The Physical Emissions Rate Estimator (PERE)

Edward Nam

MOVES Workshop

March 16, 2005

Acknowledgments

- Bob Giannelli, EPA
- Megan Beardsley, Emily Chen, Kent Helmer, John Koupal, Larry Landman, Joe McDonald, Arvon Mitcham, Gene Tierney, James Warila, and Tad Wysor. EPA
- Matthew Barth, George Scora, and Ted Younglove: UC Riverside, CE-CERT
- Feng An, Dan Santini: Argonne National Laboratory
- Robert Natkin: Ford Motor Company

MOVES

Outline

- PERE's role in MOVES
- Conventional vehicles (LD, MD, HD, Motorcycle)
- Advanced gasoline vehicles
- Advanced diesel vehicles
- Moderate & Full hybrid vehicles
- Validation
- Fuel Cell vehicles
- "Filling Holes" in MOVES

MOVES

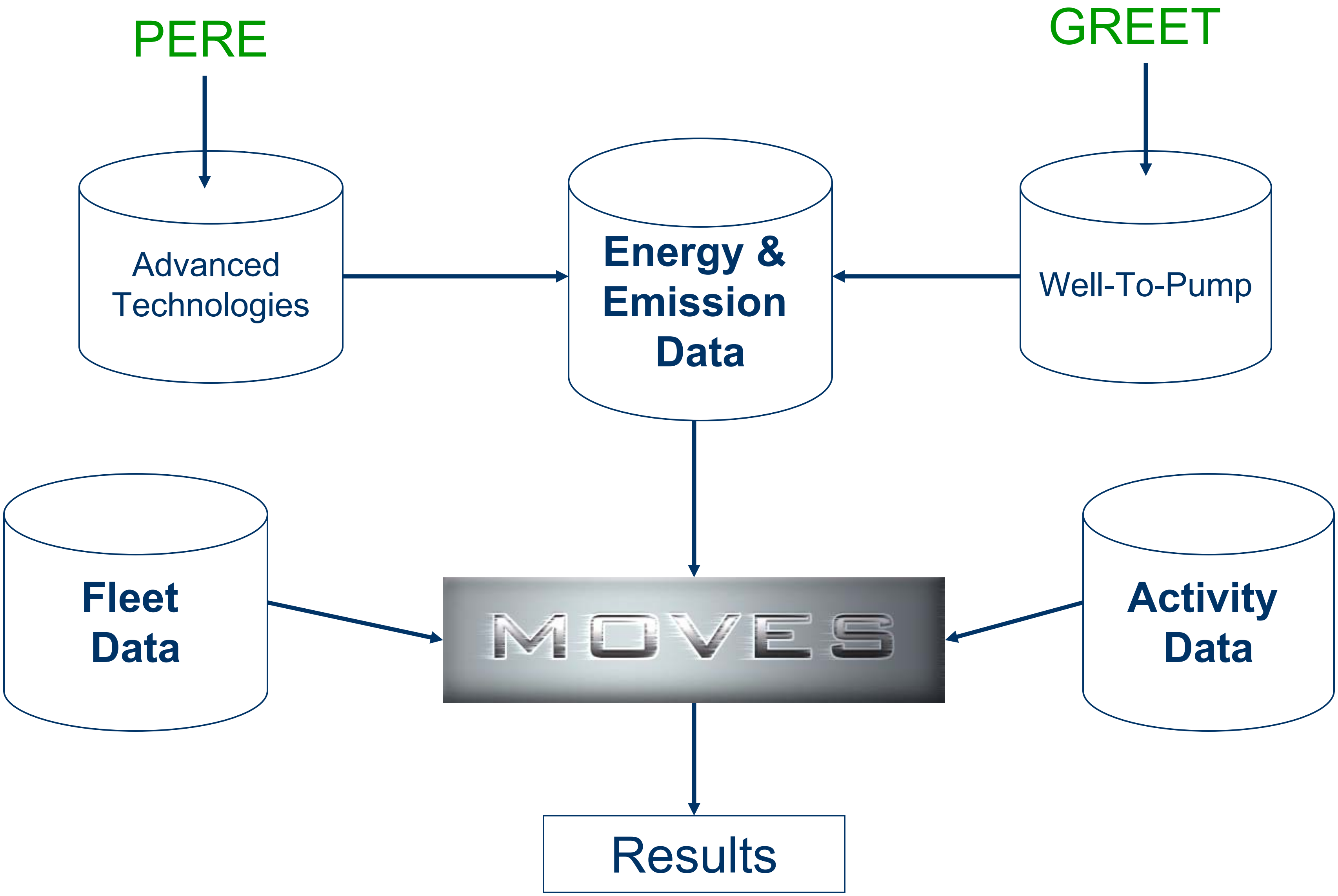
What Is PERE?

- Physical Emission (&energy) Rate Estimator
- Backwards looking model: driving cycle input, energy & emissions output
- Distributes energy required to move vehicle, to components
- Models second-by-second vehicle loads and effects on energy consumption
- Components modeled on aggregate scale
- Gives Pump-to-Wheel (PTW) estimates for a fleet of vehicles
- Currently in spreadsheet format

PERE's role in MOVES

- Fill data holes (HHDT, motorcycles, old cars, etc)
- Model advanced technology vehicles
- Provide an additional layer of quality check on some of the MOVES input data
- Due to close link with MOVES, in-house model required

PERE's role in MOVES

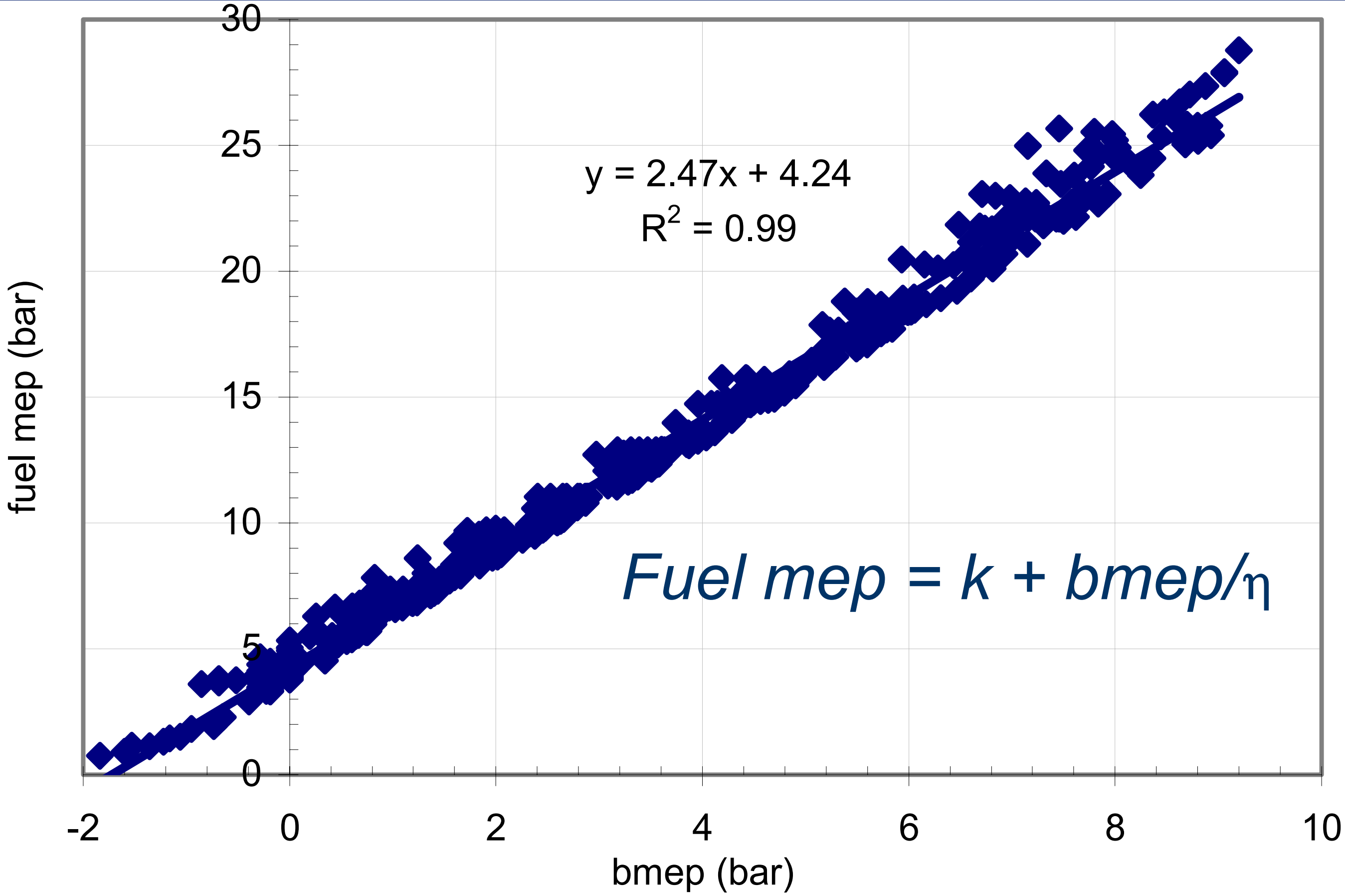


MOVES

Conventional Gasoline Vehicles

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

Willans Line for 10 gasoline engines



10 modern engines, 6 manufacturers, 2.4 - 6.8 L - Stoichiometric operation

ref: Nam (2004)

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)

Vehicle Specific Power (road load)

- **VSP = (Av + Bv^2 + Cv^3 + Mva)/M**
  - v: speed
  - a: acceleration
  - M: mass of vehicle
  - A, B, C are coast-down coefficients related to C_r, C_d, A_f.
- **Can adjust VSP coefficients for any type of vehicle**
- **Find engine friction and efficiency terms**
- **Add simple transmission model**
- **Conventional (ICE) Vehicle model**

Transmission

- Light Duty Model not very sensitive to transmission model specifics
- Required for engine speed (RPM)
- Shift points based on speed (empirical) or engine speed
- Downshift (on accel) based on max power or torque

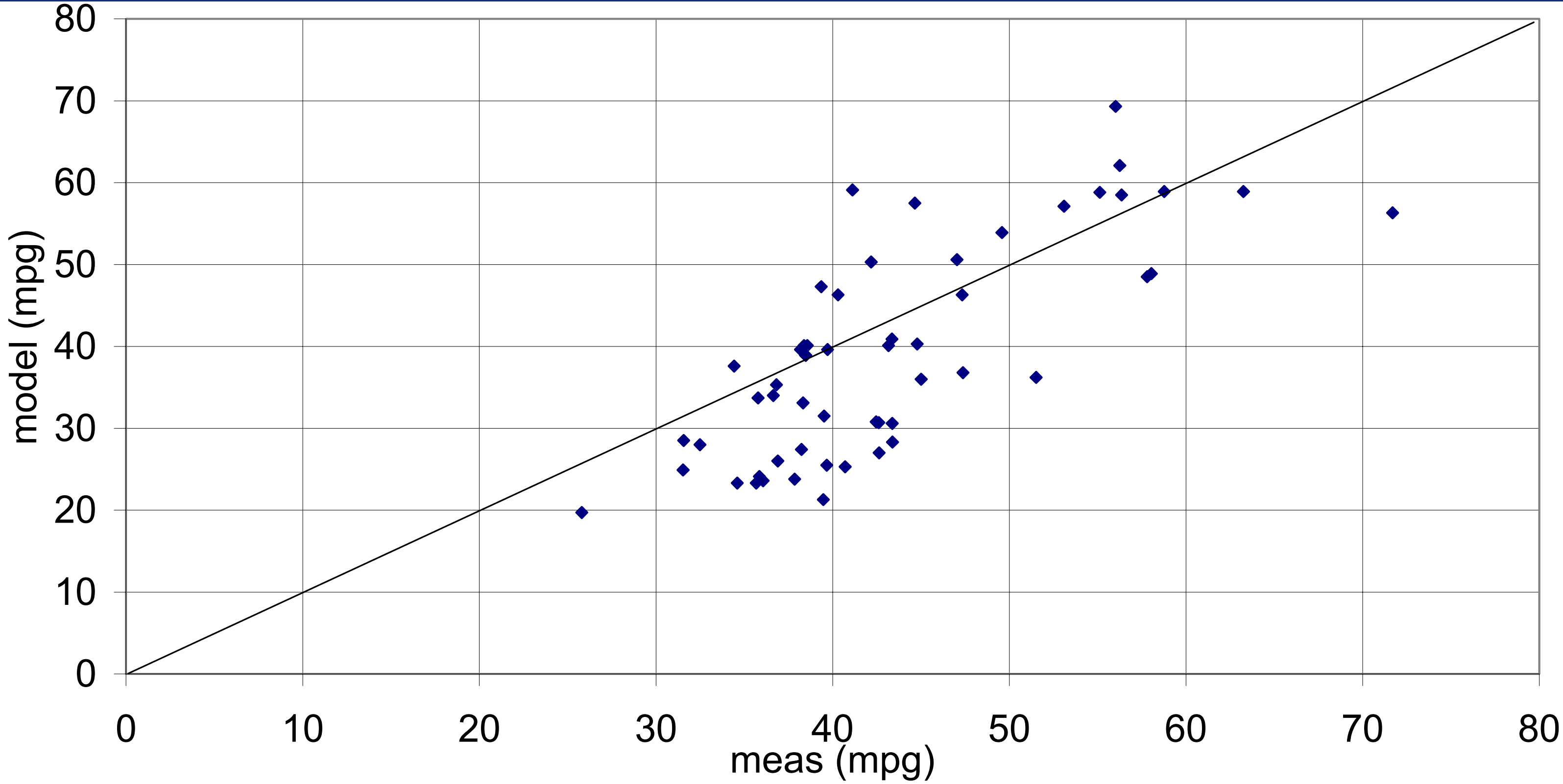
MOVES

How PERE vehicles are developed

- **Quantify engine efficiency and friction**
  - Based on a few "compressed engine maps" or on road data (for HD)
- **Estimate coast-down coefficients**
- **Estimate peak bmep (power) curves for engine**
- **Design simple transmission model**

MOVES

Motorcycle Validation (55 models)

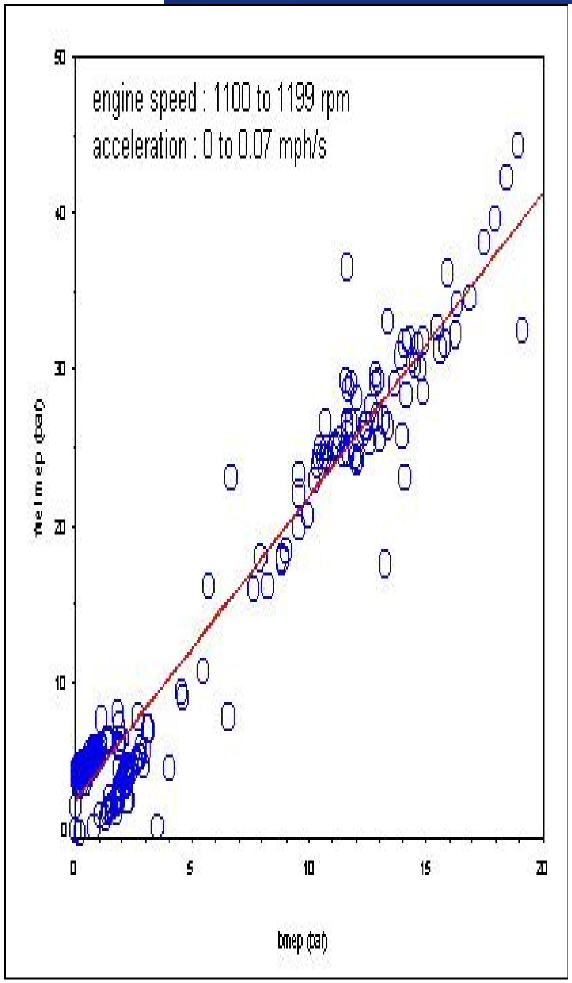


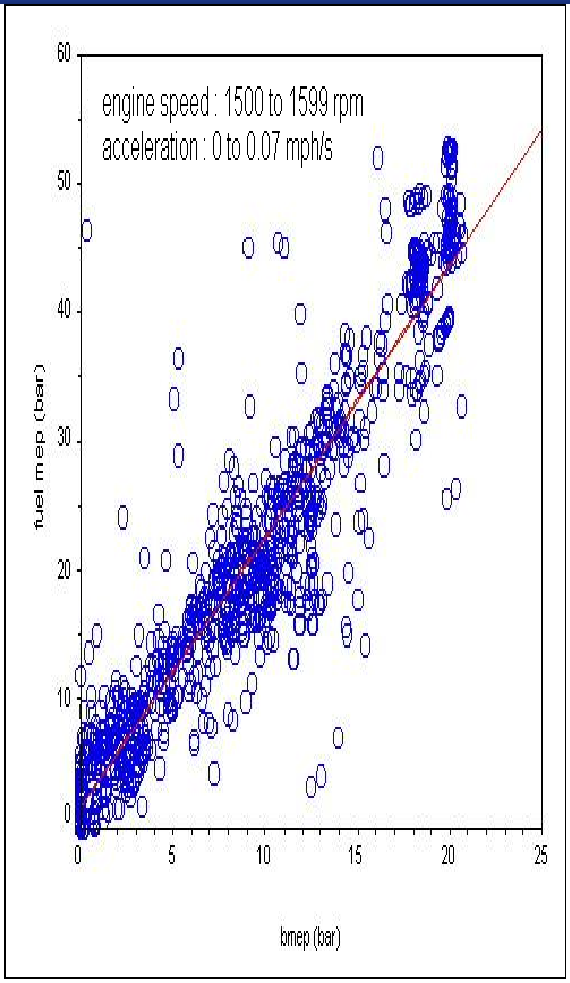
Heavy Motorcycles have car-like transmissions

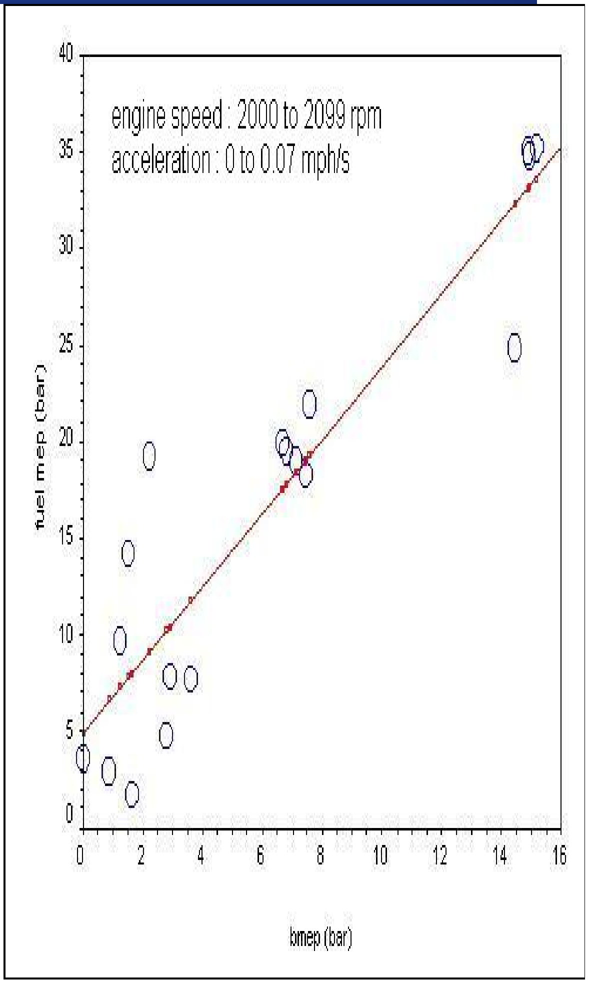
Heavy Duty Diesel Trucks

- Based on 15 in-use instrumented buses
- 12 HD trailers instrumented at UC-Riverside (CE-CERT)
- 17 non-road diesel engines (0.2 - 34.5L)
- Engine efficiency and friction determined
  - Some trucks estimated from on-road measurements
- Trends over time determined from previous publications
- Transmission shift points & gearing determined empirically
- Validations for fuel consumption within 10% of measured

Engine coefficients from on-road data (select steady state points)







MOVES

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
- Alternative fuels (such as hydrogen) require a full life cycle analysis to estimate total environmental impact

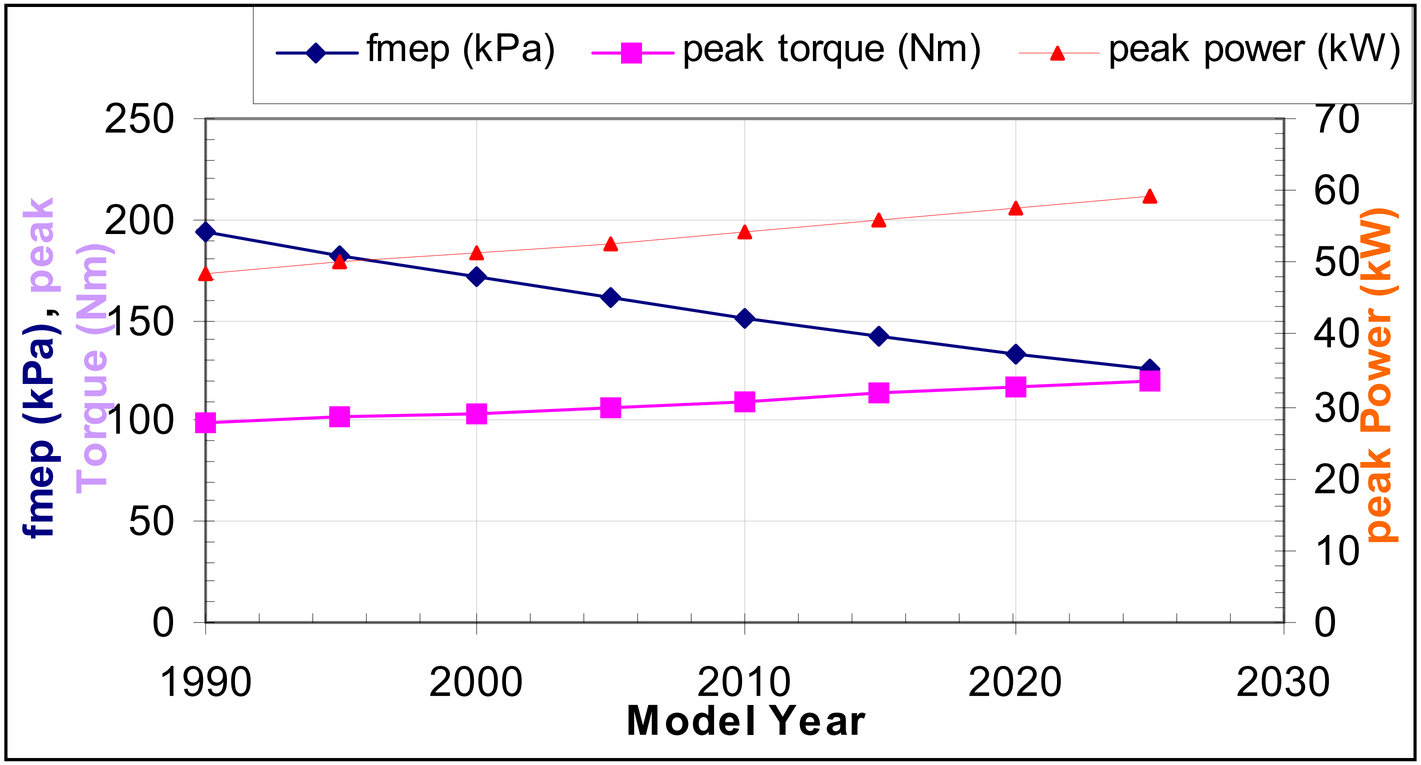
Advanced Technologies in MOVES

- Gasoline conventional (CIC) & Advanced (AIC)
- Gasoline hybrid CIC & AIC Moderate & Full
- Diesel fuel conventional (IC) and Advanced IC
- Diesel hybrid CIC & AIC Moderate & 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

Advanced Engine Targets (AIC)

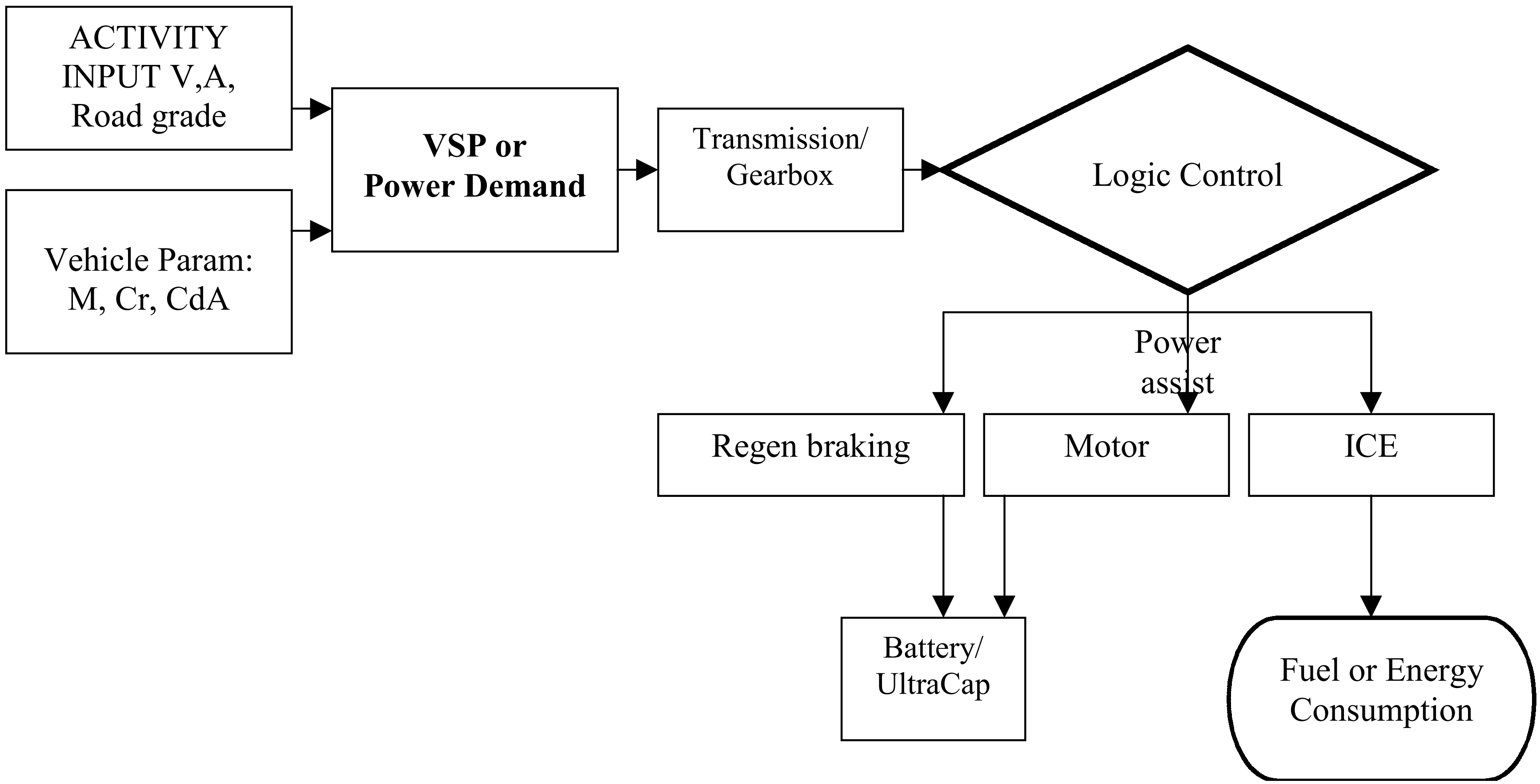
- Indicated efficiency increase ~10% (0.44 or 0.5 for diesel)
- Friction decreases to 2015 levels, 15% (extrapolated)
- Peak power trends increase (extrapolated)

Friction and peak power in advanced gasoline engines

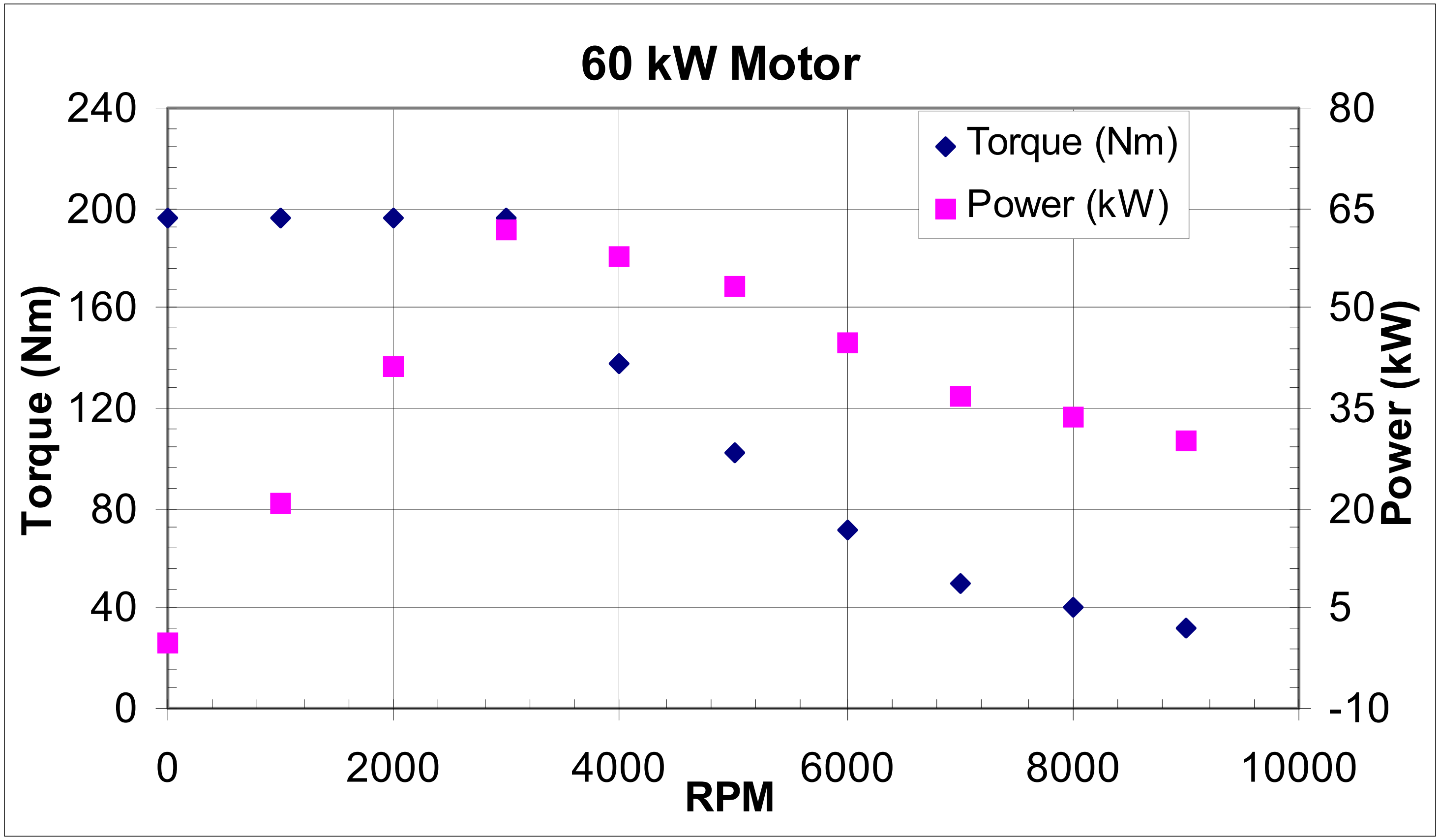


(Chon&Heywood, 2000; Nam&Sorab, 2004)

(Parallel) Hybrid vehicles



Motor peak torque & power (scaled)



Efficiency ~ 0.76

Weiss, et al. 2000

Moderate vs. Full hybrid

- **Moderate**
  - ratio of (peak) motor power to engine power ~ 0.15
  - Similar to Honda Civic
- **Full**
  - ratio of motor power to engine power ~ 0.88
  - Similar to Toyota Prius
- **Energy Storage Device**
  - Battery

Hybrid control strategy
(based on Weiss, et al. 2000)

- **Discharge:**
  - If Power demand (Pd) < hybrid threshold (Pth) then run on motor only (LAUNCH)
  - Else If Pd > maximum engine power (Pmax), then run on engine + motor (ASSIST)
  - Else run on engine only
  - accessories run on either depending on situation
- **Recharge: Regenerative braking**
- **Engine Idle/decel off**
- **No charging while engine running**

Battery (Energy Storage Device) and State of Charge

- Discharge and recharge according to power demand
- Discharge efficiency
- recharge limited to front wheel drive brake power distribution
- Additional loss on recharge
- Hybrid Power threshold determined to sustain charge over standard driving cycles

PERE control screen (EXCEL)

Run macro to get VSP bin

PERE for Light Duty

<u>Input tables</u> **- Please input values in yellow boxes**

Choices

Vehicle Parameters		
Model Year	**2005**	
Vehicle wgt (lbs)	**3750**	
adjusted vehicle wgt (kg)	**1803**	
TRLHP (hp@50mph)	n/a	
Cr0 (rolling resistance)	0.009	
Cd (drag coeff)	0.3	
A (frontal area m^2)	2.4	
A (N or W/mps)	n/a	
B (N/mps or W/mps^2)	n/a	
C (N/mps^2 or W/mps^3)	n/a	
Pacc (accessory - kW)	0.75	
Engine Parameters		
Engine Displ (L)	**1.72**	
friction k0 (kJ/Lrev)	0.150037	
fric k1 (N dependent fric)	0.001545	
eng indicated eff (eta)	0.4	
Transmission Parameters		
N/v (rpm/mph)	35.6	
Nidle (rpm)	700	
trans eff gear 1	0.72	
trans eff gear 2	0.81	
trans eff all other gears	0.88	
Shift point 1-2 (mph)	18	
Shift point 2-3	25	
Shift point 3-4	40	
Shift point 4-5	50	
Shift point 5-6	50	
g/gtop 1	4.04	
g/gtop 2	2.22	
g/gtop 3	1.44	
g/gtop 4	1	
g/gtop 5	0.9	
g/gtop 6	0.9	
Fuel Parameters		
LHV (kJ/g)	44	
density gas (kg/L)	0.744	
Motor Parameters (hybrid/FC only)		
overall efficiency	0.76	
Regen Brake Eff	0.85	
FWD power frac	0.75	
Motor peak power (kW)	**72.7**	
min regen (kW)	2.8	
Motor Energy (kWhr)	1.8	
Battery Parameters (hybrid/FC only)		
Initial SOC	0.56	
Batt Energy (kWh)	0.936	
min SOC	0.2	
max SOC	0.8	
discharge eff	0.95	
Hybrid		
hybrid threshold (kW)	**5.5**	
Fuel Cell Parameters		
Fuel Cell Power Rating	**154.7**	

Is vehicle conventional, hybrid, or electric	**h**	c = conventional
h= hybrid parallel configuration	e=electric	f = fuel cell
Is vehicle gas or diesel?	**g**	g = gas
(g for gas equivalent calculations)		d = diesel
Is transmission automatic or manual?	**a**	a = automatic
		m = manual or (auto manual a
Is vehicle LDV or LDT?	**1**	1 = passenger car
		0 = LDT (pick-up, SUV, etc)
Road Load Entry Method	**4**	1 = calculate this for me from
(Track) Coast Down Coefficients	1.72	2 = I will enter TRLHP (single coefficient)
total seconds in drive cycle?	3570	3 = I will enter known A, B, C coefficients
if >3570, then copy rows in SBSResults PERE and Transm		4 = I will enter approximated Cr, Cd and A parameters

gas	diesel
0.15003745	0.0474285
0.001545	0.00333
0.4	**0.45**
	diesel
35.6	26.7
automatic	manual
0.72	0.95
0.81	0.95
0.88	0.95

gas	diesel
44	43.2
0.744	0.8114

hybrid	dvanced fuel cell
0.76	0.8
0.85	0.95
0.75	0.85

Discharge:(kWhr):	1.15484943
Recharge (kWhr):	-1.16868854
Net SOC change (kW-hr)	-0.01383911

Coast Down Coefficients Table		
1	TRLHP from v	**15.39426**
2	TRLHP user ir	**14**
3	A (N)	**125.58**
	B (N/mps)	**-0.900**
	C (N/mps^2)	**0.4474**
4	Cr	**0.009**
	Cd	**0.3**
	A (m^2)	**2.4**

<u>OUTPUT TABLES</u>

<u>RESULTS</u>	
distance (	**27.515**
fuel (kg)	**2.0202**
fuel (gal)	**0.71731**
fuel econ.	**38.358**
mpgge	**38.358**
fuel cons (	**6.1334**
fcge	**6.1334**

<u>BINNER RESULTS (run macro)</u>

<u>vspbin</u>	<u>fr (g/s)</u>	<u>N</u>
0	**0.00000**	385
1	**0.00000**	511
11	**0.00000**	189
12	**0.06159**	241
13	**0.52744**	164
14	**1.00816**	121
15	**1.40674**	69
16	**2.08291**	45
21	**0.00000**	270
22	**0.12269**	288
23	**0.59623**	302
24	**0.92249**	176
25	**1.29175**	107
26	**2.14363**	93
33	**0.41693**	280
35	**1.01843**	251
36	**1.77902**	75

Conventional Vehicle Validation

- **Modeling methodology validated**
  - 41 vehicles on FTP & US06; 17 vehicles on 8 UCC schedules (Nam, EPA420-R-03-005.
- **Validated on motorcycles (fuel economy) and heavy duty trucks (on road)**
- **Similar model used by other researchers and validated by their papers (An, Barth, Ross, etc).**

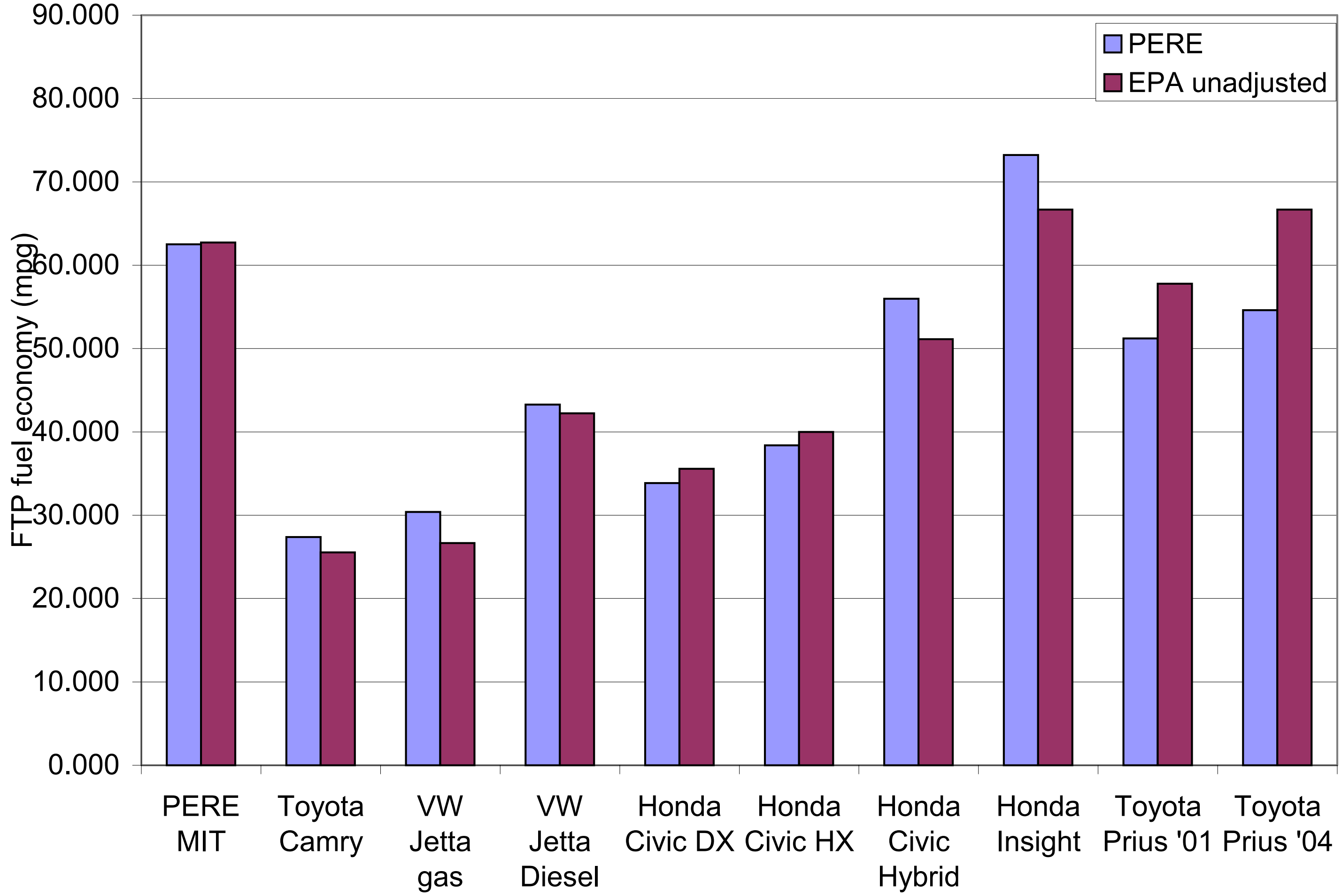
MOVES

Hybrid Validation

- 11 vehicles on 2 cycles (city/highway)
- Hybrids 7% heavier than conventional (based on production figures)

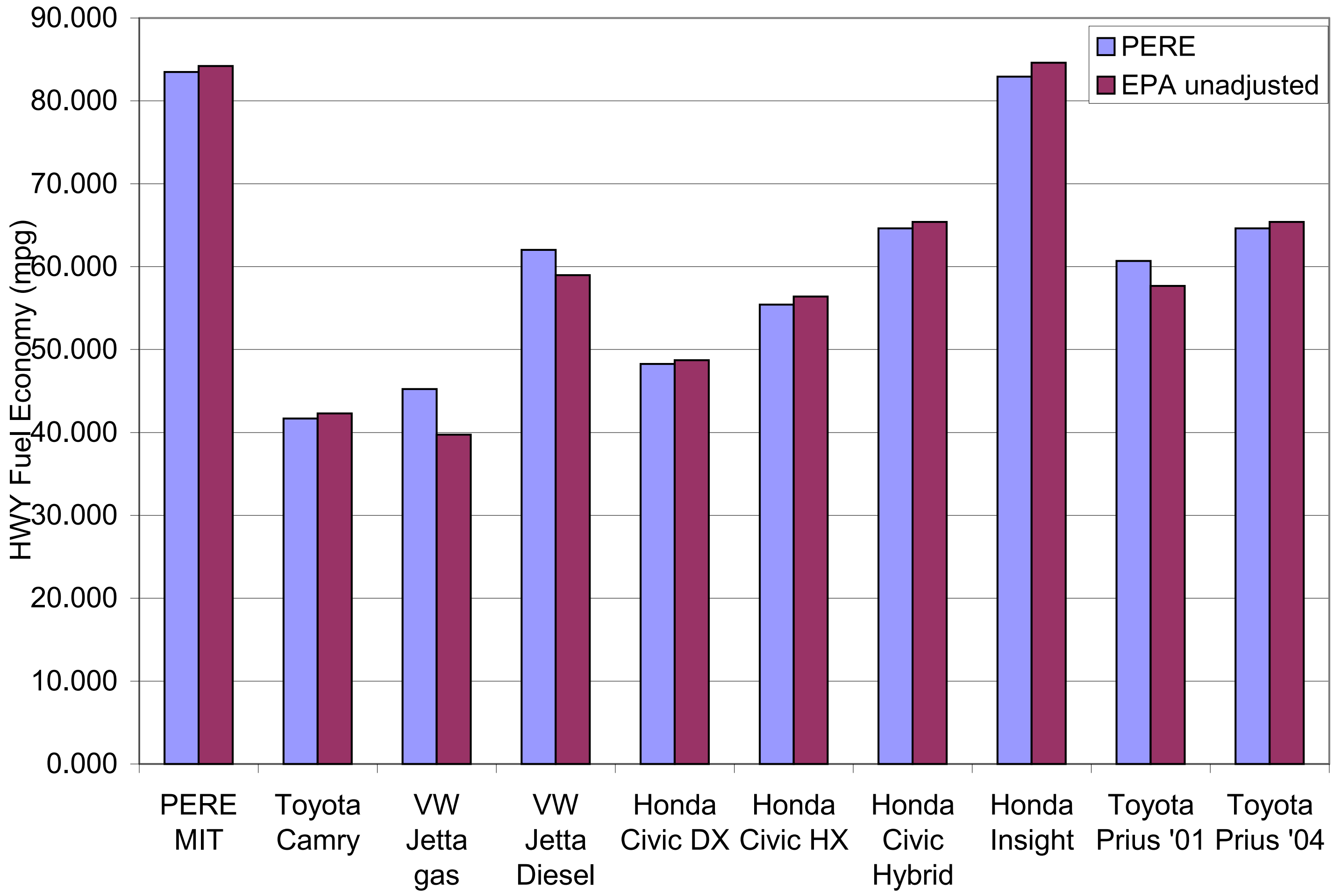
Mfr	Model
Toyota	Camry
VW	Jetta gas
VW	Jetta Diesel
Honda	Civic DX
Honda	Civic HX
Honda	Civic Hybrid
Honda	Insight
Toyota	Prius '01
Toyota	Prius '04

City Fuel Economy Validation



MOVES

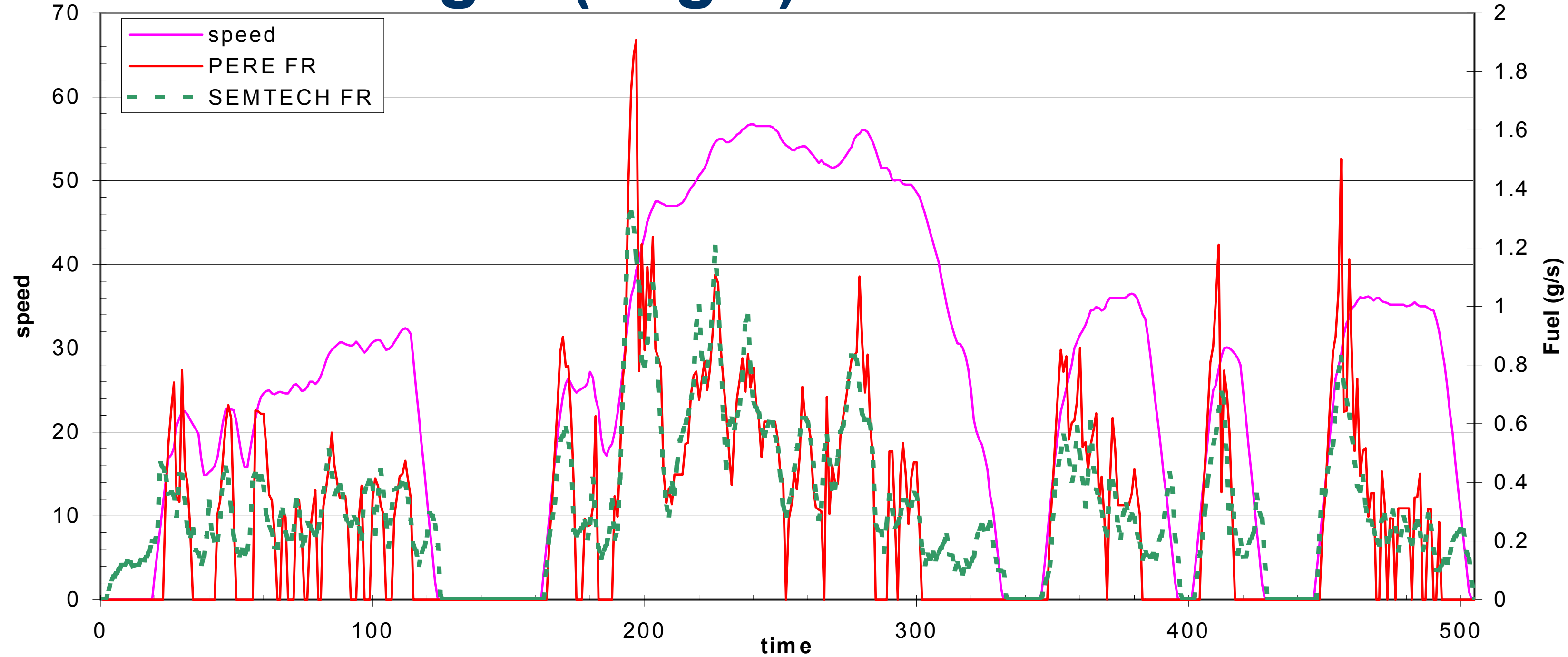
Highway Fuel Economy Validation



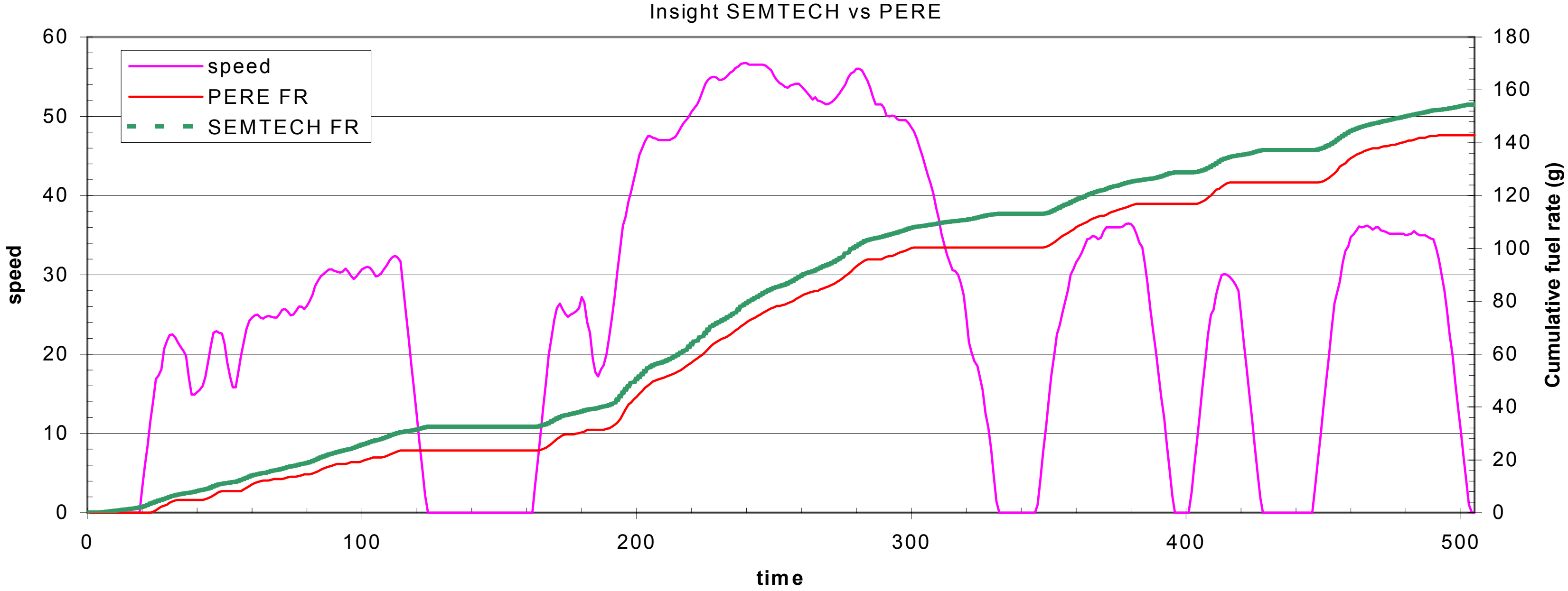
PERE Hybrid Validation Results

- **PERE (fuel consumption) model is robust**
- **Most sensitive parameters are known (mass, engine displ, efficiency, road load coefficients)**
- **All fuel economy within 10% - *except* -**
- **Only 1 conventional vehicle on and 1 production hybrid have error >10%** (compared to unadjusted EPA fuel economy)
- **Second by second results…**

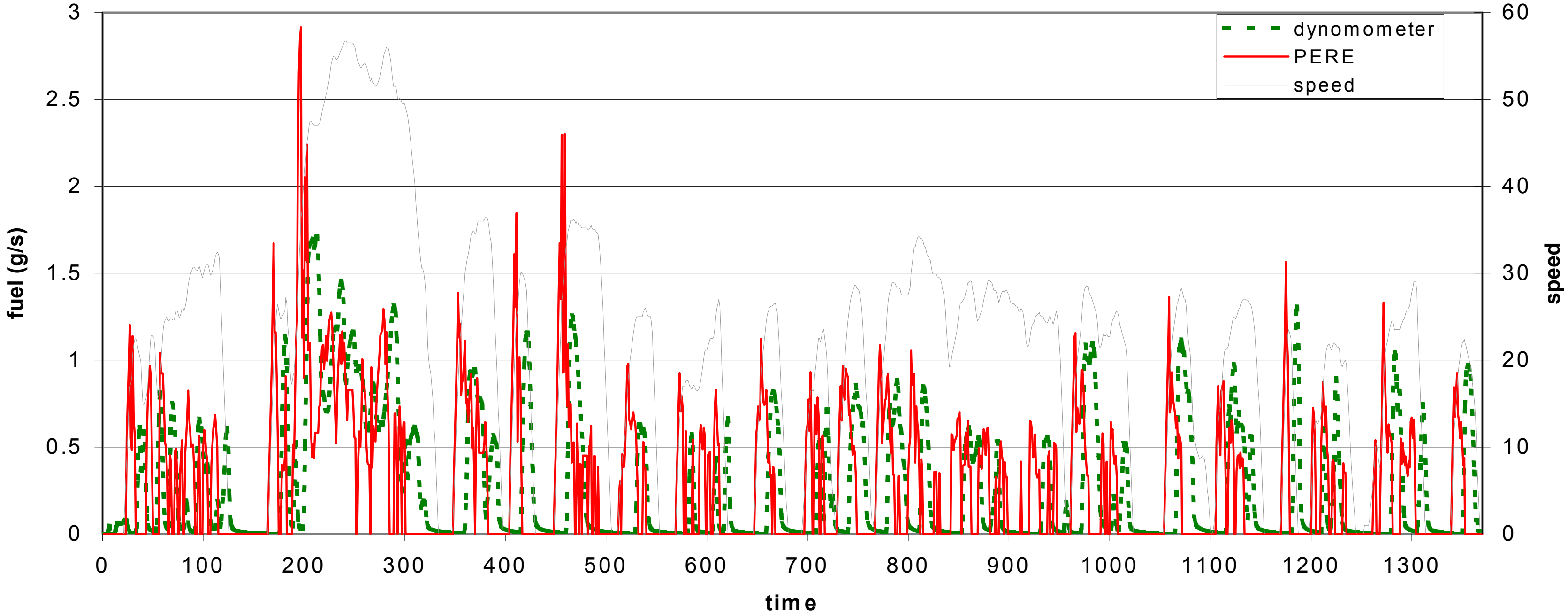
Honda Insight (bag 3)

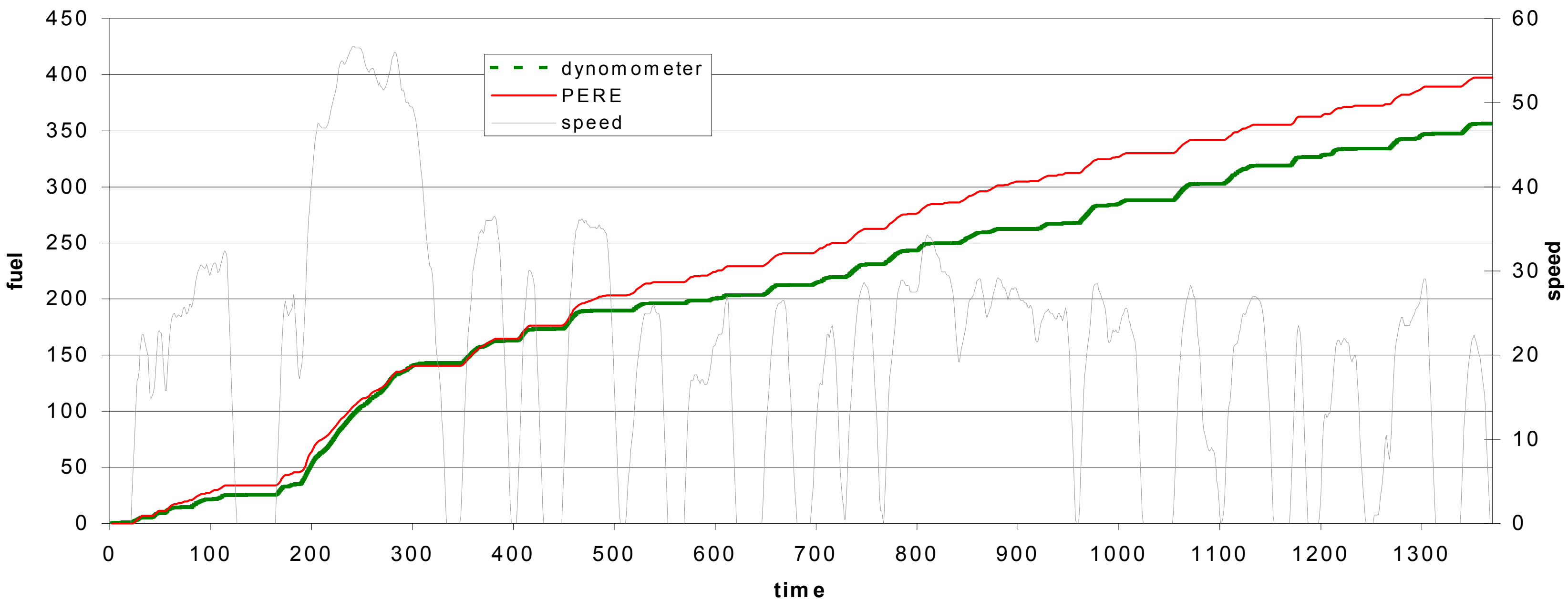


Insight SEMTECH vs PERE



Toyota Prius (bag 3, 4)



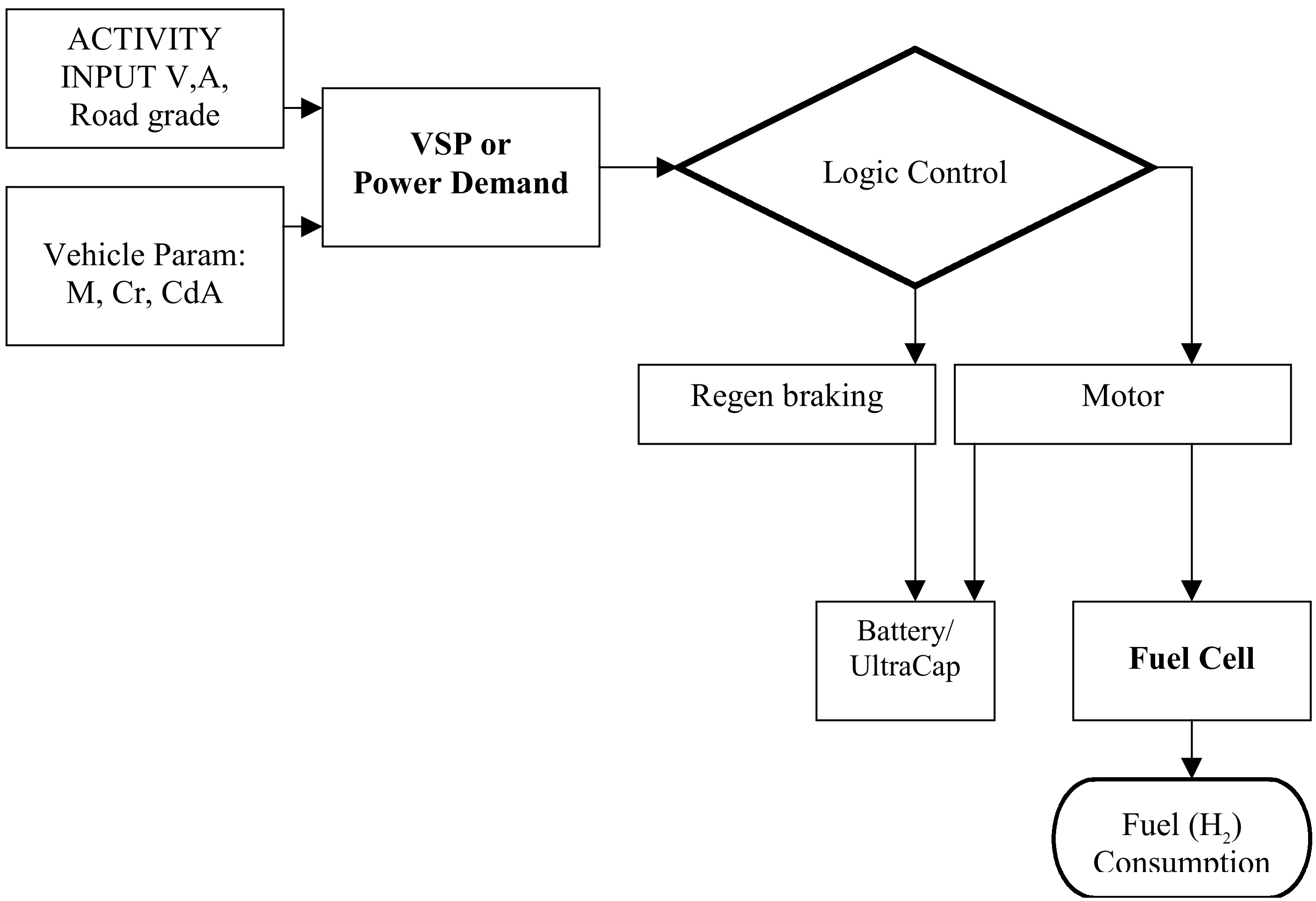


MOVES

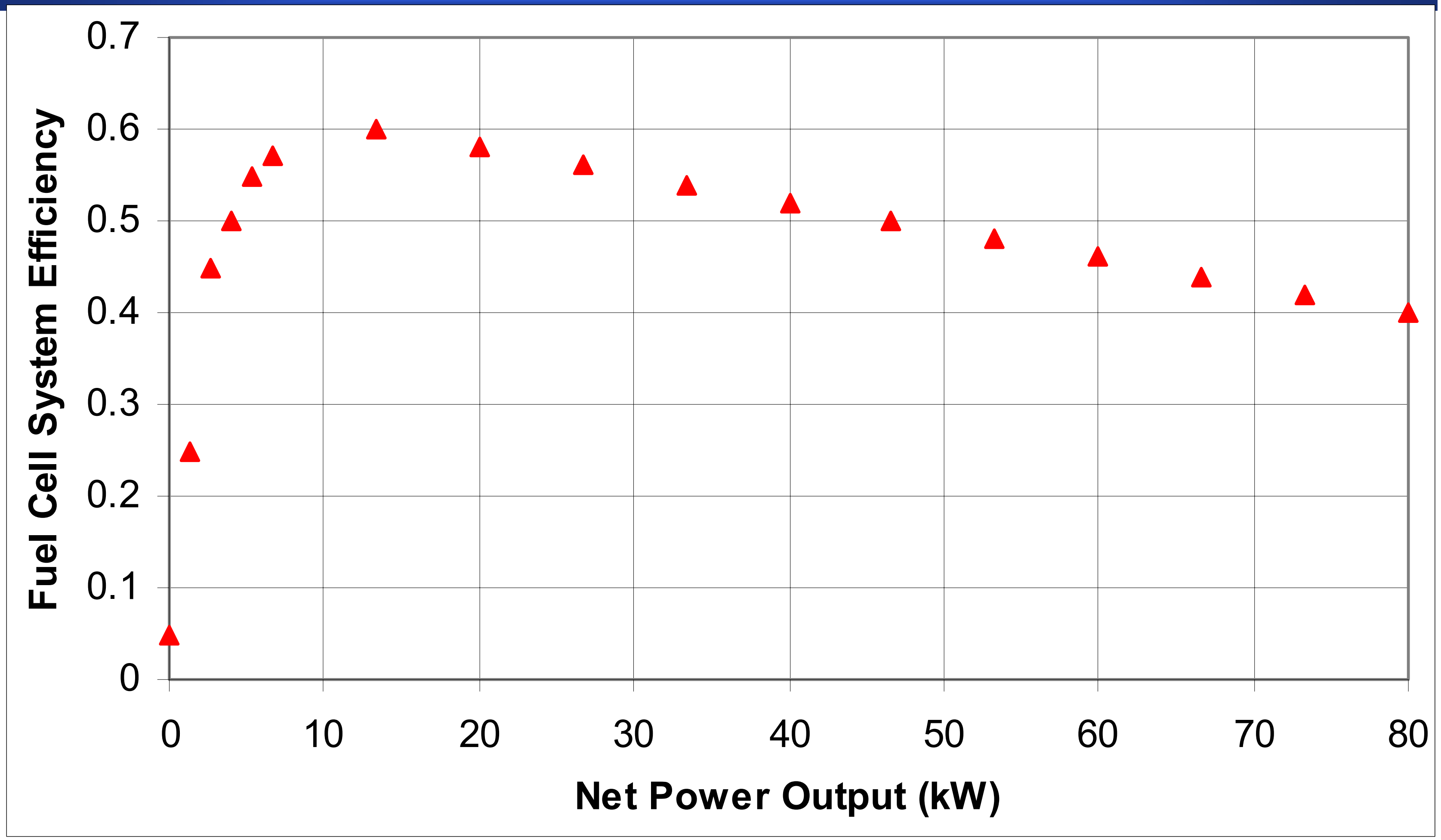
Limitations

- PERE Models typical driving accurately
- Requires modifications to model performance (0-60 acceleration, or gradeability)
- Power&weight us surrogate for 0-60 performance
- Does not have cost estimates
- Does not include component weight estimates (only aggregate vehicle weight)

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 (less efficient than MIT fuel cell)
- Hybrids are 23% heavier than conventional counterpart -based on current prototype weights, which will improve in the future
- Preliminary results show promise

Validation to Honda FCX

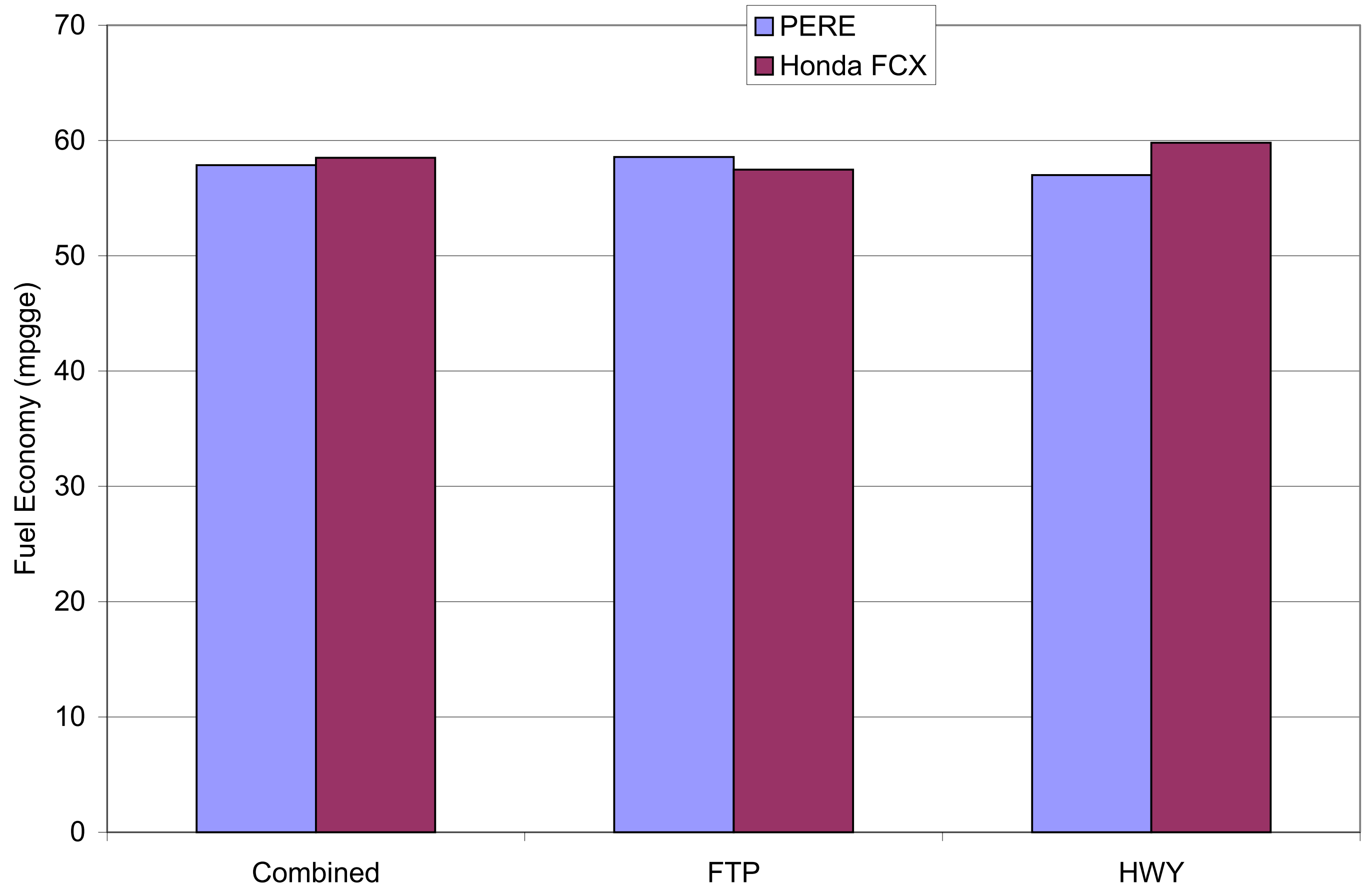


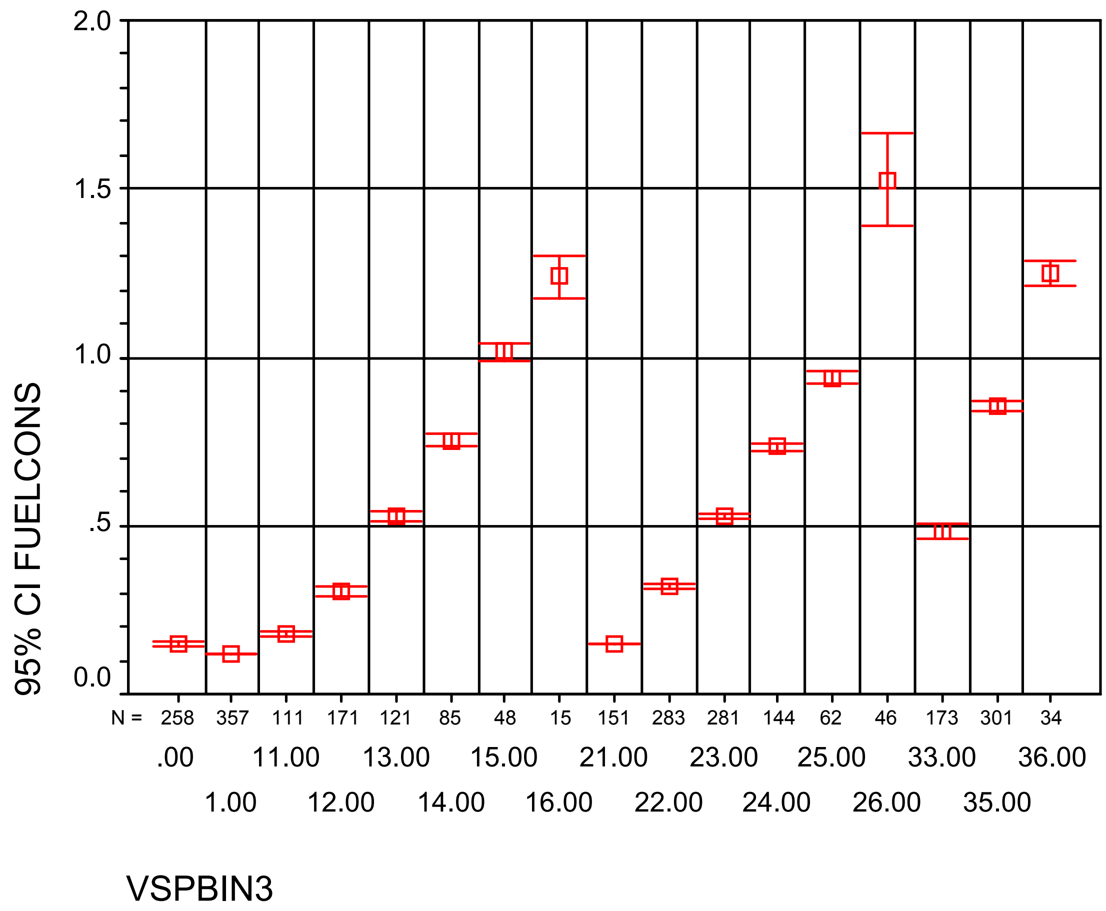
Figure shows unadjusted fuel economy numbers

MOVES

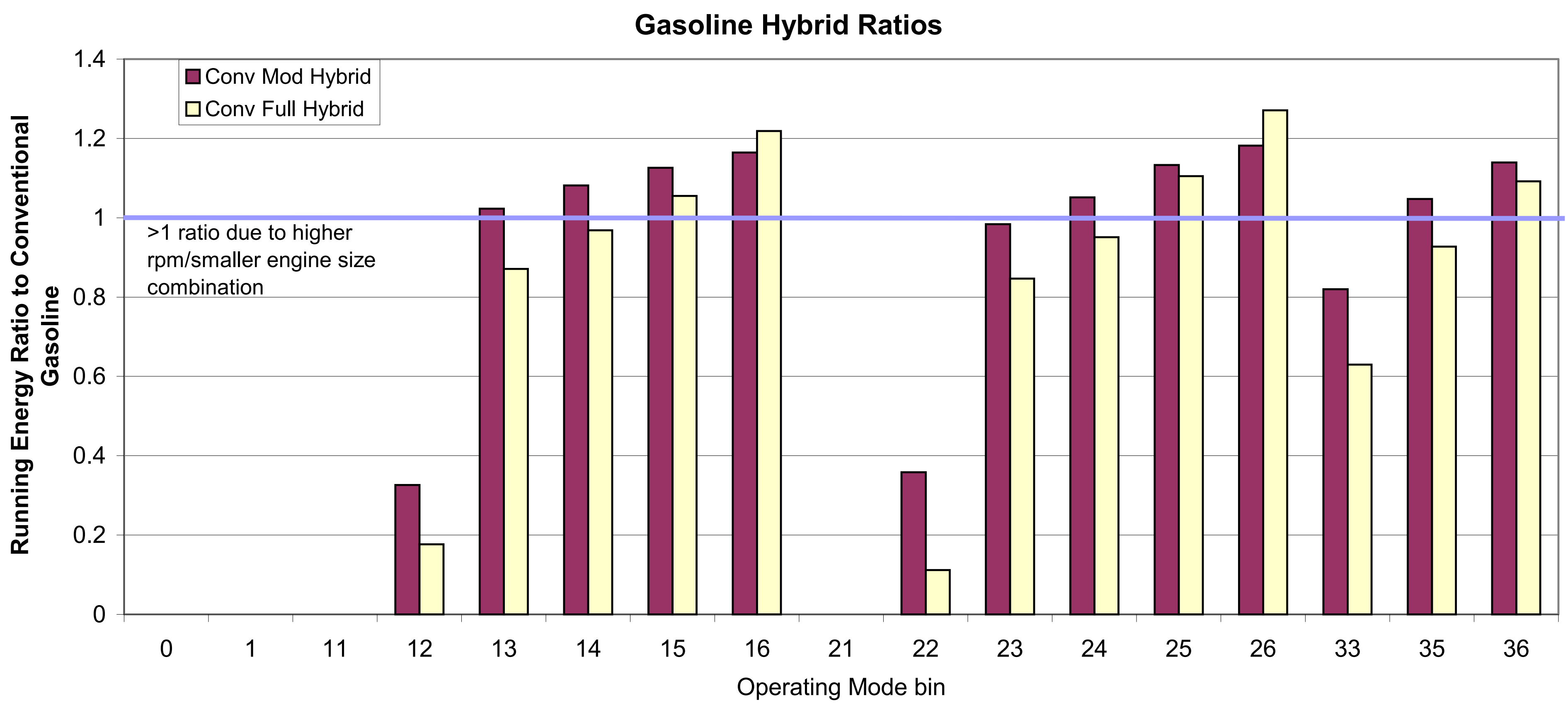
How will rates be incorporated into MOVES

- Determine source bin family (fuel, model year, adv tech type, etc)
- Choose typical (central) vehicle traits
- Define Driving Cycles (LD, MD, HD)
- Run PERE over range of weights & engine sizes
- For Adv Tech, use ratio to conventional by VSP bin

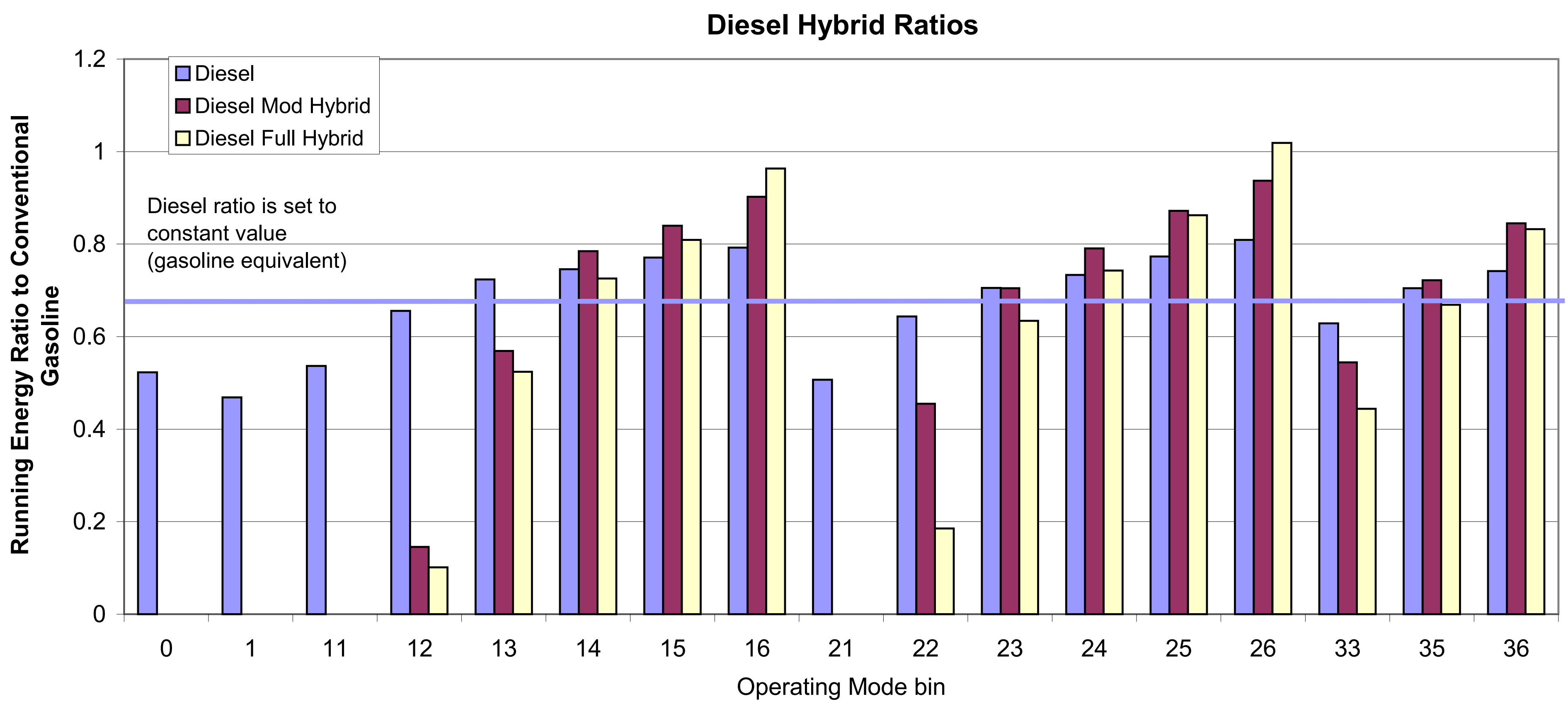
Full LD parallel hybrid example



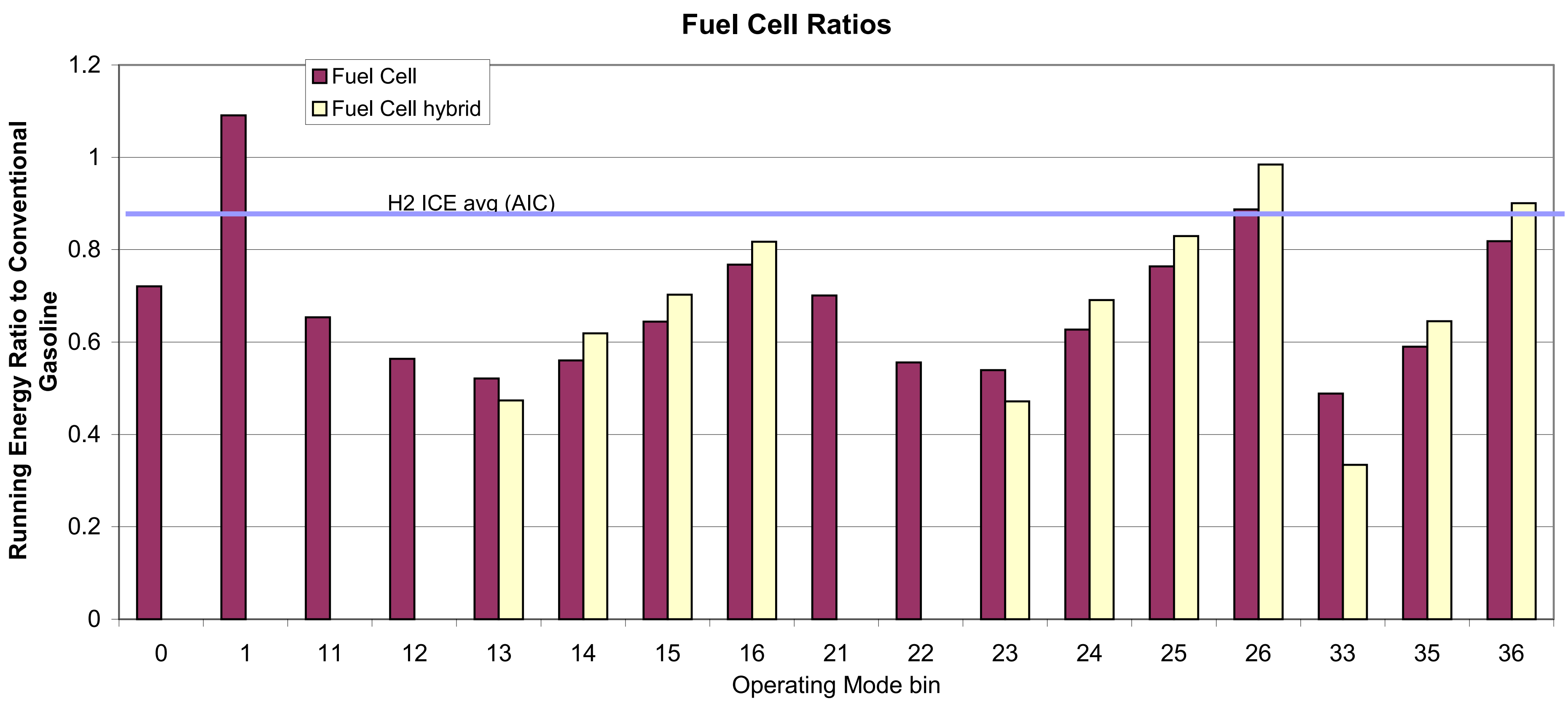
Ratios to conventional (reduce complexity)



Diesel ratios



Fuel Cell ratios



Conclusions

- **PERE based on engine combined with hybrid (motor and fuel cell) model**
- **PERE model validated for:**
  - conventional gasoline & diesel vehicles
  - motorcycles
  - production light duty hybrids (moderate and full)
  - fuel cell hybrid vehicle
- **PERE fuel economy model robust**
- **Model & Report are available & should be on website soon (EPA420-P-05-001).**
- **Future work:**