Advanced Technology Vehicle Modeling in MOVES using PERE

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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

Part 1: 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**
- **Alternative fuels (such as hydrogen) require a full life cycle analysis to estimate total environmental impact**

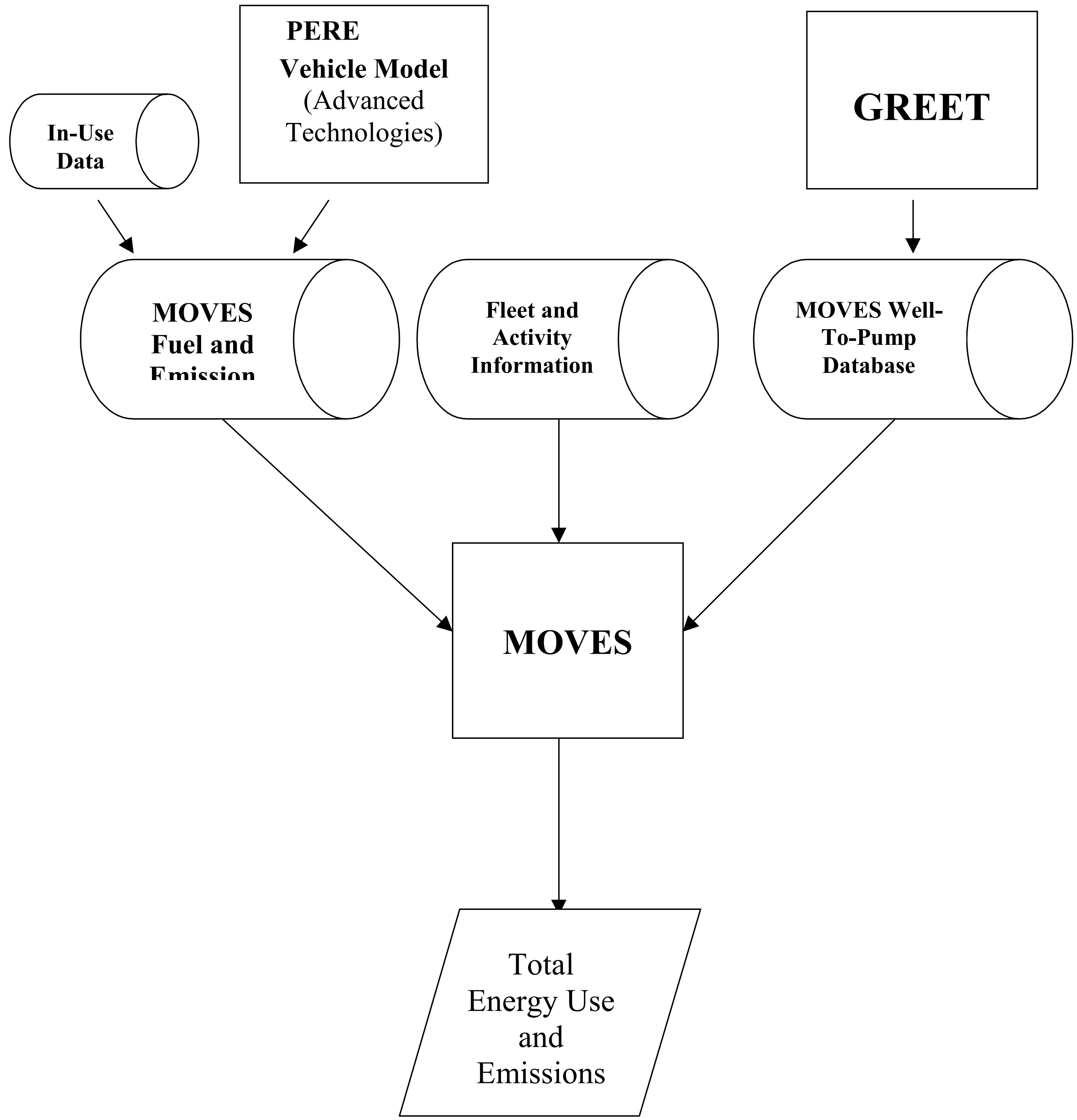
What Is PERE?

- **P**hysical **E**mission (&energy) **R**ate **E**stimator
- Backwards looking model: driving cycle input, energy & emissions output
- Models second-by-second vehicle loads and effects on energy consumption and emission
- Components modeled on aggregate scale
- 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)**

PERE's role in MOVES



Conventional Gasoline Vehicles

- Subject to certain constraints, most (indirect injection) gasoline engines behave similarly: fuel is burned - work is done
- Account for scaling factors for size and speed
- Account for “advanced” engines separately: homogenous lean-burn, Atkinson, etc.

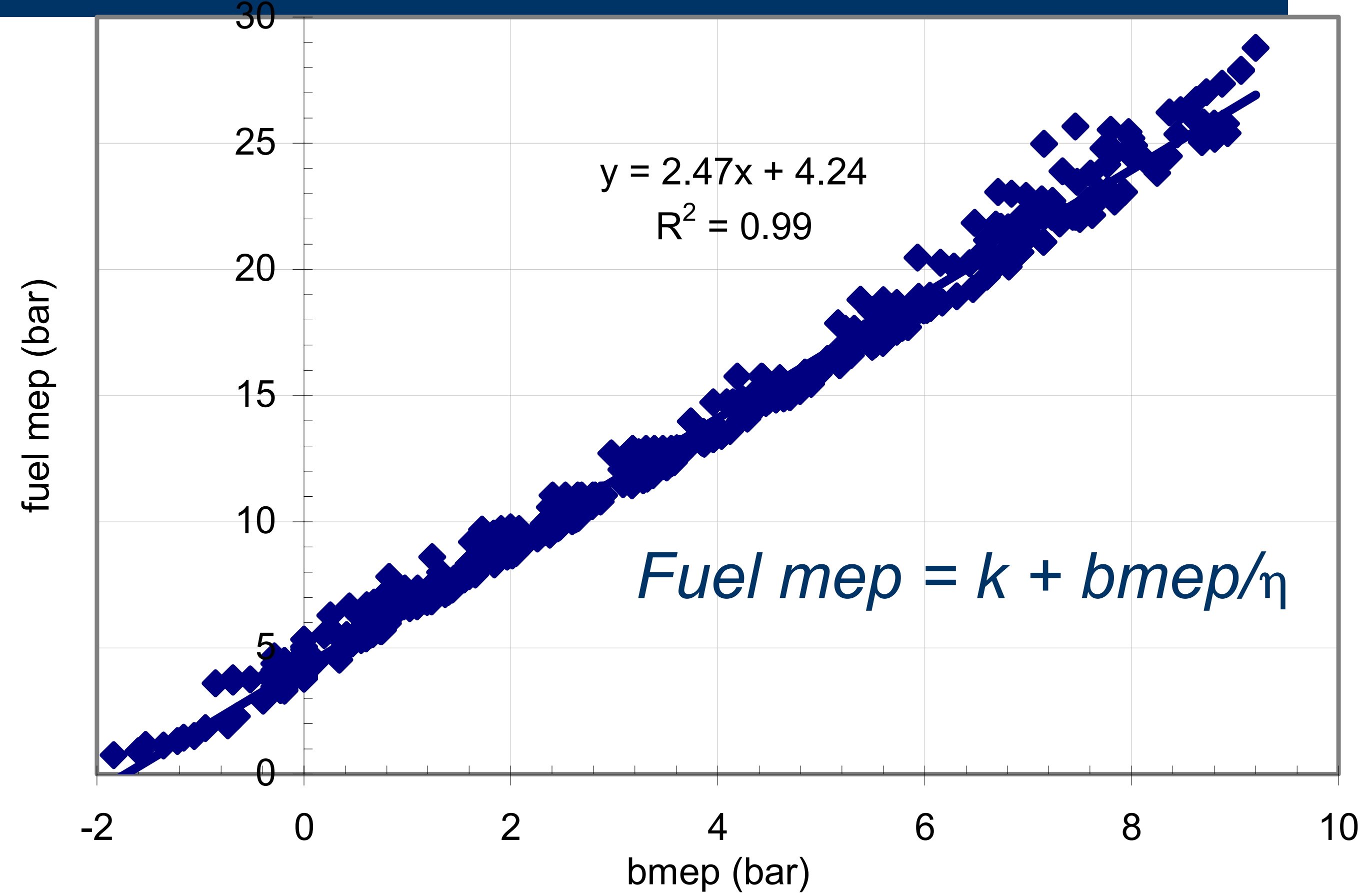
Scaling for size and speed (mep)

- **Mean Effective Pressure (bar or kPa)**
  - power per unit displacement and stroke
  - e.g. mep = Pn*1000/(VN)
    - mep in kPa
    - P in kW
    - n=1 for 2 stroke, n=2 for 4 stroke
    - V = engine displacement in Liters
    - N = engine speed in rps

Fuel consumption from brake work

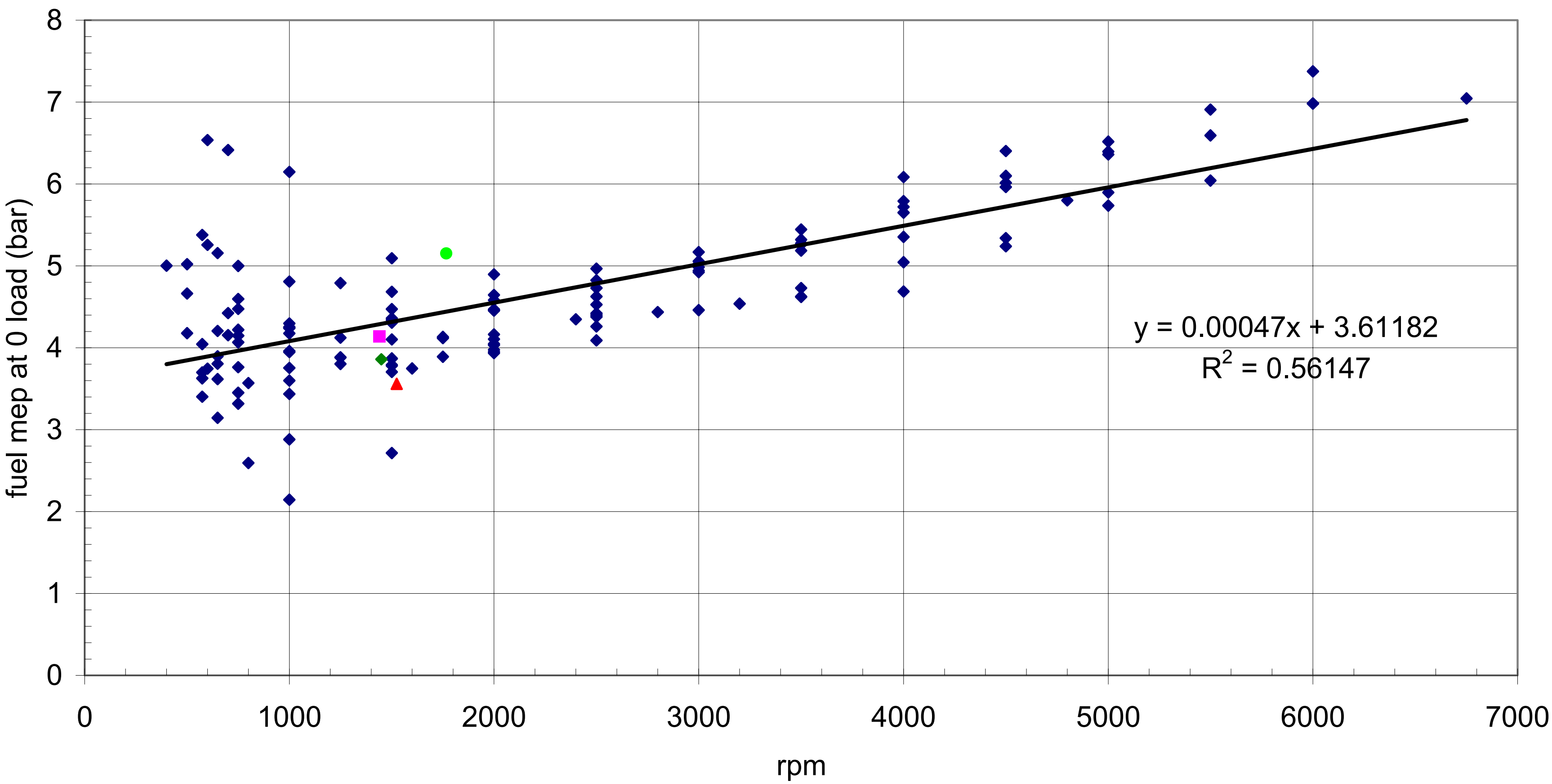
- **imep = fmep + bmep**
  - imep = indicated
  - fmep = friction
  - bmep = brake
- **Fuel mep**
  - **imep = η*fuel mep**
    - **fuel mep = 2000*P_f/VN**
    - **P_f = FR*LHV [FR in g/s, LHV in kJ/g]**
- **fuel mep = k + bmep/η**

Willans Line for 10 gasoline engines



10 modern engines, 6 manufacturers, 2.4 - 6.8 L - Stoichiometric operation *ref: Nam (2004)*

Friction (k-term)



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)

We don’t need no stinkin’ Engine Maps!

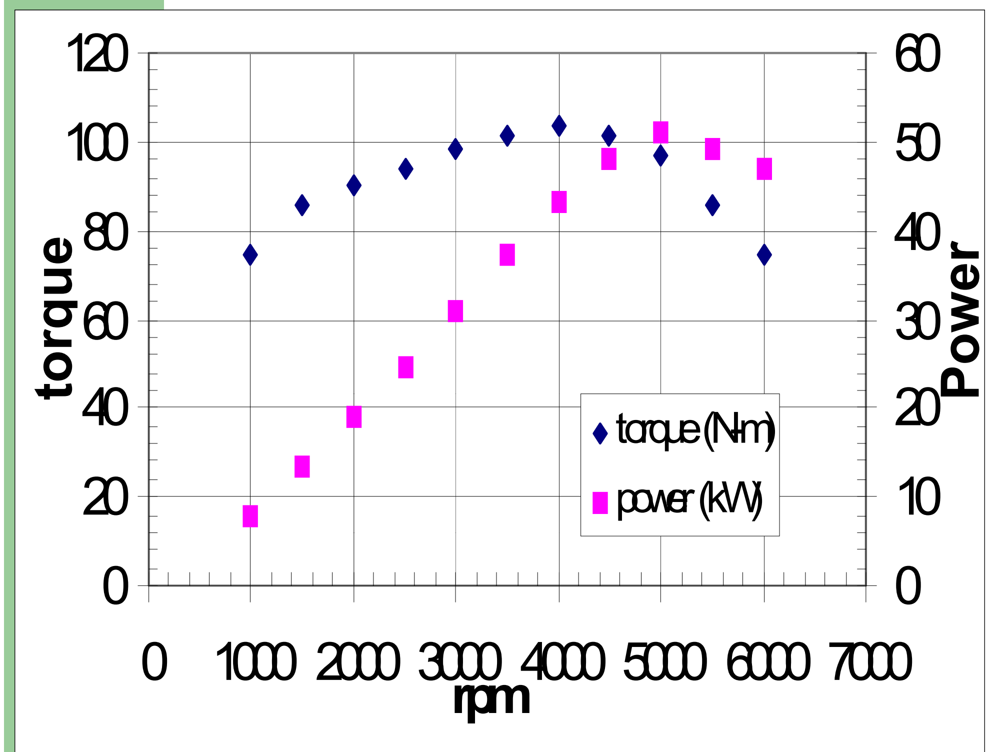
- This ‘simplified’, yet robust approach does away with the need for full engine maps
- Engine maps are required for most other powertrain models
- Engine maps are difficult to acquire
- All we need are estimated peak power curves

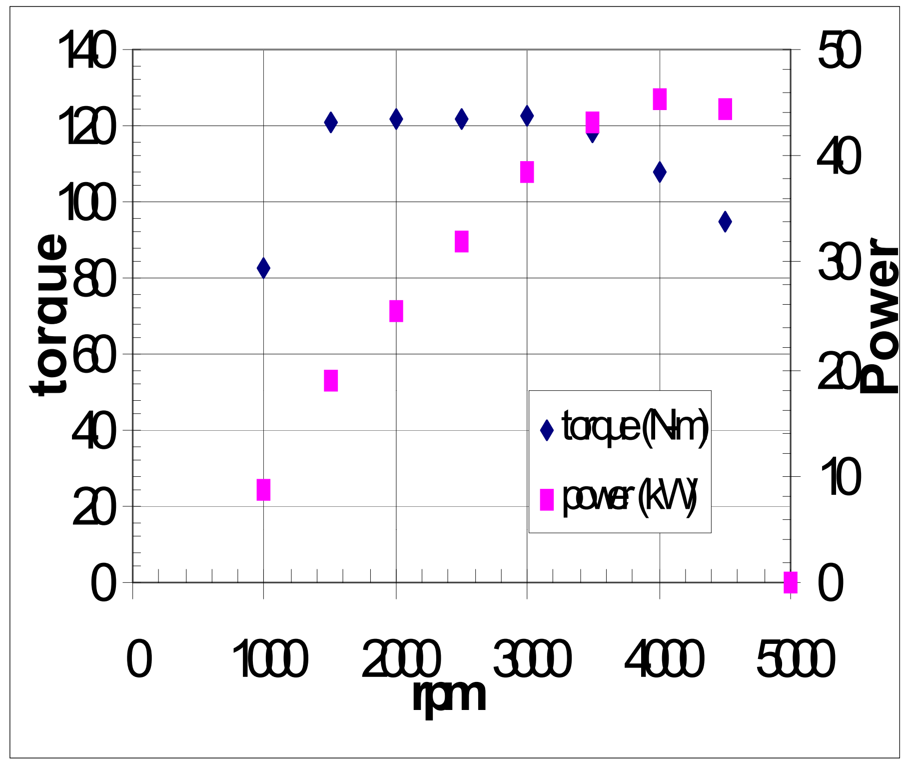
Transmission

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

Scalable Peak torque and power

Gasoline (~1.1L) Diesel



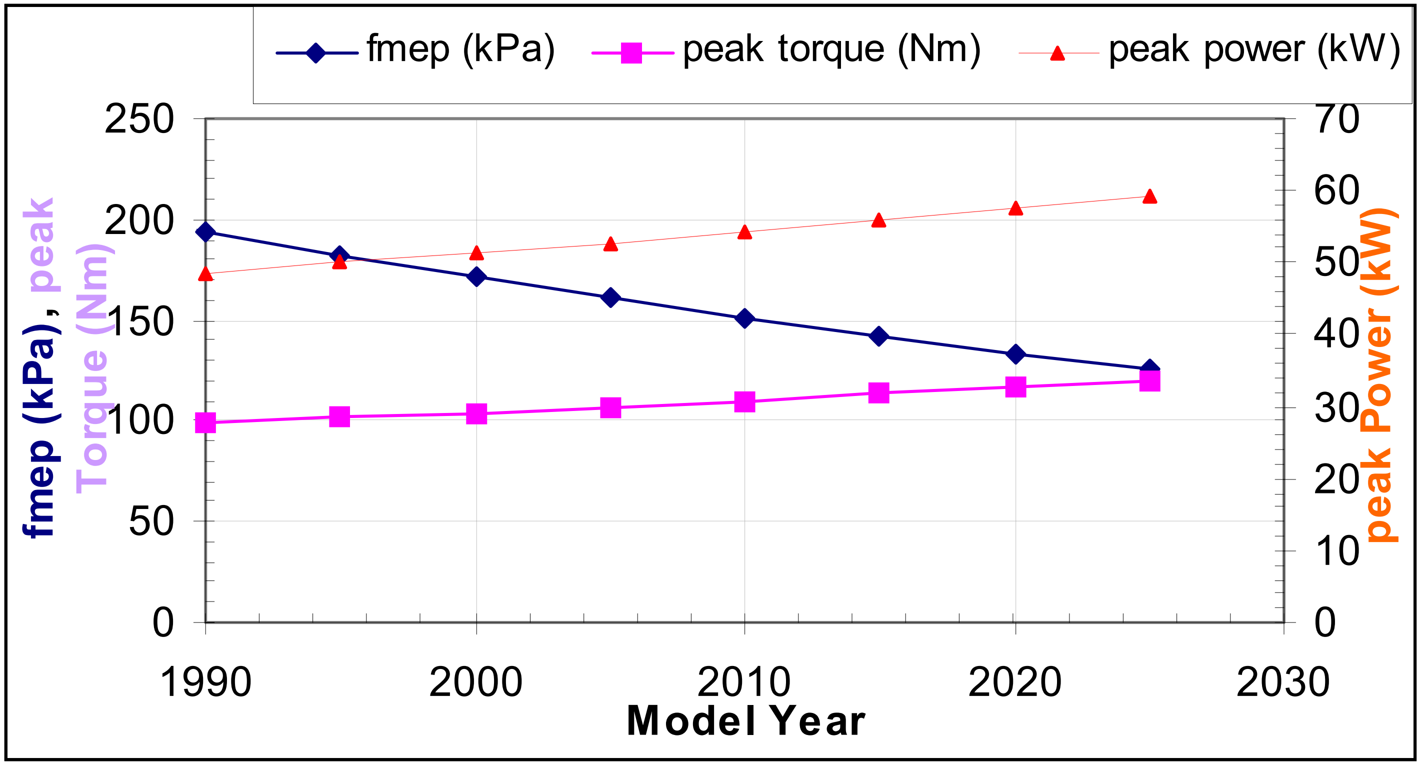


(Weiss, et al., 2000; Chon&Heywood, 2000)

Advanced Gasoline

- Efficiency remains constant (~0.4)
- Friction decreases
- Peak power trends increase
- Advanced engines such as Atkinson, lean burn, GDI can be modeled separately

Friction and peak power in advanced gasoline engines

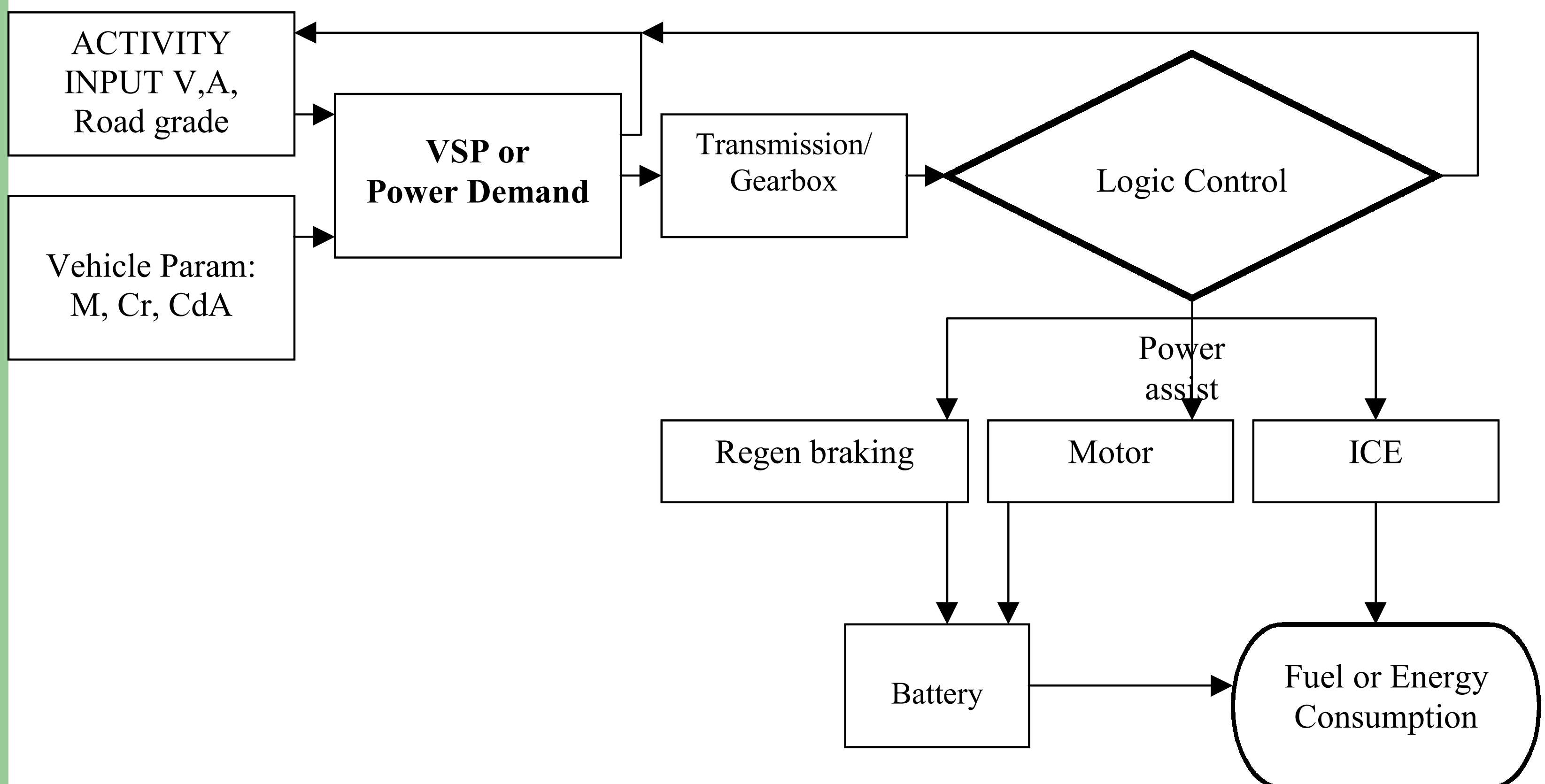


(Chon&Heywood, 2000; Nam&Sorab, 2004)

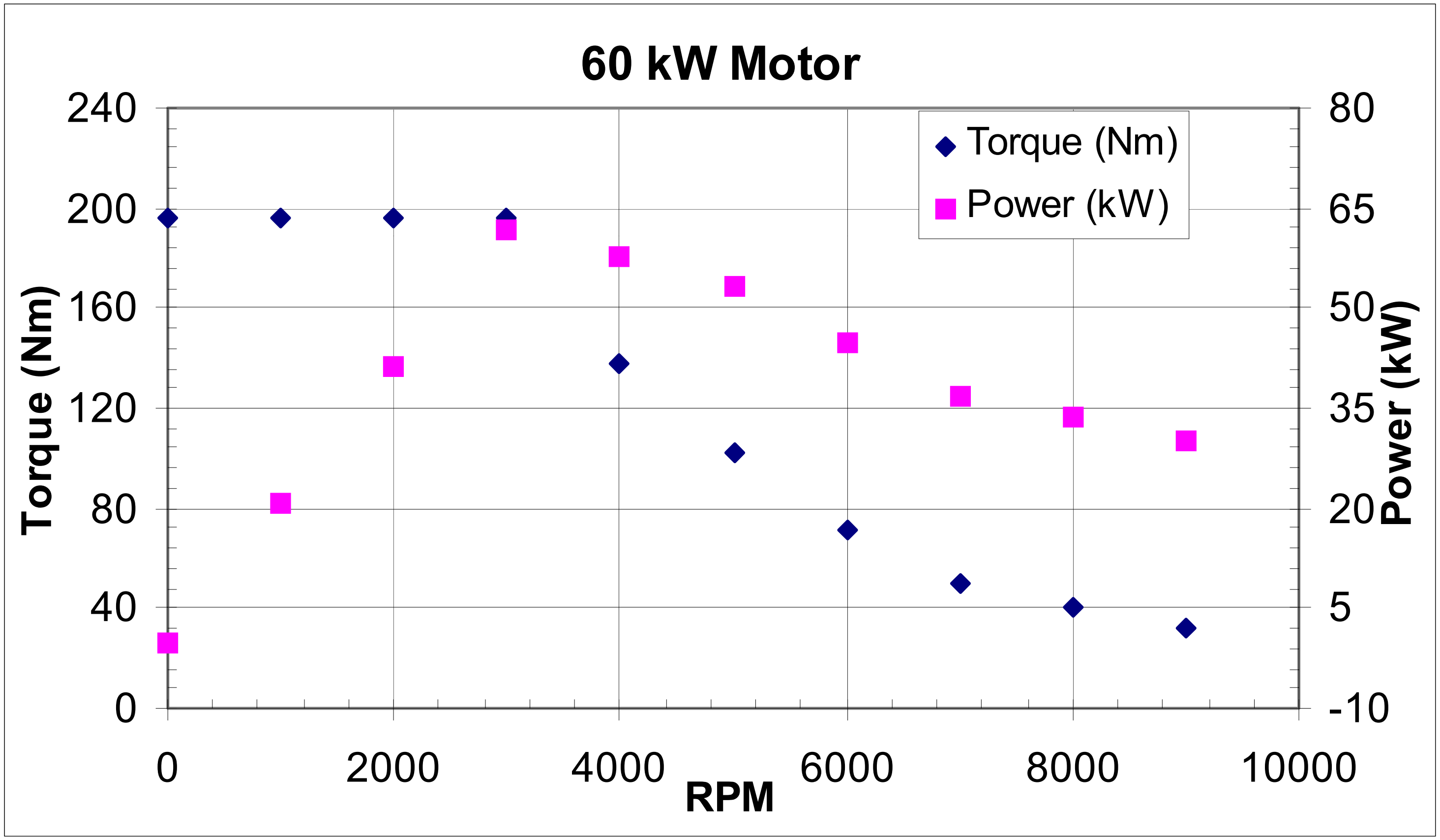
(Advanced) Diesel

- Efficiency higher (0.45 vs. 0.40)
- Different peak torque and power curves
- Lower engine speed (~3/4 gasoline)
- Aftertreatment fuel economy penalty (modeled later)
- Smaller engine, heavier mass

(Parallel) Hybrid vehicles



Motor peak torque & power (scaled)



Efficiency ~ 0.76

Weiss, et al. 2000

Mild vs. Full hybrid

- **Mild**
  - ratio of (peak) motor power to engine power ~ 0.15
  - Similar to Honda
- **Full**
  - ratio of motor power to engine power ~ 0.88
  - Similar to Toyota (& Ford Escape)

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

- **Discharge:**
  - If Power demand (Pd) < hybrid threshold (Pth) then run on battery (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**
- **May need to be modified in the future**

Battery and State of Charge

- Based on Ahr or kWhr rating
- Discharge and recharge according to power demand
- Discharge efficiency ~0.95
- recharge limited to 70% front wheel drive brake power distribution (Santini et al., 2003)
- Additional 15% loss on recharge

PERE control screen (EXCEL)

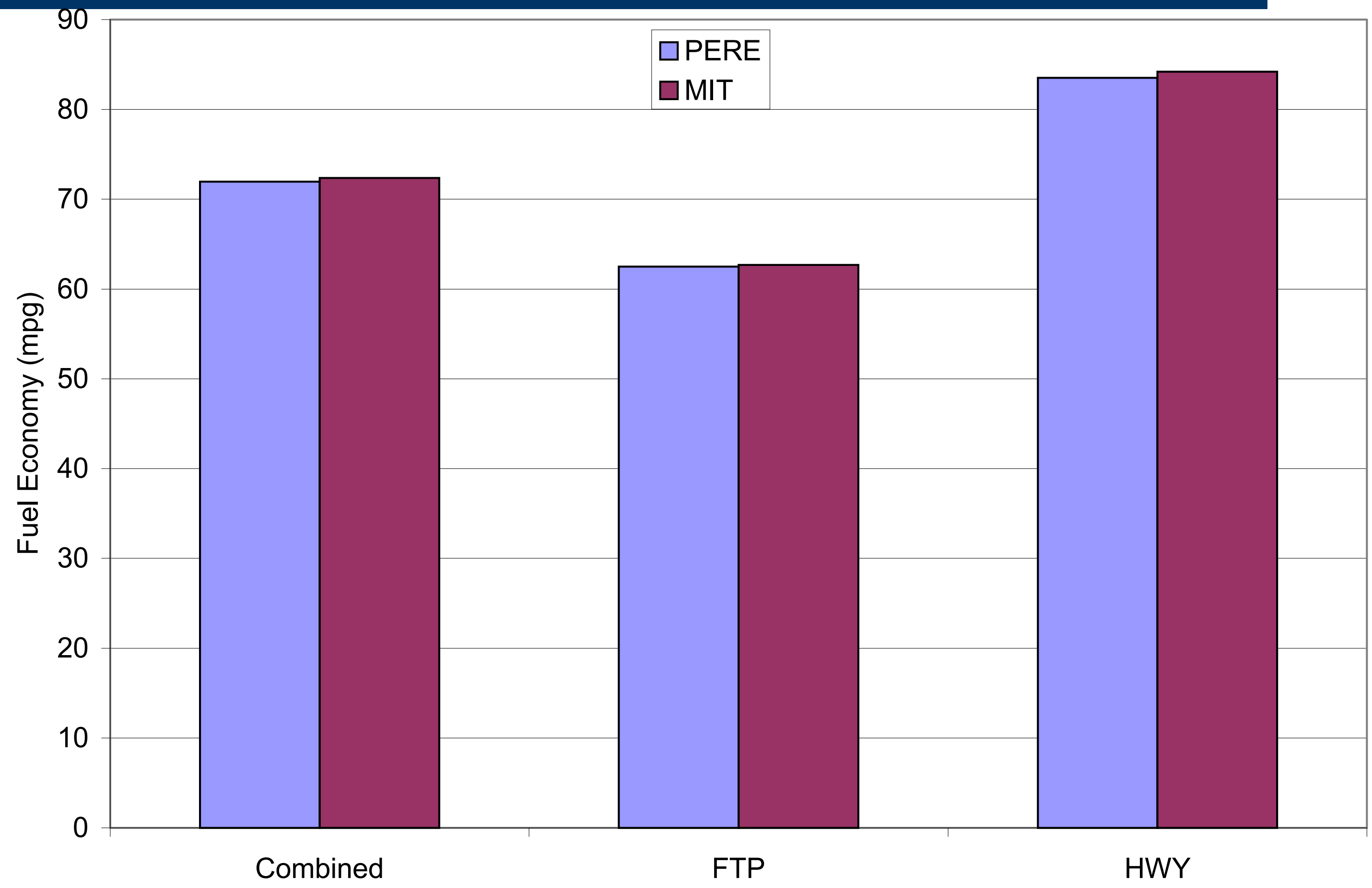
Parameters for Full Hybrid

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 (2000)
- Fuel consumption is accurate
- Battery state of charge follows the same trend, but is slightly different in magnitude
- Demonstrates that the modeling approaches are very similar

MIT hybrid (Weiss, et al. 2000)



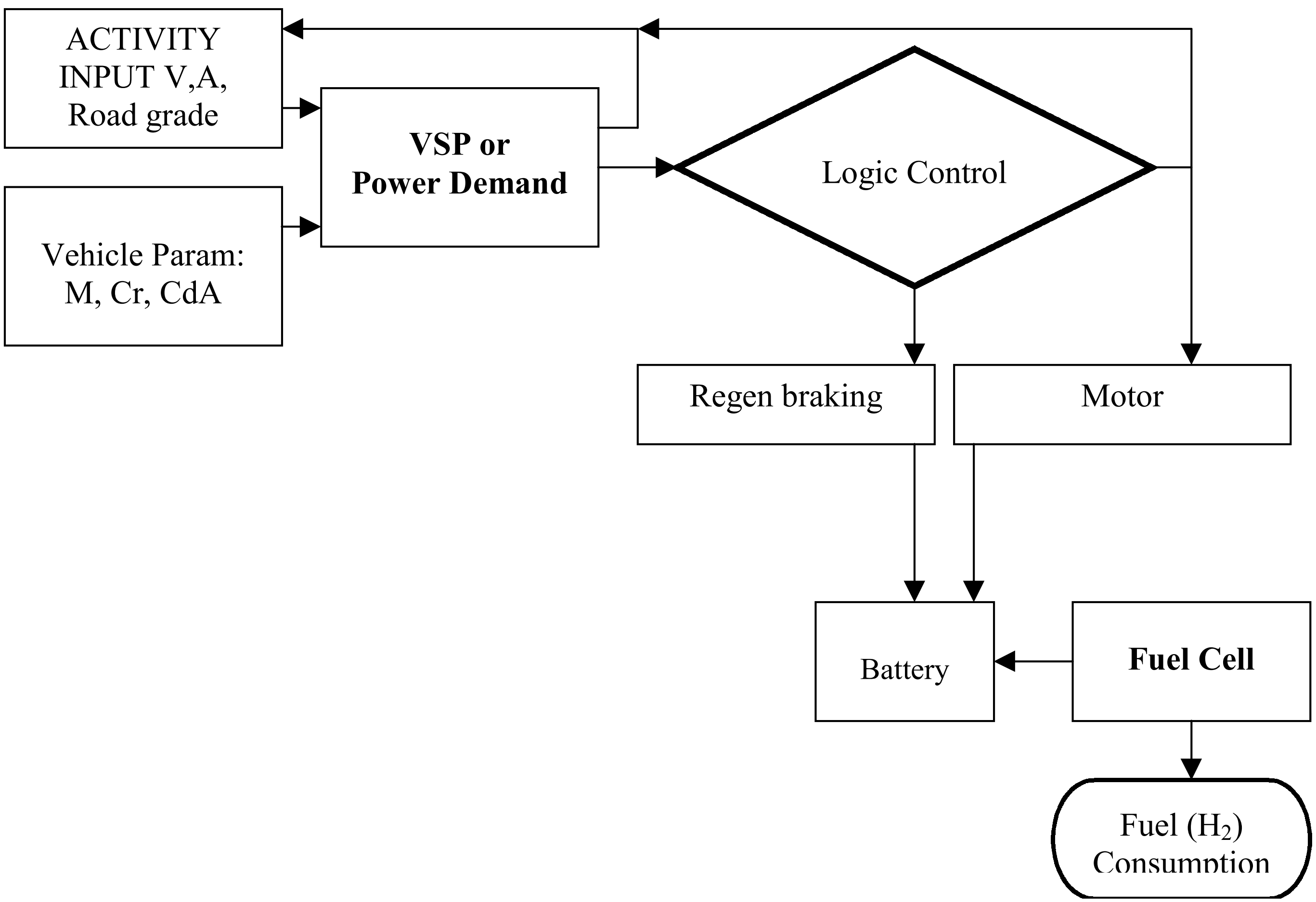
Validation

- 11 vehicles, 22 cycles (city/highway)
- Conventional gasoline vehicle
- Gas & diesel vehicle of same make/model
- Conventional vehicle vs. mild hybrid of same make/model
- Production Mild hybrid
- Production Full hybrid
- Mild SUV hybrid (prototype) vs. conventional of same make/model

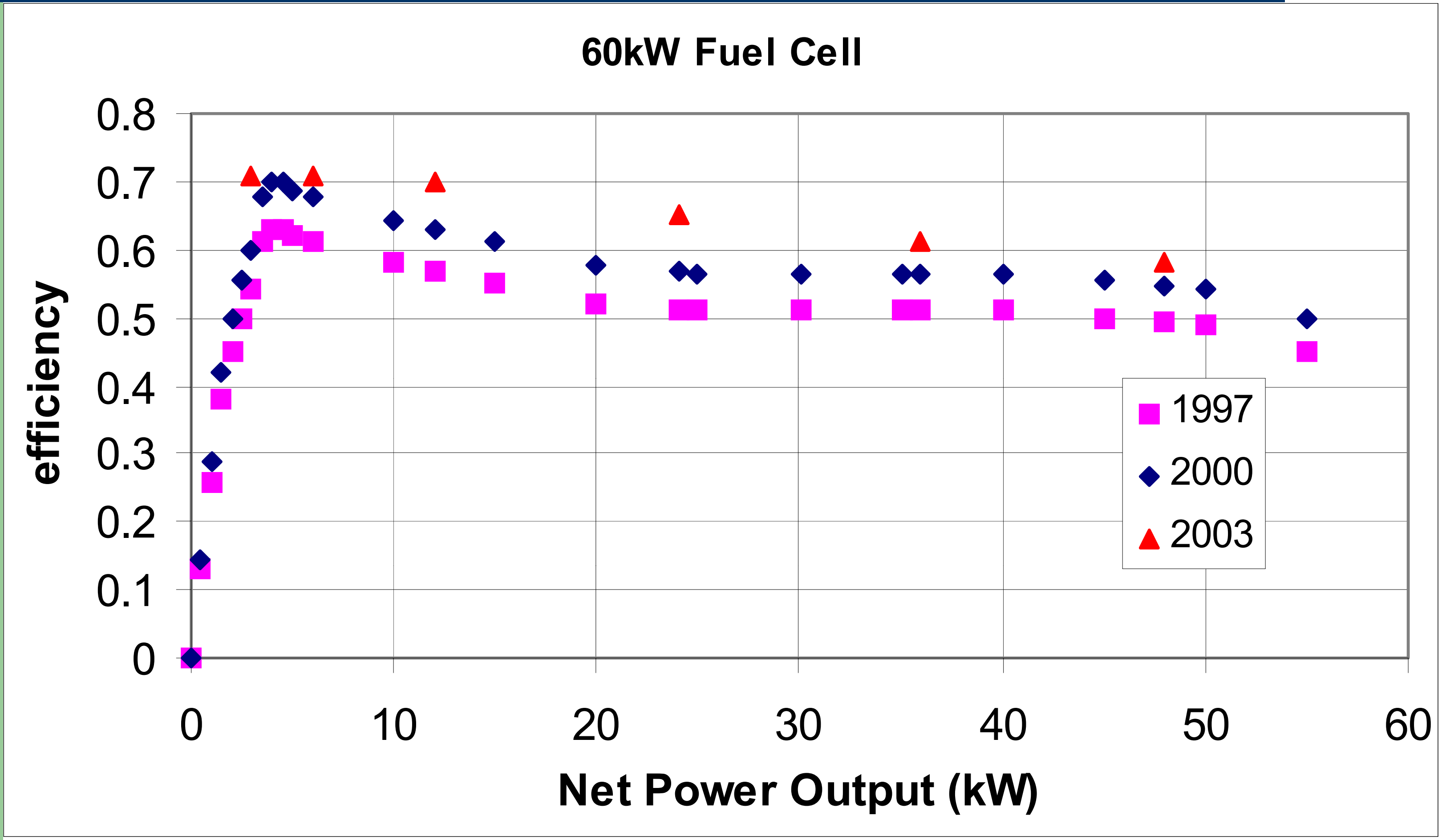
PERE Validation Results

- **PERE (fuel consumption) model is robust**
- **Most sensitive parameters are known (mass, engine displ, etc.)**
- **All fuel economy within 10% - *except* -**
- **Only 1 conventional vehicle on HWY and 1 production hybrid HWY have error >10%**
  (compared to unadjusted EPA fuel economy)

Fuel Cell Hybrid



Fuel Cell System Efficiency
(Weiss, et al. 2000, 2003)



Fuel Cell Hybrid

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

Conclusions

- **PERE based on engine combined with hybrid (motor and fuel cell) model**
- **PERE model validated for:**
  - conventional gasoline & diesel vehicles
  - production hybrids (mild and full)
- **PERE fuel economy model robust**
- **Current work: Pilot Study: PTW Projection for a common passenger car out to 2030**
- **Future study: Fuel Cell model, Heavy duty**