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Impact of Drive Cycle Aggressiveness and Speed on HEVs Fuel Consumption Sensitivity

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Phillip Sharer,

Romain Leydier,

Aymeric Rousseau,

Argonne National Laboratory

FreedomCAR & Vehicle Technologies Program

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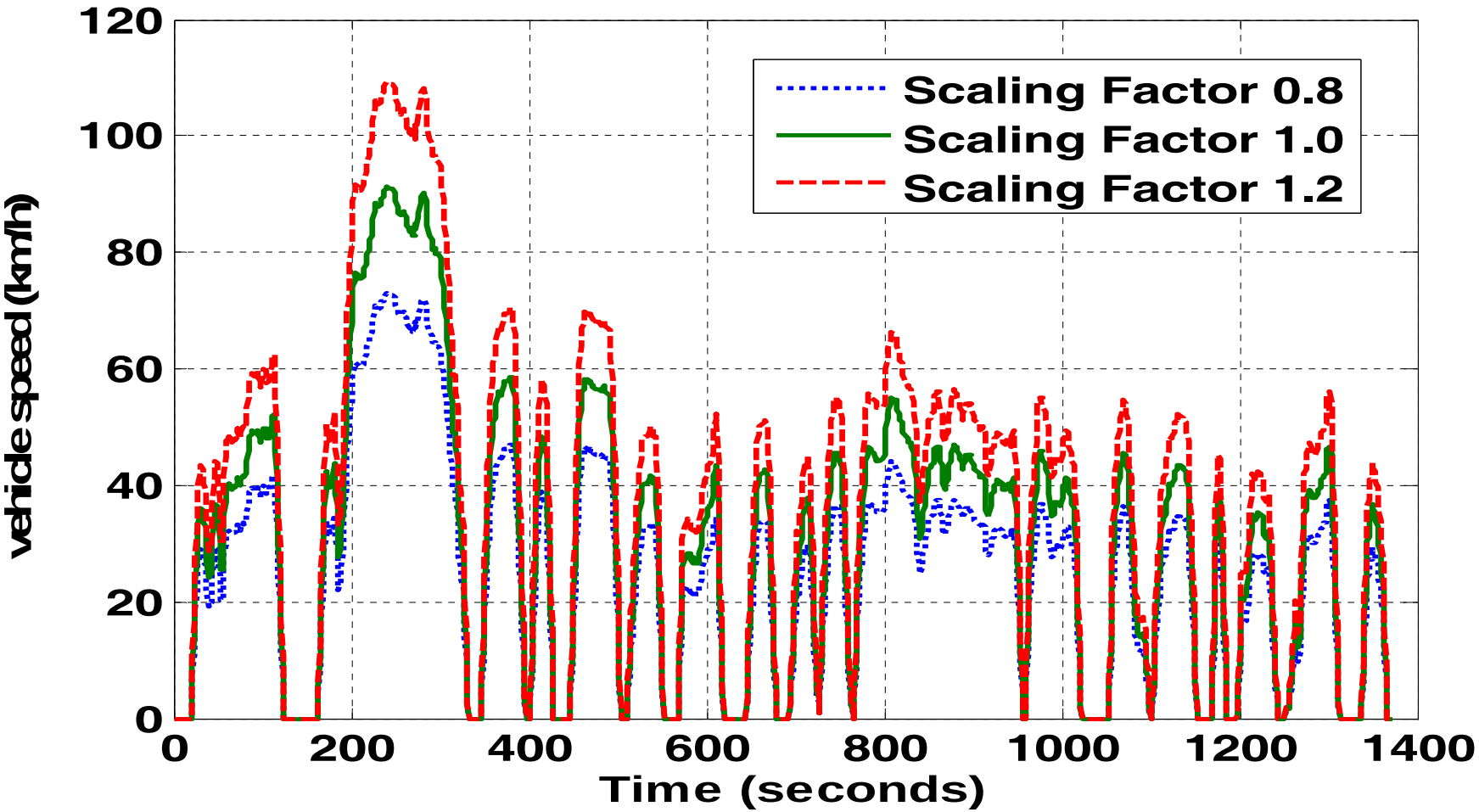
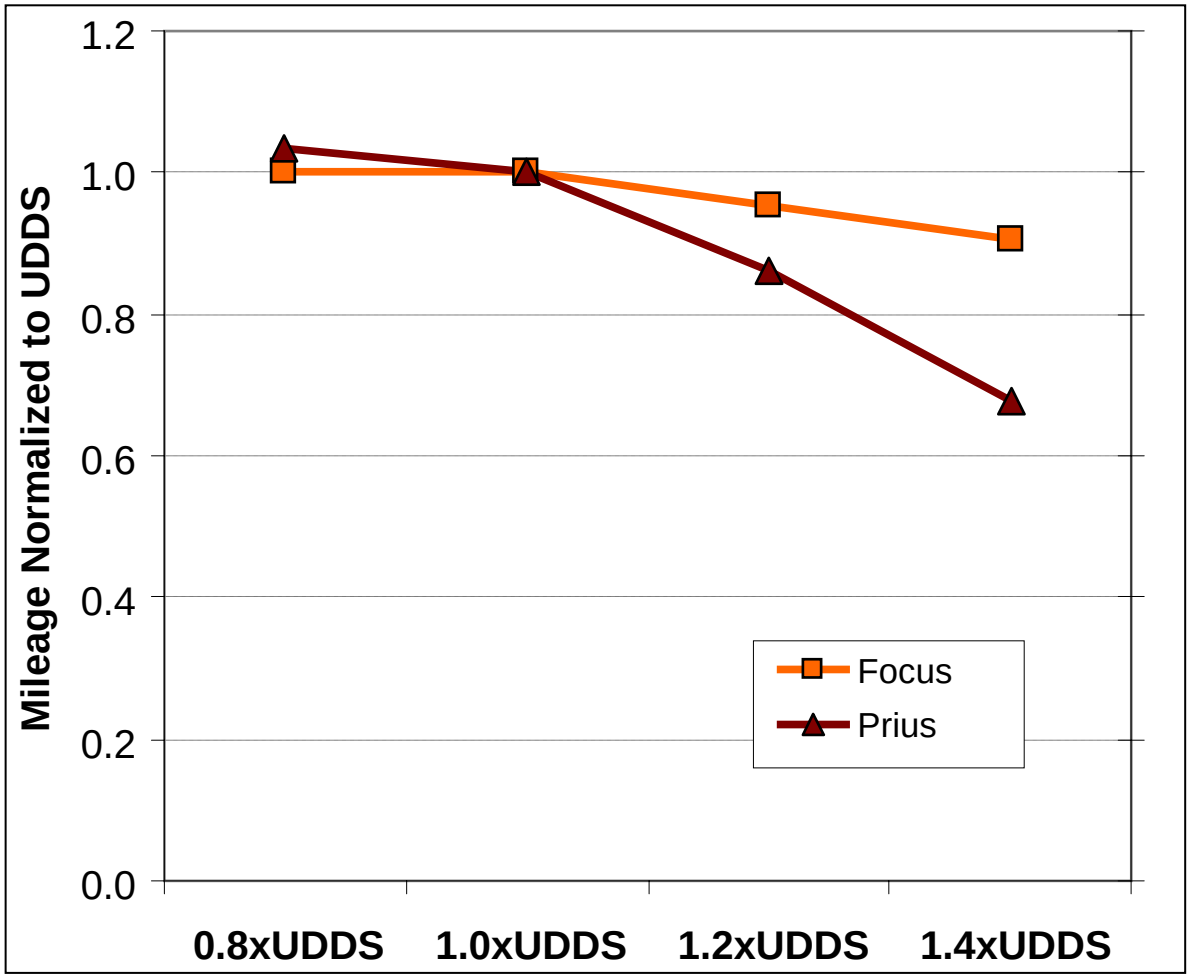
Argonne Study Demonstrated HEV's Have Higher Fuel Consumption Sensitivity to Aggressive Driving

- Many anecdotal reports from HEV owners that in-use fuel economy does not match the US EPA estimates
- "Investigating Vehicle Fuel Economy Robustness of Conventional and Hybrid Electric Vehicles", M. Duoba et al. in EVS 21 (2005) paper
  - Chassis dynamometer testing
  - 6 vehicles (2 HEVs and 4 conventional)
  - UDDS, HWFET, US06, ATDS
  - Cycle multiplier factor
  - HEV's higher sensitivity

Cycle Multiplier Factor



Initial Argonne Studied Demonstrated that Prius was More Sensitive



Simulation Study Conducted to Determine the Factors Affecting Sensitivity

- Chose Vehicles
  - Ford Focus (2004)
  - Toyota Prius (2004)
- Chose Cycles:
  - UDDS (Urban Dynamometer Driving Schedule - City)
  - HWFET (Highway Fuel Economy Test - Highway)
- Used Argonne's **P**owertrain **S**ystems **A**nalysis **T**oolkit
- Correlated Models with Test Results
- Updated Definition of Sensitivity

Things which Could Make a Big Difference which We Didn't Look at

- Air Conditioning
- Thermal Behavior
  - Cold Start
  - Elevated Operating Temperatures
- Component Wear and Maintenance
  - Tire Type, Air Pressure
  - Oil Changes
  - Tune ups
- Weather Conditions
- Road Way Conditions

PSAT Drivetrain Models Correlated with Test Results

Ford Focus

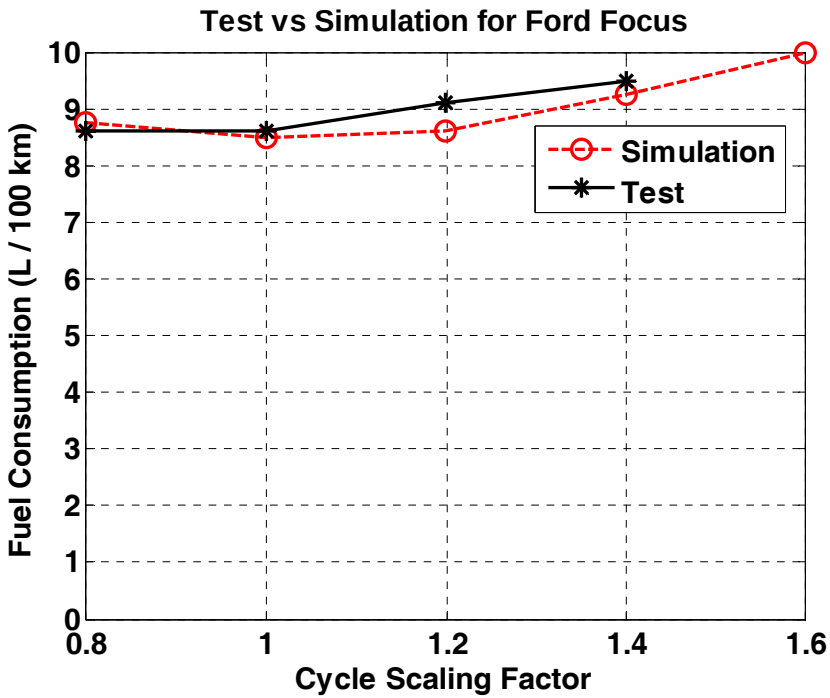
Drive Cycle	APRF Test (L/100 km)	PSAT (L/100km)	Percent Difference
UDDS	8.8	8.9	1.1%
HWFET	6.2	6.2	~0%

Toyota Prius

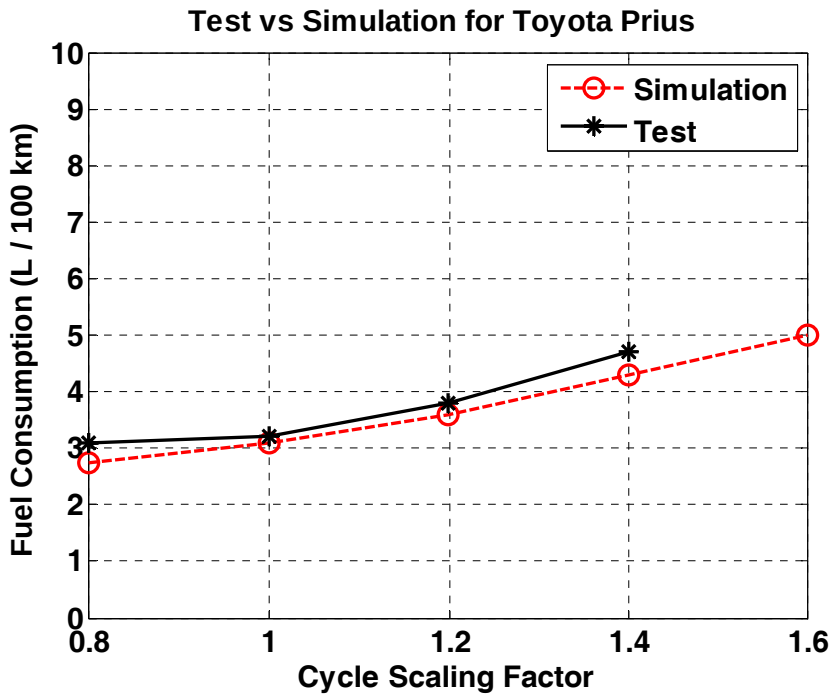
Drive Cycle	APRF Test (L/100 km)	PSAT (L/100km)	Percent Difference
UDDS	3.3	3.2	-3.0%
HWFET	3.5	3.5	~0%
US06	5.6	5.1	-9.8%
Japan1015	3.1	3.0	-3.2%
NEDC	3.4	3.4	~0%

Fuel Economy Trends are Verified

Ford Focus

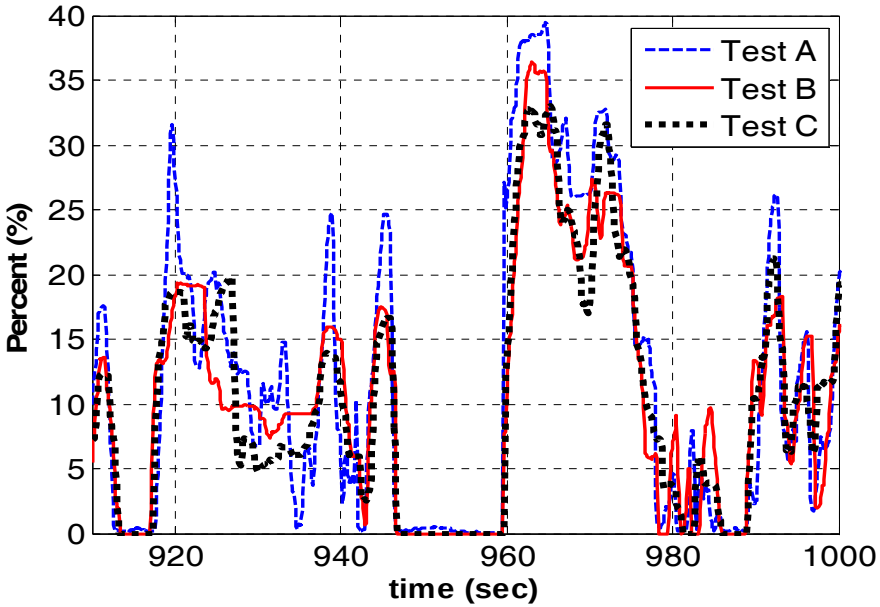


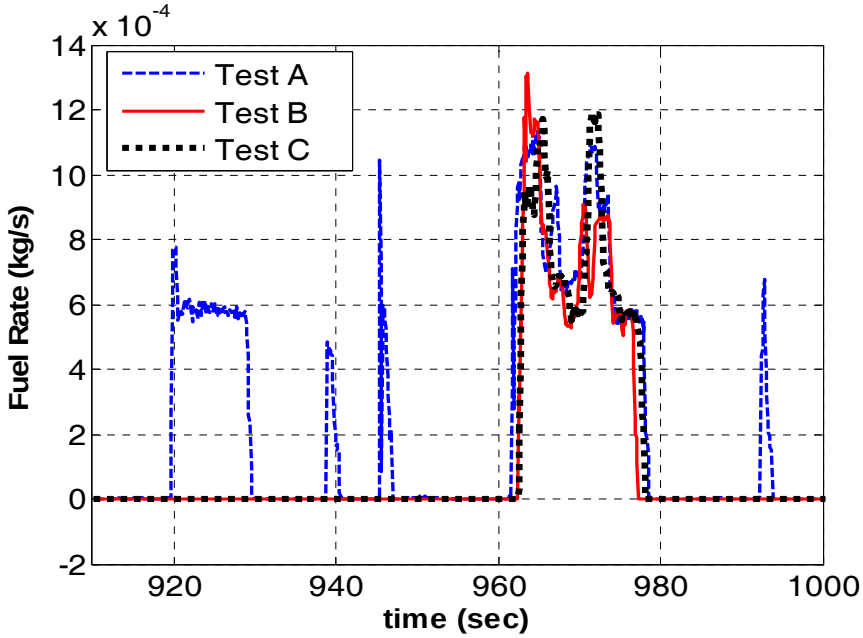
Toyota Prius



Correlation is Limited by Uncertainty of Tests and Models

Pedal position leads to unexpected engine ON/OFF





Why Update the Definition?

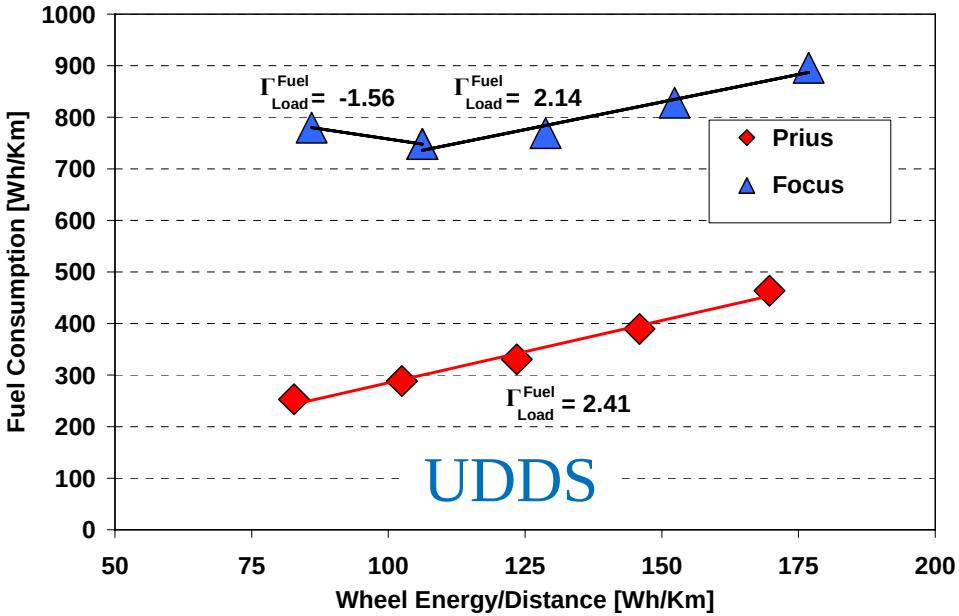
$$\frac{\Delta E_{Fuel}}{\Delta \gamma} = \frac{\Delta E_{Fuel}}{\Delta E_{Load}} \frac{\Delta E_{Load}}{\Delta \gamma}$$

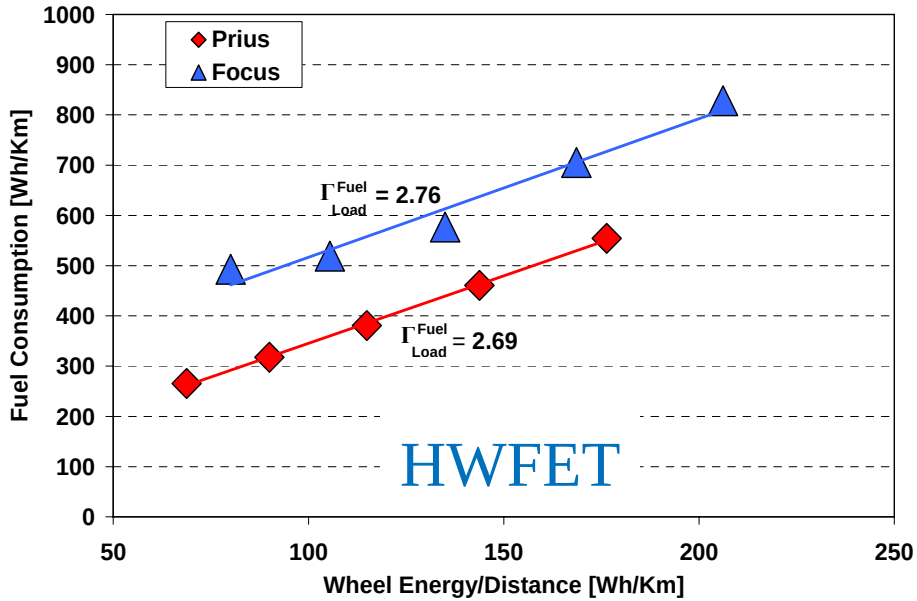
Initial Definition

Updated Definition

- Cycle multiplier - systematic way transform the cycle to vary vehicle Load
- Many other ways to transform the cycle
- $\frac{\Delta E_{Load}}{\Delta \gamma}$ Mixes in the sensitivity of the cycle to cycle Multiplier
- Drivetrain's mass sensitivity is special case (SAE 06 paper)

So, Why is the Prius More Sensitive to Aggressive Driving?



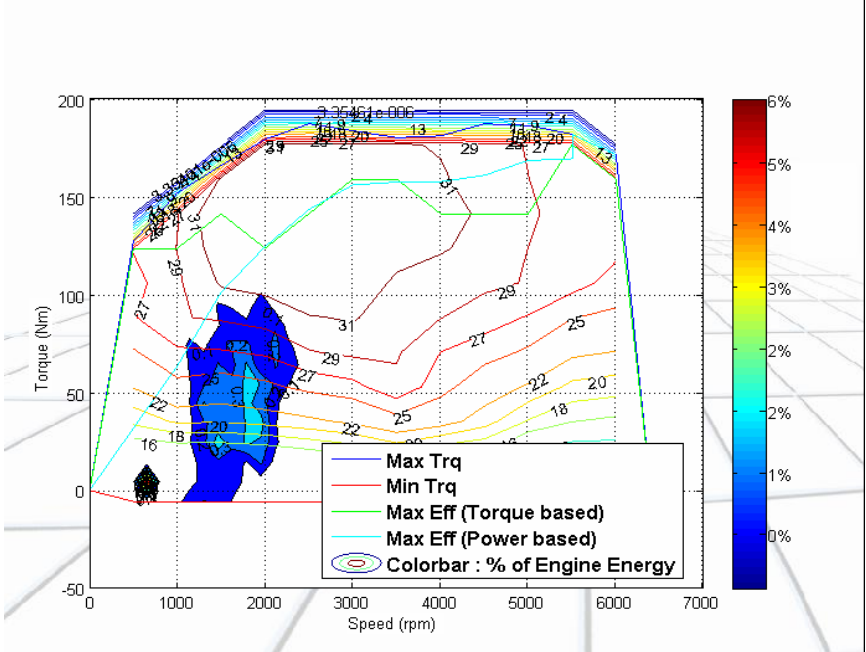


Powertrain Factors Influencing Sensitivity

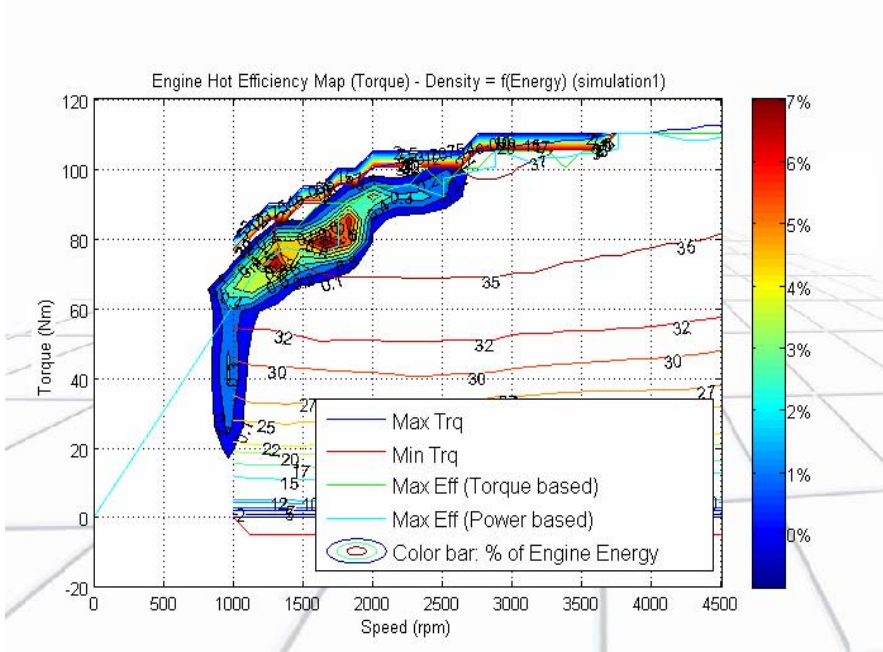
- Engine Efficiency
  - High efficiency -> low sensitivity
- Engine Efficiency Rate of Change
  - Increased efficiency with increased load -> low sensitivity
  - Decreased efficiency with decreased load -> low sensitivity
- Regenerative Braking
  - Any regenerative braking -> lowers sensitivity
  - Saturated regenerative braking -> lowers sensitivity

High Engine Efficiency Makes the Prius Less Sensitive to Aggressive Driving than the Focus

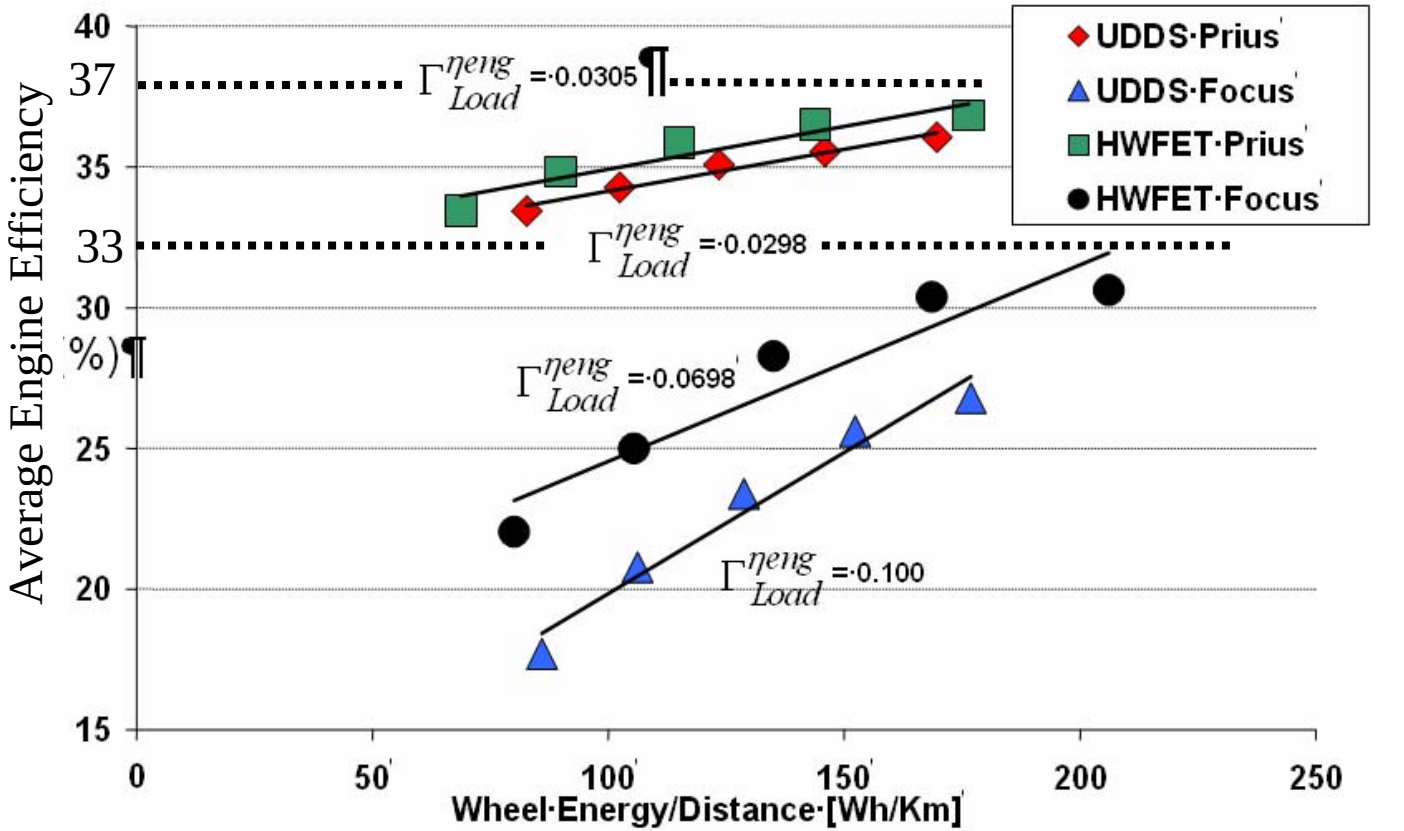
Ford Focus



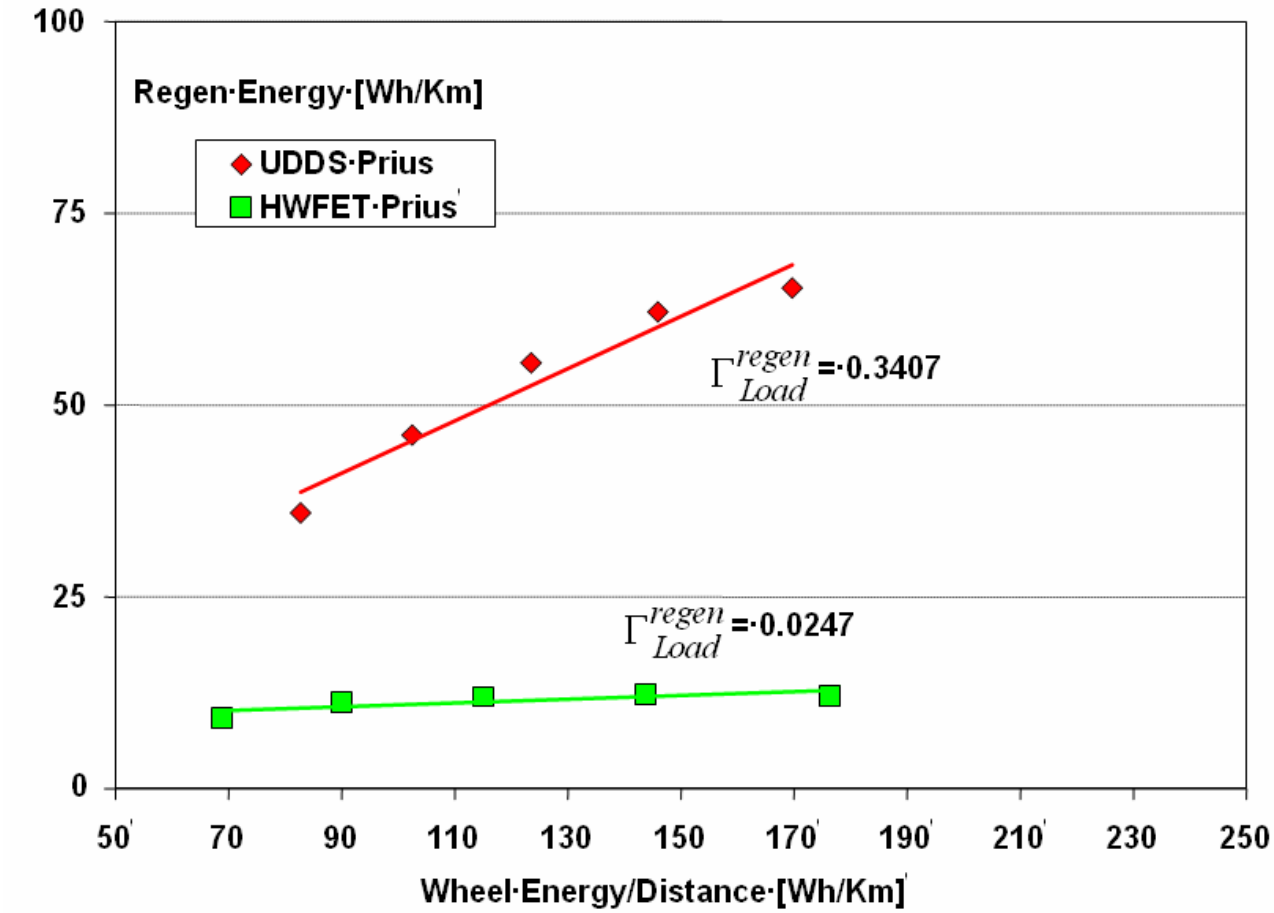
Toyota Prius



Slow Rate of Change of the Engine Efficiency Makes the Prius More Sensitive to Aggressive Driving than the Focus



Regenerative Braking Makes the Prius Less Sensitive to Aggressive Driving than the Focus



Focus Engine Becomes More Efficient During Aggressive Driving Offsetting the Increase in Demand

- Prius Engine Efficiency > Focus Engine Efficiency
  = Prius Less Sensitive
- Prius Change in Engine Efficiency < Focus Change in Engine Efficiency
  = Prius More Sensitive
- Prius Regenerative Braking
  = Prius Less Sensitive

The Change in Engine Efficiency is the Dominant Effect

	UDDS		HWFET	
	Focus	Prius	Focus	Prius
Engine Peak Efficiency	0	-	0	-
Engine Efficiency Variation	---	0	--	-
Regenerative Energy	NA	-	NA	0

+ indicates increase in sensitivity
- indicates decrease in sensitivity
0 no effect on sensitivity
NA not applicable

Prius More Sensitive on the UDDS than Focus But Similar on HWFET

- For the conventional Focus, an increase in engine efficiency when the drive cycle became more aggressive leads to a decrease in sensitivity.
- For the HWFET driving cycle, both conventional and HEV vehicles behave similarly as a result of the high vehicle speed and the low regenerative braking and vehicle stop events.
- Main factors thermal effects, air conditioning, accessory load.

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