Minimizing Fuel Cell Hybrid Truck Ownership Cost

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Optimum sizing of class 4 delivery van and class 8 linehaul truck
July 31st 2018

Overview

1. Quantify Fuel Cell Powered Trucks Requirements and Benefits
2. Develop Sizing Algorithms to Minimize Vehicle Ownership Cost.

- Develop design concepts with equivalent functionalities to conventional diesel powered trucks for multiple classes and vocations.
  - 15 class/vocation combinations selected to cover most of the Medium & Heavy duty applications.
  - Performance based sizing approach
- Optimize component sizes for minimizing overall ownership cost, considering initial & recurring costs
  - Class 4 delivery truck & Class 8
    - Architecture comparison
    - Optimum component sizing for each case.

- **Objective :** Share current status and gather feedback for next steps
  - The vehicles presented here are deployed through Autonomie and are used across multiple studies.

Vehicle Performance Assumptions

Cargo weight, Acceleration, Grade speed

Developed Based on Conventional Vehicle Simulations

Properties		Class 2	Class 3			Class 4	Class 5	Class 6		Class 7		Class 8				
		Van	Closed Van	Service/Utility	School bus	Walk In	Utility	Pickup & Delivery	Construction Dump Truck	School bus	Flat Bed	Transit Bus	Construction	Refuse	Tractor	Linehaul
Summary	Daily driving range (mi)	153	163	150	150	200	150	150	200	150	150	150	200	150	400	400
	Baseline Power (kW)	187	140	298	187	149	224	225	149	169	169	243	160	242	261	336
Performance	Cargo Mass (lb)	1388	5898	5720	5500	5280	10340	10326	14227	17600	17600	4000	19934	27280	31900	43890
	Cruising Speed (mph)	70	70	70	70	70	65	70	65	60	60	60	60	60	60	60
	6% Grade Speed (mph)	66	49	70	68	41	65	33	30	38	38	27	21	28	27	31
	0-30mph accel time (s)	7.6	7.6	6.3	7.1	8	9.3	12.6	12.5	14.8	14.8	15	20.8	15	16.7	17.1
	0-60mph accel time (s)	22	24.8	14.3	20.5	34.2	23.6	48	47.2	54.4	54.4	62	100	56.5	63.3	61.1

Continuous performance

Transient performance

FCETs are sized to match target performance & daily driving range, while carrying the same cargo mass. Vehicle test weight could vary based on component technology and size.

Fuel Economy Estimates for Conventional and FCETs

Reference model		Dodge Promaster HR	Sprinter 3500 HR DRW	Ford F-350	GMC Savanna	Freightliner MT-45 SRW	International TerraStar SFA	Freightliner MT-55	International DuraStar	IC Bus	International DuraStar	Nova LFS 40	International WorkStar 7300	Mack TerraPro MRU612	Freightliner M2-112	Freightliner Cascadia
Fuel economy		**Class 2**	**Class 3**			**Class 4**	**Class 5**	**Class 6**		**Class 7**		**Class 8**				
		Van	**Closed Van**	**Service / Utility**	**School bus**	**Delivery**	**Utility**	**Delivery***	**Construction Dump Truck**	**School bus***	**Flat Bed***	**Transit Bus***	**Construction Dump Truck**	**Refuse**	**Tractor**	**Linehaul**
Conventional	ARB Transient	20.8	22.4	23.7	21.5	17.0	13.2	8.4	15.1	9.8	9.6	5.5	9.9	8.7	7.1	5.8
	EPA 55 mph	23.2	18.7	20.2	19.0	12.4	15.5	10.5	14.7	14.4	14.1	8.7	10.8	9.7	7.3	6.4
	EPA 65 mph	17.5	15.2	16.9	15.2	9.6	12.5	8.5	12.0	12.7	12.3	7.6	8.2	8.0	5.9	5.4
FCET	ARB Transient	41.2	35.5	33.4	33.6	30.6	24.3		24.9	13.8		8.9	15.2	14.4	11.4	8.2
	EPA 55 mph	26.4	22.6	26.6	20.4	14.3	20.5		17.9	16.9		11.5	10.8	10.0	8.0	7.0
	EPA 65 mph	21.1	18.3	22.4	16.4	10.5	17.7		14.8	13.6		9.3	7.9	8.2	7.1	6.3
	FleetDNA cycles	23.6	15.5	15.7	19.5	11.9	11.1		13.5	11.1			9.2	7	6.2	5.6
	# of cycles	82	87	160	38	250	62		544	422		339	152	675	986	1153

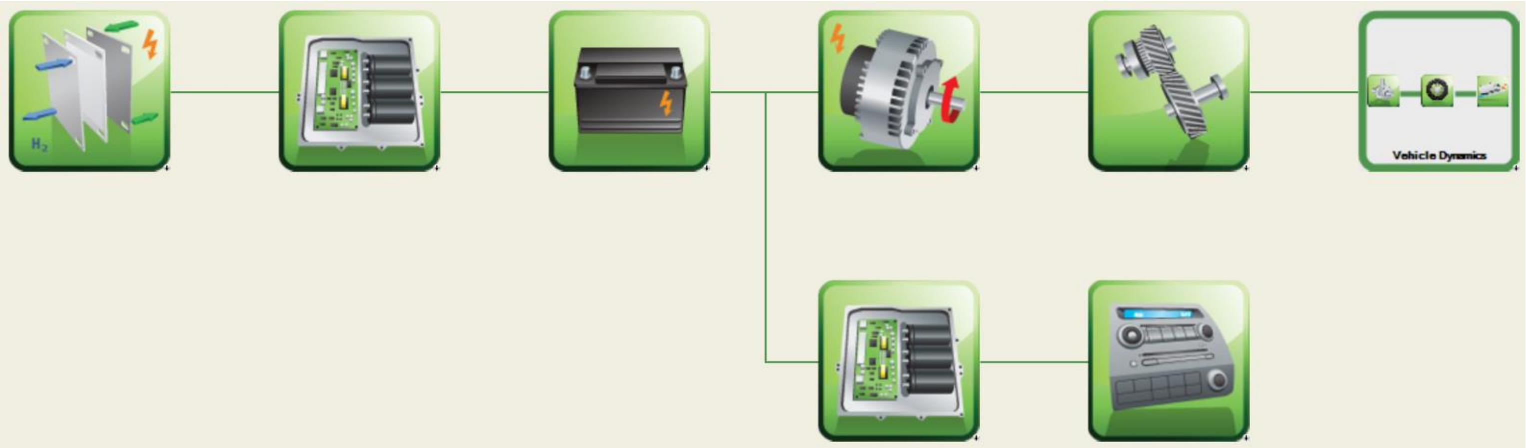
* uses Phase 2 test procedure from EPA.

Demonstrating FCETs Technical Feasibility

Goal: Match or Outperform Conventional Vehicles

FCETs Rule Based Design Assumptions

Control algorithms and component sizes determine whether the vehicles are a charge sustaining or a range extended hybrids



- **FCREx : Battery Powered Electric Vehicle with a Fuel-cell Range Extender**
  - Electric machine is sized to match baseline vehicle performance.
  - FC will meet continuous loads. Battery can assist during grade (11 miles)
  - Battery is sized to drive 50% of dialing driving range in EV mode. H_2 storage is sized to extend this range.
- **FCHEV : Fuel-cell Hybrid Electric Vehicle**
  - FC is sized to meet continuous loads (cruise and grade)
  - Electric machine is sized for performance.
  - Battery is sized for performance and regenerative braking
  - H_2 storage is sized to meet the daily driving requirements

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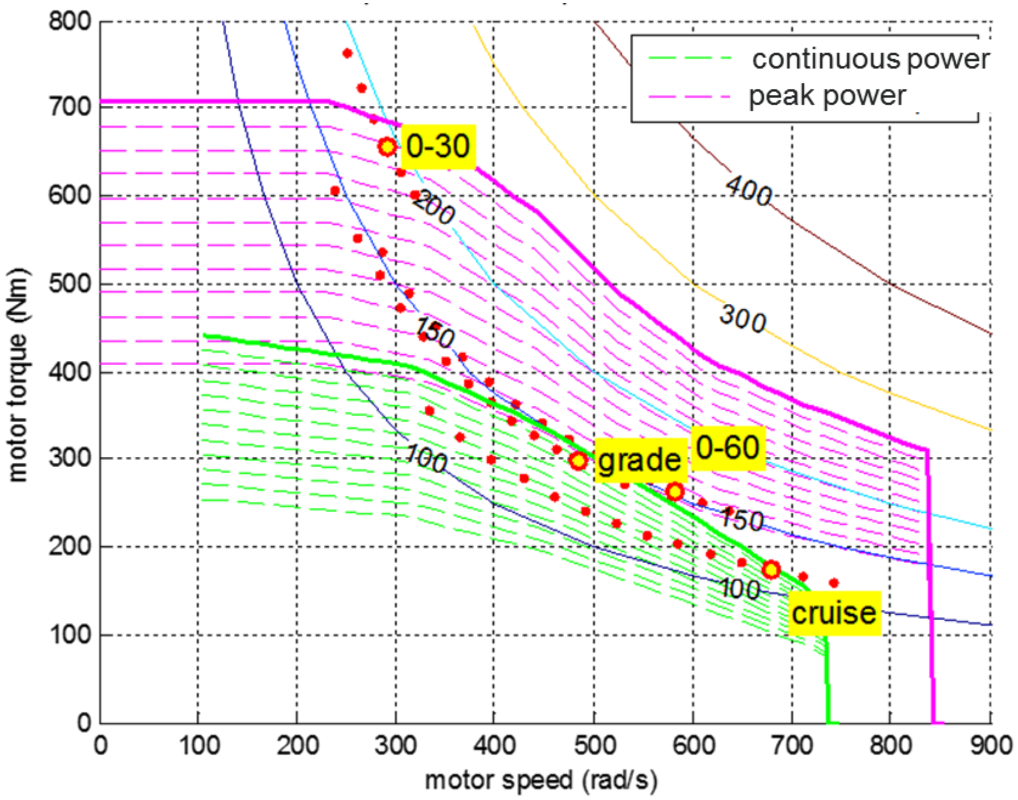
Performance Based Sizing Approach for FCHEV*

Similar methodology valid for range extenders

Parameters	Grade	Cruise	0-30	0-60
Motor Power Required (kW)	**144**	118	-	-
Motor Peak Power Rating (kW)	-	-	**224**	152
Fuel Cell Power (kW)	**164**	154	-	-
Battery Power (kW) @60% SOC	-	-	**54**	9
Min Usable Battery Energy (Wh)	-	-	29	**47**
Min Total Battery Energy (Wh)	-	-	-	**235**



Sample results from Class4 Delivery truck

- Continuous and transient power requirements are estimated through simulations. Motor should meet all these requirements. FC meets all continuous requirements.
- Battery should have the sufficient power and energy to meet the transient power requirements.
  - In FCHEV, battery is sized to maximize regenerative braking
  - In FCREx, battery is sized for the desired electric range.

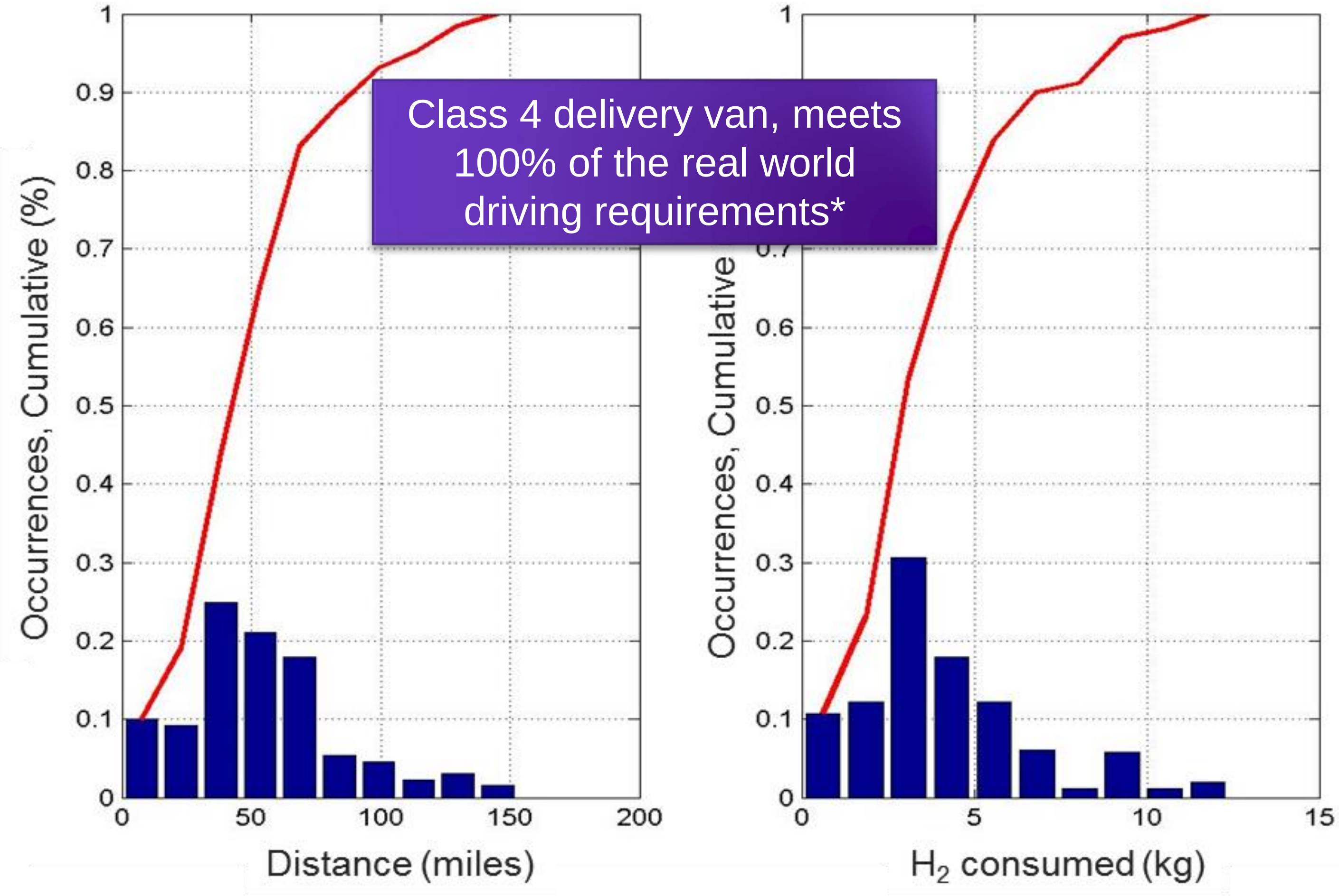
* J.Marcinkoski et al, "Medium & Heavy Duty FCET component sizing". EVS29, Montreal, Canada

Technical Feasibility & Real World Use Cases Are Verified

Cycles from NREL's FleetDNA were used to simulate daily driving requirements

- Vehicles were designed for 200 mile range. Assuming 10.5 mpkg, 19 kg H_2 was stored.
  - Fuel economy was measured in all 3 regulatory cycles and worst case fuel economy was used to size the tank
- Real world fuel economy was 12 mpkg
- With 12kg of H_2, all the real world requirements are satisfied.

- Prior studies have shown a potential to store 20-25kg H_2 in those trucks, depending on the wheelbase.



Conclusion:

FCETs can match or outperform conventional vehicles, with no sacrifices in payload.

Next:

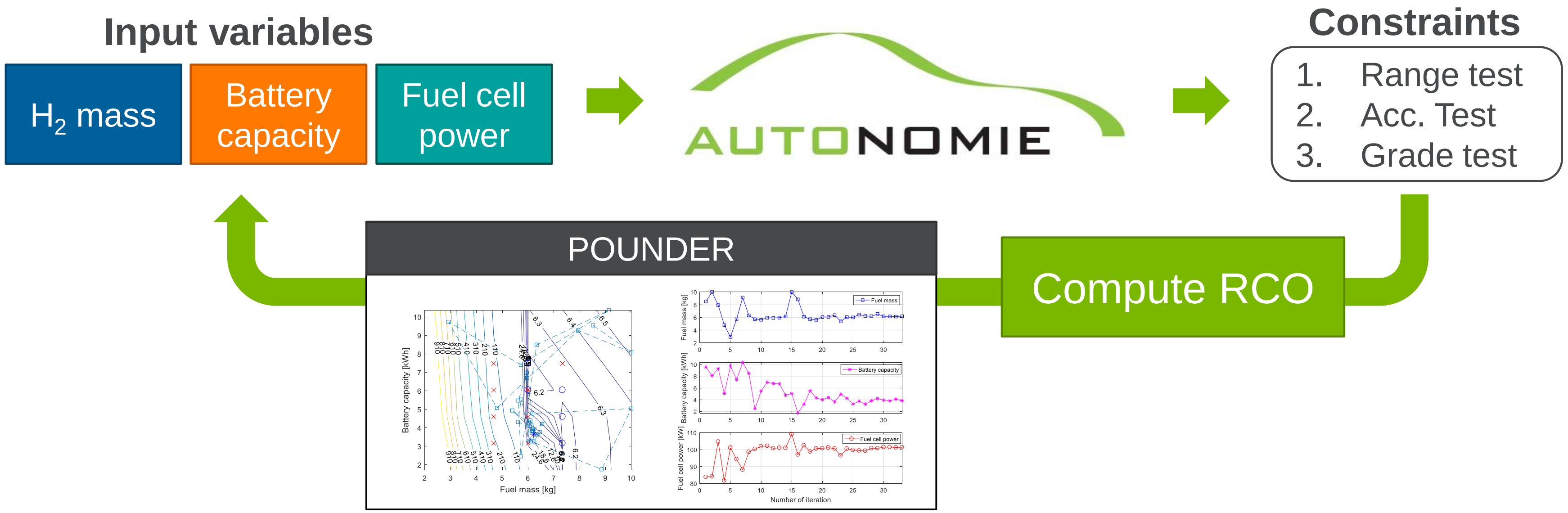
Minimize Cost of Ownership, for commercial acceptance

Sizing Based on Cost of Ownership & Performance

How will sizing change if we minimize ‘Relevant Cost of Ownership’ (RCO)

Approach : Perform trade off between H_2 storage & battery pack

- Define performance based FCET vehicles in Autonomie
  - FCREx & FCHEV
- Optimize onboard H_2 storage & battery pack size to minimize ownership cost
  - Ensure that all performance requirements are met within a 2% tolerance



Relevant Cost of Ownership (RCO)*

- RCO is the net present value for owning and operating the vehicle.
- Assumptions
  - Vehicle lifetime : 15 years
  - Ownership period : 5 years (actual value depends on class & vocation)
  - Yearly driving distance : 14k miles/year (vocational) , 100k miles/year (linehaul)
  - Depreciation rate : 5%
  - H_2 cost : $4/gge (evaluated $12/gge case as well)
  - Residual value = f(initial cost, VMT, discount rate)

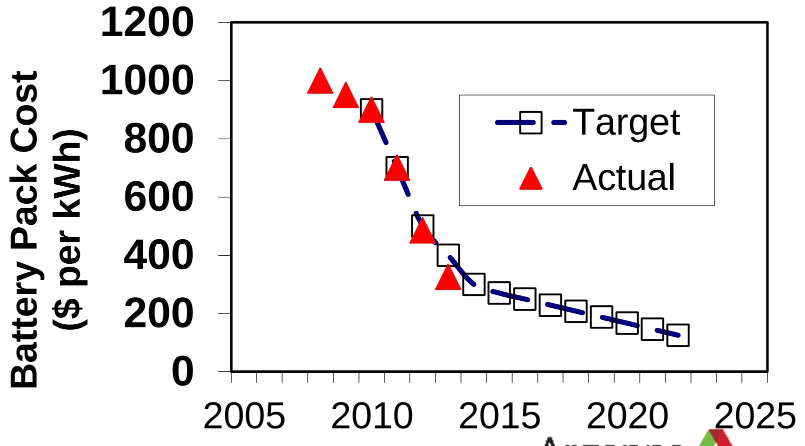
Purchase price and Fuel/Energy cost are the primary variables for RCO.
All other factors are either constants or function of the purchase price.

* A. Rousseau, et al., "Comparison of Energy Consumption and Costs of Different Plug-in Electric Vehicles in European and American Context," EVS28, 2015

Additional Cost and Component Mass Assumptions

- Manufacturing cost
  - Battery : $243/kWh (energy), 20$/kW (power)
  - H_2 tank: $595/kg usable H_2 @ 4.4% weight ratio of storage
  - Fuel cell : $200/kW and 59.5% peak efficiency
    - FC is sized to meet continuous loads, FC power remains largely unchanged in the sizing process.
- Manufacturing cost is estimated based on component cost. Purchase price is set at 1.5 times the cost of manufacturing.
- Specific power
  - Fuel cell system: 659 W/kg
  - Motor: 1.9 kW/kg
- Infrastructure cost is not considered.
  - This needs to be factored in later when comparing the RCO of different powertrains

US DOE Vehicle Technologies program targets



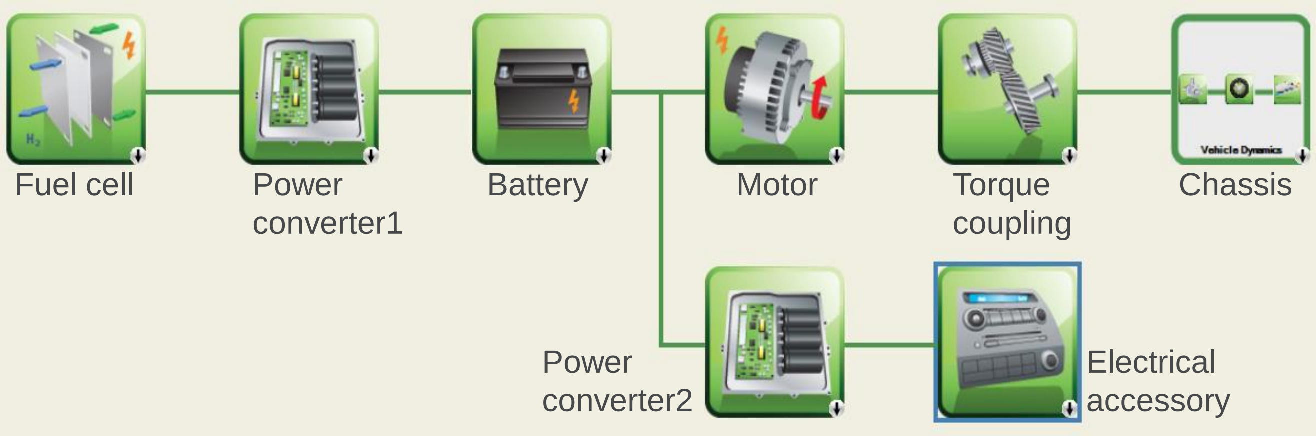
Based on 2017 FCTO/VTO Benefit Analysis Assumptions

Minimizing RCO through Component Sizing Optimization

Case 1 : Class 4 FCREx

Starting point: Rule Based Class 4 Delivery Van (FC REx)

- Requirements
  - Range : 150 miles on ARB Transient cycle
  - Acceleration time (0-60mph) : < 34s
  - 6% Grade speed : 41 mph +/- 2%



Powertrain structure: Fuel cell vehicle in Autonomie

- Cargo mass : 2800kg same as conventional baseline
- Not much change is expected in FC power or Motor power, as the vehicle should still meet performance requirements

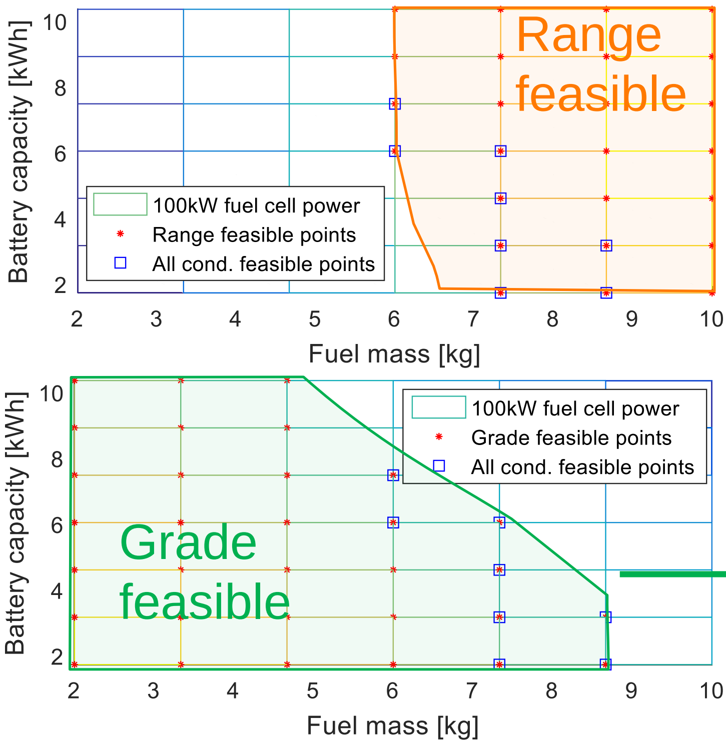
Vehicle specification

Component	Value	Component	Value	Component	Value
Medium Duty	Class 4	Drag coefficient	0.70	Battery type	Li-ion
Vehicle mass	7300 kg	Electric motor	220 kW	Battery energy	59 kWh
Frontal area	7.50 m^2	Fuel cell power	100 kW	On board H_2 storage	4 kg

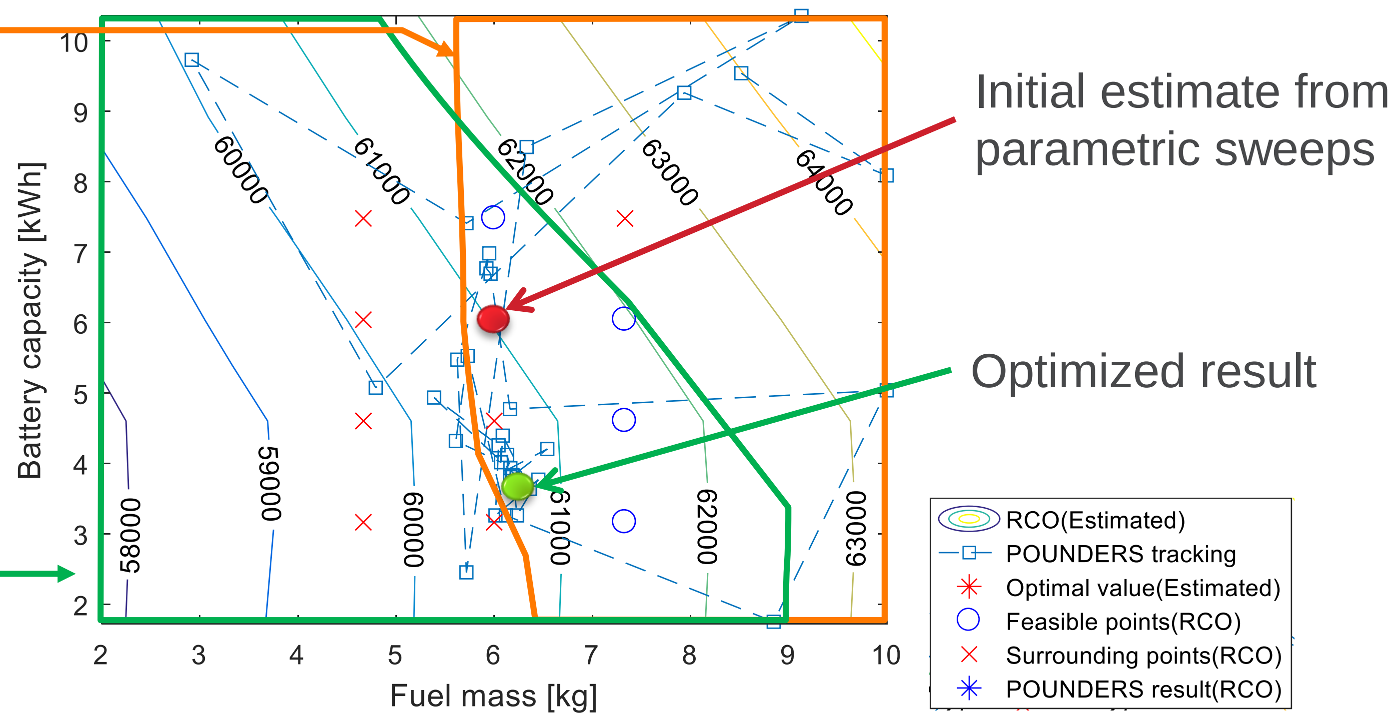
Optimization Results Verified against Parameter Sweeps for Test Cases

The Optimization is 4 times faster than parameter sweeps and yields better results.

- The estimated value missed the optimal point because of low resolution (7x7).
- POUNDER uses fewer iterations and smaller step sizes to arrive at a better solution.



Range and grade feasible points



Cost function value

Optimized FCREx has Similar Component Size as FCHEV

- There is trade off of fuel mass and battery capacity.
  - The optimized vehicle has lower battery capacity and higher H_2 mass.
  - Some performance parameters are lower than the rule based sizing, but still meet requirements
    - The acceleration time increased, but is still better than the conventional vehicle.
    - Grade speed dropped, as battery is no longer assisting the FC during grades.
    - Total vehicle mass is largely unchanged, with a small reduction of 76kg.

Results	Fuel mass [kg]	Battery capacity [kWh]	FC power [kW]	RCO [$]	Acc. time [sec]	Range [mile]	Grade speed [mph]
REx initial	4.0	58.7	100.0	80k	17.3	141.4	46.4
REx optimized (POUNDER)	6.2	3.6	101.5	61k	21.9	150.0	39.9
Δ[%]	55.0%	-93.9%	1.5%	-24.2%	26.6%	6.1%	-14.0%

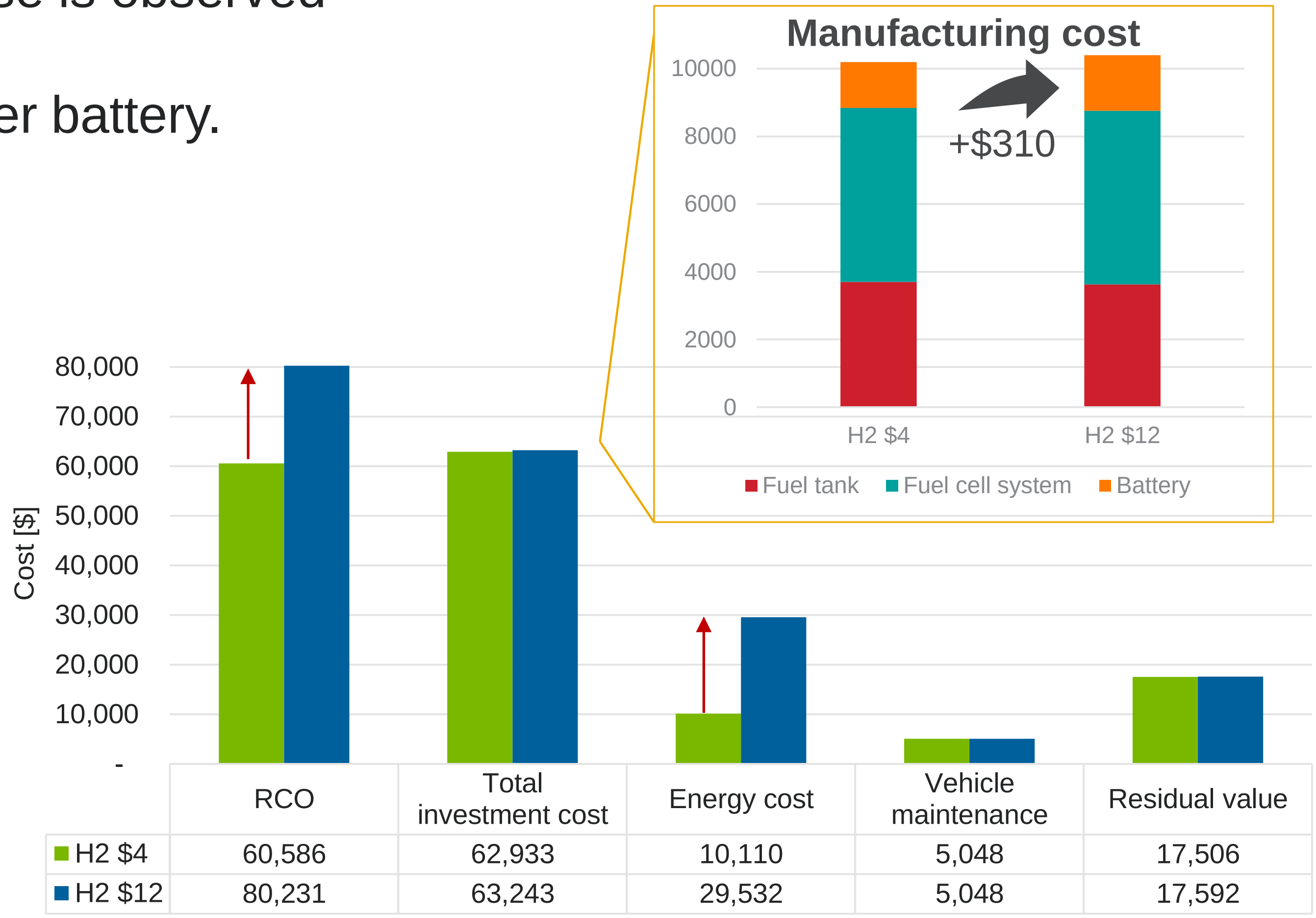
- Results are independent of FC cost, as FC power remains the same in both cases.
- In this case, ~100kW power is needed for cruising at highway speeds. Hence FC cannot be further downsized. More aerodynamic vehicles may show a different trend.

Optimum Solution Changes with Increased H_2 Cost ($4/gge to $12/gge).

- Larger battery capacity & reduced H_2 fuel use is observed as H_2 cost was increased.
  - The manufacturing cost rises with a larger battery.
  - The energy cost increases.
- The RCO increased by ~$20k.
- Design remains fuel cell dominant

Comparison of different hydrogen costs

H_2 Cost	Fuel mass [kg]	Battery capacity [kWh]	Fuel cell power [kW]	RCO [$]	Range [mile]
$4	6.2	3.6	101.5	60,586	150.0
$12	6.1	4.4	101.2	80,231	149.9
Δ [%]	-1.6%	22.2%	-0.3%	32.4%	-0.1%



RCO and component costs of different hydrogen costs

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Minimizing RCO through Component Sizing Optimization

Case 2 : Class 4 FCHEV

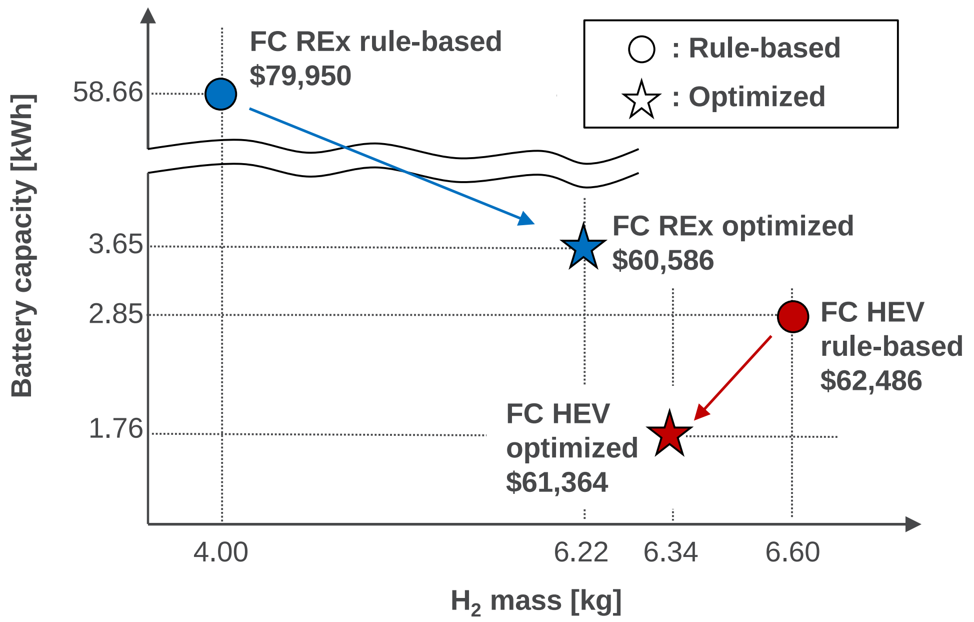
FCHEV Battery Size Optimization

- Using the rule based method, the battery is sized for maximum regenerative braking. This helps improve overall vehicle fuel economy.
- Optimization to minimize RCO shows that a 38% smaller battery is a better choice.
  - This results in higher fuel consumption and higher operating cost.
  - Optimization strikes the right balance between higher initial cost vs. higher operating cost.
- By optimizing FC HEV components, the fuel mass and battery capacity decrease and the fuel cell power increases while satisfying vehicle performance.

FC HEV	Rule-based	Optimized
H_2 mass	6.60kg	6.34kg
Battery capacity	2.9kWh	1.8kWh

FC REx	Rule-based	Optimized
H_2 mass	4.00kg	6.22kg
Battery capacity	59kWh	3.7kWh

Summary of results for FC HEV and FC REx



Comparison of FC HEVs and FC REXs

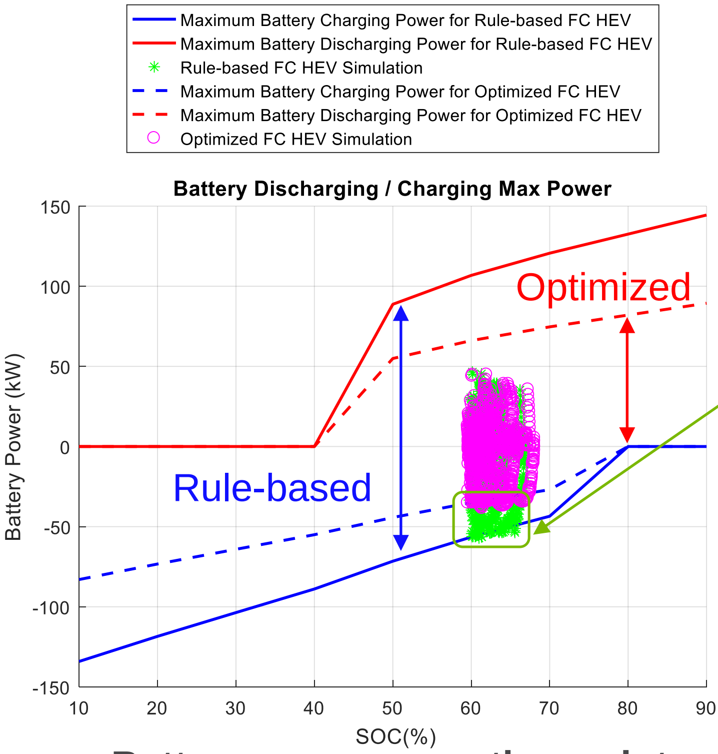
Class 4 FCHEV

Smaller Battery Pack Reduces Fuel Economy in the Vehicle Optimized for Ownership Cost

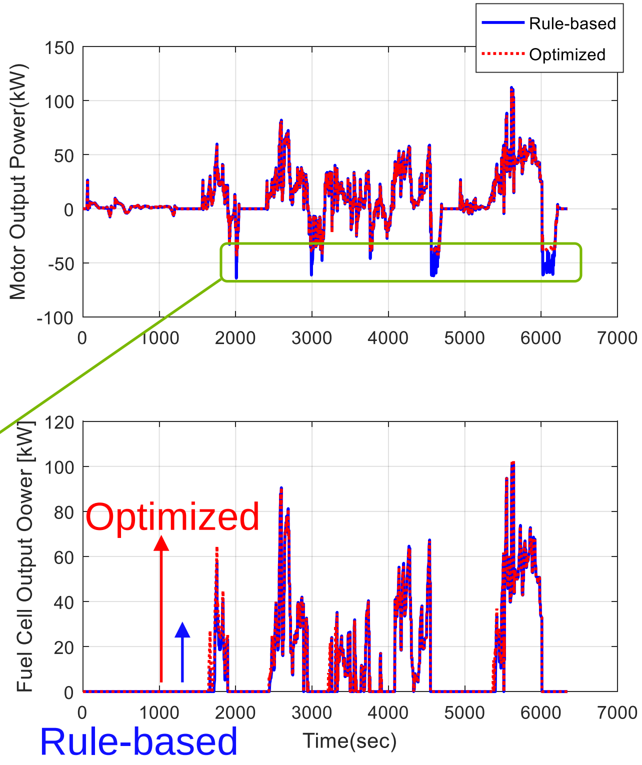
- Electric Machine size remains unchanged due to performance requirements.
- For the rule-based, the battery is sized to maximize regenerative braking.
- In the optimized design, only the RCO value is considered for component sizing.
- Both methods provide similar performance

Comparison of results

FC HEV	Rule-based	Optimized
Fuel economy gasoline equivalent	25.2 mpg	24.4 mpg
Percent regenerative braking at battery	74.1%	63.0%
Battery capacity	2.85kWh	1.76kWh



Battery power operating points



Motor and fuel cell power

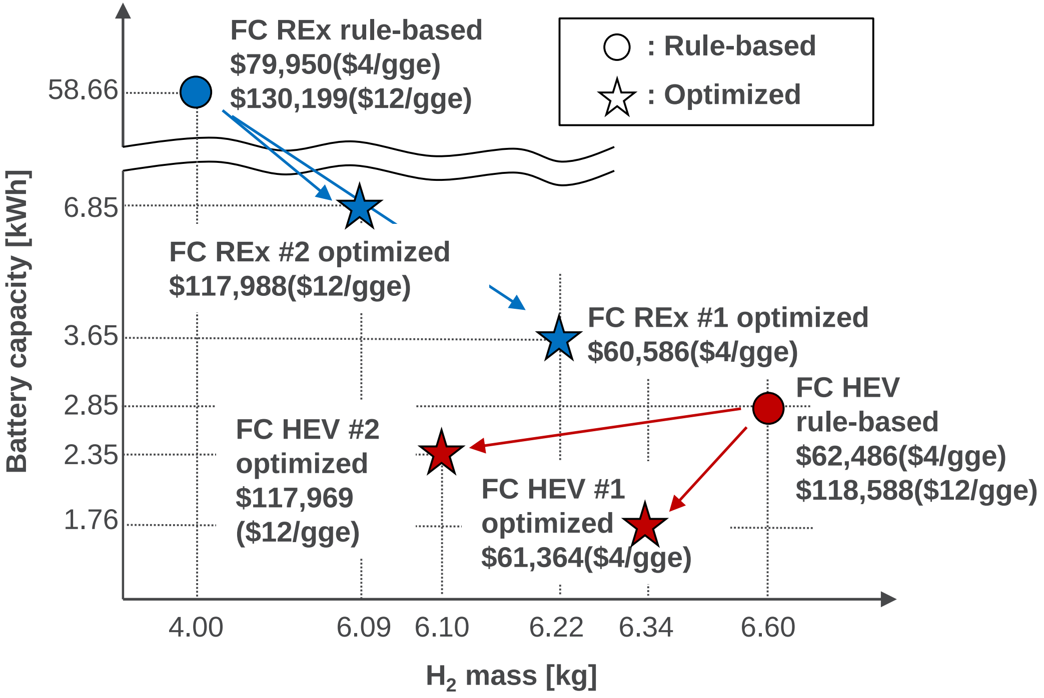
Optimum Solution Changes when the Ownership Period and H_2 Cost Increase (10 years ownership period and $12/gge)

- Fuel economy gains more importance due to higher fuel cost, making a larger battery feasible
  - This gets closer to the battery size needed to minimize fuel consumption.
  - The optimization led to a 0.7% drop in fuel economy, but reduced RCO by ~$1k

Summary of results for FC HEV

FC HEV	Rule-based		Optimized #1	Optimized #2
Ownership period	5 years	10 years	5 years	10 years
H_2 cost	$4/gge	$12/gge	$4/gge	$12/gge
H_2 mass	6.60kg		6.34kg	6.10kg
Battery capacity	2.9kWh		1.8kWh	2.35kWh
Fuel economy gasoline equivalent	25.2 mpg		24.4 mpg	25.0 mpg
RCO	$62,486	$118,588	$61,364	$117,969

*Discount rate 5%, vehicle life 15 years, and average annual driving distance 14,000 miles



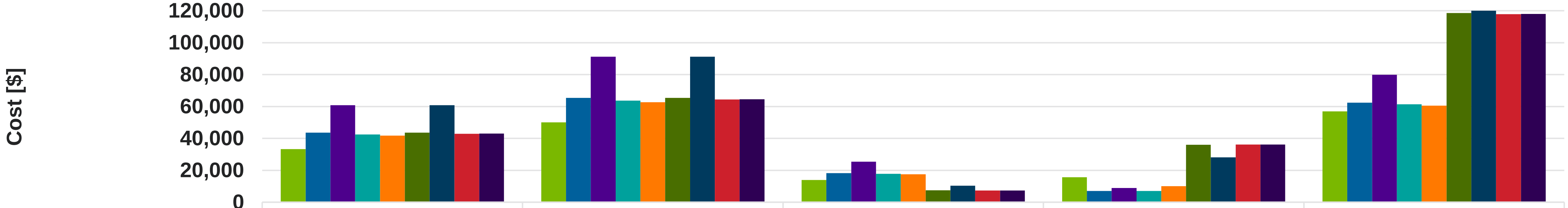
Comparison of FC HEVs and FC RExs

The optimum solution is sensitive to ownership periods and H_2 cost assumptions

RCO Comparison: Rule Based vs Optimization

- Optimized FCREx is cheaper than the optimized FCHEV by ~$800
  - Infrastructure cost is not considered in this analysis.
  - There is no cost assigned to downtime associated with charging.

Powertrain (H_2 cost)	Reduction of RCO
FC HEV ($4/gge)	-1.8%
FC REx ($4/gge)	-24.2%
FC HEV ($12/gge)	-0.5%
FC REx ($12/gge)	-9.4%



	Vehicle Manufacturing	Vehicle Purchase Price	Vehicle Residual Value	Present Value of Fuel	RCO of Vehicle
Conventional	33,364	50,045	13,973	15,717	57,024
FC HEV; rule-based #1	43,658	65,487	18,268	7,023	62,486
FC REx; rule-based #1	60,786	91,179	25,415	8,952	79,950
FC HEV; optimized #1	42,483	63,724	17,778	7,129	61,364
FC REx; optimized #1	41,832	62,747	17,506	10,110	60,586
FC HEV; rule-based #2	43,658	65,487	7,501	35,989	118,588
FC REx; rule-based #2	60,786	91,179	10,435	28,187	130,199
FC HEV; optimized #2	42,917	64,376	7,374	36,245	117,970
FC REx; optimized #2	43,023	64,534	7,392	36,161	117,988

*Discount rate 5%, ownership period 5 years, vehicle life 15 years, and average annual driving distance 14,000 miles

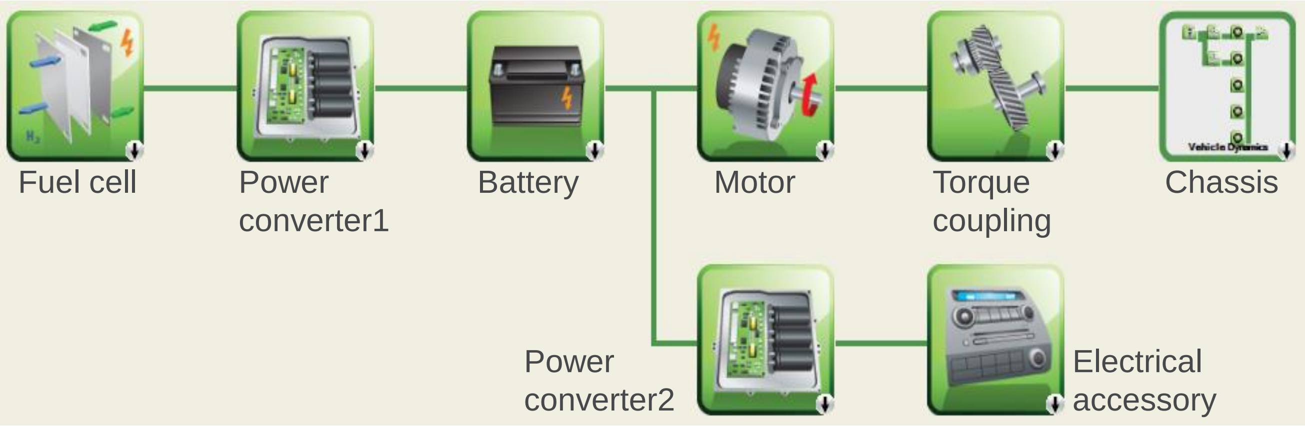
** FC HEVs rule-based #2 and optimized #2 have ownership period of 10 years when H2 cost is $12/gge.

Class 8 Truck Line Haul

FCHEV

Class 8 Linehaul Truck

- Optimization requirements
  - Constraints
    - Range: 300 miles on EPA 65 mph cycle
    - Acceleration time (0-60mph) : <64sec
    - 6% Grade speed : 30mph
    - Cargo mass : 19950kg
  - Objective : minimize RCO



Powertrain structure: FCET in Autonomie

FCREx Vehicle specification

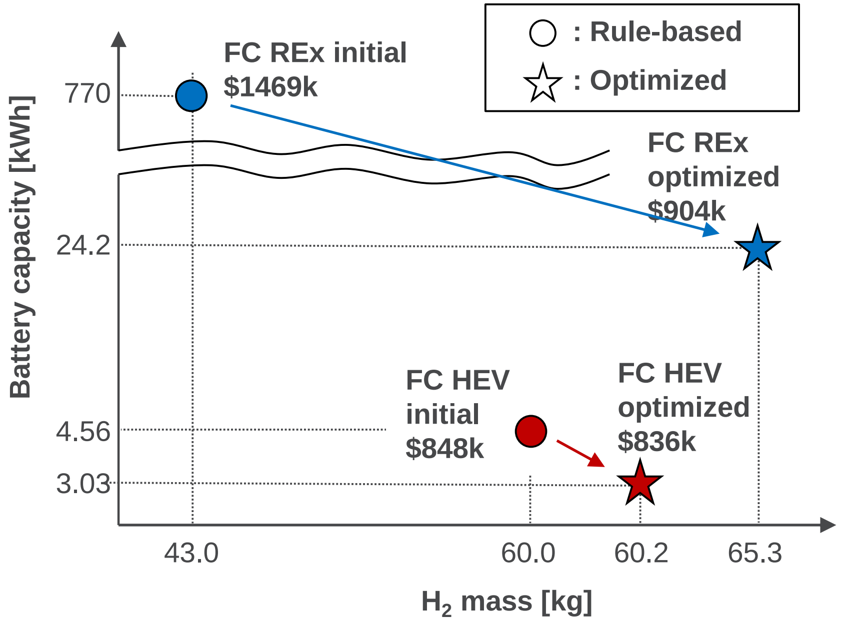
Component	Value	Component	Value	Component	Value
Medium Duty	Class 8	Drag coefficient	0.55	Battery type	Li-ion
Test mass	41723 kg	Electric motor	870 kW	Battery energy	770 kWh
Frontal area	10 m^2	Fuel cell power	340 kW	H_2 storage	43 kg

Class8 truck has modified assumptions : VMT of 100k mile/year, FC costs $200/kW, due to durability requirements

Class8 Linehaul: FCHEV is cheaper than FCREx. Optimized FCREx Relies Primarily on Onboard H_2 Storage

- Battery size reduced from 770kWh to 24kWh, runs mostly in charge sustaining mode.
  - Arbitrarily sizing the battery for half the daily driving in battery power is not optimum
- Fuel cell power(+50kW) and H_2 storage (+22kg) compensates for the reduction in battery size.
- FCHEV sizing remains largely unchanged from the rule based approach
  - Slightly smaller FC and Battery was chosen. This is likely because the optimization utilized the 2% tolerance allowed in grade speed and acceleration.

Class 8 H_2 cost: **$4/gge**	**Fuel mass [kg]**	**Battery capacity [kWh]**	**FC power [kW]**	**RCO [$]**	**Acc. time [sec]**	**Range [mile]**	**Grade speed [mph]**
HEV initial	60.0	4.56	391.3	848k	45.2	300.5	31.0
REx initial	43.0	770	340.0	1469k	30.6	300.0	32.0
HEV optimized	60.2	3.03	369.7	836k	40.5	300.7	29.7
REx optimized	65.3	24.2	391.0	904k	25.2	302.3	29.8

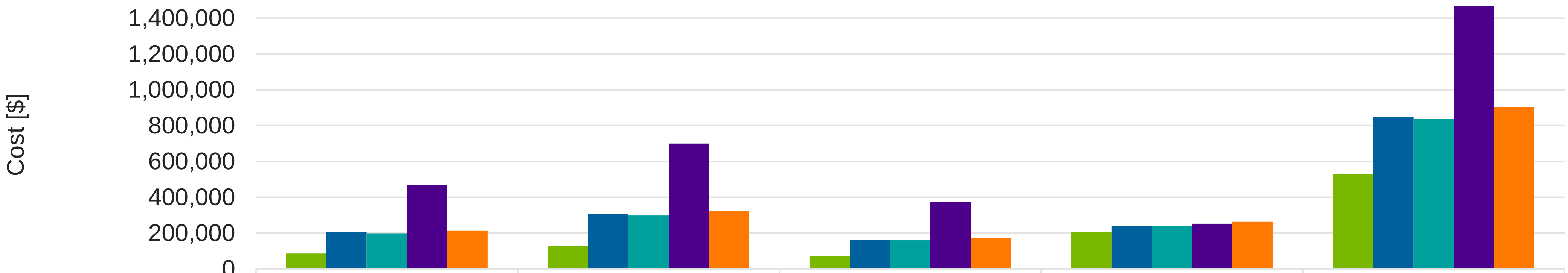


Comparison of FC HEVs and FC RExs

*Annual travel of 100,000 miles/year and fuel cell cost of $200/kW

Drivetrain Cost Comparison

- Fuel cell dominant hybrid is the most economical design choice for a Class8 Linehaul FCET
- PV of fuel costs is almost as high as the purchase price. This indicates the dependence of the design solution on VMT, energy cost, and duration of ownership.
- FCHEV has lower fuel cost in this case



	Vehicle Manufacturing	Vehicle Purchase Price	Vehicle Residual Value	Present Value of Fuel	RCO of Vehicle
Conventional	85,541	128,312	68,766	207,416	528,408
FC HEV; rule-based	204,082	306,123	163,923	239,830	847,681
FC HEV; optimized	198,369	297,553	159,337	241,154	836,418
FC REx; rule-based	466,645	699,968	374,691	251,421	1,468,853
FC REx; optimized	214,249	321,373	172,084	263,081	904,309

*Discount rate 5%, ownership period 5 years, vehicle life 15 years, and average annual driving distance 100,000 miles
H_2 cost is assumed to be $4/gge

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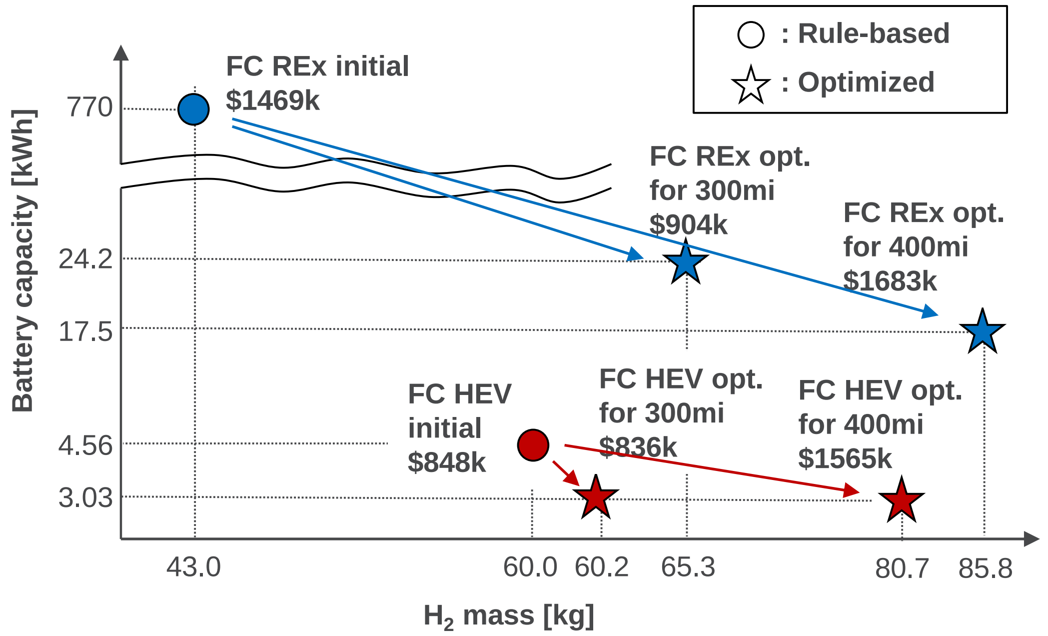
Class8 Linehaul: Optimum Design for Longer Range (400 miles) Higher H_2 Cost ($12/gge) Relies More on Onboard H_2 Storage

- H_2 storage increases (+20kg) for additional 100 miles range. Heavier vehicle requires more fuel cell power to sustain continuous loads.
- Higher FC power helps achieve the acceleration and grade performance with a smaller battery pack.
- EPA65 has little regenerative braking opportunity. A larger battery is not improving fuel economy enough to justify the higher initial cost and weight.

- FCHEV is economically a better choice than FCREx for various range and H_2 cost assumptions.

REx optimized	Fuel mass [kg]	Battery capacity [kWh]	FC power [kW]	RCO [$]	Acc. time [sec]	Range [mile]	Grade speed [mph]
HEV optimized for 400mi	80.7	3.02	377.6	1565k	40.6	400.1	29.8
REx optimized for 400mi	85.8	17.5	440.0	1683k	27.6	399.9	33.3

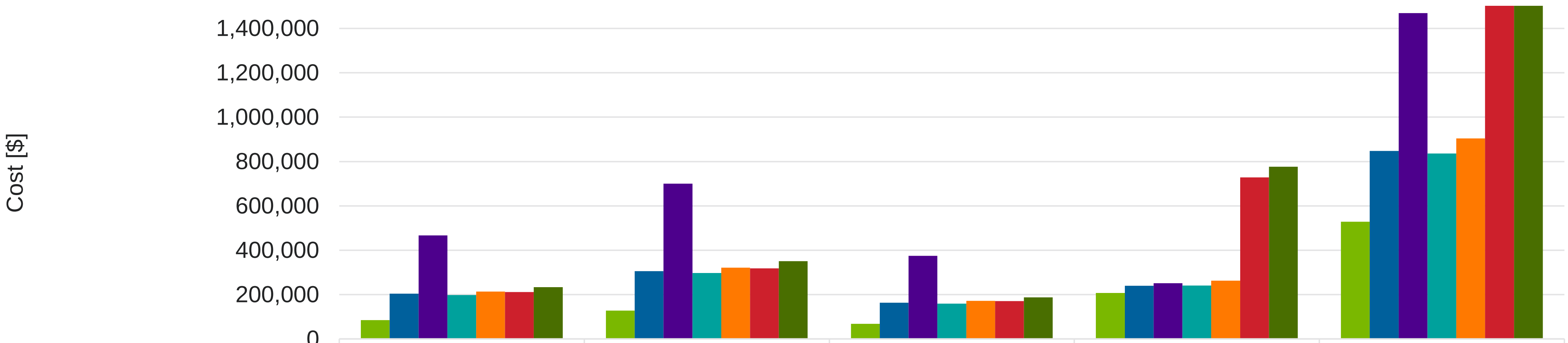
*Annual travel of 100,000 miles/year and fuel cell cost of $200/kW



Comparison of FC HEVs and FC REXs

Drivetrain Cost Comparison

- Fuel cell dominant hybrid is the most economical design choice for a Class8 Linehaul FCET
- PV of fuel costs is the important contributor to RCO, when H_2 cost is assumed to be $12/gge.
- FCHEV has lower fuel cost under all the assumptions for Class 8 Linehaul truck.



	Vehicle Manufacturing	Vehicle Purchase Price	Vehicle Residual Value	Present Value of Fuel	RCO of Vehicle
Conventional	85,541	128,312	68,766	207,416	528,408
FC HEV; rule-based	204,082	306,123	163,923	239,830	847,681
FC REx; rule-based	466,645	699,968	374,691	251,421	1,468,853
FC HEV; optimized	198,369	297,553	159,337	241,154	836,418
FC REx; optimized	214,249	321,373	172,084	263,081	904,309
FC HEV; optimized for 400mi	212,135	318,202	170,387	728,684	1,564,588
FC REx; optimized for 400mi	233,718	350,578	187,713	776,554	1,682,675

*Discount rate 5%, ownership period 5 years, vehicle life 15 years, and average annual driving distance 100,000 miles
H_2 cost is assumed to be $12/gge only on the 400mi case

Summary

- Optimum component size for FCREx depends on cost of H_2 and powertrain components, ownership period and VMT. Optimum component sizing for FCHEV is less sensitive to these factors.
  - The optimum design for FCREx relies primarily on onboard H_2 storage for energy.
- The proposed sizing method finds economically optimum design solutions for FCETs while ensuring no tradeoff in performance.
  - For Class 4 delivery trucks, the optimized FCREx & FCHEV have comparable component sizes and RCO estimates.
    - Ownership costs of FCREx is slightly less than that of FCHEV
  - For Class 8 linehaul truck, RCO of FCHEV is lower than that of FCREx design
    - Energy cost has an equal share as initial cost. So, higher H_2 cost could affect the solution.
- Cost associated with infrastructure or downtime for charging are not considered in this study.

Next Steps, Improvements

- Use representative real world cycles for sizing and cost estimates
- Linking FC cost to the power and operating conditions (load levels, duration etc)