Project ID # TV150

Sizing a Fuel Cell Powered Truck : Minimizing Ownership Cost

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Project Overview

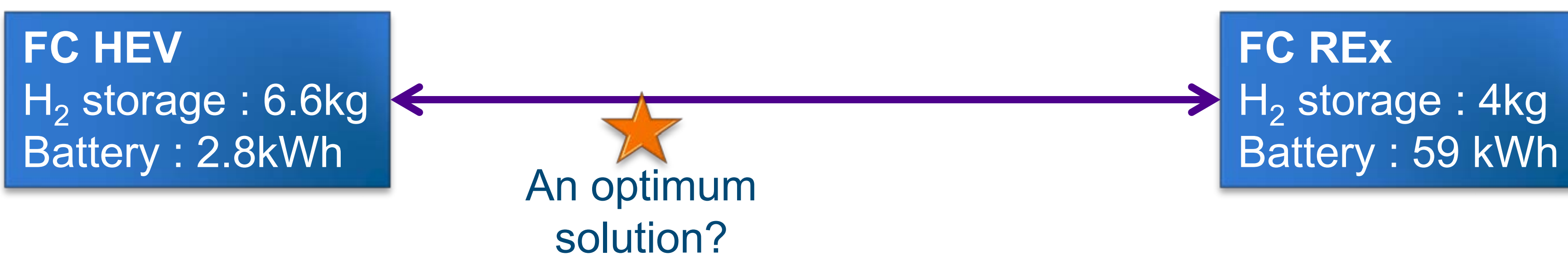
Timeline	Barriers
• Project start date : Sep 2017 • Project end date : Aug 2018 • Percent complete : 60%	• Lack of Fuel Cell Electric Vehicle and Fuel Cell Bus Performance and Durability Data (A) • Lack of Data on Stationary Fuel Cells in Real-World Operation (B) • Hydrogen Storage (C) http://energy.gov/sites/prod/files/2015/06/f23/fcto_myrdd_tech_valid.pdf
Budget	**Partners**
• FY18 Funding : $25k • Percent spent : 60%	• Argonne Fuel Cell Team

Objectives

- Fuel cell powered vehicles (FCEVs) have two onboard energy storage systems namely the H_2 tank and the battery pack. The right balance of these two energy storage systems can help minimize the overall ownership cost of the FCEV.
- This study uses a FCEV model developed in Autonomie, along with an optimization algorithm to find the component sizing resulting in minimum ownership cost.
- All design solutions should meet or exceed the performance and cargo capacity of a conventional baseline vehicle.

Approach

- Fuel Cell Hybrids (FC HEV) and Fuel Cell Range Extenders (FC REx) are two design choices found in production and prototype vehicles.
- Rule based component sizing logics do not consider component cost or ownership cost of the trucks. Real Cost of Ownership (RCO) is an important factor for commercial truck operators.
- The proposed method determines the component sizes that minimize the ownership cost of the truck.
  a) Larger H_2 tank might reduce initial cost, but results in a heavier vehicle and increase H_2 consumption.
  b) Larger battery pack will result in lower fuel consumption, but higher initial cost.



RCO Assumptions

- Real Cost of Ownership (RCO) depends on initial cost, residual cost and recurrence cost involved in owning and operating the vehicle over its service period.

$$RCO = Cost_{inv} + Cost_{pv\_energy} + Cost_{pv\_maint} + Cost_{pv\_batt\_replace} + Cost_{residual}$$

- Assumptions
  - Vehicle miles travelled : 14,000 miles/year
  - Service period : 5 years
  - Fuel Cost
    - Diesel → $3/gge
    - H2 → $4/gge
  - 5% yearly depreciation in value for computing residual value.
  - No battery replacement is expected.

** Full assumptions and reference is available in backup slides*

Process Demonstration
Class 4 Pickup and Delivery Van

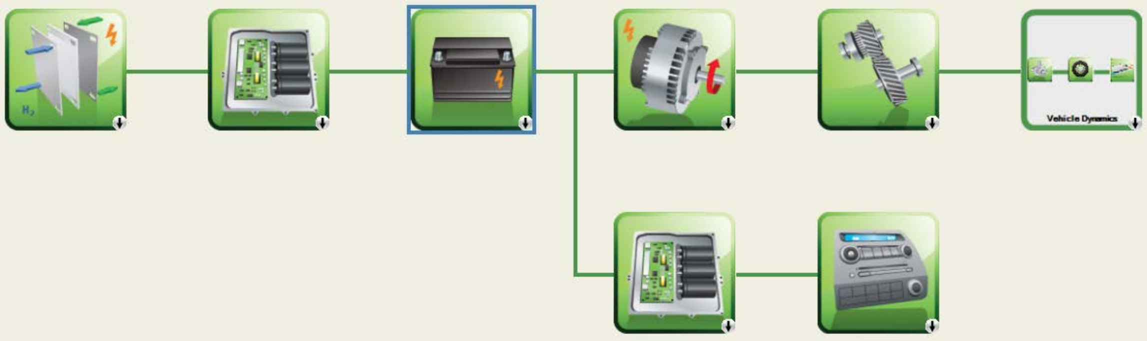
Reference Vehicle Specifications

Class 4 pickup and delivery van

- Requirement: 3000kg payload for 150 miles on ARB Transient* cycle.
- Series fuel cell range extender is sized to match or exceed the performance of a conventional baseline vehicle.
  - FC power rated to sustain highway cruising (65mph)
  - Motor power is rated for acceleration, grade and cruise
  - Battery is sized for 75 miles electric range
  - H_2 storage is sized for meeting the remaining range requirement.

Requirement based

Arbitrary



Powertrain structure: Range Extender Hybrid

Vehicle specification

Component	Value	Component	Value	Component	Value
Medium Duty	Class 4	Drag coefficient	0.70	Battery type	Li-ion
Vehicle mass	7317 kg	Electric motor	211 kW	Battery energy (usable)	59 kWh
Frontal area	7.50 m^2	Fuel cell power	100 kW	On board H_2 storage	4 kg

** Only transient cycle among the three regulatory cycles used by EPA for medium & heavy duty vehicles.*

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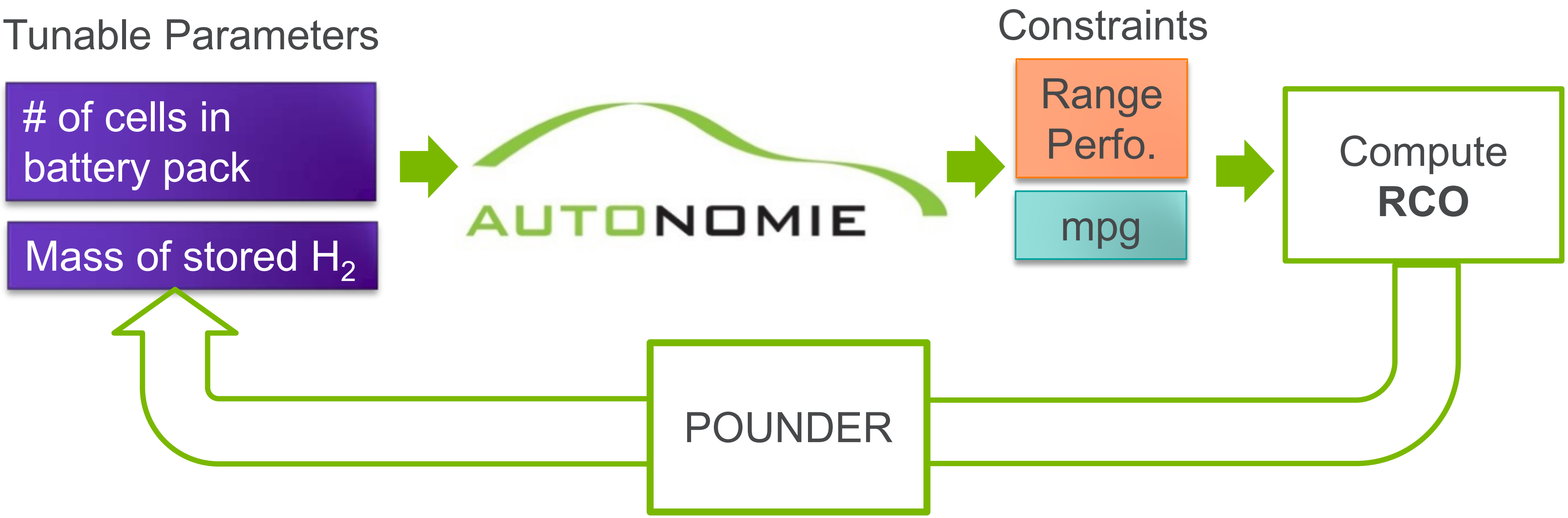
Optimization Process: POUNDER

POUNDER* was developed by Argonne MCS division



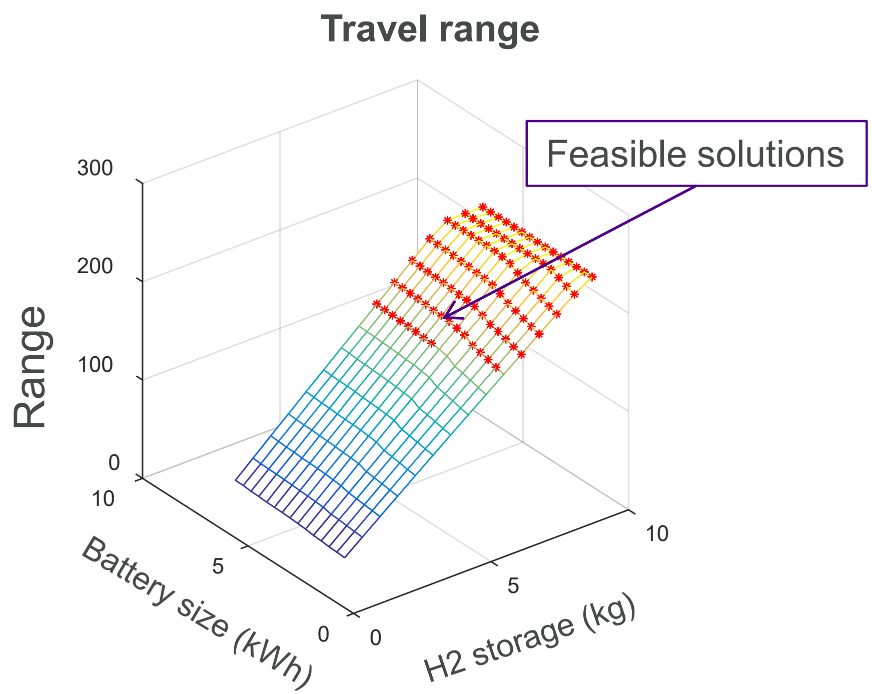
- Optimization problem was defined in Autonomie and solved using POUNDER.
- POUNDER requires ~30 iterations to find the optimum solution.
- The solution was consistent with the result from a global search for the minimum RCO value

*S.Aithal & S.Wild, “Development of a fast, robust numerical tool for the design, optimization, and control of IC engines”, Proceedings of the SAE 11th International Conference on Engines & Vehicles (ICE2013), Capri, Italy, September 2013

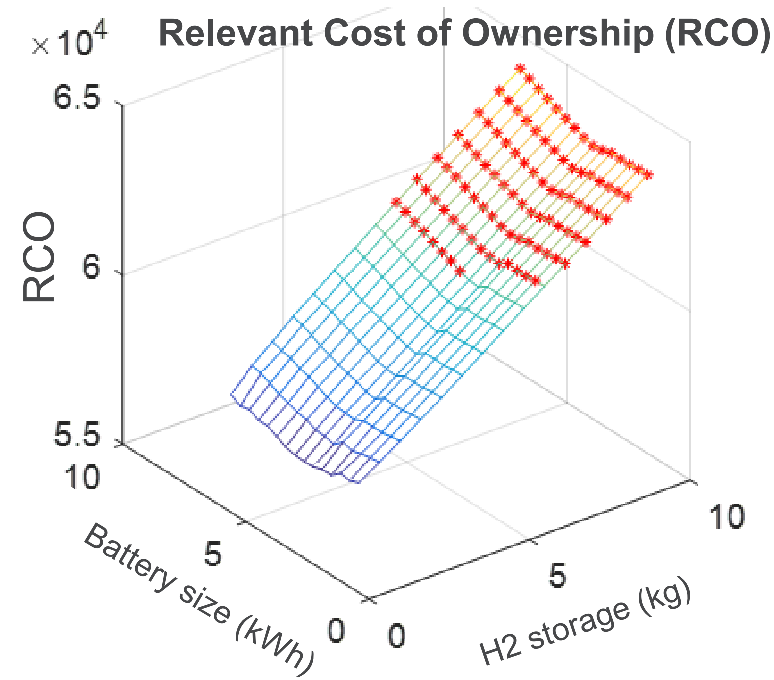
Verified the Existence of a Minimum Solution

Sweep of battery size and H_2 storage mass shows that among the multiple feasible solutions, one with minimum cost can be found.

- Acceleration time is used as a constraint to ensure that feasible solutions have acceptable performance characteristics.



As battery module and fuel mass increase, the range increases.

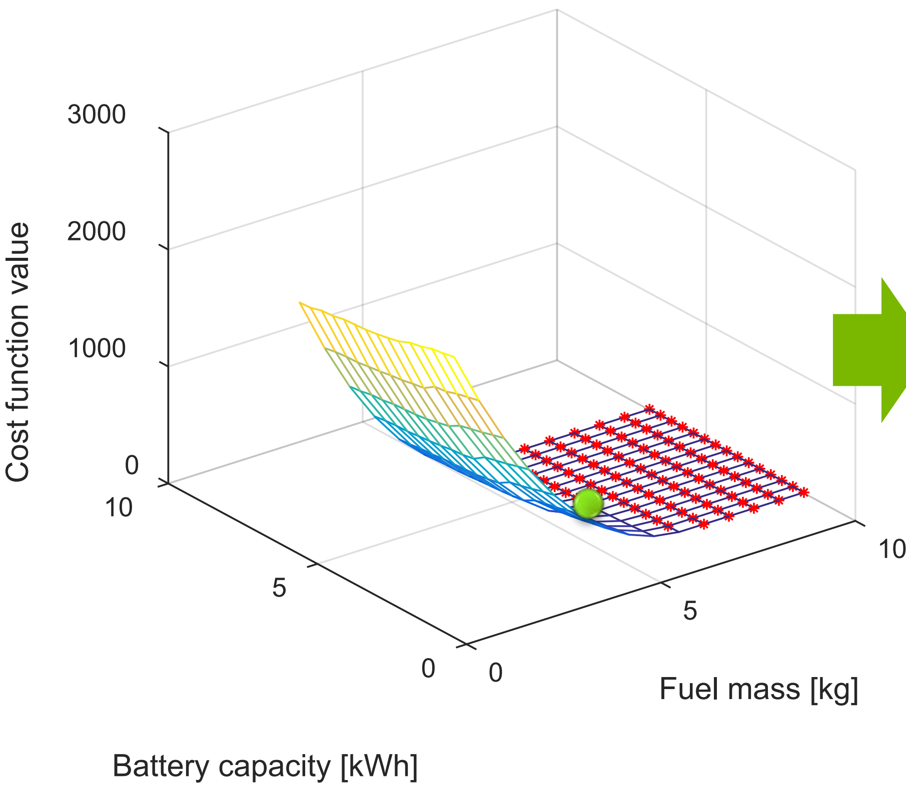


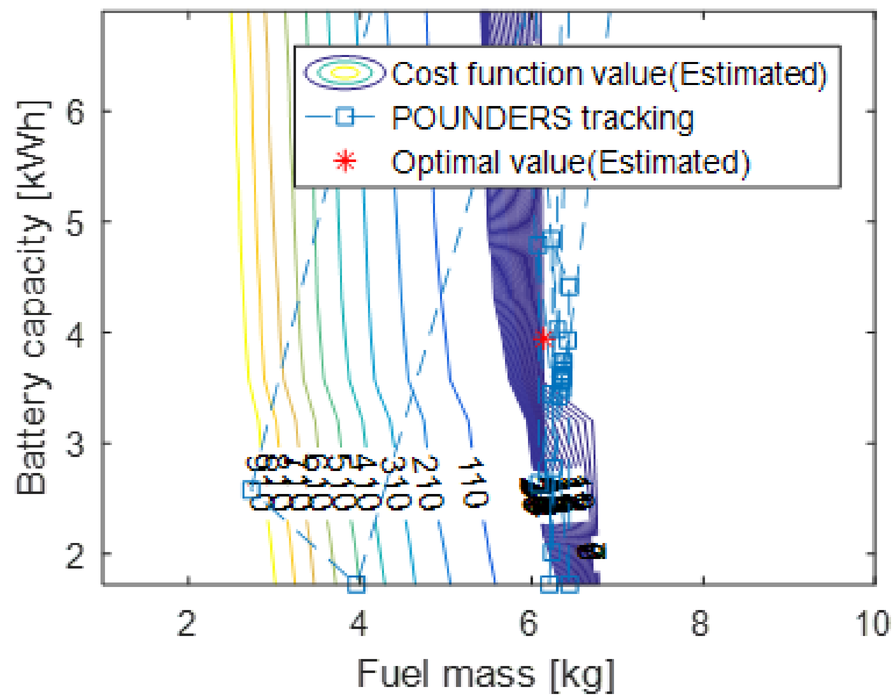
RCO increases when the battery module number and fuel mass increase. RCO is more sensitive to battery size than to H_2 mass

Developed a Customizable Process to Minimize RCO

No trade off in performance or range.

- Optimization approach
  1. ✓ Finding the balance between H_2 storage and battery size
  2. ✓ Ensure performance for the design solution (acceleration, grade, cruise)
  3. Add control parameters to explore blended operation.





POUNDER Achieves Significantly Lower RCO Compared to the Rule Based Algorithm

In this study, it is assumed that the PHEV should run 50% of the daily driving distance with electric power alone.

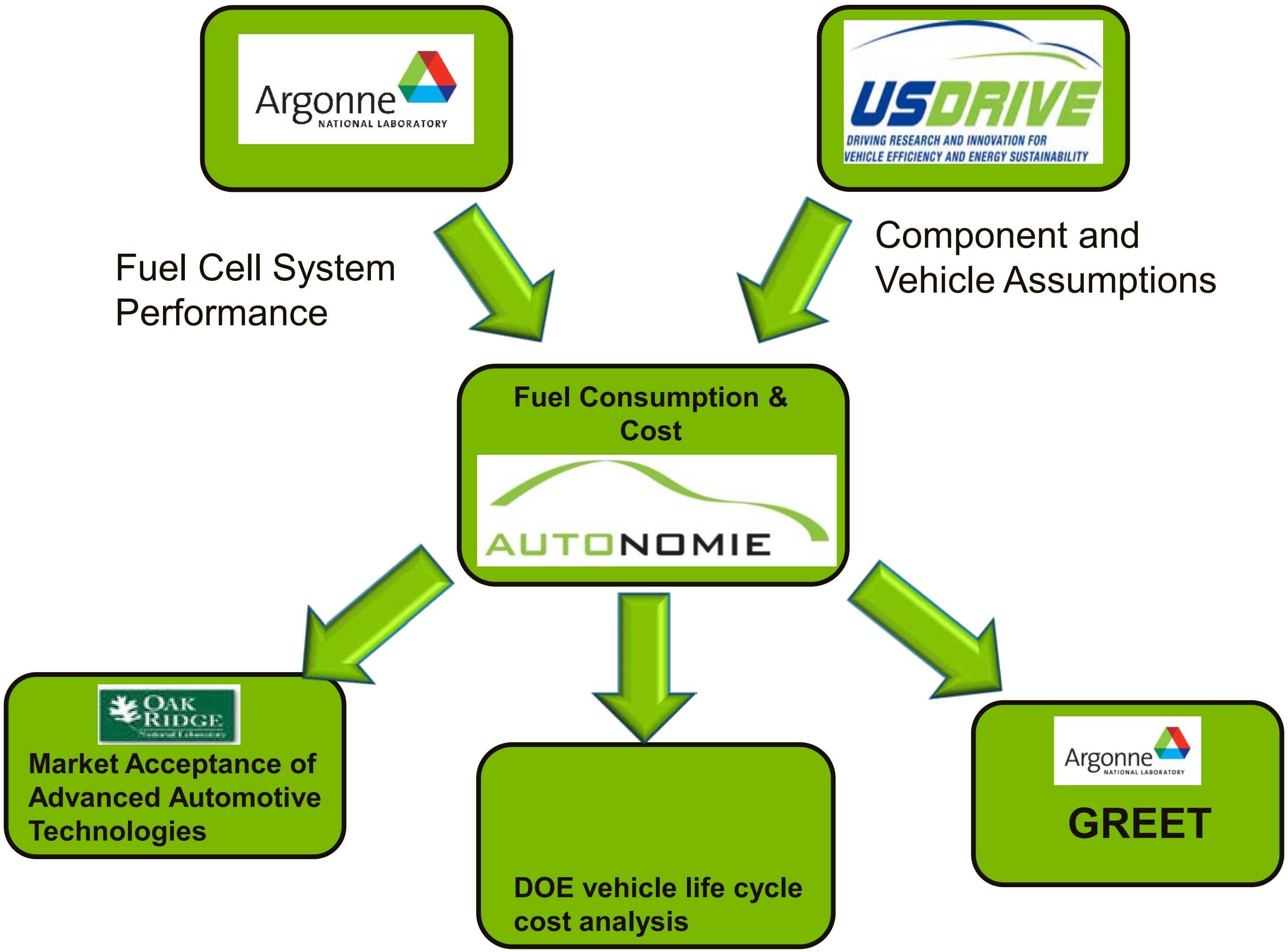
Type	H_2 [kg]	Battery [kWh]	Vehicle Manuf. Cost [$]	Vehicle Price [$]	Vehicle Resale Value [$]	Present Value of Fuel [$]	RCO of Vehicle [$]
FCHEV	6.6	2.9	45k	68k	19k	11k	64k
FC REx Rule based	4.0	58.7	61k	91k	25k	7k	80k
FC REx Optimized	6.3	3.6	42k	63k	17k	10k	61k

Preliminary results

Response to Reviewer Comments

- Reviews were very encouraging and positive for the last study done on sizing of fuel cell powered trucks (2016 AMR TV-032)
- Comment: Establishing a methodology for sizing truck components while balancing the fuel cell with the battery is critical to a successful integration effort
  - *This study is a direct attempt at finding that balance.*
- Comment: Taking the analysis one step further by conducting a life-cycle cost analysis that incorporates cost and durability would be of value
  - *This study looks at the cost of owning and operating the vehicle.*
- Comment: unclear why truck companies were not involved.
  - *The study was a pre-cursor to a competitive prototype building project. Truck companies were not involved based on DOE guidance.*
  - *Outside of this project, Argonne continues to work with several OEMs and DOE's advisory groups such as 21CTP to improve medium and heavy duty vehicle modelling capabilities.*

Collaboration and Coordination with Other Institutions



Next Steps: Expand the Analysis to Additional Classes & Vocations

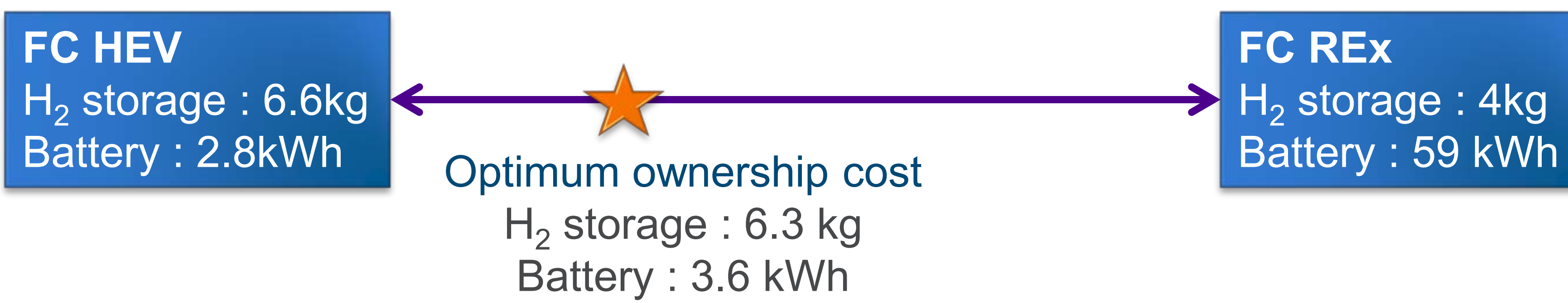
Vehicle models are already available

- 13 class vocation combinations are already available in Autonomie, developed through various FCTO & VTO funded projects *(2016 AMR:TV032 & 2017 AMR: VAN023)*
- More vehicles need to be evaluated to verify the process.
  - Check whether any new rule can be developed based on these results, for FCEV sizing which could result in lower ownership costs.
- Include control parameters in optimization problem to verify whether the FC-REx could be further improved

Summary

Developed and demonstrated a process to minimize ownership cost of a FCEV.

- Based on the preliminary results, an optimum balance between onboard H_2 storage and energy storage in battery pack can be determined for Class 4 pickup and delivery vans.
- The proposed solution has a lower ownership cost than a FC REx sized using rule based algorithm, reducing the vehicle ownership cost by ~$20k
  - It is also cheaper than the FCHEV solution by ~$4k
- The proposed solution has no trade off in cargo capacity, performance or range as it meets or exceeds the performance of a conventional class 4 van.
- The process is being expanded to additional vehicle classes, including Class 2B.



Backup Slides

Full RCO Assumptions

- Real Cost of Ownership (RCO) depends on initial cost, residual cost and recurrence cost involved in owning and operating the vehicle over its service period.

$$RCO = Cost_{inv} + Cost_{pv\_energy} + Cost_{pv\_maint} + Cost_{pv\_batt\_replace} + Cost_{residual}$$

– Total investment: $Cost_{inv} = Cost_{purchase} + Cost_{init\_registr} + Cost_{home\_EVSE} - Cost_{PEV_{incentive}}$
  - $Cost_{purchase} = Cost_{manuf} \times (1 + profit_{margin} + tax_{added})$
  - $Cost_{init\_registr} = 186$ [\$] $Cost_{home\_EVSE} = 0$ [\$] $Cost_{PEV_{incentive}} = 0$ [\$]

– Present value energy cost: $Cost_{pv\_energy} = (on\_road\_kWh/km \times \$_{elec/KWh} + baseline\ liter/km \times \$_{gas/liter}) \times distance_{trvl\ yr}/f_{cap\_recov}$
  - $\$_{elec/KWh} = 0.135$, $\$_{gas/liter} = 0.793 = 3\ [\$/gasoline\ equivalent\ gallon]\ (\$_{H_2/kg} = 4)$
  - $distance_{trvl\ yr} = 22530.823\ \text{km} = 14000\ \text{mile}$

– Present value maintenance: $Cost_{pv\_maint} = (Cost_{maint} \times distancev_{trvl\ yr} + Cost_{ownership\_registr})/f_{cap\_recov}$
  - $Cost_{maint} = 0.08/1.60934\ [\$/km]$ $Cost_{ownership\_registr} = 46$ [\$]

– Present value battery replacement cost: $Cost_{pv\_batt\_replace} = 0$

– Residual value: $Cost_{residual} = -Cost_{inv} \times (1 - 15 \times 10^{-7} \times time_{service} \times distance_{trvl\ yr} - 0.476) \times (1 + rate_{discount})^{-time_{service}}$
  - $time_{service} = 5\ [yr]$ $rate_{discount} = 0.05$

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