Advanced Technology Vehicle Fuel Consumption Modeling in PERE

14TH CRC ON-ROAD VEHICLE EMISSIONS WORKSHOP

San Diego, California

March 29, 2004

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Acknowledgments

- Bob Giannelli, John Koupal, Joe McDonald, James Warila: EPA
- Feng An, Dan Santini: Argonne National Laboratory

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Outline

- The need for advanced technology vehicle models
- PERE’s role in MOVES
- Conventional vehicles
- Advanced gasoline vehicles
- Advanced diesel vehicles
- Mild & Full hybrid vehicles
- Validation
- Fuel Cell vehicles
- “Filling Holes” in MOVES

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The need for advanced technology vehicle modeling

- MOVES must provide emissions and energy consumption forecast going out 30 years
- Hybrid vehicles are likely to contribute to a larger fraction of the fleet over time
- Hybrids may be the stepping stone to fuel cell vehicles in ~10 years
- Important to consider upstream (Well-to-Pump) emissions
- Alternative fuels (such as hydrogen) require a full life cycle analysis to estimate total environmental impact

What Is PERE?

- Physical Emission (&energy) Rate Estimator
- Backwards looking model: driving cycle & vehicle input, energy & emissions output
- Models second-by-second vehicle loads and effects on energy consumption and emission
- Components modeled on aggregate scale (systems)
- Gives Pump-to-Wheel (PTW) estimates
- Currently in spreadsheet format

PERE's role in MOVES

- Fill data holes
- Model advanced technology vehicles
- Provide an additional layer of quality check on some of the MOVES input data (when needed)
- Other models exist, but are not suitable for MOVES
- In-house model required

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Conventional Gasoline Vehicles

- Subject to certain constraints, most internal combustion engines behave similarly:
- Engines characterized by indicated efficiency & friction (don't need engine maps)
- Account for scaling factors for size and speed
- Include simple transmission model
- Model "advanced" engines separately: homogenous lean-burn, Atkinson, direct injection, etc.

Fuel Rate - gas or diesel (g/s)

- $FR = [K*N*V_d + (VSP*m/\eta_t + P_{acc})/\eta] / LHV$
  - *K*: is the power independent portion of engine friction, dependent on N.
  - *N*: is the engine speed (rps)
  - V_d: is the engine displacement volume (Liters)
  - η : is a measure of the engine indicated efficiency (~0.4 gasoline, ~0.45 for diesel)
  - *VSP:* is vehicle specific power (kW/tonne)
  - *m:* mass of vehicle in metric tonnes
  - η_t: transmission efficiency
  - *Pacc*: is the power draw of accessories such as air conditioning. (Without AC ~ 0.5-1.0 kW)
  - *LHV*: is the lower heating value of the fuel (~44kJ/g for gasoline)

Advanced Technologies in MOVES

- Gasoline conventional (CIC) & Advanced (AIC)
- Gasoline hybrid CIC & AIC Mild & Full
- Diesel fuel conventional (IC) and Advanced IC
- Diesel hybrid CIC & AIC Mild & Full
- Compressed Natural Gas (CNG), Liquid Propane Gas (LPG), Ethanol (E85 or E95), Methanol (M85 or M95) CIC
- Gaseous hydrogen Advanced IC & hybrid
- Gaseous hydrogen hybrid (& non-hybrid) Fuel Cell
- Liquid hydrogen (hybrid & non-hybrid) Fuel Cell
- Electricity electric only

*List still in development

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Advanced Gasoline/diesel

- Indicated efficiency can be higher (>0.4)
- Friction may decrease
- Peak power trends may increase
- Variable everything...
- Aftertreatment
- More on Heavy-Duty diesel modeling on poster

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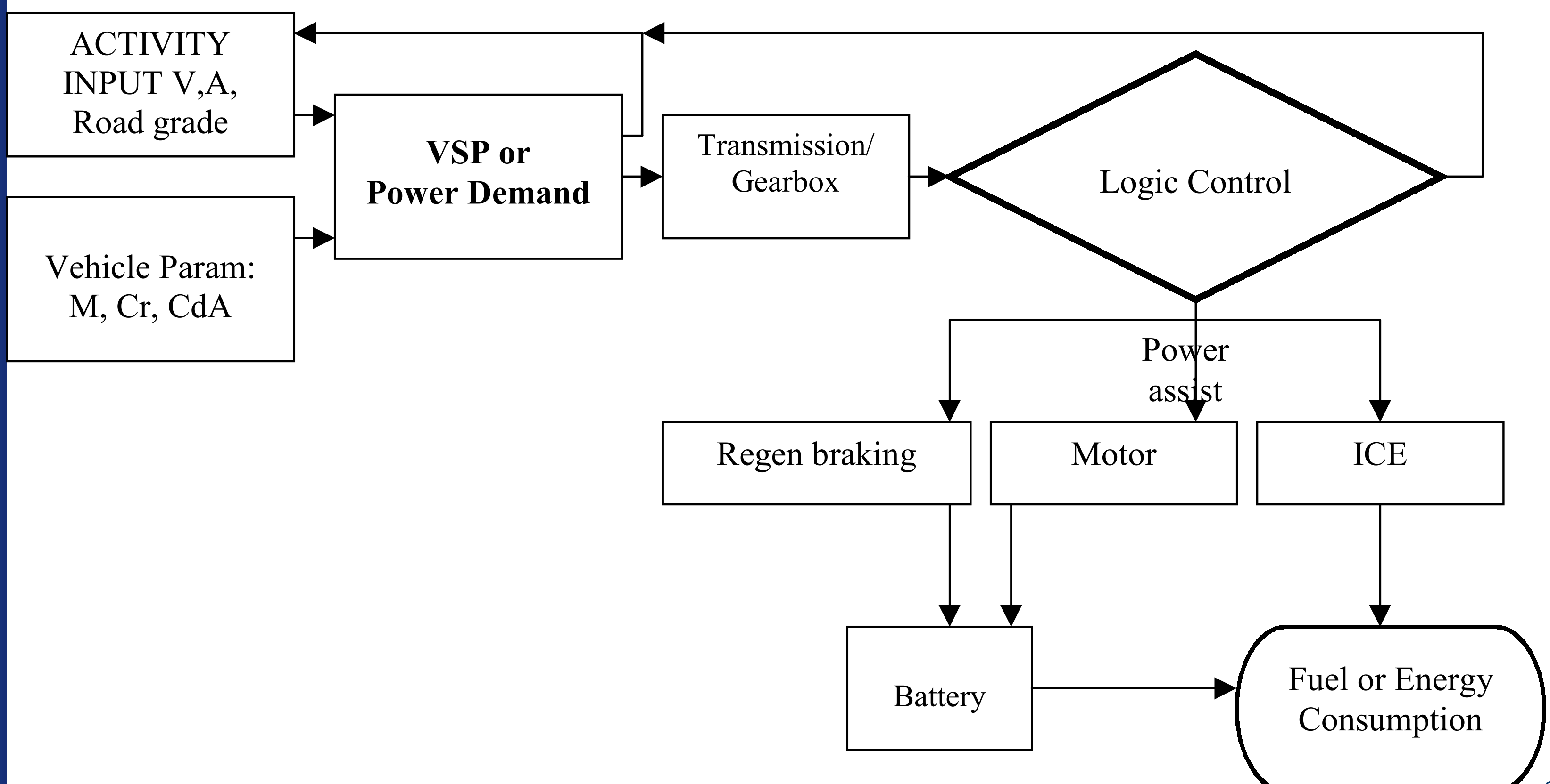
(Parallel) Hybrid vehicles



Mild vs. Full hybrid

- **Mild**
  - ratio of (peak) motor power to engine + motor power ~ 0.25
  - Similar to Honda Civic Hybrid
- **Full**
  - ratio of motor power to engine+ motor power ~ 0.47
  - Similar to Toyota Prius (& Ford Escape)
- **Energy Storage Device**
  - Battery, Ultracapacitor, Hydraulics, etc.

PERE control screen (EXCEL)

Parameters for Full Hybrid

Vehicle	
Model Year	2000
Vehicle wgt (kg)	1659
Cr0 (rolling resistance)	0.009
Cd (drag coeff)	0.3
A (frontal area m^2)	2.4
Pacc (accessory - kW)	0.5
Engine	
Engine Displ (L)	1.1
fmep0 (N indep friction kJ/Lr	0.08546
fmep1 (N dependent fric)	0.00063
P/T indicated eff (eta)	0.4455
Transmission	
N/v (rpm/mph)	35.6
Nidle (rpm)	700
trans eff	0.88
Shift point 1-2 (mph)	18
Shift point 2-3	25
Shift point 3-4	40
Shift point 4-5	50
g/gtop 1	4.04
g/gtop 2	2.22
g/gtop 3	1.44
g/gtop 4	1.00
g/gtop 5	0.90
Fuel	
LHV (kJ/g)	43.7
density gas (kg/L)	0.737
Motor	
overall efficiency	0.76
Regen Brake Eff	0.85
FWD power frac	0.7
Motor peak power (kW)	50
min regen (kW)	2.8
Motor Energy (kWhr)	1.8
Battery	
Initial SOC	0.56
Batt Energy (kWh)	1.3104
min SOC	0.2
max SOC	0.8
discharge eff	0.95
Hybrid	
hybrid threshold (kW)	1.5

Calibration

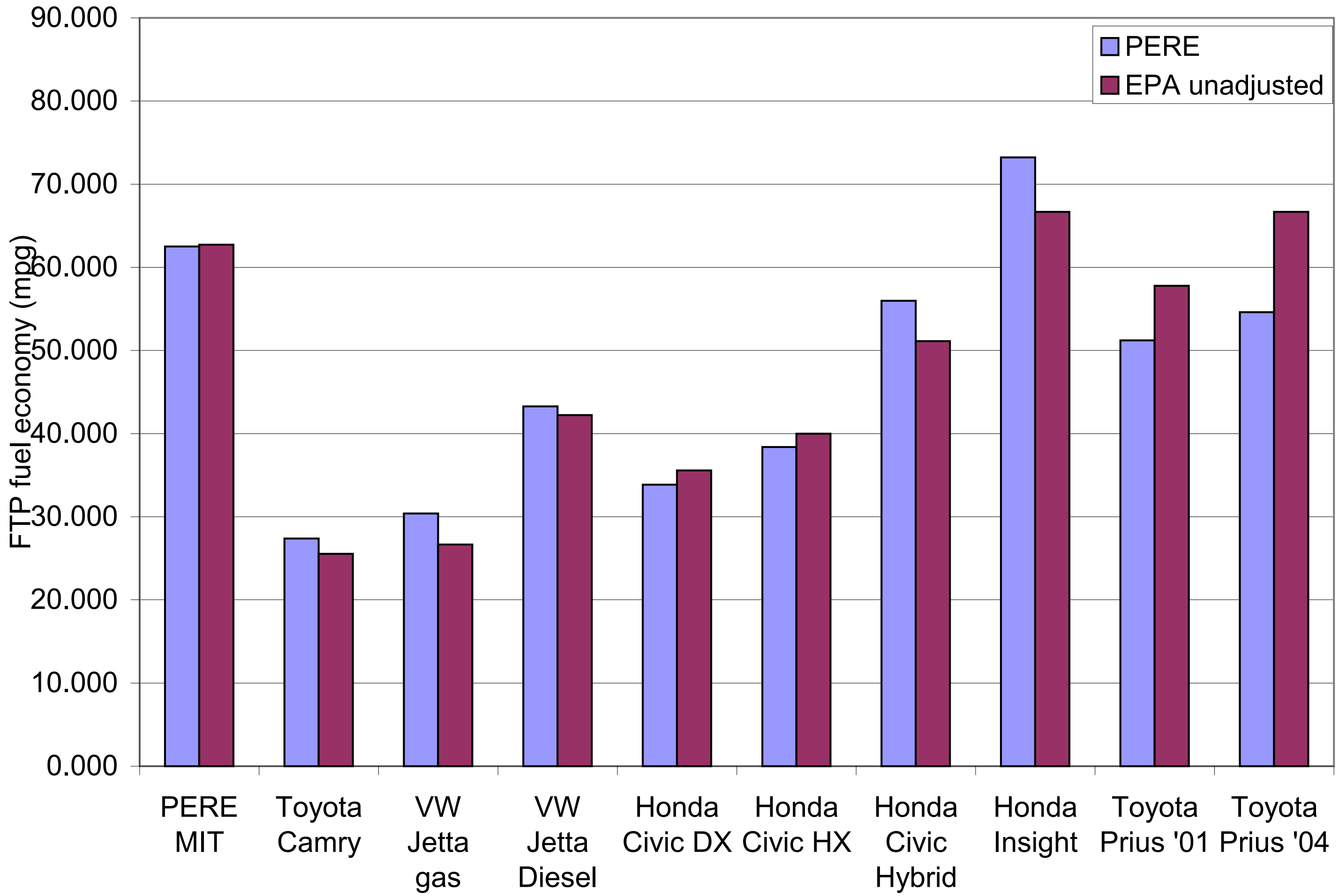
- Calibrated to MIT model hybrid vehicle (Weiss et al., 2000)
- Fuel consumption is accurate
- Battery state of charge follows the same trend
- Demonstrates that the modeling approaches are very similar

Hybrid Validation

- 11 vehicles on 2 cycles (FTP city/highway)
- Results are good

Mfr	Model
Toyota	Camry
VW	Jetta gas
VW	Jetta Diesel
Honda	Civic DX
Honda	Civic HX
Honda	Civic Hybrid
Honda	Insight
Toyota	Prius '01
Toyota	Prius '04

City Fuel Economy Validation



*unadjusted figures

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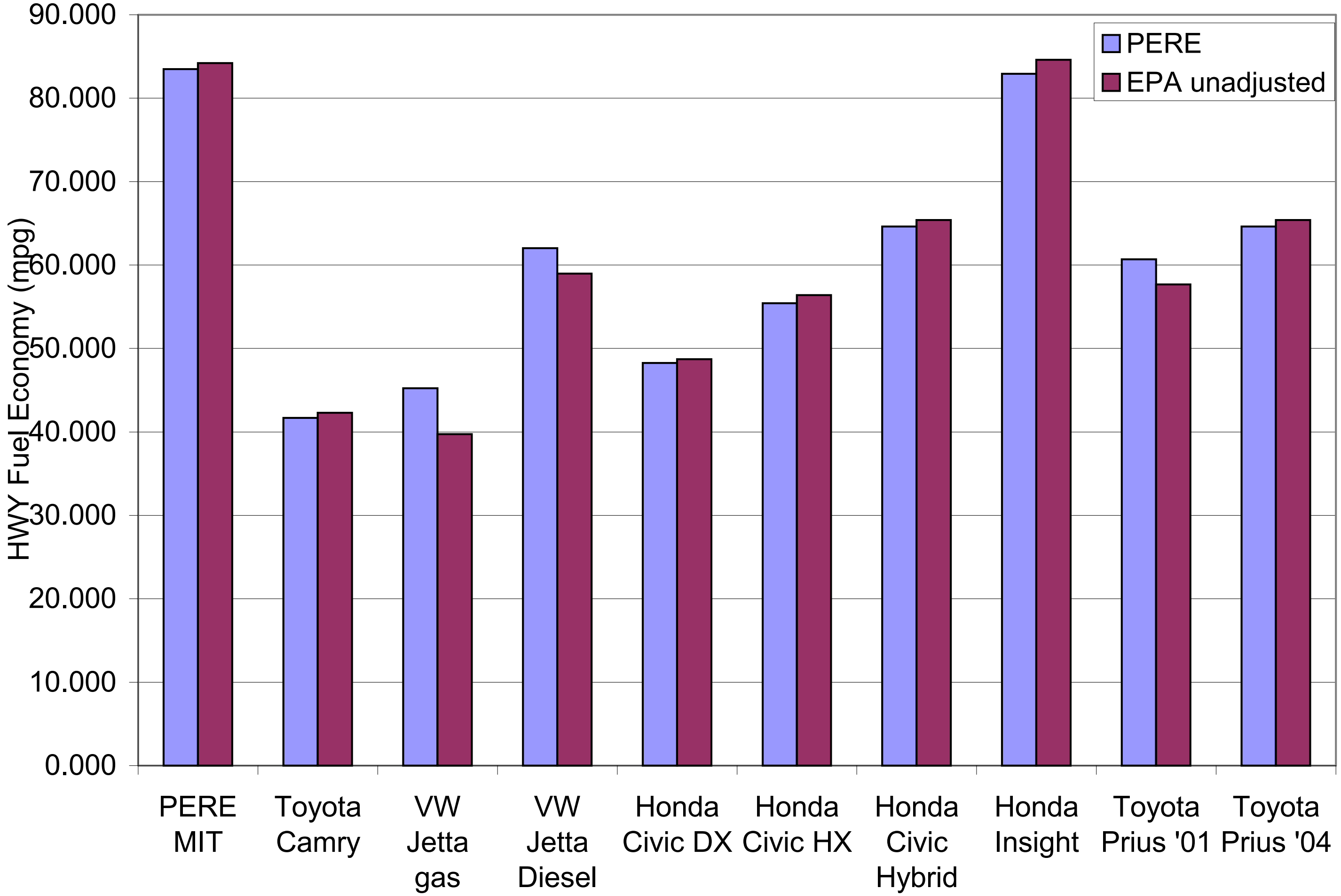
Highway Fuel Economy Validation



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Limitations

- Models fuel rate from typical driving accurately
- Requires modifications to model performance (0-60 acceleration, or gradeability)
- Does not have cost estimates
- Does not include component weight estimates (aggregate weights)
- Model not coded yet

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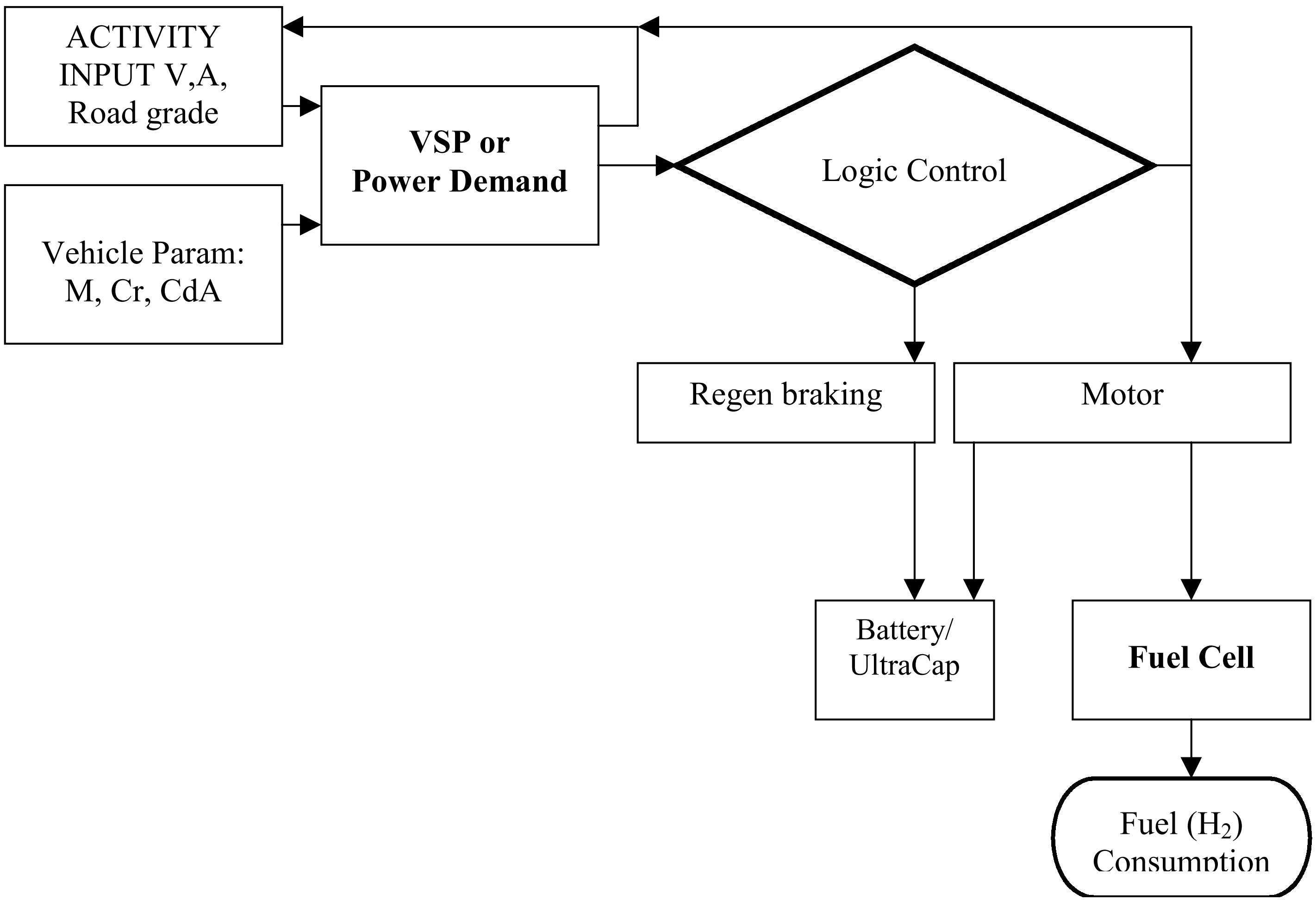
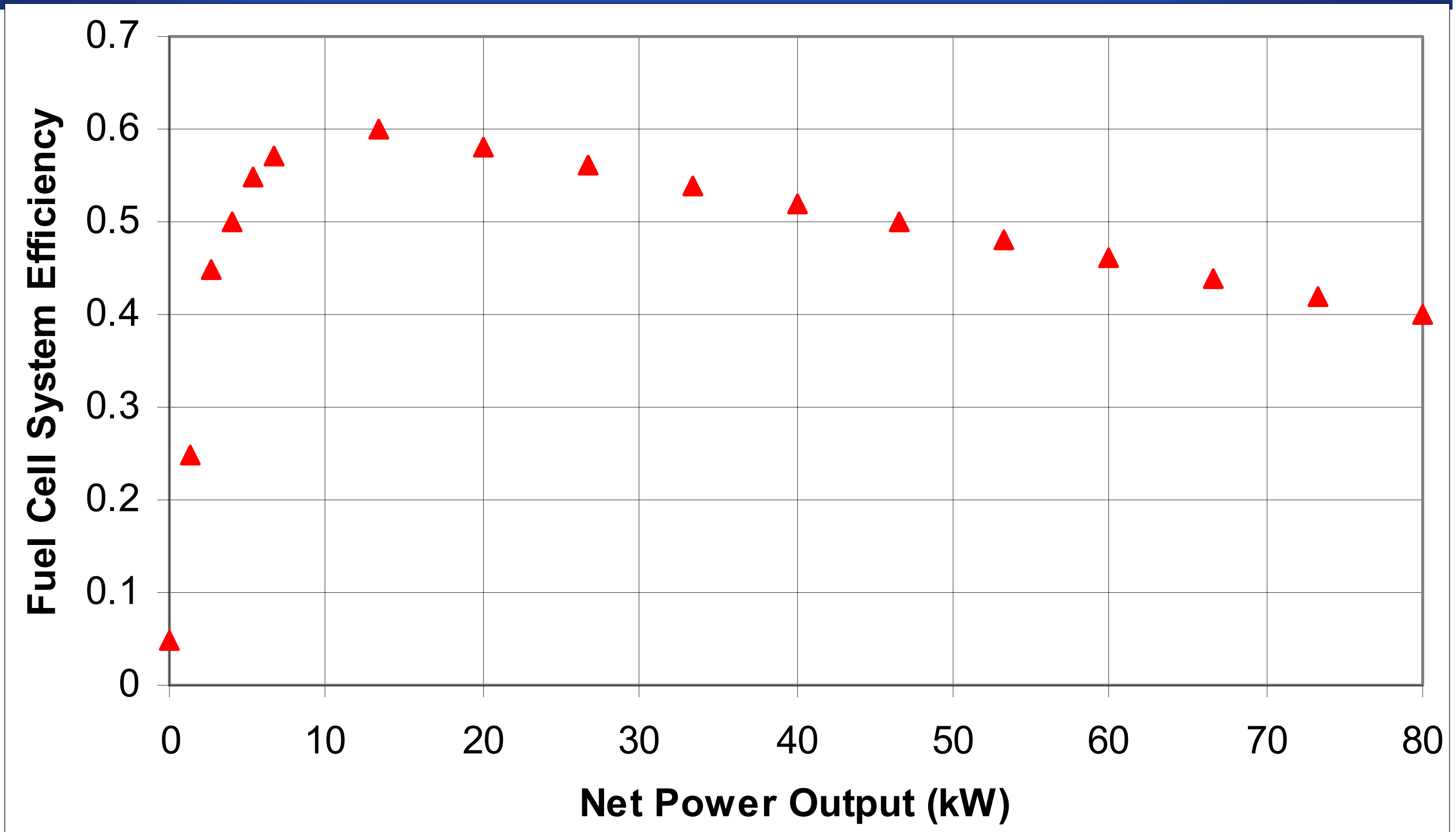
Fuel Cell Hybrid



PEM Fuel Cell System Efficiency
(Nelson 2003, 80kW stack)



Fuel Cell Hybrid

- Use model architecture of Weiss, et al. 2003
- Similar to hybrid, but replace engine with fuel cell
- Preliminary results show promise

Validation to Honda FCX

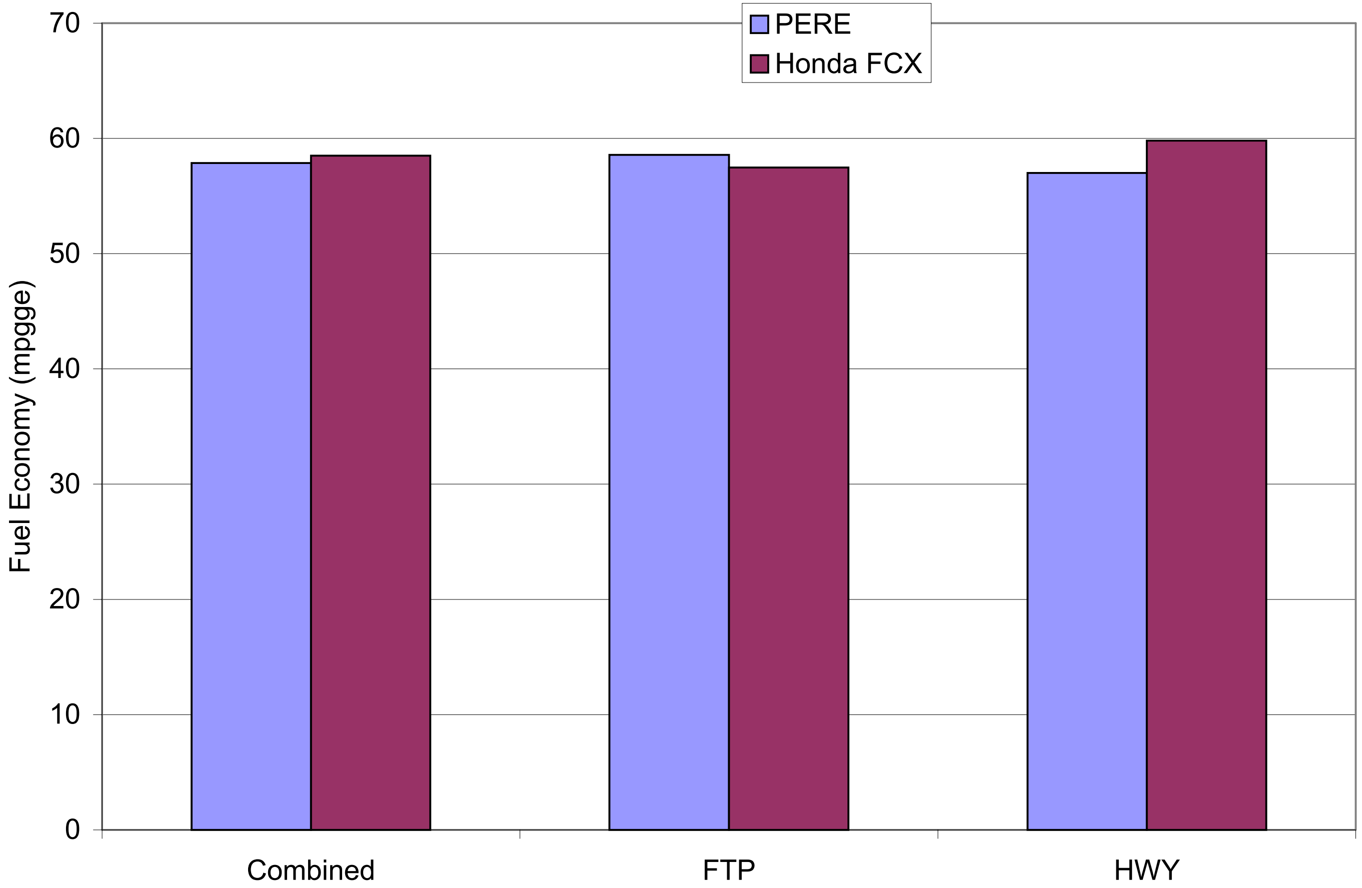


Figure shows unadjusted fuel economy numbers

PERE Static Sensitivity Analysis
(conventional vehicle)

RANK	Parameter	Error City
1	P/T indicated eff (eta)	4.93
2	Engine Displ (L)	4.57
3	trans eff	4.46
4	Vehicle wgt (kg)	3.98
5	k0 (N indep friction kJ/L	3.72
6	N/v (rpm/mph)	3.31
7	TRLHP	1.95
8	Shift point 3-4	1.31
9	g/gtop 4	1.26
10	Shift point 2-3	1.24
11	Shift point 4-5	1.11
12	Cr0 (rolling resistance)	1.05
13	g/gtop 5	0.96
14	Cd (drag coeff)	0.93
15	A (frontal area m^2)	0.93
16	Nidle (rpm)	0.90
17	k1 (N dependent fric)	0.85
18	Pacc (accessory - kW)	0.52
19	g/gtop 1	0.38
20	g/gtop 2	0.22
21	g/gtop 3	0.16
22	Shift point 1-2 (mph)	0.04
23	torque curve up 10%	0.03

RANK	Parameter	Error Hwy
1	P/T indicated eff (eta)	5.92
2	trans eff	5.55
3	TRLHP	5.14
4	Engine Displ (L)	3.49
5	Cd (drag coeff)	3.11
6	A (frontal area m^2)	3.11
7	Vehicle wgt (kg)	3.01
8	k0 (N indep friction kJ/L	2.75
9	Nidle (rpm)	2.27
10	g/gtop 2	2.25
11	g/gtop 1	2.25
12	Shift point 2-3	2.22
13	Shift point 1-2 (mph)	2.21
14	N/v (rpm/mph)	1.89
15	g/gtop 3	1.88
16	Cr0 (rolling resistance)	1.88
17	Shift point 4-5	1.46
18	Shift point 3-4	0.91
19	k1 (N dependent fric)	0.74
20	g/gtop 4	0.67
21	Pacc (accessory - kW)	0.40
22	g/gtop 5	0.23
23	torque curve up 10%	0.00

Sensitivity for hybrid

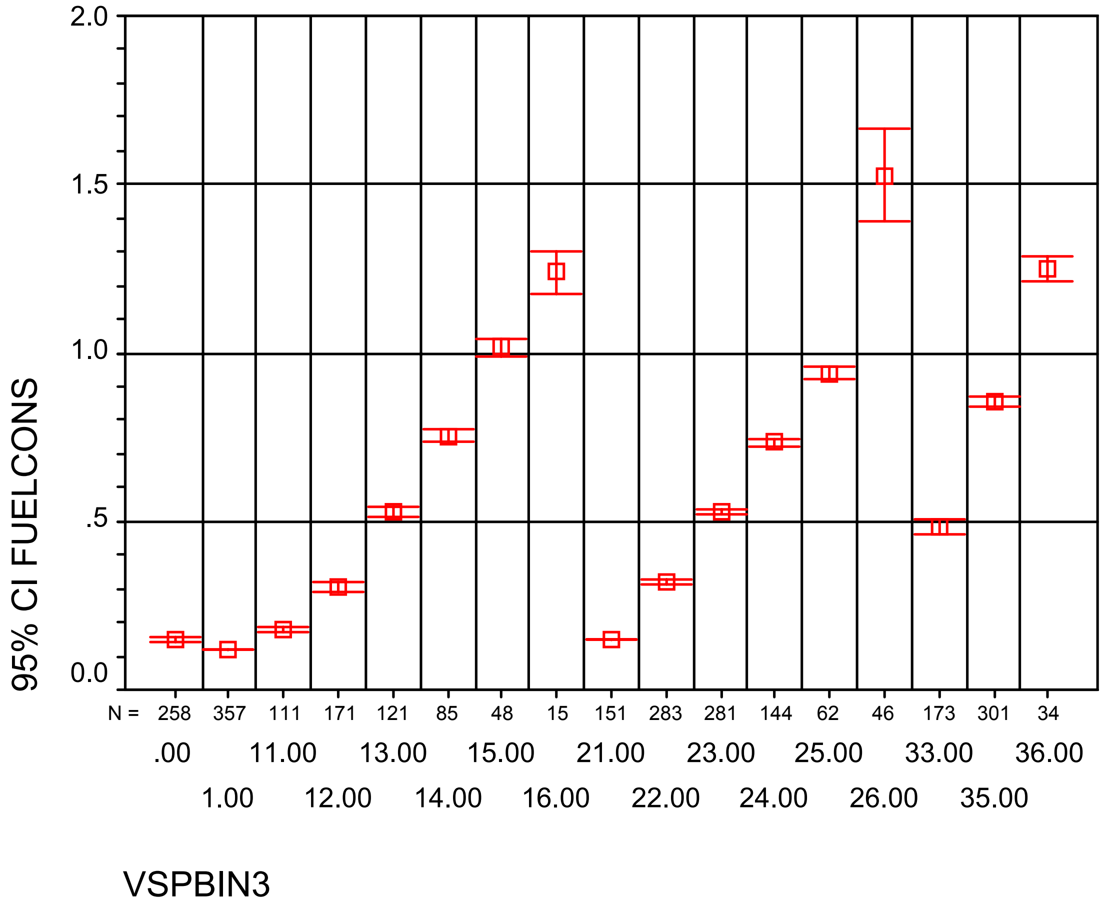
RANK	Parameter	Error City
1	P/T indicated eff (eta)	8.11
2	Vehicle wgt (kg)	7.18
3	Engine Displ (L)	5.42
4	overall motor efficiency	3.38
5	Cr0 (rolling resistance)	3.32
6	Cd (drag coeff)	3.12
7	A (frontal area m^2)	3.12
8	torq curve up 10%	2.96
9	Regen Brake Eff	1.99
10	FWD power frac	1.99
11	Motor peak power (kW)	1.08
12	fmep0 (N indep friction kJ	1.01
13	Pacc (accessory - kW)	0.73
14	fmep1 (N dependent fric)	0.39

RANK	Parameter	Error Hwy
1	P/T indicated eff (eta)	8.52
2	Cd (drag coeff)	3.47
3	A (frontal area m^2)	3.47
4	Vehicle wgt (kg)	2.35
5	Cr0 (rolling resistance)	2.21
6	Engine Displ (L)	2.08
7	fmep0 (N indep friction kJ	1.81
8	overall motor efficiency	0.61
9	fmep1 (N dependent fric)	0.49
10	Pacc (accessory - kW)	0.44
11	Regen Brake Eff	0.30
12	FWD power frac	0.30
13	torq curve up 10%	0.24
14	Motor peak power (kW)	0.05

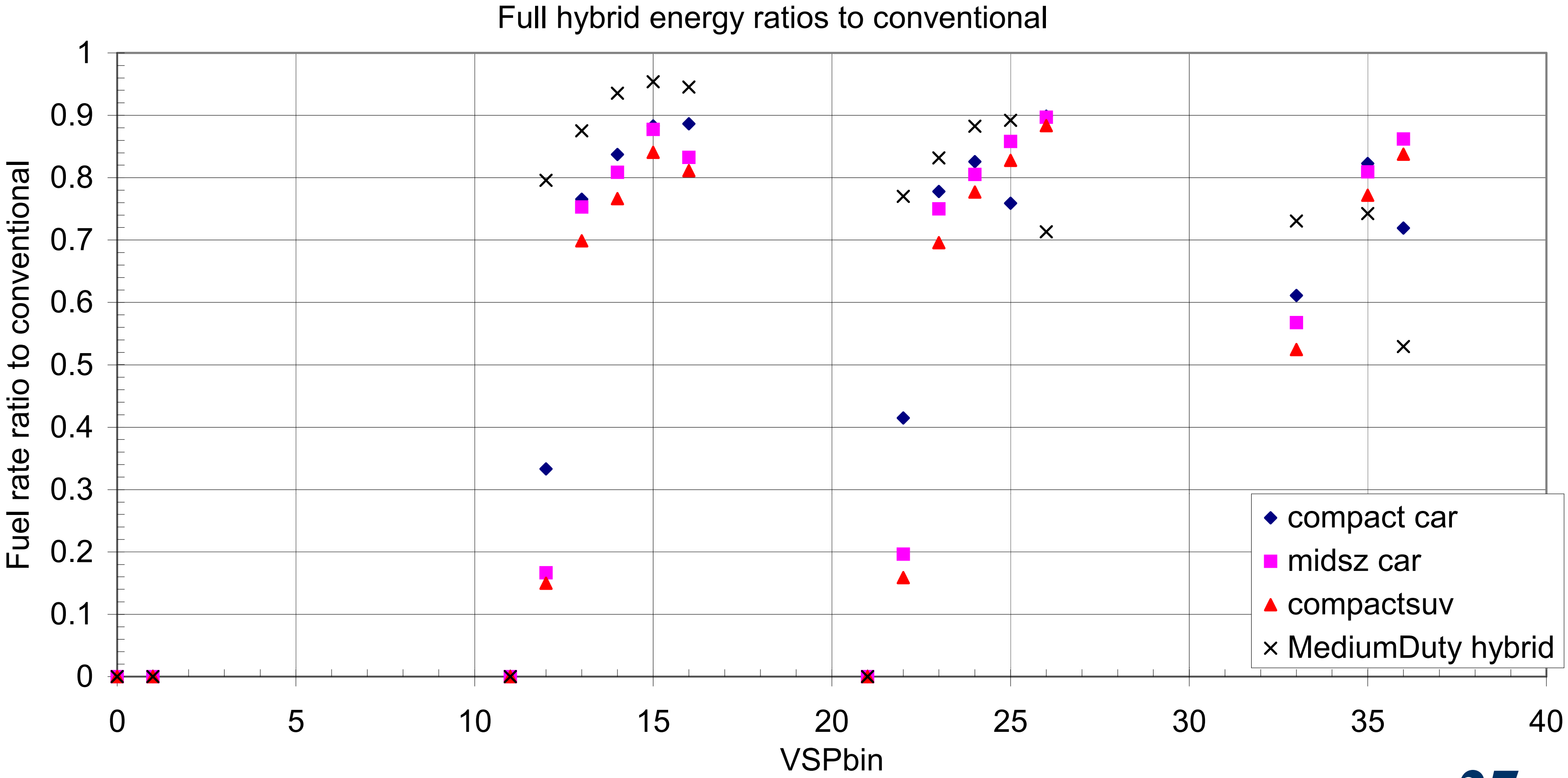
How will rates be incorporated into MOVES

- **Still under development**
- **Process 1**
  - Determine source bin family (fuel, model year, adv tech type, etc)
  - Choose typical vehicle traits
  - Run over MOVES Driving Cycles (LD, MD, HD)
  - Run PERE over range of weights
  - Repeat
- **Disadvantageous, too many bins**

Full LD parallel hybrid example



Or use ratios to conventional (Process 2 to reduce complexity) bar graph



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Conclusions

- **PERE based on engine combined with hybrid (motor and fuel cell) model**
- **PERE model validated for:**
  - conventional gasoline & diesel vehicles
  - production light duty hybrids (mild and full)
  - Fuel Cell hybrid vehicle
- **PERE fuel economy model robust**
- **Report is available & should be on website soon (EPA420-D-04-002). Accepting comments**
- **Future work: Cold Start**