Fuel Economy and CO_2: The Next Round

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But, What is Fuel Economy?

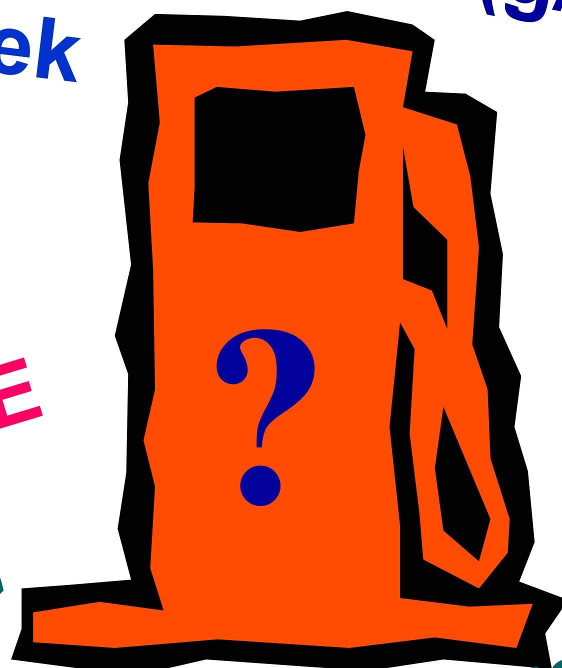
FE (mpg)

Fill-Ups Per Week

BSFC (g/kW-hr)

Label FE

Regulatory Cycles



CAFE

Driving Range

GE-FE

FE (km/l)

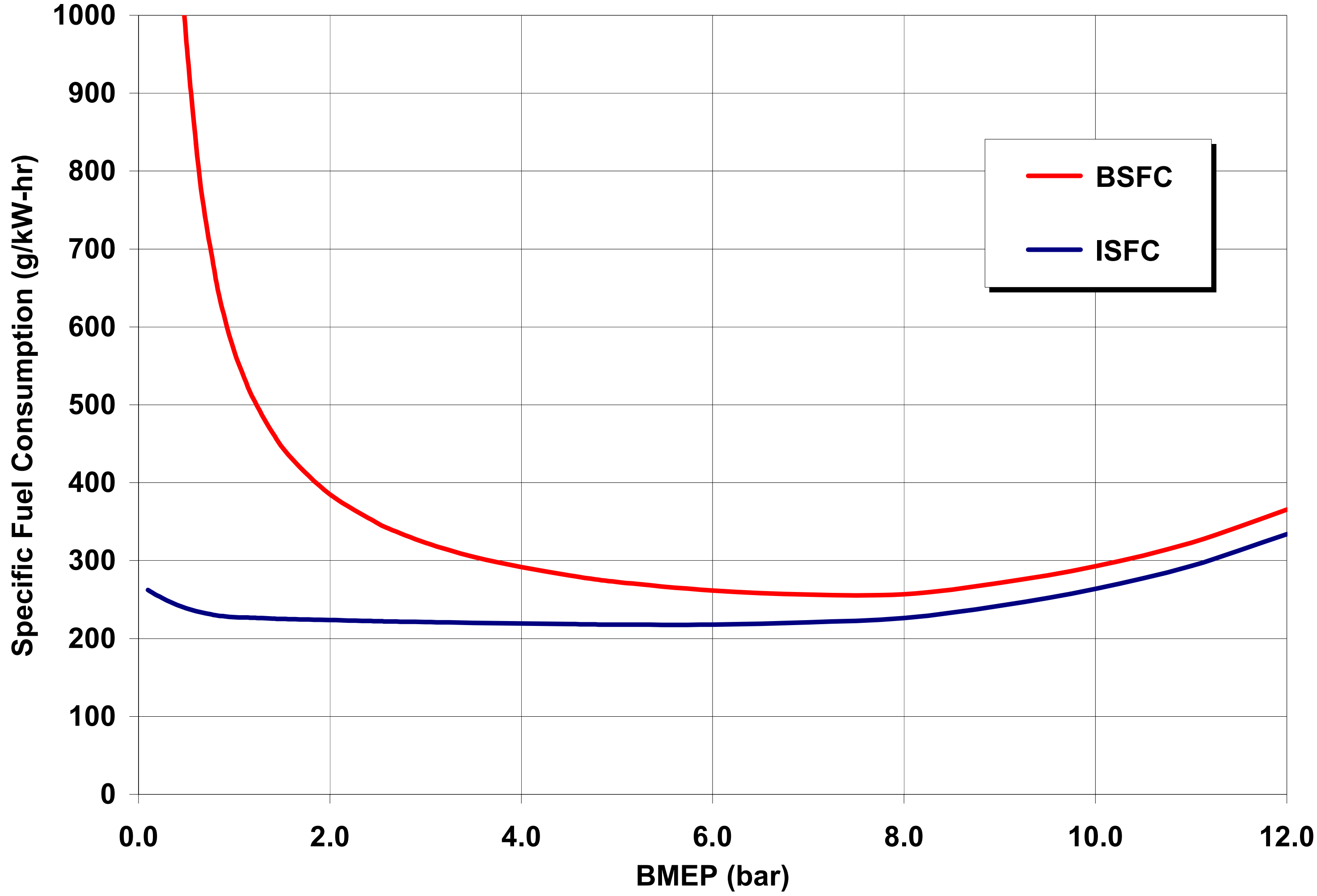
FC (l/100 km)

Highway FE

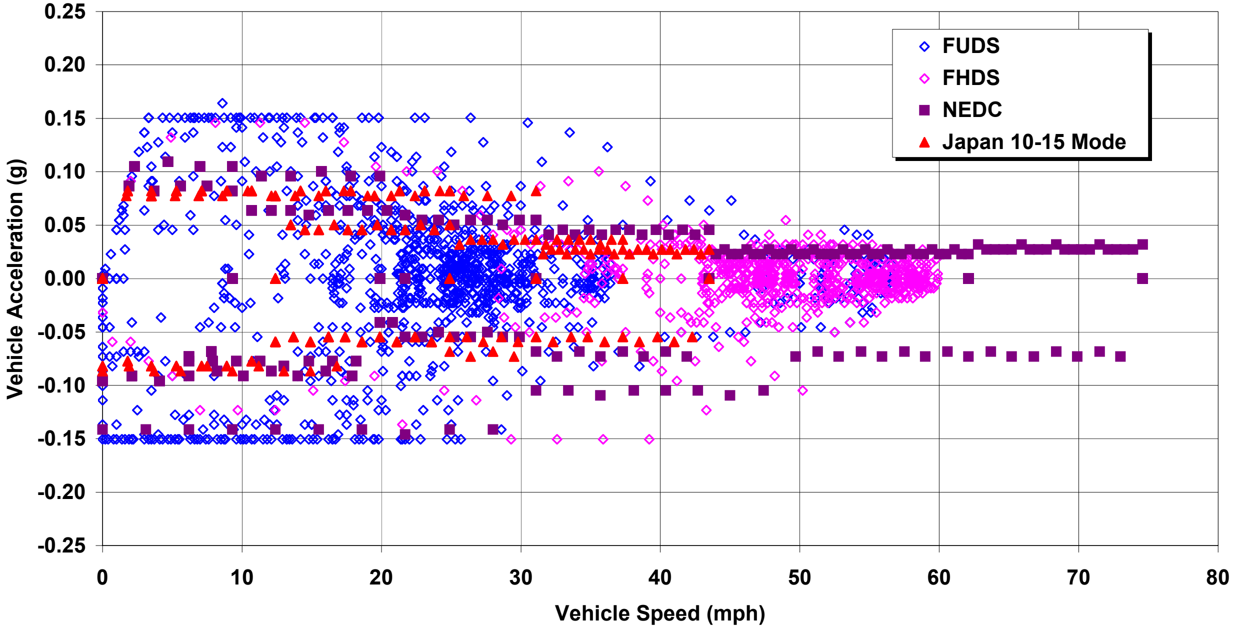
Fleet Average CO_2 (g/km)

Customer Driving

Specific Fuel Consumption



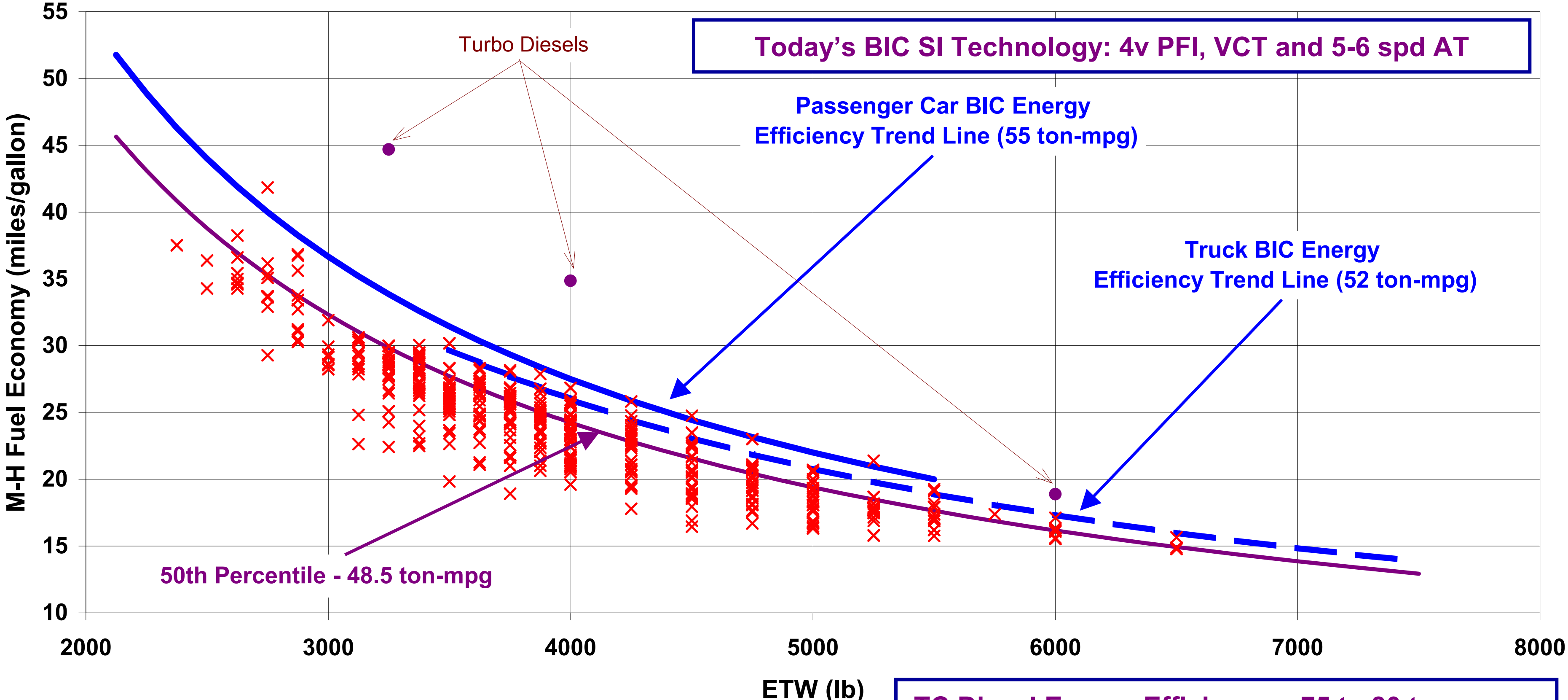
Regulatory Drive Cycles



		FUDS	FHDS	NEDC	Japan 10-15
Time	sec	1372	765	1180	660
Distance	miles	7.45	10.26	6.84	2.59
Max Accel	g	0.164	0.146	0.109	0.082
Max Speed	mph	56.7	59.9	74.6	43.5
Avg Speed	mph	19.5	48.2	20.9	14.1

Unadjusted FE and Efficiency

AT Vehicles: North American Fleet



TC Diesel Energy Efficiency – 75 to 80 ton-mpg

Hybrid Energy Efficiency – 80 to 100 ton-mpg

Relationships (1)

$$\text{M-H FE (mpg)} = (0.55/FE_{FUDS} + 0.45/FE_{FHDS})^{-1}$$

$$\text{LABEL FE} = (0.55/(0.9*FE_{FUDS}) + 0.45/(0.78*FE_{FHDS}))^{-1}$$

$$\eta_{Energy} = FE_{MH}\text{ (mpg)} * ETW$$

Label FE is an adjustment that attempts to consider the differences between regulatory cycle and customer driving for conventional SI vehicles

Relationships (2)

$$FE\ (mpg) \sim \rho_f\ (LHV)_f\ \eta\ /\ E_{Demanded}$$

where:

$$\eta = f\ \text{(Technology, Operating Conditions)}$$

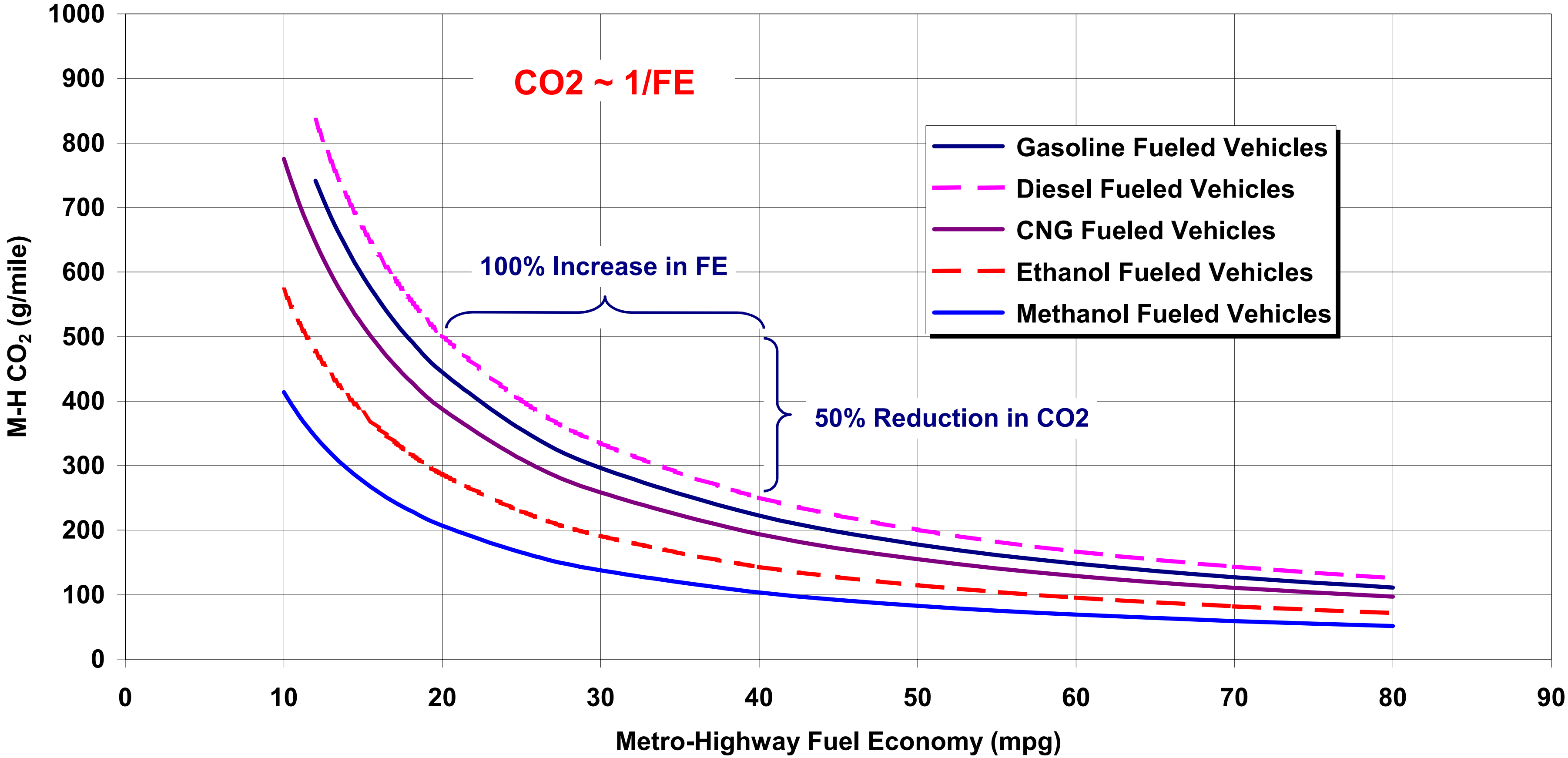
$$E_{demanded} = f\ \text{(Vehicle, Operating Conditions)}$$

$$GE\text{-}FE = FE_f\ (\rho_g/\rho_f)\ (LHV_g/LHV_f)$$

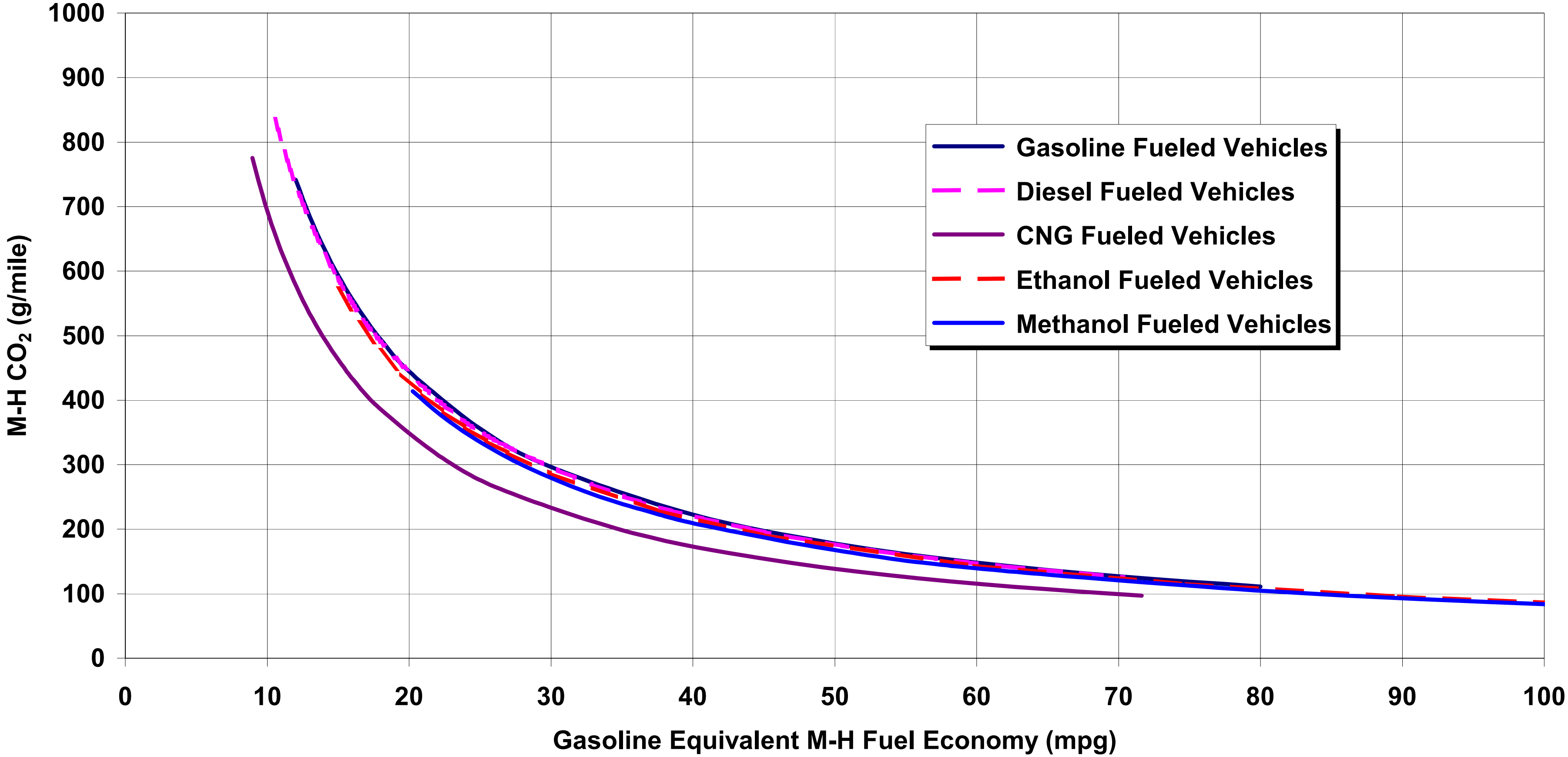
$$\text{Fuel Consumption} \sim 1\ /\ FE$$

$$CO_2 \sim (m_{CO2}/m_f)\ /\ FE$$

FE and CO_2


CO2 ~ 1/FE
100% Increase in FE
50% Reduction in CO2
Gasoline Fueled Vehicles
Diesel Fueled Vehicles
CNG Fueled Vehicles
Ethanol Fueled Vehicles
Methanol Fueled Vehicles
M-H CO2 (g/mile)
Metro-Highway Fuel Economy (mpg)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90

GE-FE and CO_2



M-H CO2 (g/mile)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
100
Gasoline Equivalent M-H Fuel Economy (mpg)
Gasoline Fueled Vehicles
Diesel Fueled Vehicles
CNG Fueled Vehicles
Ethanol Fueled Vehicles
Methanol Fueled Vehicles

Customer Driving

Higher rates of acceleration and deceleration (>0.2 G)

Higher vehicle speeds

Longer idling periods

Longer and shorter trips

Colder starts

Hotter and colder, more humid ambient conditions

Higher climate control loads (heater and AC)

Higher electrical (60 A vs 22A) and accessory loads

Consequently, technology benefits vary depending on customer driving habits

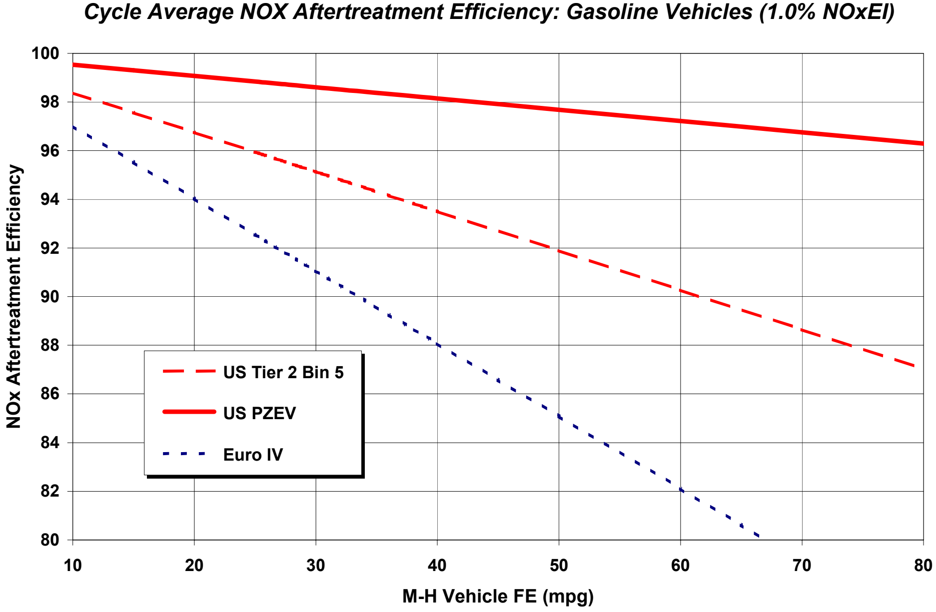
What Does Customer Driving Mean?

Customers could be disappointed if regulatory driving cycle FE benefits for new technologies are not realized in their vehicles when they use them

Customer FE improvements can be obtained from technologies that have little, or no, benefit on the regulatory drive cycles, such as:

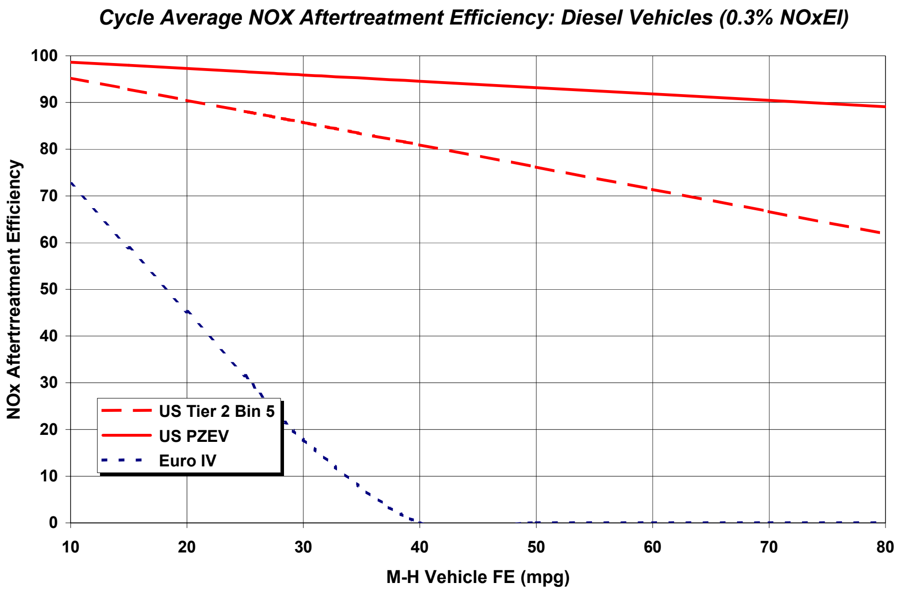
- Low ε glazing
- Cabin insulation
- Efficient A/C
- Lower electrical loads

Tailpipe Emissions Constraint



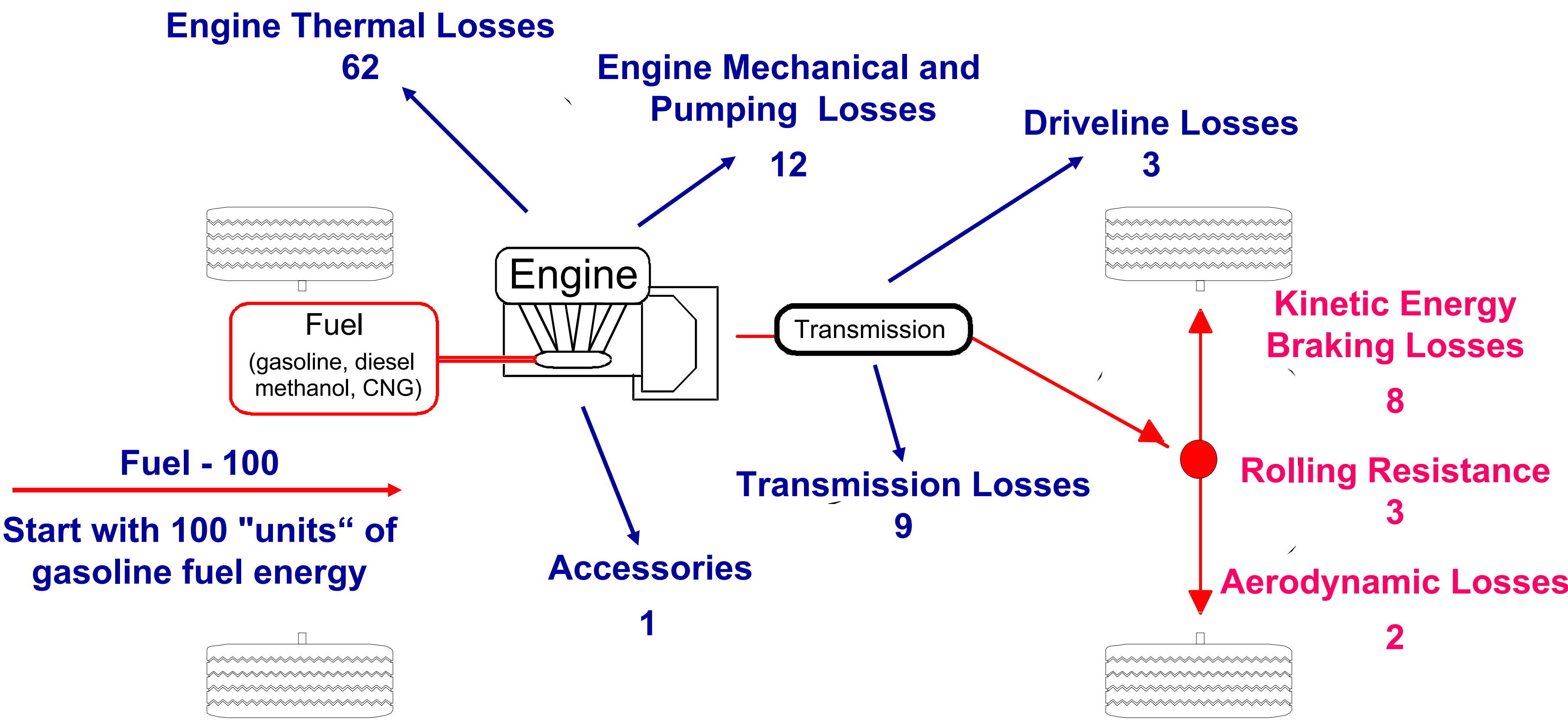
Emission compliance with lean SI engine calibrations is becoming more challenging

European diesel tailpipe NOx emission standards are more lenient than those in the US

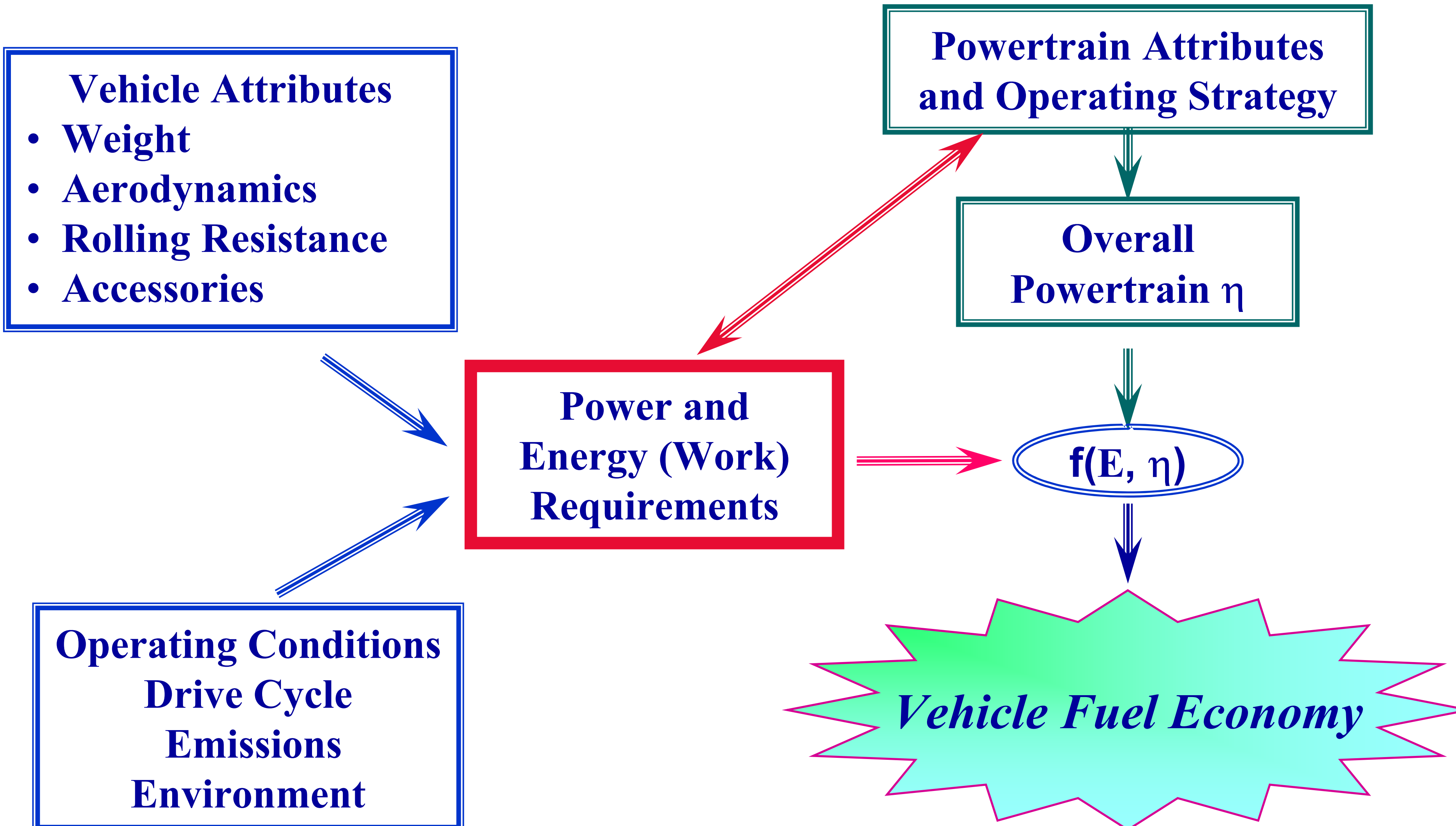


How Do We Get FE?

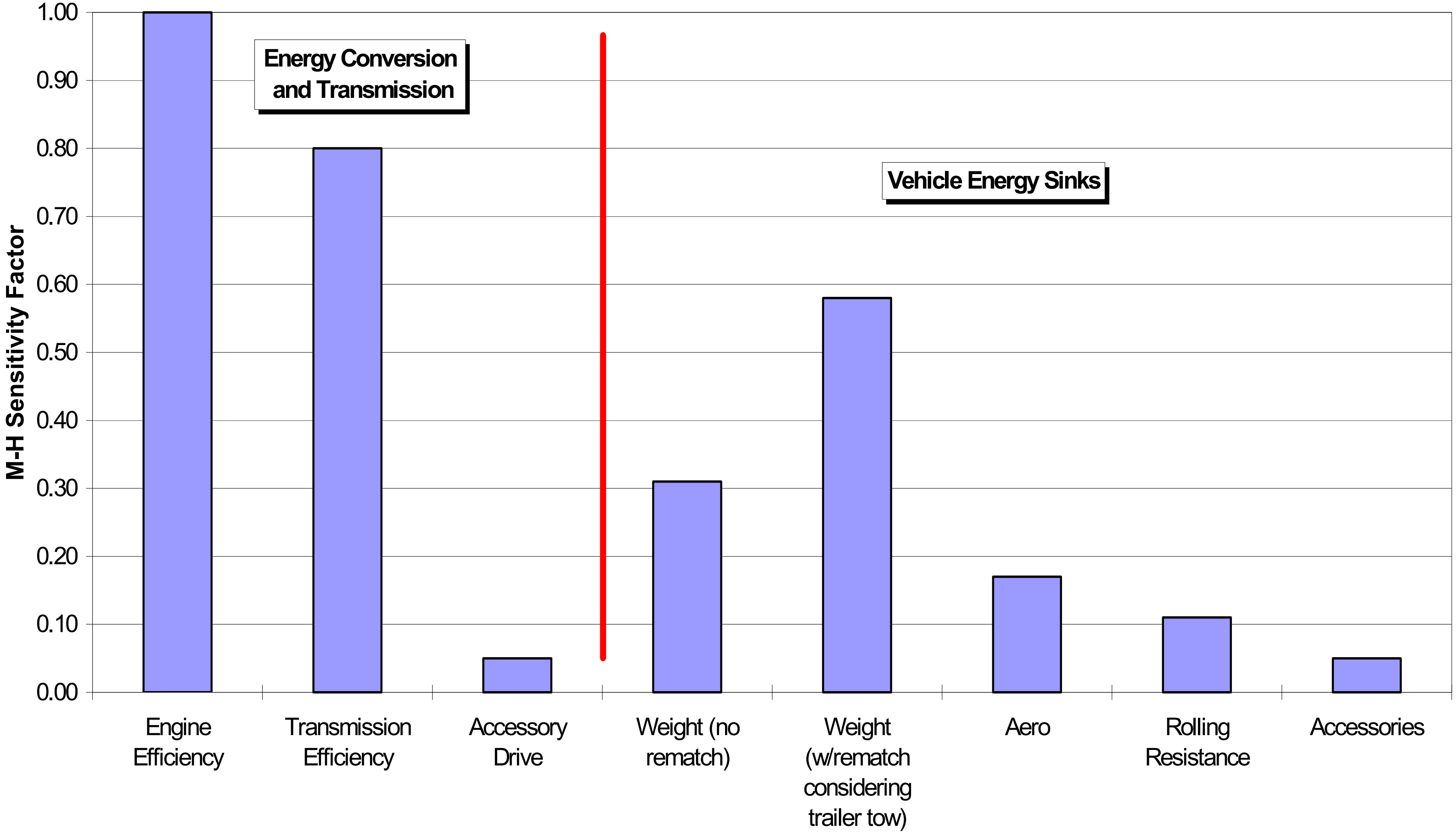
Typical Energy Utilization in an Spark Ignition Engine AT Vehicle



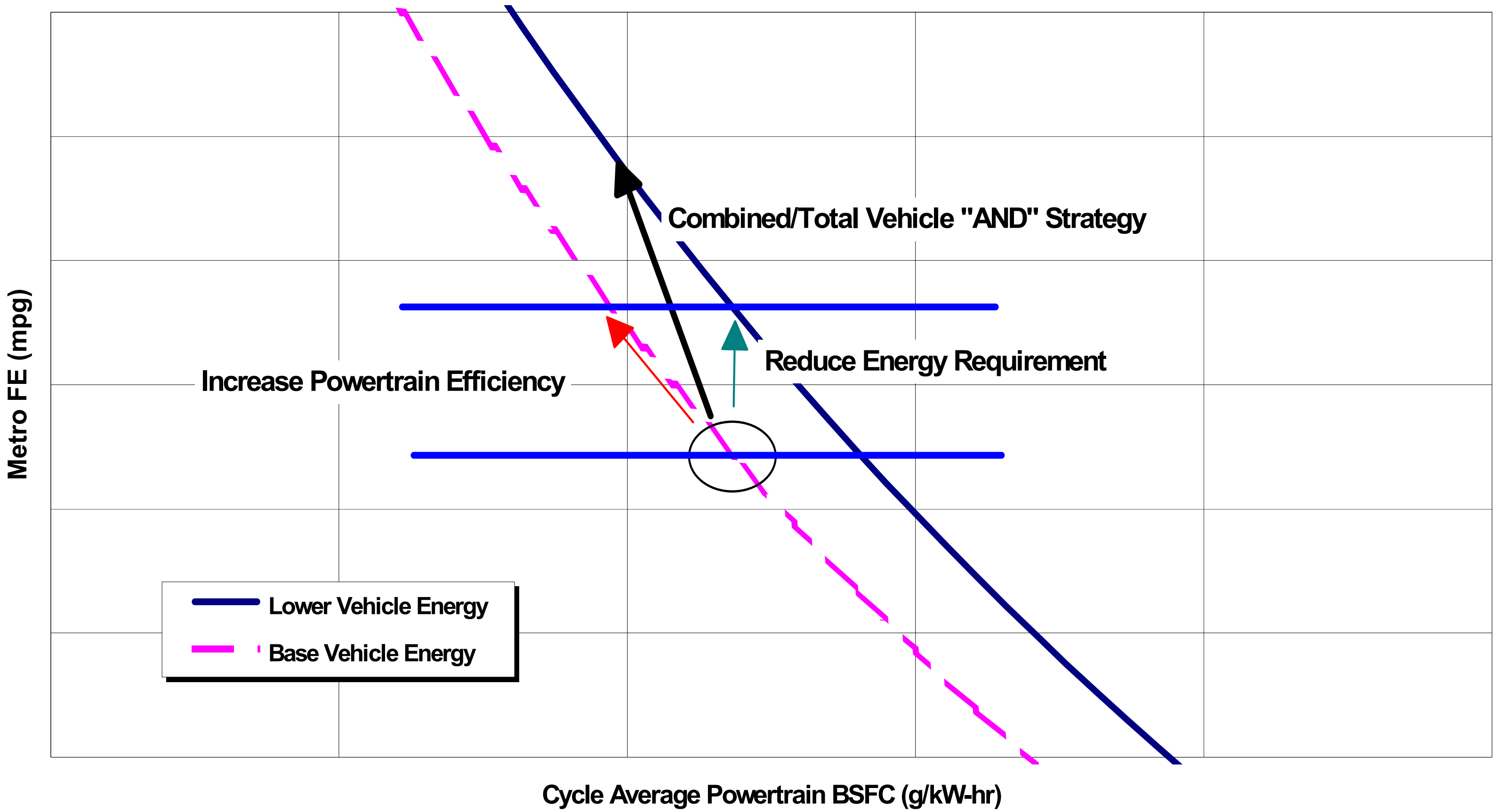
Factors Affecting Vehicle FE



Sensitivity of M-H Fuel Economy to Vehicle Parameters (SUV)



Strategies for Improving FE



Optimally: Efficiency must increase and energy demand must decrease

Powertrain Attributes - Engine

Engine Attributes

Parasitic Losses

Mechanical Friction
- Rubbing Losses
- Accessories

Pumping Losses
- Throttling

Thermal Efficiency

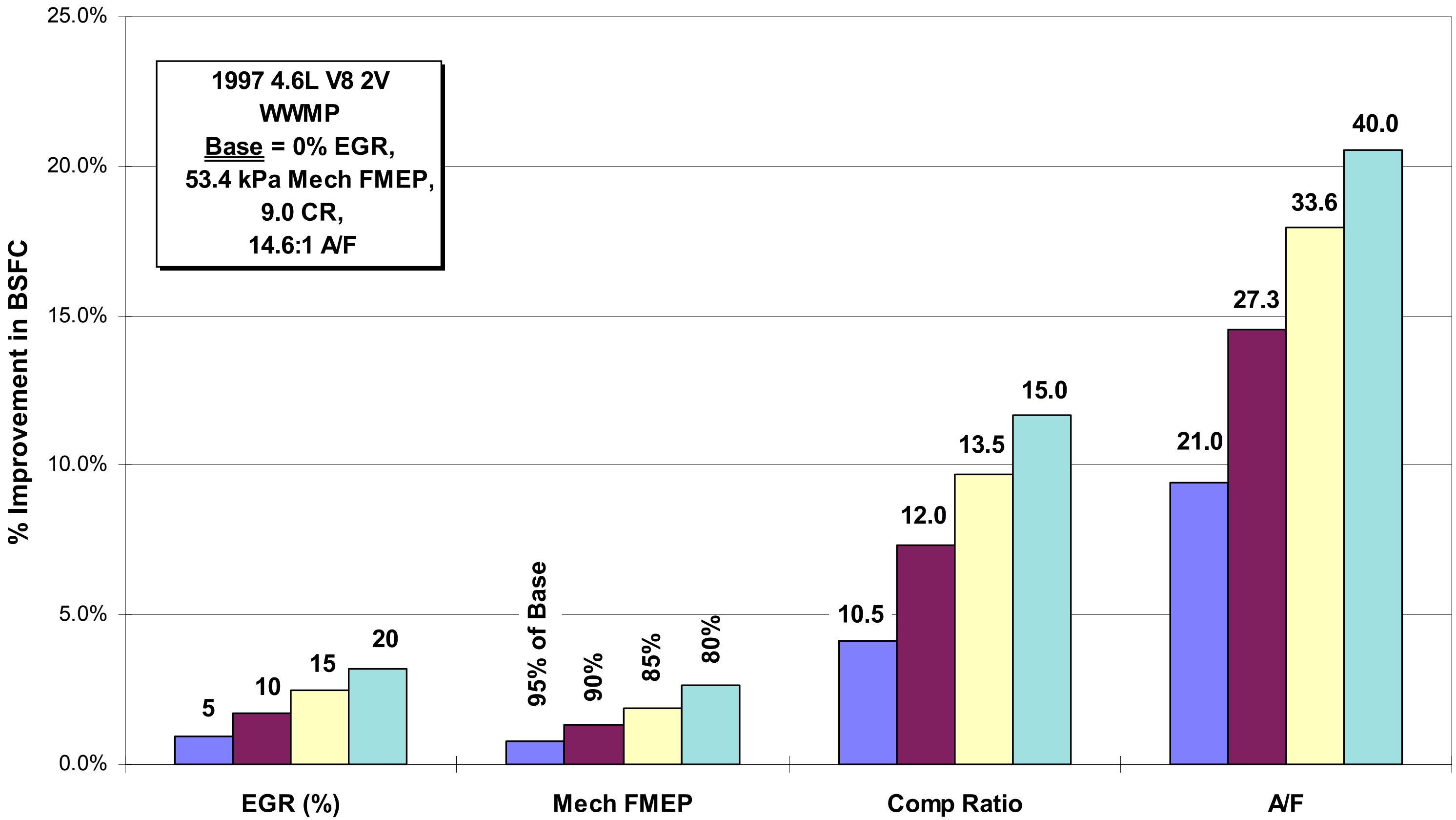
- Compression Ratio
- Equivalence Ratio
- Load Factor
- Cylinder Displacement
- Dilution (EGR)
- Combustion Efficiency
- Combustion Stability

Dynamic Range

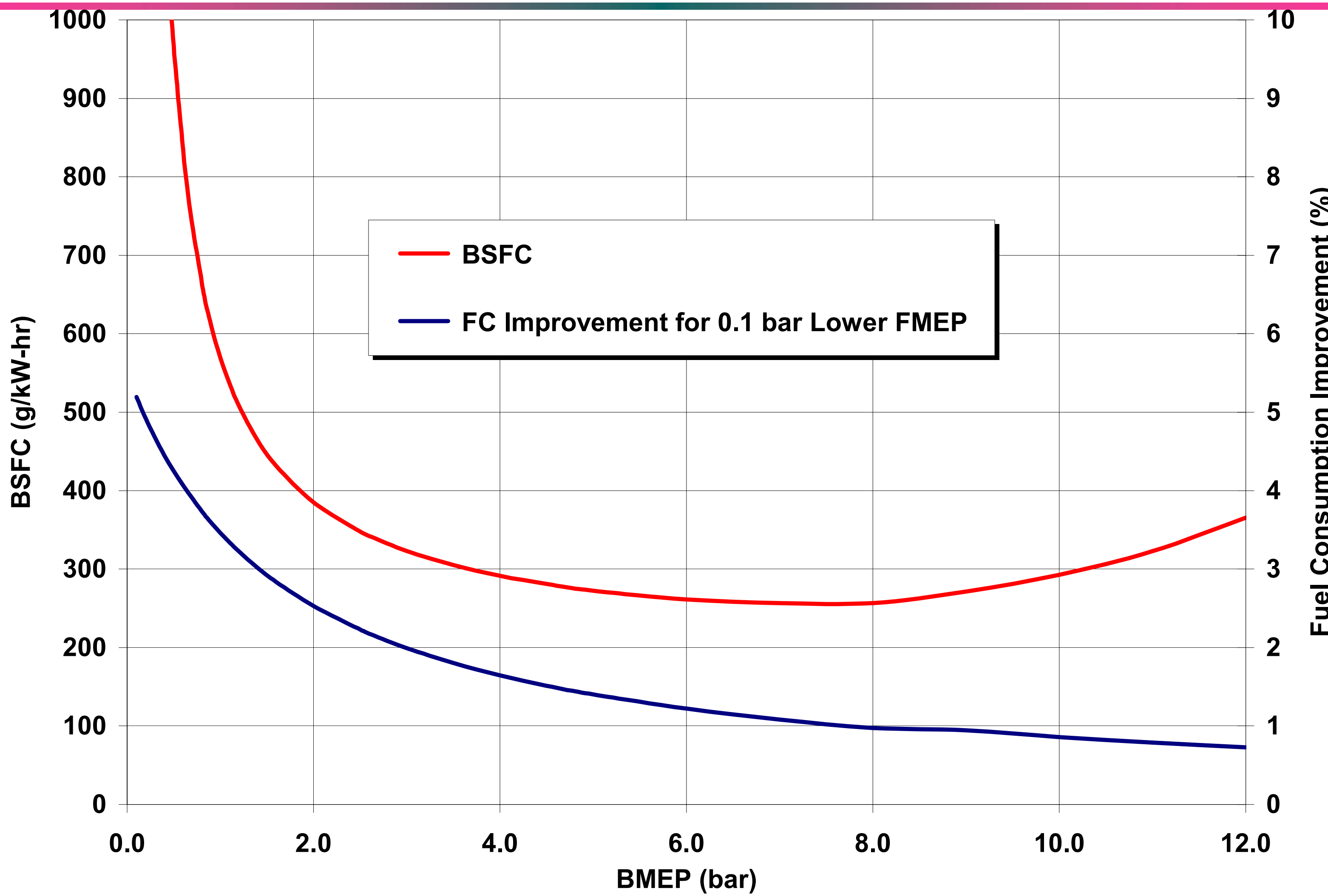
<u>Speed</u>
- 3 - Valve
- 4 - Valve

<u>Boosting</u>
- Turbocharging
- Supercharging

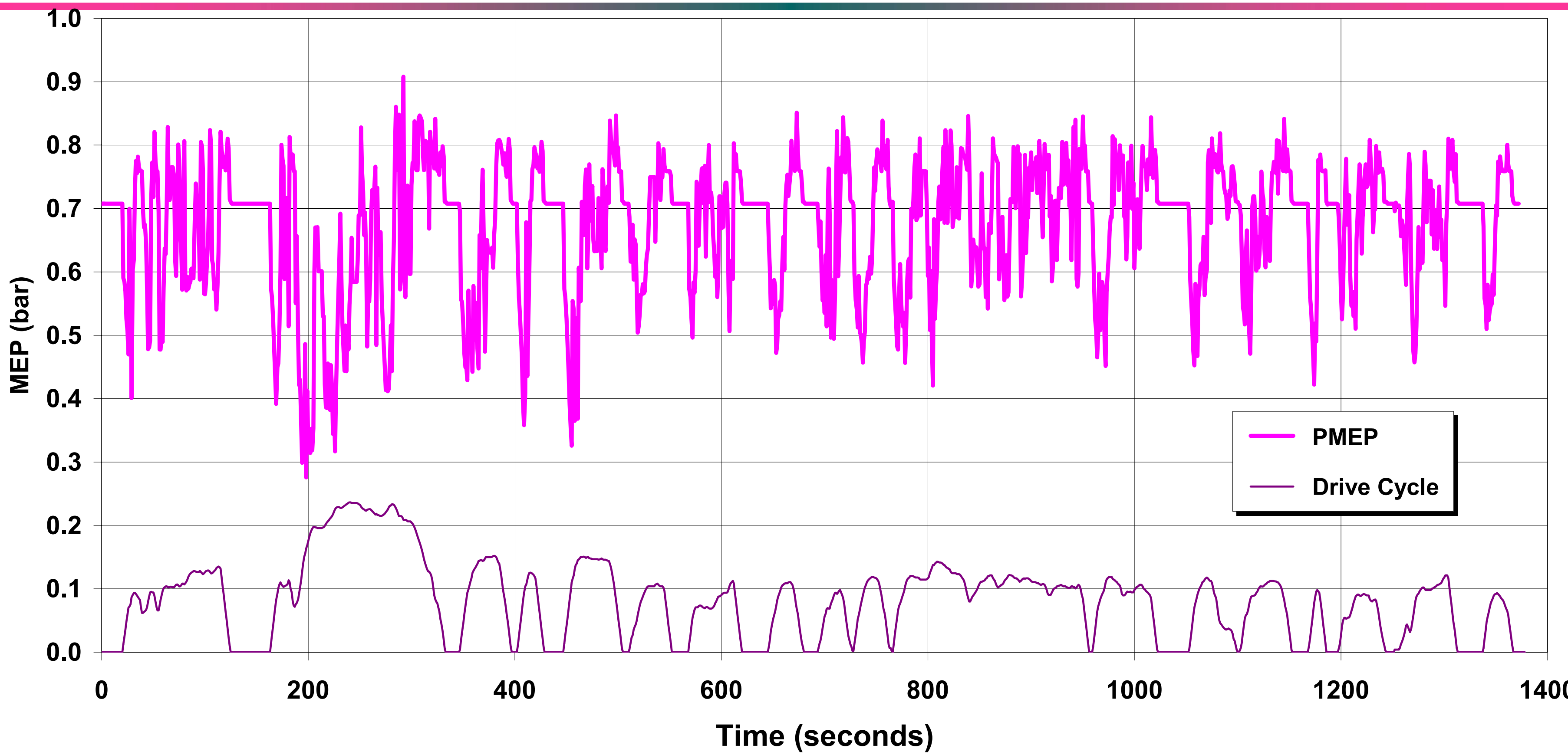
Effect of Engine Parameters on BSFC



Effect of Friction Reduction



Elimination of Pumping Work



Eliminating all pumping work could increase M-H FE by 12%, if there are no offsetting consequences; the practical potential is ~10%

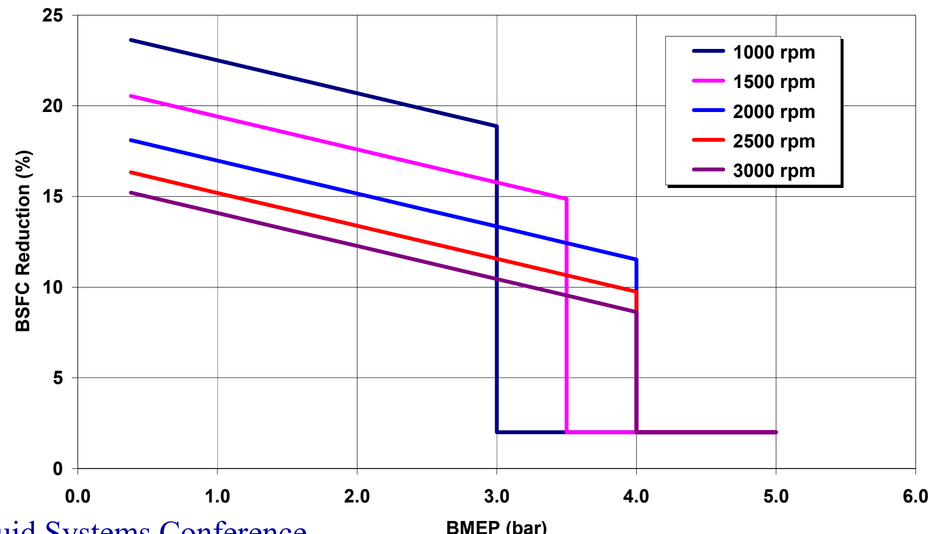
DI-SC Example

Time Allocation on NEDC Drive Cycle

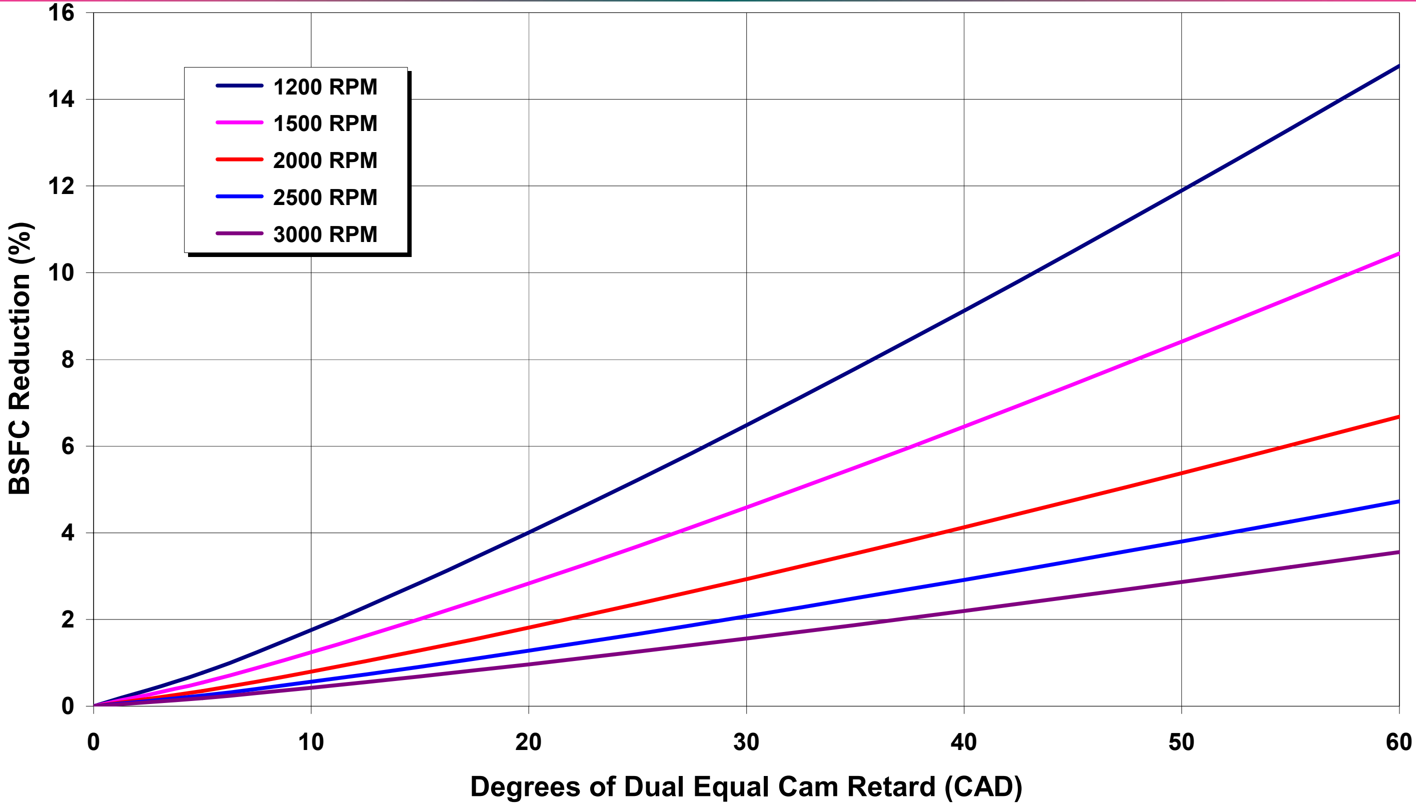
BMEP (bar) \ Engine Speed (rpm)	650	750	1000	1250	1500	1750	2000	2250	2500	2750	3000	3250	3500	3750	4000	4500	5000	5500	6000	6500
12.0										0	0	0	0	0	0					
11.5								0	0	0	0	0	0	0	0	0	0			
11.0						0	0	0	0	0	0	0	0	0	0	0	0	0	0	
10.5					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.0				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.5			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.0			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	2	0	0	7	2	0	0	0	0	0	0	0	0	0	0	0
7.0	0	0	0	0	2	0	2	5	0	0	0	0	0	0	0	0	0	0	0	0
6.5	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0
6.0	0	0	0	0	0	14	2	0	0	0	0	0	0	0	0	0	0	0	0	0
5.5	0	0	0	0	21	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.0	0	0	0	0	0	8	0	0	10	0	0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	9	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.0	0	0	0	5	10	24	50	0	0	0	0	0	0	0	0	0	0	0	0	0
3.5	0	0	0	10	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.0	0	0	0	13	109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.5	0	0	13	13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.0	0	0	9	0	117	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.2	305	37	0	0	155	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	0	14	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	0	98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.0	0	0	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.5	0	0	2	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-1.0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-1.2	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-1.5	0	0	0	0	0	2	4	2	0	0	0	0	0	0	0	0	0	0	0	0
-2.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Stratified operation is constrained to below 4.0 bar and 3000 rpm. Outside of this region, operation is at λ=1, and the FE benefits are significantly smaller.

FE benefits strongly depend on physical constraints, speed and load; therefore the gains are drive cycle dependent



Dual Equal VCT



Maximum cam retard depends on engine load and speed; so that the resulting FE benefit on the M-H cycle will be between 3% and 3.5% over an EGR calibration, depending on the vehicle

Diesel Engines

Efficiency Improvements

- Increased CR
- Unthrottled Operation
- Lean Calibration
- Smaller Displacement

Offsets

- Friction
- Mixture Inhomogeneity
- DPF Fueling Penalty
- Lean NOx Fueling Penalty

ΔFE ~ 35% to >50% M-H

ΔGE-FE ~ 20% to >32%

ΔFC ~ -26% to –34% M-H

ΔCO_2 ~ -17% to –25%

Powertrain Attributes - Transmission

Transmission Attributes

Parasitic Losses

- Gearbox Efficiency
- Torque Convertor Lock Schedule
- Fluid Viscosity
- Operating Temperature
- Clutch Design
- Hydraulic Pump Losses

Dynamic Range

- Ratio Span
- Ratio Steps
- Shift Scheduling

Powertrain Attributes - Hybridization

Hybridization

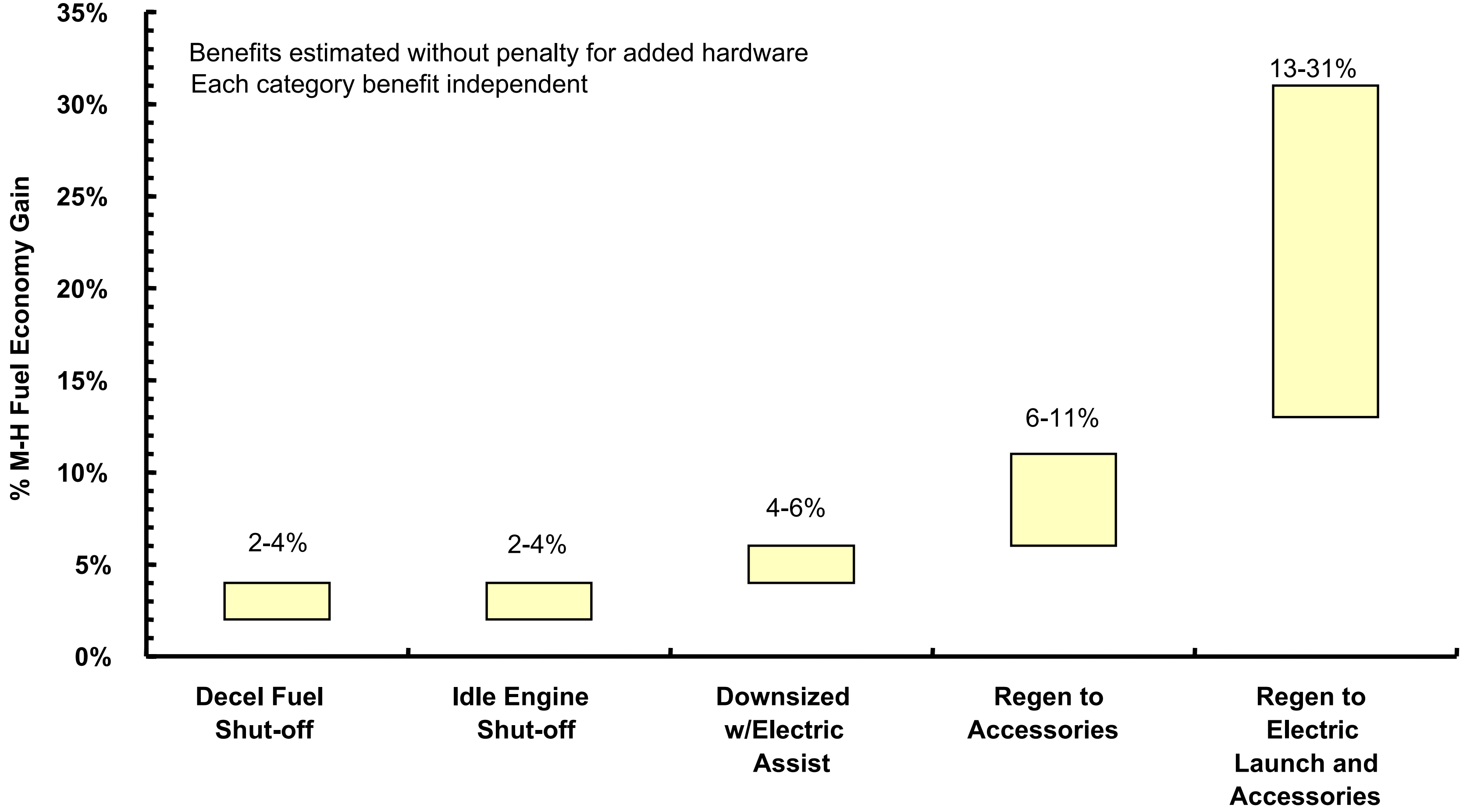
Increase Average Efficiency

- Engine Boost With Electric Motor
- Electric Drive Capability
- Engine Redesign for Fuel Efficiency

Reduce Losses

- Decel Fuel Shutoff
- Engine Off at Idle
- Regenerative Braking

Benefits of Hybridization



Key Powertrain Technologies

Engine
- Variable Cam Timing
- Direct Injection
- Variable Displacement
- Friction Reduction
- Boosting and Downsizing
- HCCI

Diesel Engines
- VNT
- Piezo Fuel Injector
- pHCCI

Transmission
- 6 Speed Automatic
- CVT
- Auto-Shift Manual

Strategy Refinement
- Torque Converter Lockup
- Decel Fuel Shutoff
- Low Idle Speed
- Energy Management

Hybridization

Observations
(Benefit of A) + (Benefit of B) < |Benefit of A| + |Benefit of B|
FE benefit for eliminating pumping work can only be claimed once

Crystal Ball: Automotive Industry

	Today	2020
US Car & LDT Sales	~17 M	~20M
Hybrid	0.3%	Up to 25%
Diesel	3%	Up to 15%
H_2 ICE/FCV/FCEV	nil	Up to 5%
US Car & LDT Fleet	215 M	235 M to 245 M
Hybrid	<0.2%	Up to 15%
Diesel	3%	Up to 10%
H_2 ICE/FCV/FCEV	nil	Up to 2%
Customers		
Pay for	Quality, Function, Performance	Quality, Function, Performance, ???
Do Not Pay for	Low Emissions, FE	???

Conclusions

Improving vehicle FE and reducing CO_2 are clearly becoming more important

There is no single technical prescription for improving FE on all vehicles in all markets

Compliance with regulatory FE and CO_2 standards depends on the ability of new technologies to meet customer expectations and satisfy customer needs.

All measures of FE/CO_2 have to be explicitly considered in developing vehicles to address these demands