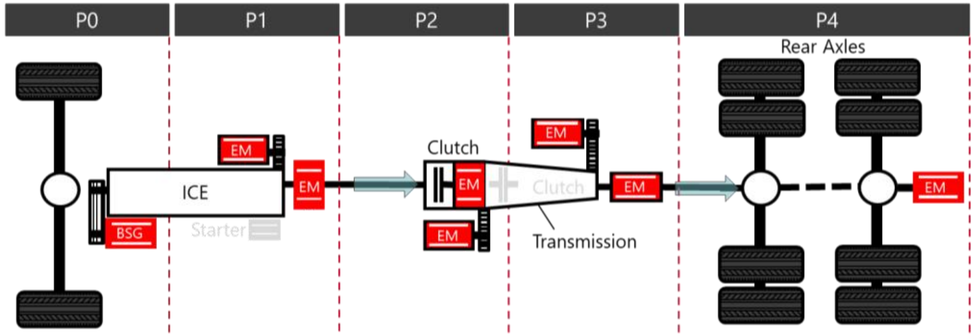
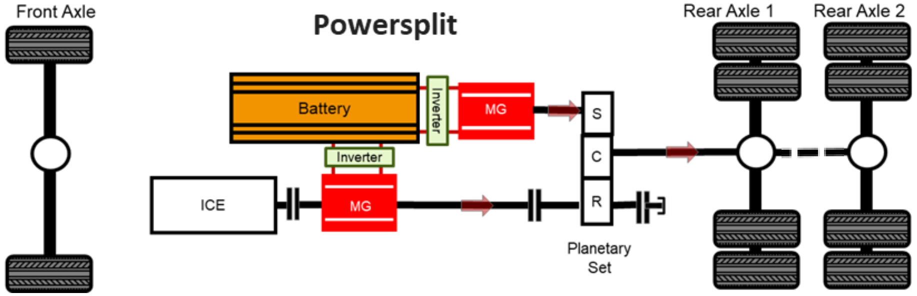
POWERTRAIN CONCEPT DEVELOPMENT



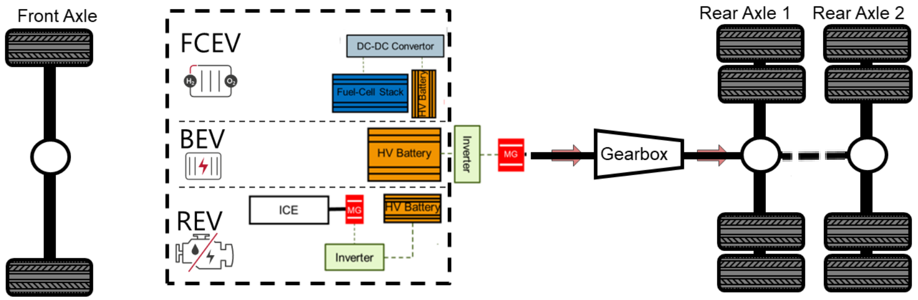
Parallel Hybrids
(P0, P1, P2, P3, P4)
Series-Parallel Hybrids
(P1-P2, P1-P3, P1-P4)



Power-Split
Hybrids



xEV Concepts
(BEV, FCEV, REV)



The tool also provides down-selection of technologies for a dedicated hybrid engine that have special requirements

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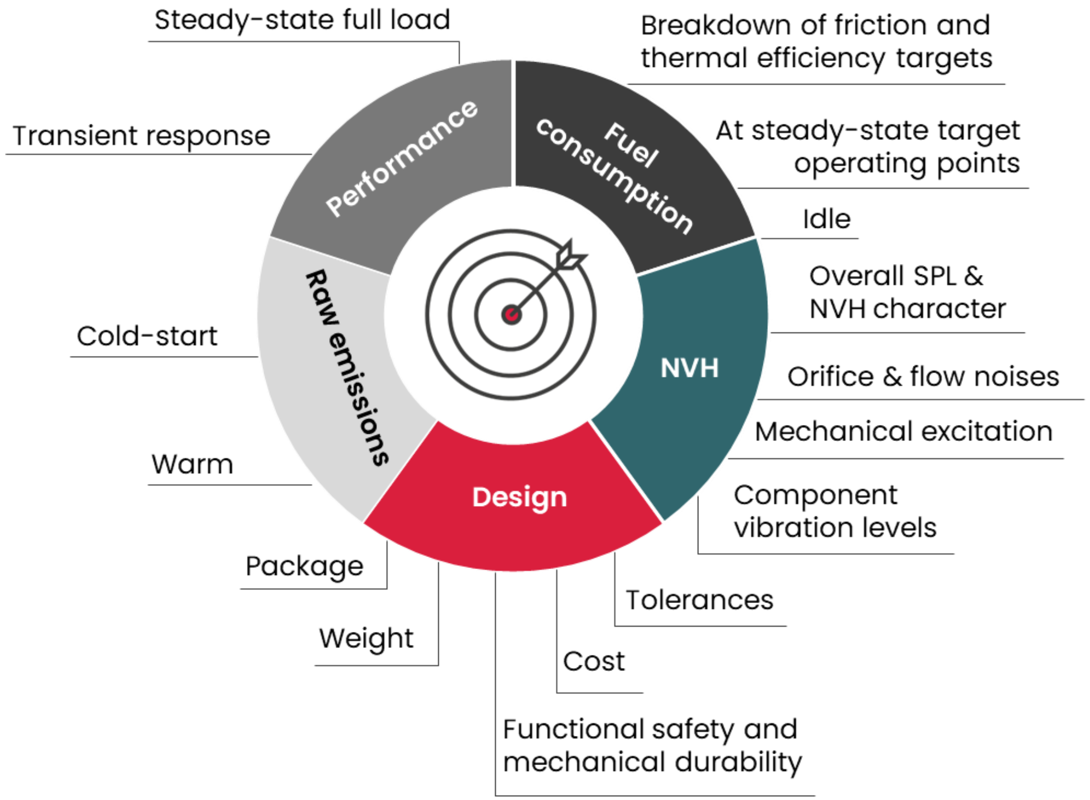
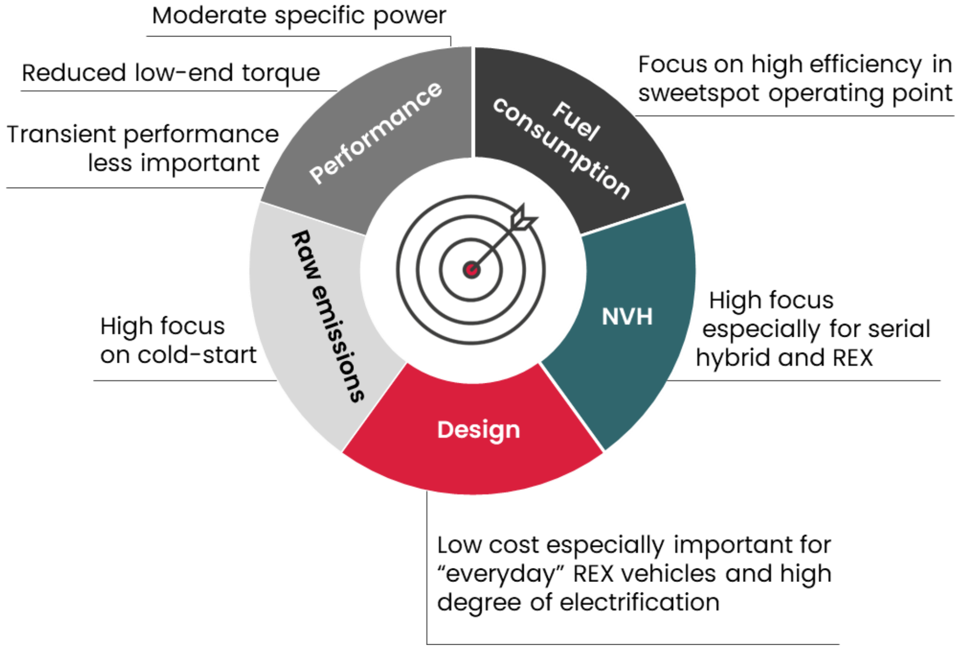
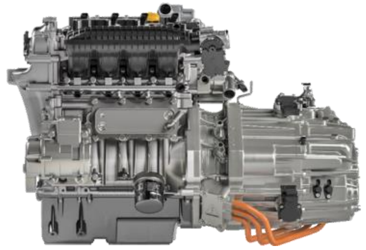


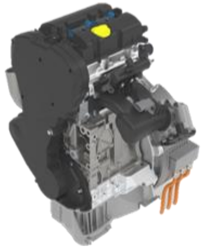


P2 parallel hybrid



Two Paths

Serial hybrid / REX



Once the leading concepts are down-selected, FEV's modular simulation platform enables seamless virtual development for these hybrid powertrain

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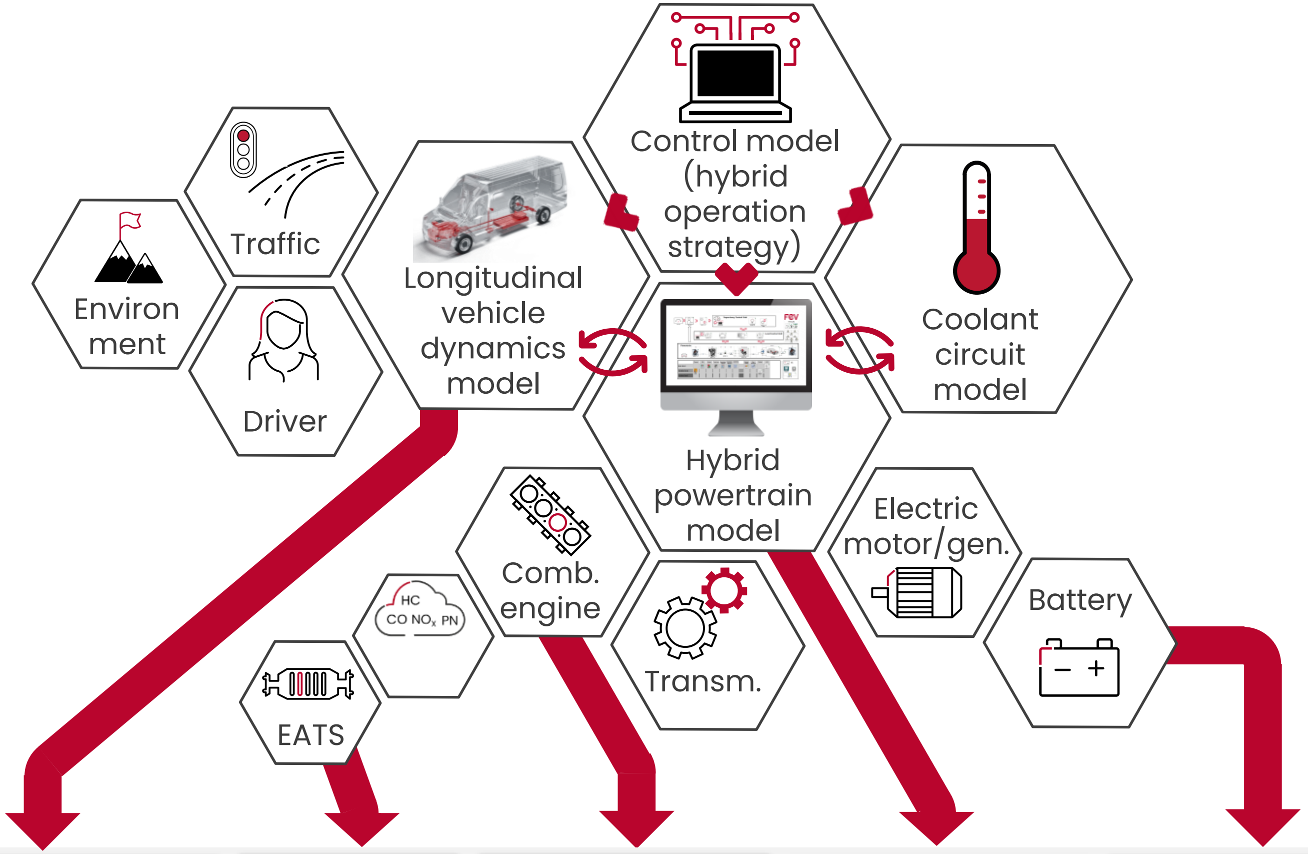


- Simulation contains advanced optimal control strategy to control the hybrid system
  - Control parameters included in optimization process
- All powertrain component models containing sub-models for thermal behavior and derating characteristics
- Once architecture is determined, further model use for propulsion/thermal component sizing and XiL calibration

Acceleration time Towing capacity Offroad performance Drive-off on slop	Tailpipe emissions	Cruising range Fuel economy	NVH emissions	Electric driving range

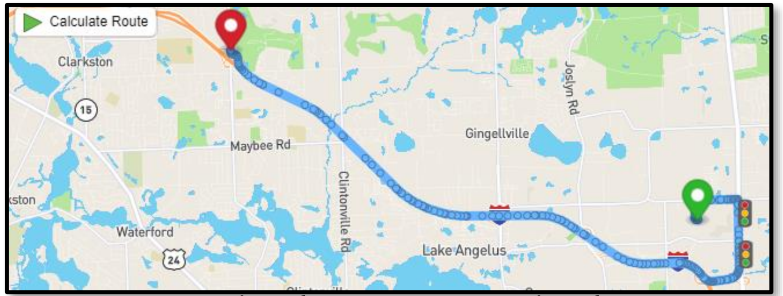
High fidelity hybrid powertrain model for model-based development

Example model development and validation for Class 8 truck application with diesel powertrain and predicitive cruise control

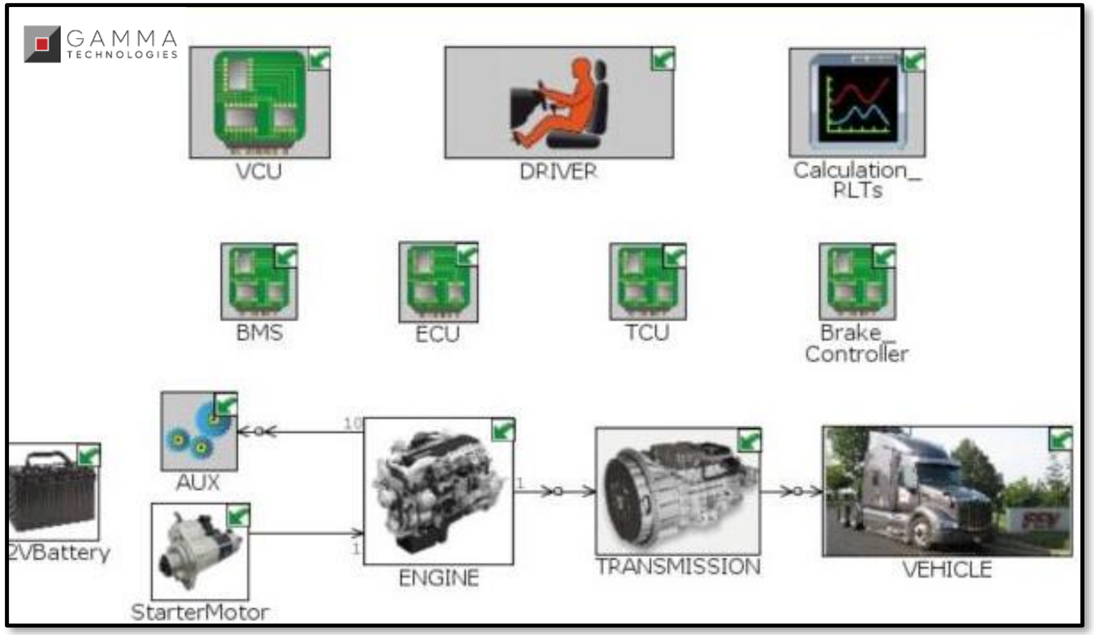
Paccar MX 13
455 HP @1600rpm

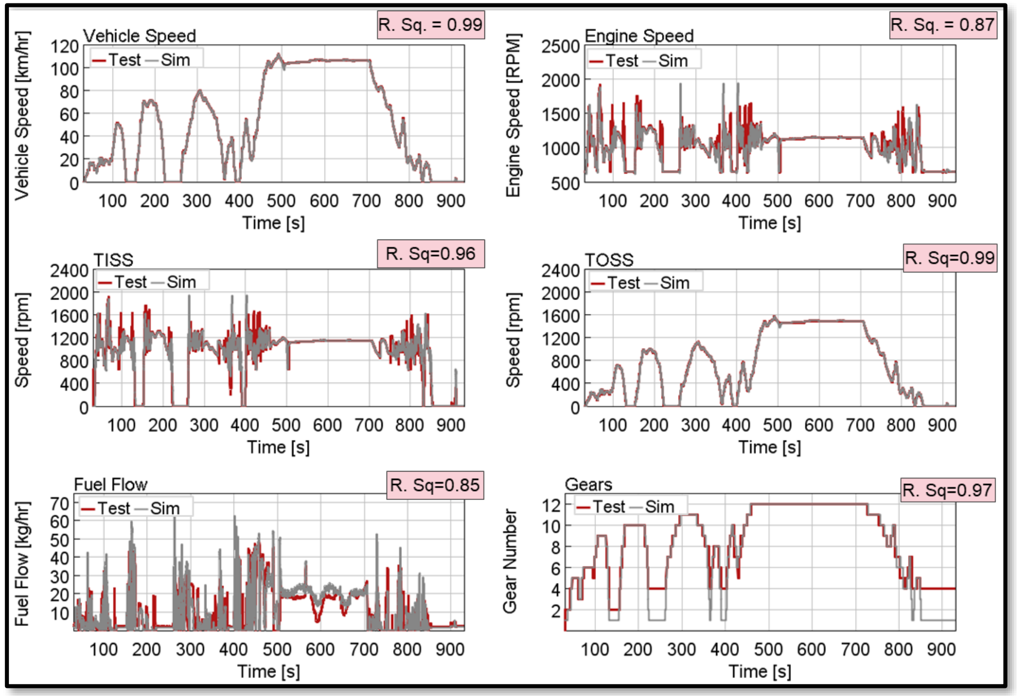
Peterbilt 579 Sleeper Cab

Eaton Endurant
HD 12 Speed



Route Elevation from GT RealDrive for PCC





Source: FEV

Propulsion and thermal systems modeled for multiple architectures using GT-SUITE and component sizes/control strategy optimized

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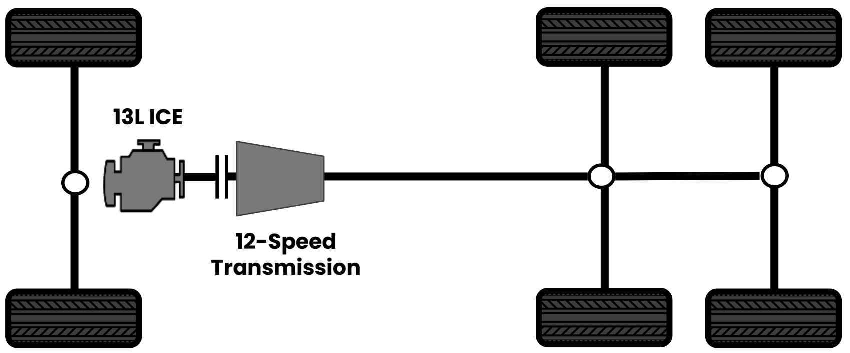
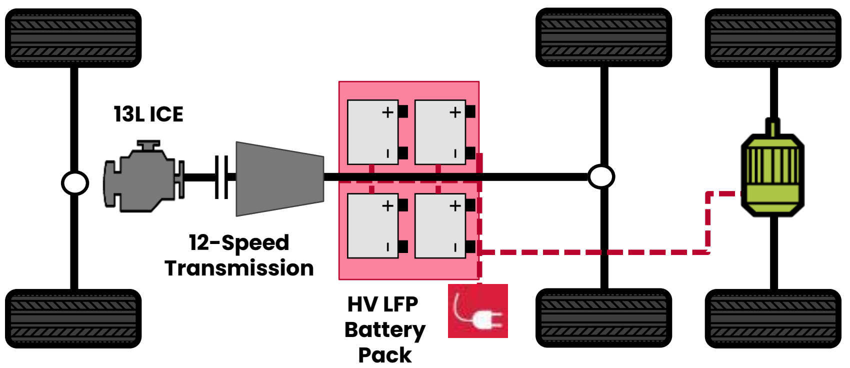
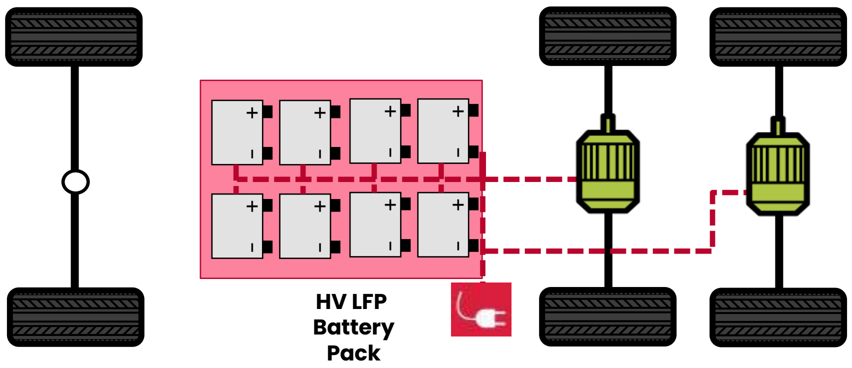
Conventional ICE



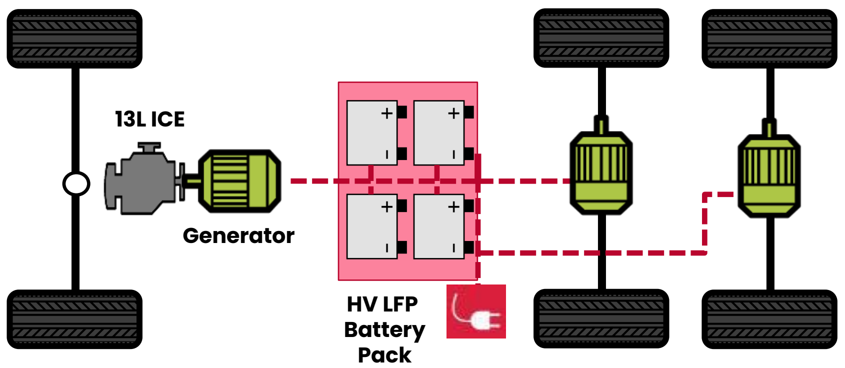
P4 PHEV



BEV



Hybrid BEV



Target drive cycle development is key in optimization and evaluation of hybrid powertrain architectures; especially for CV applications

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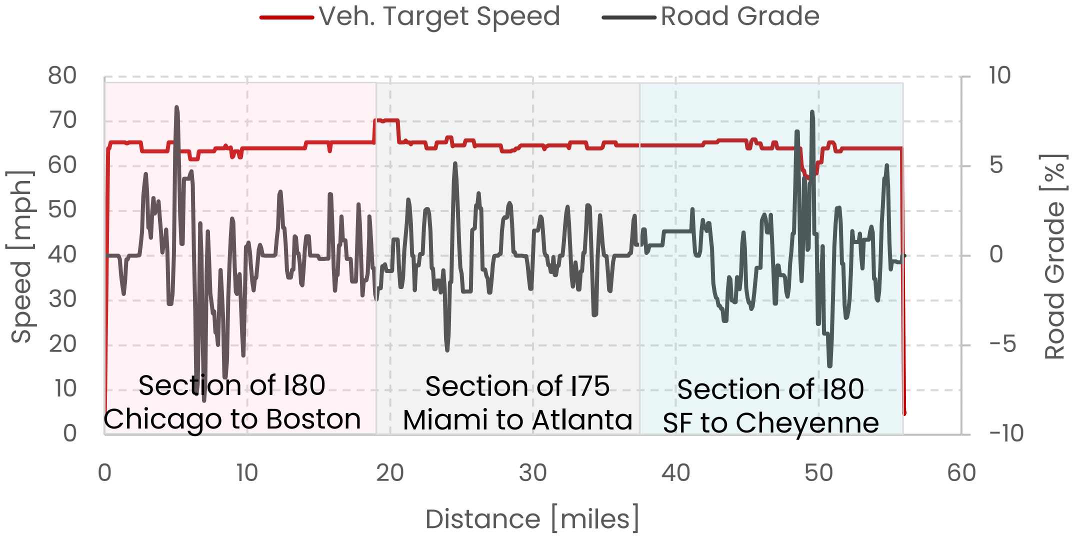
Drive Cycle Attributes	Value
Average Target Speed	64.25 mph
Average Grade	0.015 %
Standard Deviation of Speed	8.71
Standard Deviation of Grade	2.04
Maximum Speed	70.24 mph
Maximum Grade	8.31 %
Minimum Grade	-8.11 %
Total Distance	56 miles

- **GT-Suite Real Drive** Map box functionality was applied to develop the cycle characteristic e.g., elevation, target speed and cycle distance
- Considered major heavy duty truck routes across the US
    - **San Francisco to Cheyenne I-80, Chicago to Boston I-80/I-90, and Miami to Atlanta I-75**
- Altitude data smoothing algorithm (Annex IIIA Appendix 7b 4.4.2)
- Reference: Commission Regulation (EU) 2018/1832 of Nov 5, 2018
- **FEV's MATLAB based cycle generation tool** utilized to filter Elevation data to prevent any abrupt changes in grade or vehicle speed



PHEV battery pack optimization key for understanding the tradeoff between EV sales reduction and PHEV cost/weight/emission/payload/modularity

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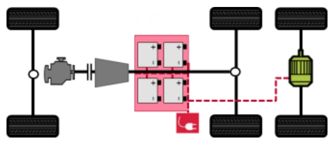
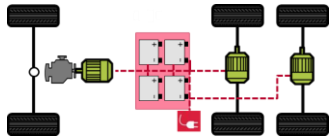
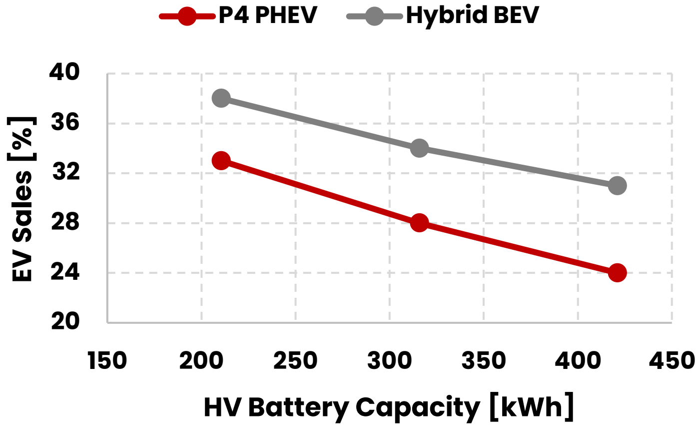
BATTERY PACK SIZING TRADEOFF FOR P4 PHEV AND HYBRID BEV ARCHITECTURES

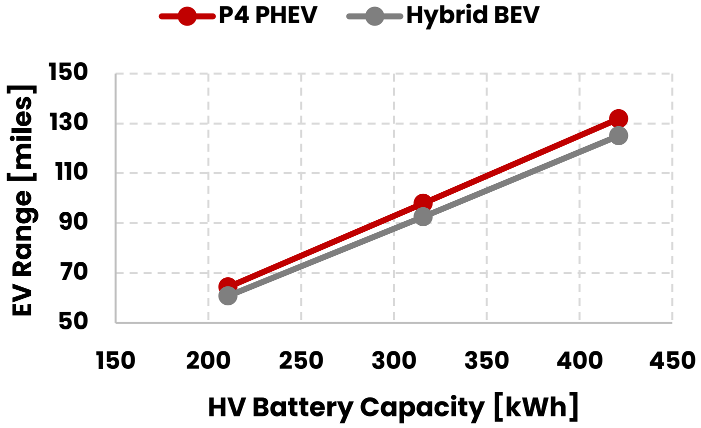
P4 PHEV



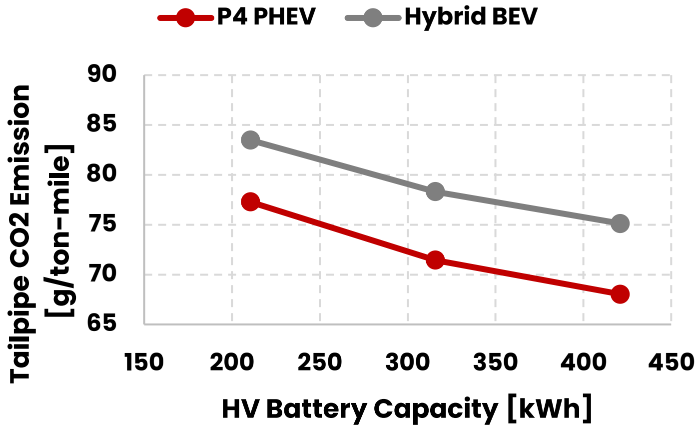
Hybrid BEV

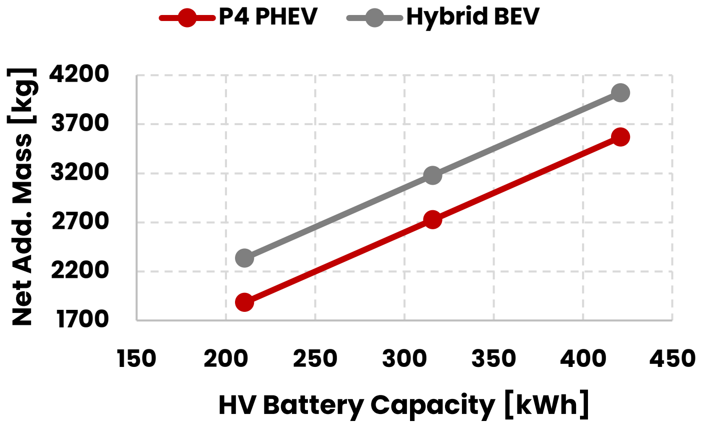






- Without PHEVs 40% EV sales required to meet fleet-average CO2 target in g/ton-mile
- Tailpipe CO2 emission reduction in PHEVs due to EV mode driving, little to no-benefit in charge sustaining mode

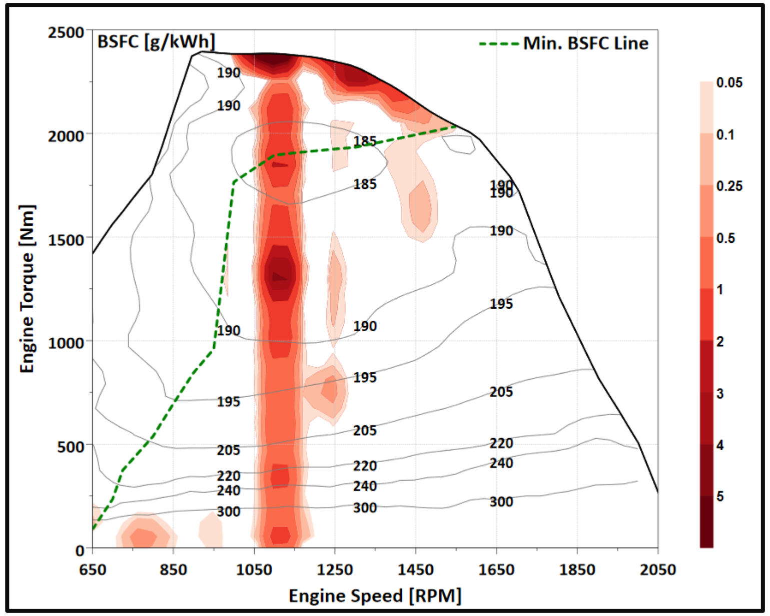


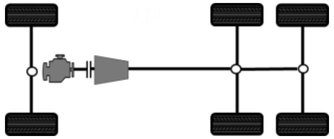


EV range/Tailpipe CO2 calculated for 19 US-ton payload on the real-world drive cycle

Dedicated hybrid engines for commercial applications expected to focus on reduced transient capability and even narrower speed range operation

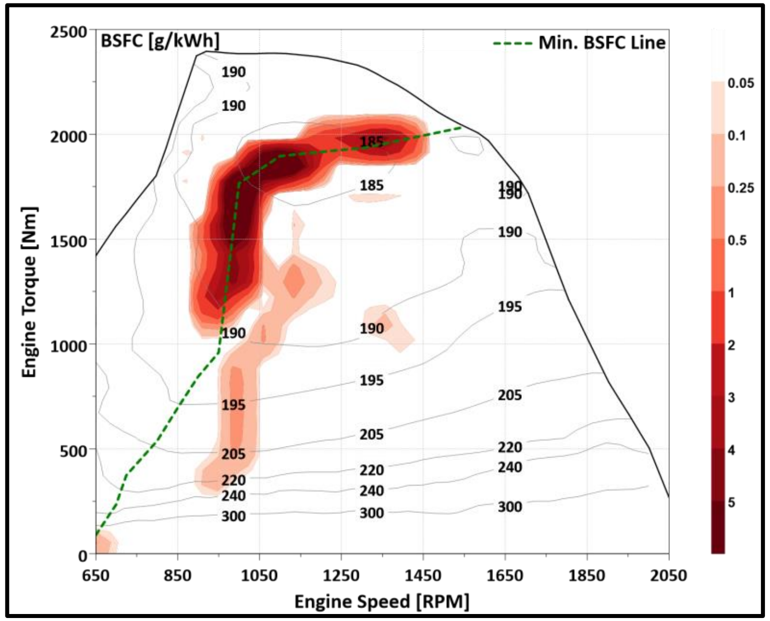
Conventional Diesel
Avg. BTE: 45.0%

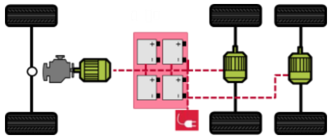




- Decoupled engine operation from vehicle driveline can drive significantly different engine performance requirements
- Reduced transient capability and reduced operating speed range opens door for optimization for cost and efficiency

Hybrid BEV
Avg. BTE: 45.4%





For class 8 application, tailpipe GHG benefits from PHEVs will be primarily from external charging; may need ensure it happens regularly!

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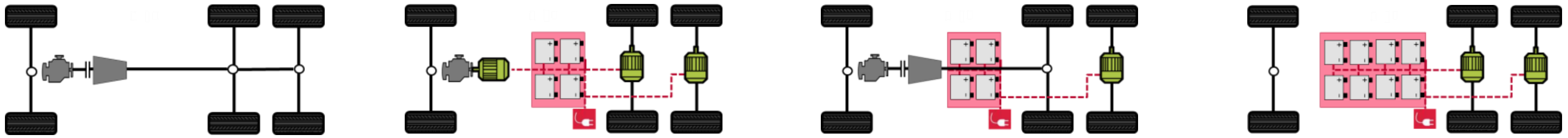

Parameter	Conventional Diesel	Hybrid BEV	P4 PHEV	BEV
Vehicle Chassis Mass (Payload)	*22,708 lbs (38,000 lbs)*	27,858 lbs (38,000 lbs)	26,861 lbs (38,000 lbs)	38,146 lbs (29,000 lbs)
**Est. Upfront Cost [$]	*160,000*	204,705	197,113	298,984
Propulsion System	*455HP MX13, 12 speed AMT*	400HP MX13 Genset 540HP Cont. 2x2-speed E-axles 210kWh Battery Cap.	455HP MX13, 12 speed AMT 270HP 1x3-speed E-axle 210kWh Battery Cap.	540HP Cont. 2x2-speed E-axles 1050kWh Battery Cap.
Acceleration 0-60 mph @80k lbs GVWR (0-30 mph)	*60 s (13 s)*	**38 s** Hyb / **47 s** EV (**11 s** Hyb / **13** s EV)	**36 s** Hyb / 65 s Low SOC / **88 s** EV (**10 s** Hyb / 15 s Low SOC /**19 s** EV)	**38 s** **(11 s)**
Max Speed @80k lbs GVWR	*89 mph*	**81 mph**	**86 mph**	**81 mph**
Startability (Peak) @80k lbs GVWR	*37.5%*	**20.0**	Hyb **37.0%**/ Low SOC 30.0% / EV **17.0%**	**20.0%**
Max. Speed at 5% Grade with High SOC (Low SOC) @80k lbs GVWR	*33 mph (33 mph)*	**31 mph** **(30 mph)**	Hyb **45 mph**/ EV 26 mph **(31 mph)**	**31 mph** **(30mph)**
*Real-world Drive Cycle Fuel Economy (CO2 Emission)	*6.16 mpg (86.91 g/ton-mile)*	**5.63 mpge** CS (**-8.5%**) / **6.05 mpge** CD+CS (**-1.7%**) (83.47 g/ton-mile)	**6.04 mpge** CS (**-2%**)/ **6.51 mpge** CD+CS (**5.7%**) (77.28 g/ton-mile)	**13.74 mpge**
***Real-world Drive Cycle Based EV Range (Total Range 150 Gal. Tank)	*NA (924 miles)*	**60 miles** (908 miles)	**63 miles** (977 miles)	**318 miles**

*Charge Sustaining (CS), Charge Depletion (CD), Utility Factor is based on daily driving distance of 500 miles and EV range, relative percentages for fuel economy are compared to baseline Diesel, all fuel economy numbers are in DGE, **HV LFP Battery Cost: $155/kWh, ***EV range/Tailpipe CO2 calculated for 19 US-ton payload on the real-world drive cycle

Using model-based approach, FEV has recently led the development of multiple electrified propulsion and thermal systems!

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Thank you!
Questions?

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