MEDIUM AND HEAVY DUTY DIESEL VEHICLE MODELING USING A FUEL CONSUMPTION METHODOLOGY

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Abstract

Recent efforts of the EPA MOVES emission modeling team include the development of a fuel consumption model, Physical Emission Rate Estimator (PERE), which allows for inclusion of vehicle tractive power together with vehicle power-train parameters, such as engine friction, engine efficiency, and engine speed. Analysis of in-use data for city buses, heavy duty diesel tractor-trailer vehicles (M.Barth, G.Scora, and T.Younglove, "A Modal Emission Model for Heavy Duty Diesel Vehicles", submitted to Transportation Research Board, 2004), and dynamometer non-road diesel engines has enabled a determination of model parameters for a variety of engine types. Analysis of certification data is also included for light duty diesel modeling. Model parameters determined from this analysis and a comparison of the model results to CO_2 emissions and fuel consumption will be presented.

Overview

- Vehicles and Engines
- Test Cycles
- Road load coefficients
- Engine friction and efficiency
- Transmission modeling
- Fuel consumption and CO_2 emissions

Vehicle Summary

source	# of vehicles or engines	model year range	vehicle weight range	odometer range	rated torque@RPM	engine displacement	# of gears
-	-	-	pounds	kmiles	ft-lbs	liters	-
CE-CERT (in-use/ on road)	12	1997 to 2001	58,500 to 62,050	8 to 5,211	1350@1200 to 1750@1200	10.8 to 14.6	9 to 13
EPA AATA bus (in-use/ on road)	15	1995 to 1996	26,500	199 to 284	890@1200	8.5	6
EPA nonroad engines (dynamometer)	17	1988 to 1999	-	-	170@2200 to 2645@1400	0.2 to 34.5	-

Vehicle Test Cycles

- CE-CERT trucks : in use, about 20 on-road/highway and engineered trips from which we used the on-road/highway and the vehicle coast down from 55 mph[1]
- AATA buses : in use bus routes used by Ann Arbor Transit Authority[2]
- EPA non-road engines - engine dynamometer test at differing load points[3]

1- M. Barth, G.Scora, and T. Younglove, "A Modal Emission Model for Heavy Duty Diesel Vehicles", Transportation Research Board, 2004

2- C. Ensfield, "On-Road Emissions of 18 Tier 1 Passenger Cars and 17 Diesel Powered Public Transport Buses", Sensors, Inc., 2002

3- S.G. Fritz and M.E.Starr, "Emission Factors for Compression Ignition Nonroad Engines Operated on No. 2 Highway and Nonroad Diesel Fuel", Southwest Research Institute, 1998, and M.E.Starr, "Transient and Steady State Emissions Testing of Ten Different Nonroad Diesel Engines Using Four Fuels", Southwest Research Institute, 2003

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Fuel Rate Equation

$$FR = \frac{(N \bullet V / 2000)}{LHV \bullet \eta_i} \bullet (fmep + bmep)$$

$$FR = \frac{1}{LHV} \bullet \left(\frac{k \bullet N \bullet V}{2000} + P / \eta_i \right), \quad k = \frac{1}{\eta_i} fmep$$

FR is the fuel mass flow rate
N is the engine speed
V is the engine displacement
LHV is the lower heating value of the fuel
fmep is the friction mean effective pressure
bmep is the brake mean effective pressure
η_i is the engine indicated efficiency
k is the engine friction

Tractive and Accessory Power

$$P = \frac{P_{trac}}{\eta_t} + P_{acc}$$

$$P_{trac} = Mg\left(v\mu_0^{tireroll} + v^2\mu_1^{tireroll}\right) + \left(Mg\,\mu_2^{tireroll} + AC_{drag}\,\rho_{air}\right)v^3 + Mv\left(a + g\sin\theta\right)$$

$\mu_0^{tireroll}$, $\mu_1^{tireroll}$, and $\mu_2^{tireroll}$ are the 0th, 1rst and 2nd order in speed coefficients of tire rolling friction

C_{drag} is the vehicle's coefficient of aerodynamic drag

ρ_{air} is the density of air

A is the vehicle's cross sectional area

M is the vehicle mass

v is the vehicle speed

a is the acceleration

g is the acceleration due to gravity

$sin\theta$ is the road grade

P_{acc} is the power used by accessories

η_t is the transmission efficiency

Road Load Coefficients

- Most complete data set in the literature : V.A. Petrushov, "Coast Down Method in Time-Distance Variables", SAE 970408
- CE-CERT truck data included coast downs from about 55 mph from which road load coefficients were extracted and then compared to the Petrushov results

Road Load Coefficients for Heavy Duty Trucks and Buses				
	8500 to 14000 lbs (3.855 to 6.350 tonne)	14000 to 33000 lbs (6.350 to 14.968 tonne)	>33000 lbs (>14.968 tonne)	Buses
A (kW*s/m)	$\frac{0.0996 \bullet M}{2204.6}$	$\frac{0.0875 \bullet M}{2204.6}$	$\frac{0.0661 \bullet M}{2204.6}$	$\frac{0.0643 \bullet M}{2204.6}$
B ($kW*s^2/m^2$)	0	0	0	0
C ($kW*s^3/m^3$)	$1.47 + \frac{5.22 \times 10^{-5} \bullet M}{2204.6}$	$1.93 + \frac{5.90 \times 10^{-5} \bullet M}{2204.6}$	$2.89 + \frac{4.21 \times 10^{-5} \bullet M}{2204.6}$	$3.22 + \frac{5.06 \times 10^{-5} \bullet M}{2204.6}$

Road load parameters developed from V.A.Petrushov. (Note: B’s from the CE-CERT coast downs were typically < 0 and, although the frontal area of the trucks in the study were relatively smaller than the CE-CERT trucks the aerodynamic drag terms were similar and within statistical and measurement error.)

Engine Friction and Efficiency

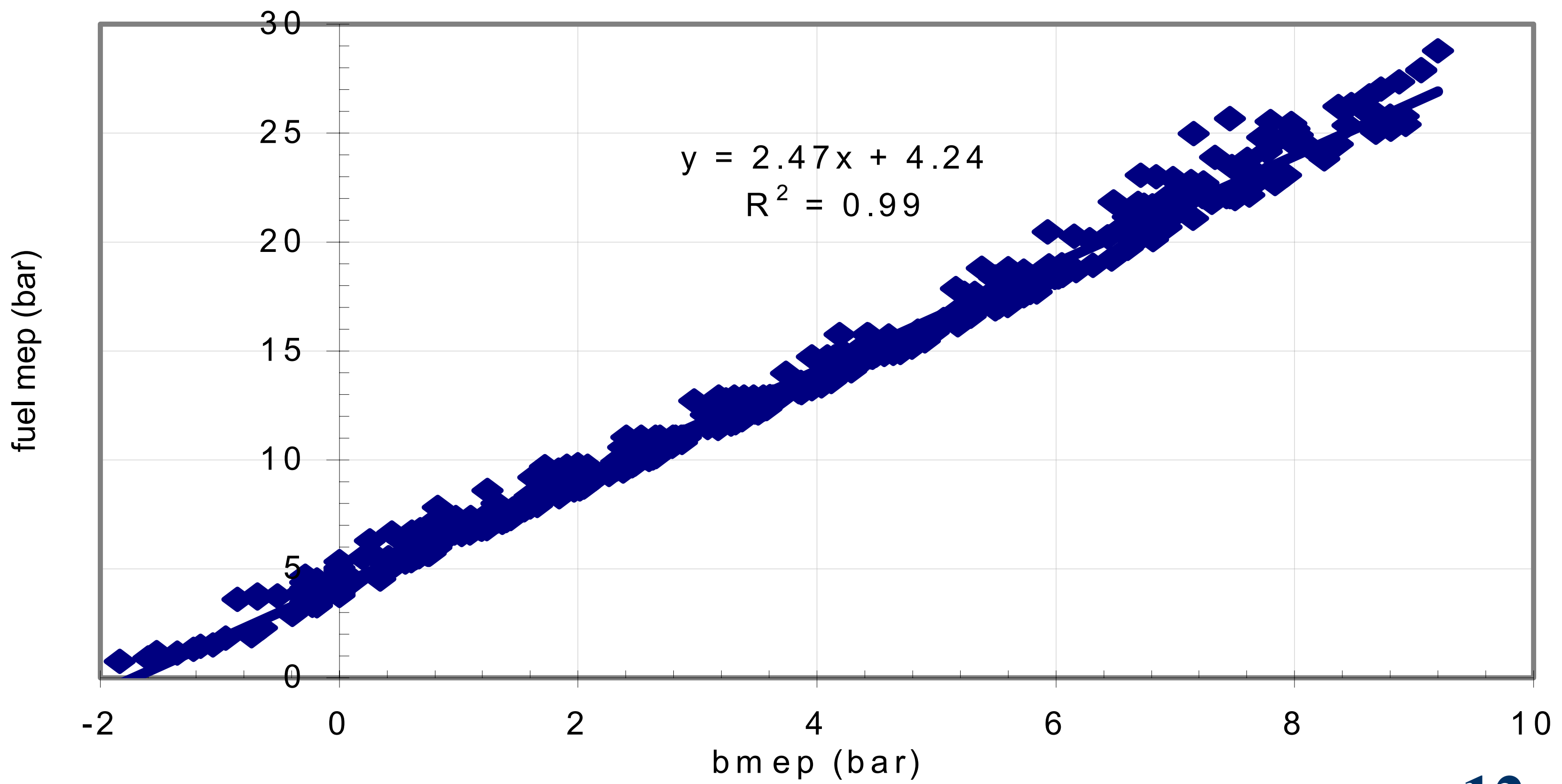
- Willans curve methodology as used by Ross, An, Nam, Wu, etc. i.e., engine friction amd efficiency are determined from measurements of fuel consumption(fuel mep), engine load and engine maps (bmep)

- New approach: the measurements are from in-use fuel consumption and engine load rather than using an engine dynamometer

Willans Methodology : Fuel consumption from brake work

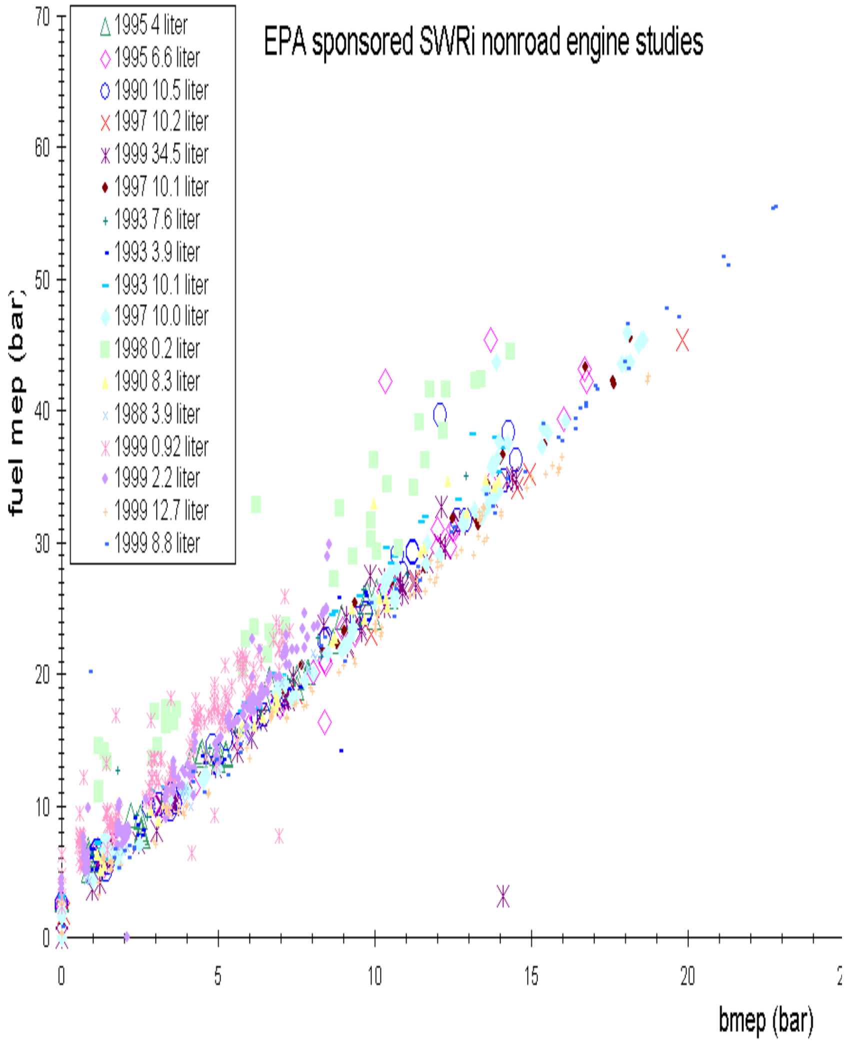
- imep = fmep + bmep
  - imep = indicated
  - fmep = friction
  - bmep = brake
- Fuel mep
  - imep = η*fuel mep
    - fuel mep = 2000*P_f/VN
    - P_f = FR*LHV [FR in g/s, LHV in kJ/g]
- fuel mep = k + bmep/η
  - same as fuel rate equation presented earlier

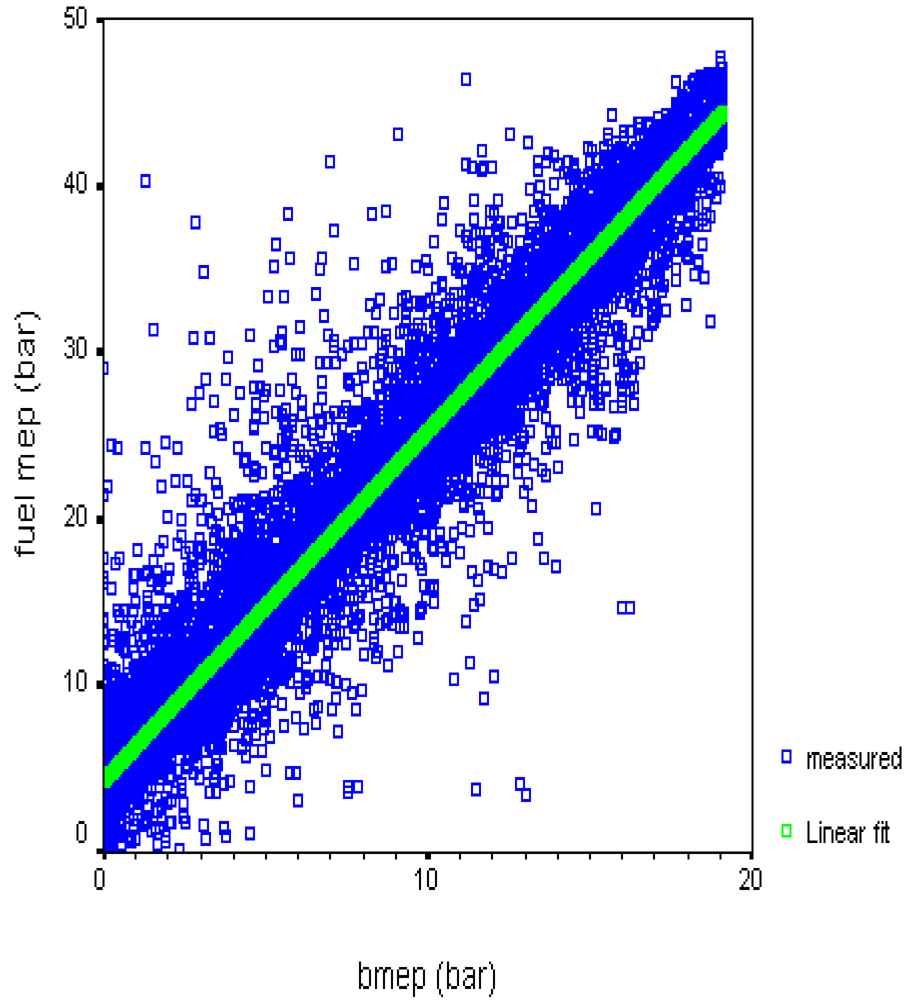
Willans methodology : Willans Line for 10 gasoline engines



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

Indicated Engine Efficiency from fuel mep - bmep relationship





nonroad dynamometer based measure-ments of fuel consumption and brake mean effective pressure

CE-CERT truck 1 on road based measurements of fuel consumption and brake mean effective pressure using engine maps and % load

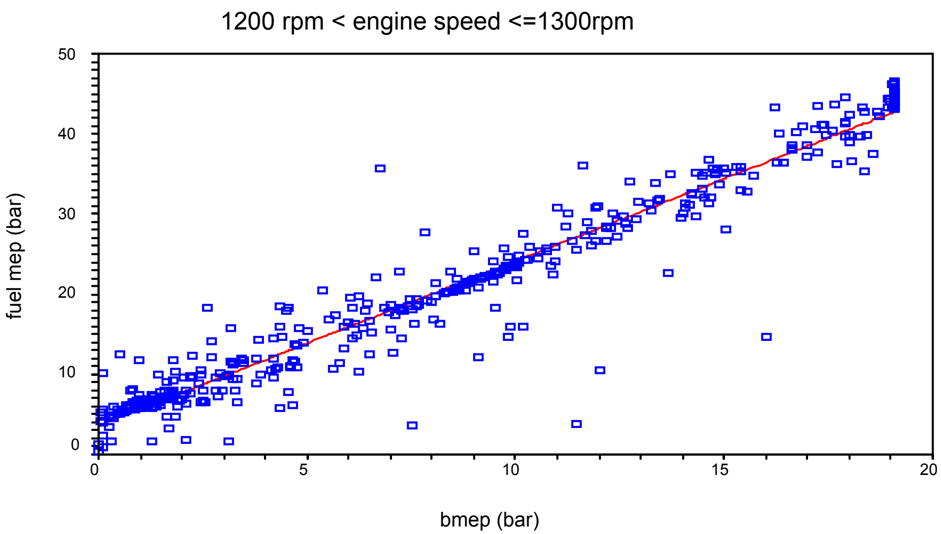
Indicated Engine Efficiencies

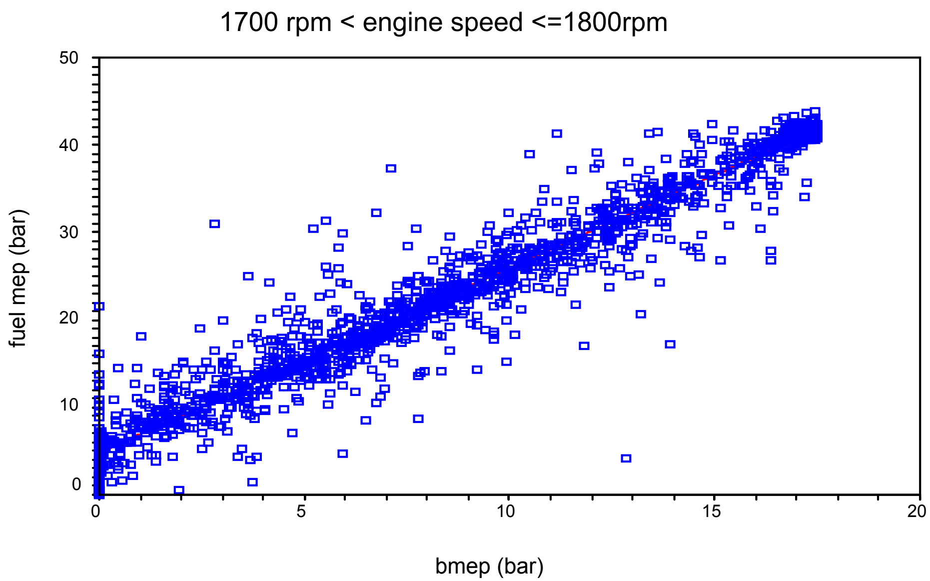
source	average efficiency	standard deviation between vehicles	engine displacement range	fuel delivery	# of vehicles or engines
-	-	-	(liters)	-	-
CE-CERT trucks	48%	2%*	10.8 to 14.6	Turbo- EUI	8
AATA buses	46%		8.5	TDI	15
Nonroad engines	43%	2%*	0.2 to 34.5	varied	17
Wu and Ross[1]	47% to 49%		1.08 to 2.46	TDI	4

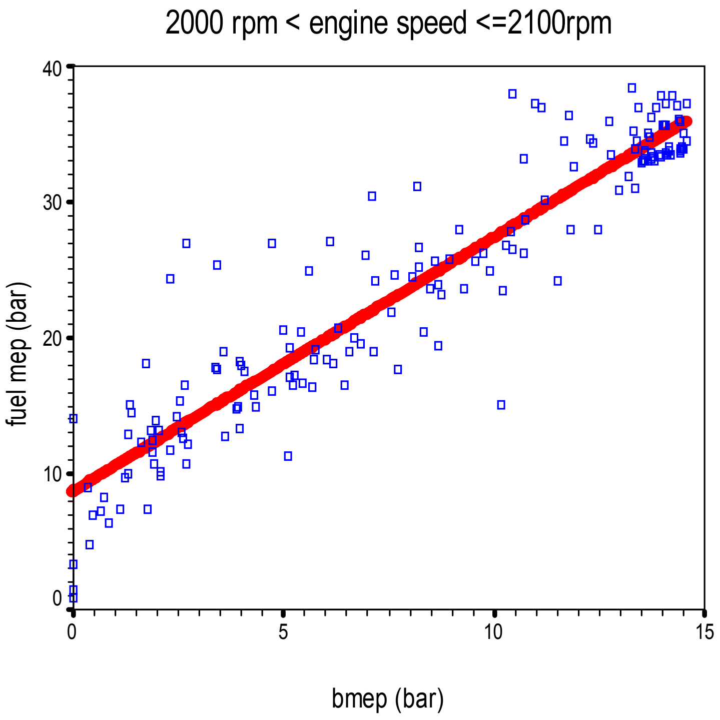
*R^2 of the fits are typically at or better than 0.9 and the standard errors in the slope parameter of the linear fits are about 20% of the fit value. So the total percent error in these engine efficiencies is about 25%.

[1]W.Wu and M.Ross, "Modeling of Direct Injection Diesel Engine Fuel Consumption", SAE 971142

Engine Friction Dependence on Engine Speed Determined from in-use Measurements of Fuel Consumption (fuel mep), Engine load (bmep), and Engine Maps (bmep)







Engine Friction Results for CE-CERT Trucks

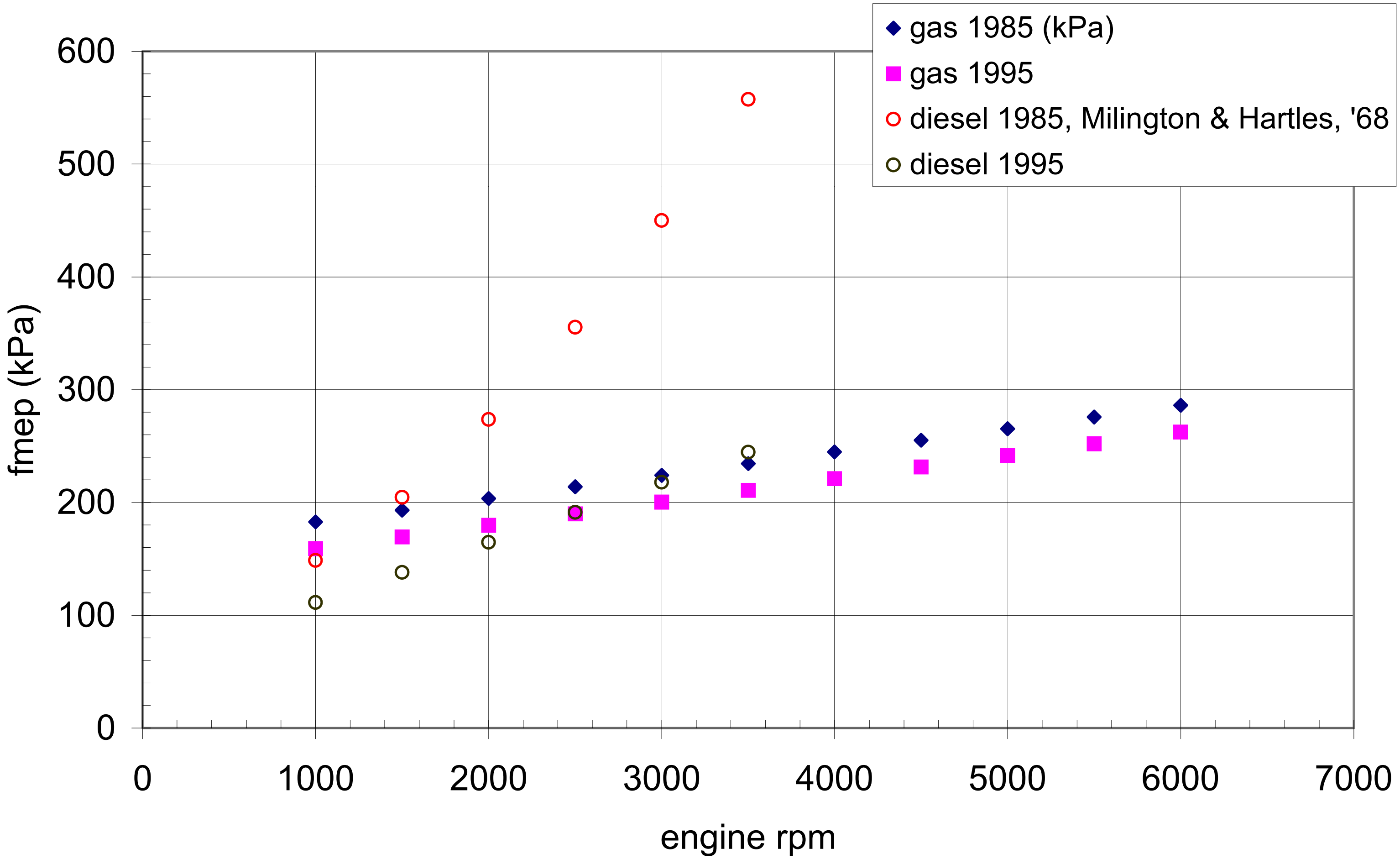
Acceleration range (mph/s)	k_0 (kPa)	k_1 (kPa / rps)	k_2 (kPa / (m/s))
(1) 0.001<accel<0.25	-9.32	12.6	-
(2) 0.001<accel<0.2	13.7	11.4	-
(3) 0.001<accel<0.15	96.1	7.85	-
(4) 0.001<accel<0.1	157	5.17	-
(5) 0.001<accel<0.07	109	6.98	-
Ave. of ranges 3, 4, and 5	121 (+/-32*)	6.66 (+/-1.37*)	0
Millington and Hartles**	179	6.1	0.83

These fits had large R^2 and large standard errors in fit parameters. So different ranges of accelerations were used to eliminate transients (ideally, a single-value of engine load for a single value of engine speed).

*Values are standard deviations in the averages. Actual uncertainties are larger.

**B.W.Millington and E.R.Hartles, "Frictional Losses in Diesel Engines", SAE 680590

Modeled Engine Friction vs RPM



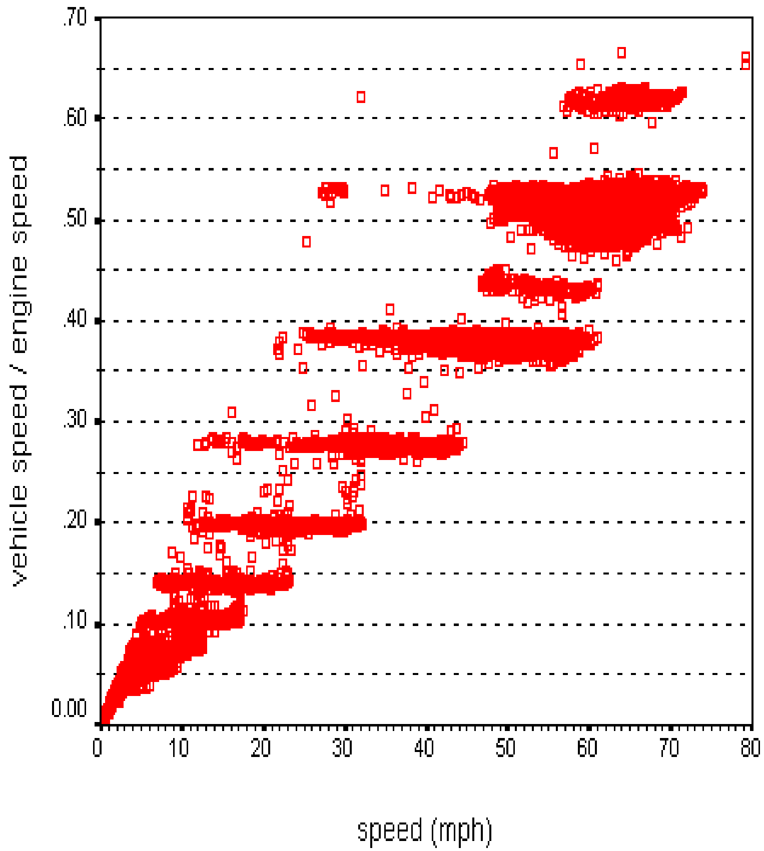
Engine Friction and Efficiency Friction Results

- Indicated Engine Efficiency for heavy duty diesel trucks is about 48% and AATA in-use buses about 46%
- Indicated Engine Efficiency for non-road engines is about 43%
- Engine Friction determined for CE-CERT trucks with uncertainties in the range of 30%, are comparable with previous work, and indicate decreases in engine friction

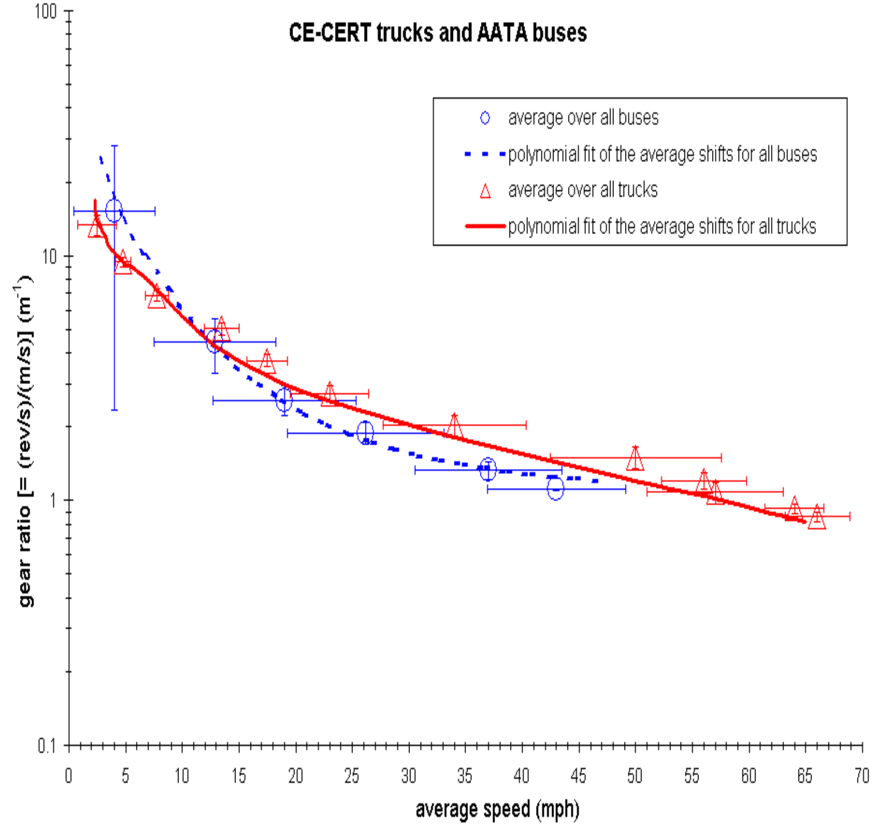
Truck and Bus Transmission Models

- **Empirically determined vehicle speed and engine speed relationships**
  - → average shift point speeds
  - → gear ratios
- **Vehicle downshifting (during acceleration) was determined with an engine maximum bmep value**

Truck and Bus Transmission Models



CE-CERT truck 1vehicle speed to engine speed ratios plotted against vehicles speed to determine average speeds for a given gear



Final engine speed - vehicle speed relationships for buses (red) and the heavy duty trucks (blue). The error bars are standard deviations determined from the distributions depicted in vehicle speed - engine speed ratio graph

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Truck and Bus Transmission Models - Downshifting

- Downshift whenever vehicle tractive power is greater than the maximum engine power/ torque at a given engine speed

- Used an average over 638 diesel engines ranging in size from 1.8 to 27 liters

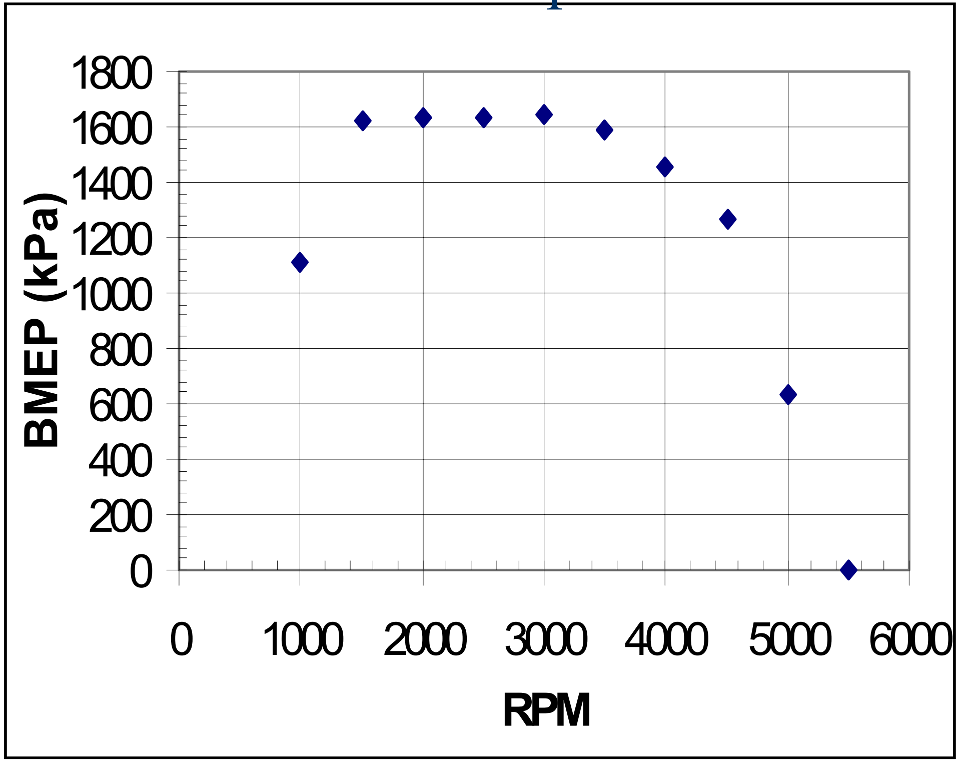
$$bmep_{\max} = \frac{2\pi n_R \tau_{\max}}{V_d}$$

$$\overline{bmep_{\max}} = 1648 \pm 440^{*}\ N \cdot m$$

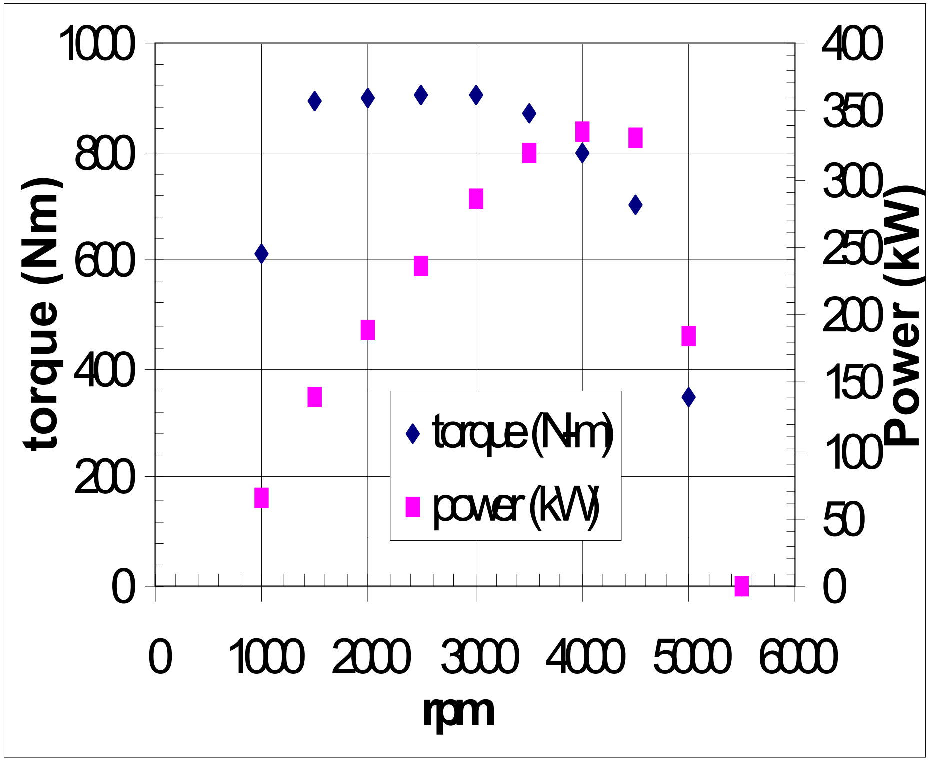
*standard deviation of the mean

Modeled Peak curves
(for downshifting and hybrid model)

Scalable bmep curve



7L diesel



Based on shape from Weiss et al, 2000)

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Validations with Measured Fuel Consumption and CO_2

vehicle/ trip	fuel	CO_2
	% difference between measured and calculated mass values	
AATA bus 1	9%	0%
AATA bus 2	-2%	1%
AATA bus 3	4%	5%
AATA bus 4	-5%	-5%
AATA bus 5	-6%	-4%
CE-CERT truck 1, Vistorsville	9%	8%
CE-CERT truck 1, Palm Springs	-1%	3%

Comparisons with Measured Fuel Consumption and CO_2

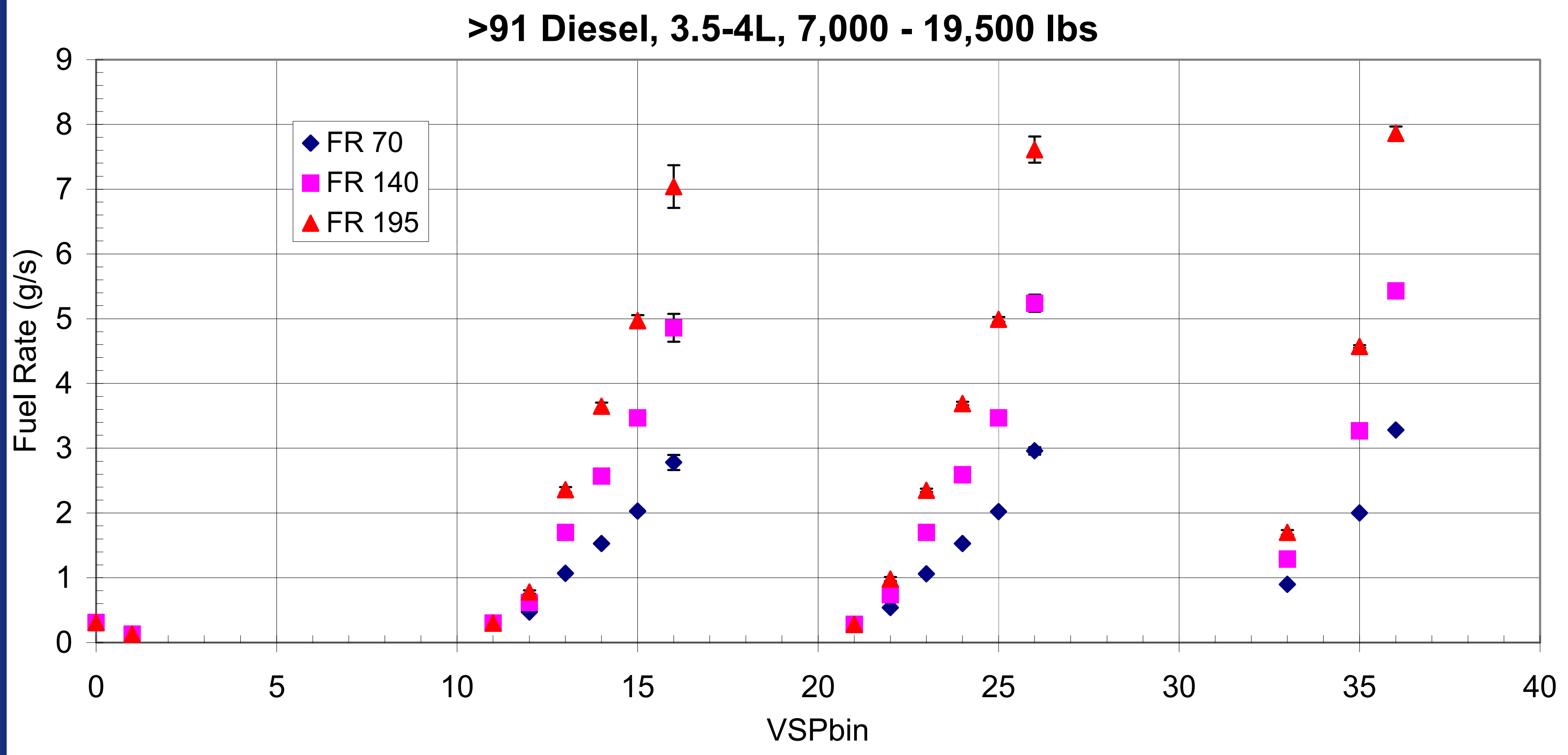
- Calculated fuel consumption for buses and trucks within 10% of measured values

- Calculated CO_2 for buses and trucks within 10% of measured values

- Validation for Vehicles outside of calibration set to be completed

- Model is can determine emissions from diesel vehicles with weights ranging from 7,000 lbs and with engine sizes ranging from 3 to 15 liters

Example of MOVES "hole-filling"



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Conclusions

- Determination of in-use engine friction and efficiency for 27 heavy duty diesel vehicles and diesel transit buses (measurement and statistical uncertainties of about 20%)
- Determined vehicle speed - engine speed relationship for bus and heavy duty vehicles
- Limited road load parameters for heavy duty vehicles, but current data is sufficient - improvements needed for vehicle size and first order in speed rolling resistance and rotational inertia
- Parameters used with PERE are within 10% of measured values of fuel consumption and CO_2 for individual vehicle trips
- Model will be used to fill data gaps in MOVES

Acknowledgements

- Ted Younglove, Matt Barth, and George Scora, CE-CERT, UC Riverside, Riverside, CA
- Kent Helmer, John Koupal, Megan Beardsley, Edward Glover, James Warila, NVFEL EPA, Ann Arbor, MI