ARGONNE NATIONAL LABORATORY
TRANSPORTATION
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Comparing Cost Estimates for U.S. Fuel Economy Improvement by Advanced Electric Drive Vehicles

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This is a "Study of Studies" of Cost Effectiveness of ICE and FC HEVs vs. Conventional Vehicles in U.S. Driving

- Studies that simulate energy economy on U.S. driving cycles are used to assess energy savings per km for comparable vehicles
  - Fuel consumption measured in km/L of gasoline energy equivalent
  - U.S. "Combined" weighted FTP and Highway cycles
  - Focus - CV, SI ICE HEV, CI ICE HEV & H2 HEV FCV
  - Degree of hybridization, effects of mass reduction, series vs. parallel
- Studies also examining vehicle cost are used to examine cost effectiveness
  - Cost effectiveness metrics used in U.S. are criticized
  - After investigation, liters saved per 10,000 km driven per $1000 of incremental cost was selected as reliable cost effectiveness metric
  - Incremental cost = lower km/L vehicle price minus higher km/L vehicle price

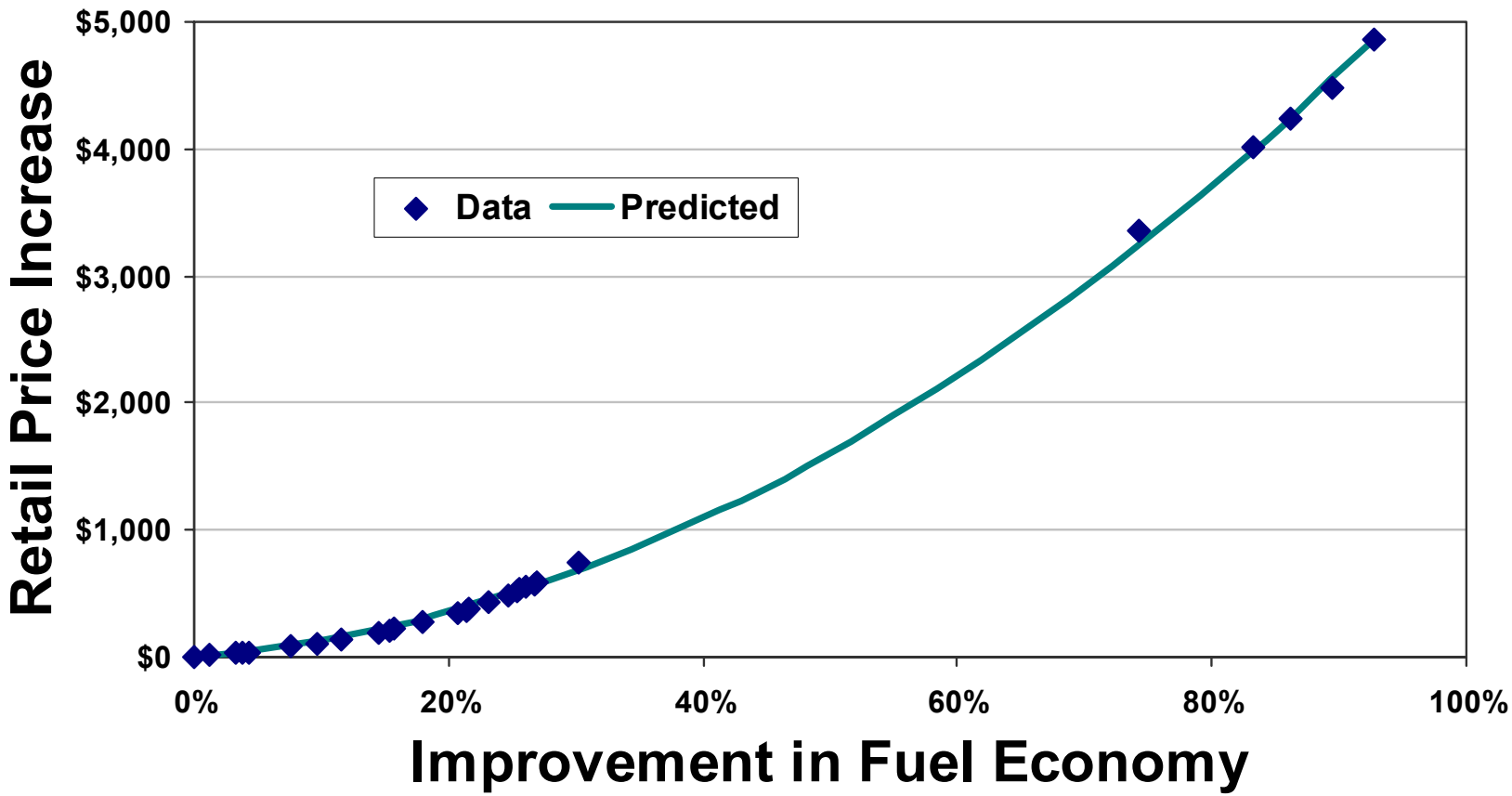
Studies Provide Multiple Estimates for More Than 10 Technology Changes

	ADL	ANL 1	EPRI	MIT	DTI	EF	J&H	GM	ANL 2
Vehicle w Contemporary Loads	X		X	X		X		X	
Load Reduction (mass, Cd, Cr)		X	X	X	X	X			X
Gasoline CV Engine Upgrades			#	X		X			
Transmission Switches		X	X	X	X	X		X	X
Gasoline CV Hybridization	X	X	X	X	X	X		X	X
Varying Battery/Motor Sizes	X	X	X			X	X		
Gasoline Hybrid ZEV Capability		X	X					X	
CV Dieselization	X			X				X	X
Diesel CV Hybridization	X			X	X			X	X
H2 FCV w/o Hybridization	X				X		X	X	
H2 FCV with Hybridization	X			X	X		X	X	

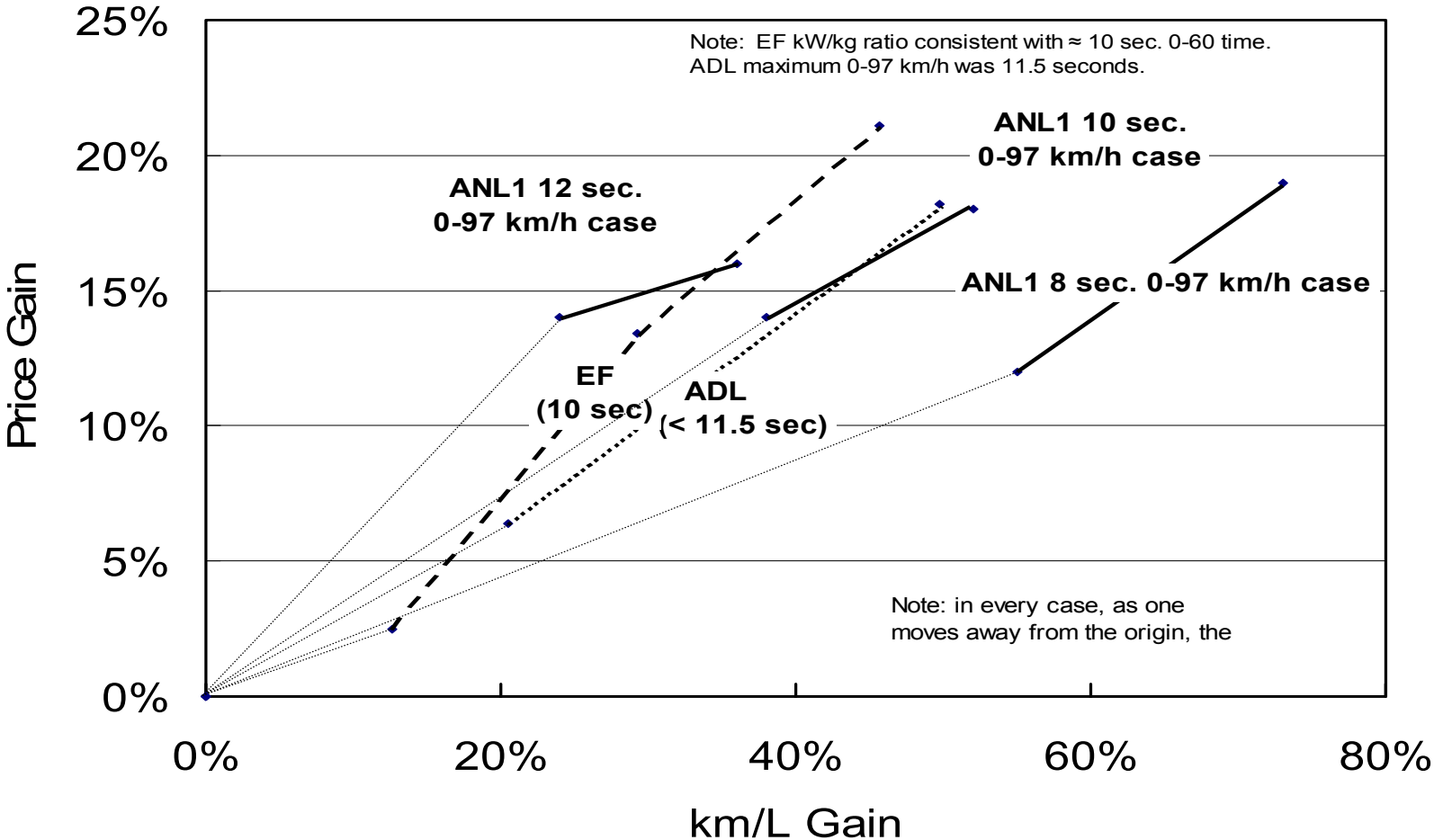
Quality and Detail of Information and Documentation Vary Considerably

	ADL	ANL 1	EPRI	MIT	DTI	EF	J&H	GM	ANL 2
Detailed Vehicle Specifications		X	X	X	X	X			X
Models other than Mid-Size Car?	X				X	X	X	X	
Stated Performance Limits		X	X					X	X
EV Operation Performance Limits?	n/a	X	X	n/a	n/a	n/a		No	n/a
Performance Goals Variation		X							
Aggressive Driving Cycles?		X			X				
Base U.S. Driving Cycle(s)	1	3	3	3	3	3	1	3	3
Retail Price Estimates	X	X	X	X	X	X	X		
Component Price or Tech. Details		X	X	X	X	X	X		
Data Modified for This Paper?						X	X		

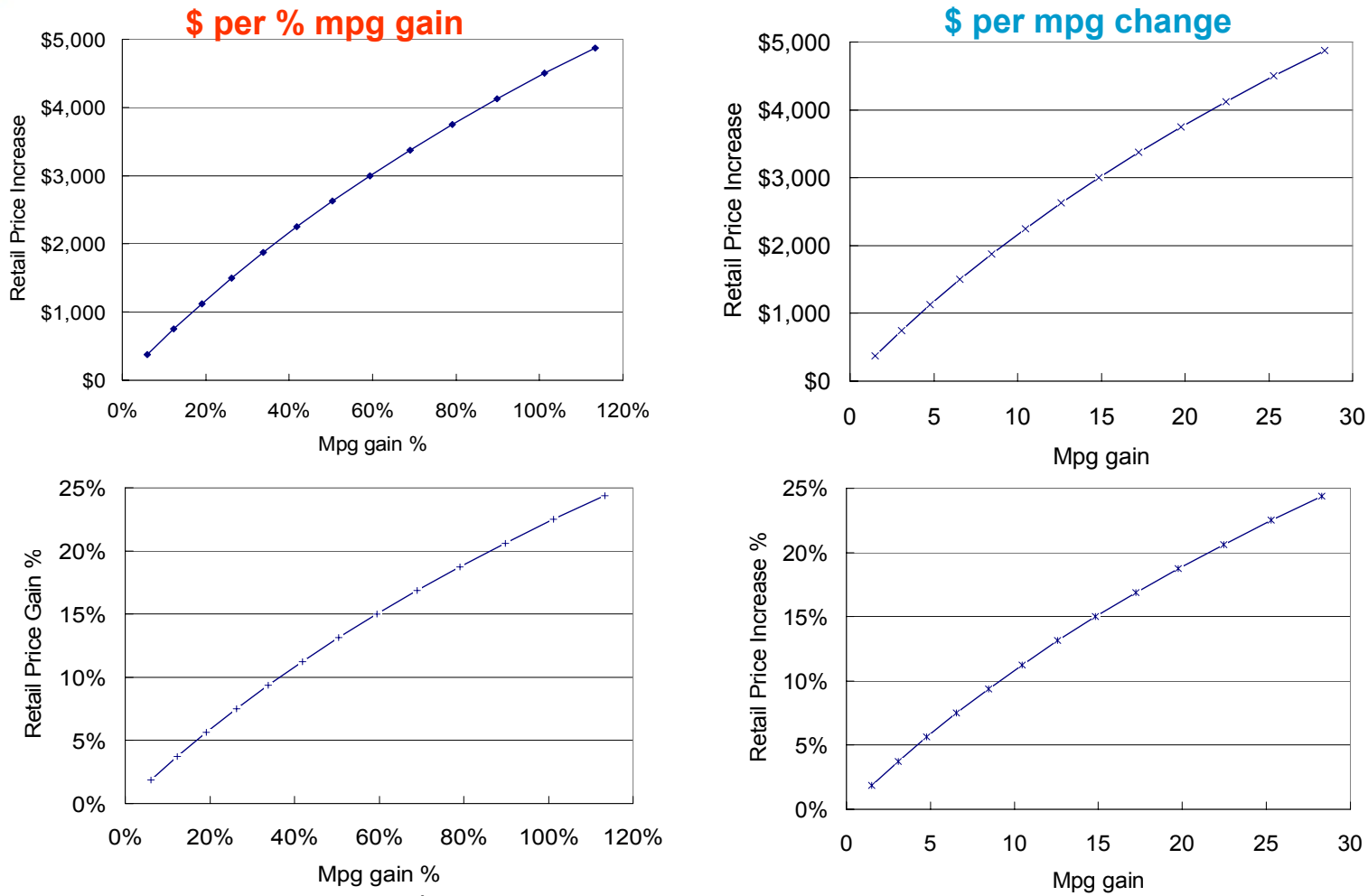
U.S. Studies' Cost Effectiveness Plots Imply Ordering from Most to Least Cannot Cause a Negative Slope



The Usual U.S. Cost Effectiveness Measure Implies Some Full Hybrids are More Cost Effective Than Mild Hybrids

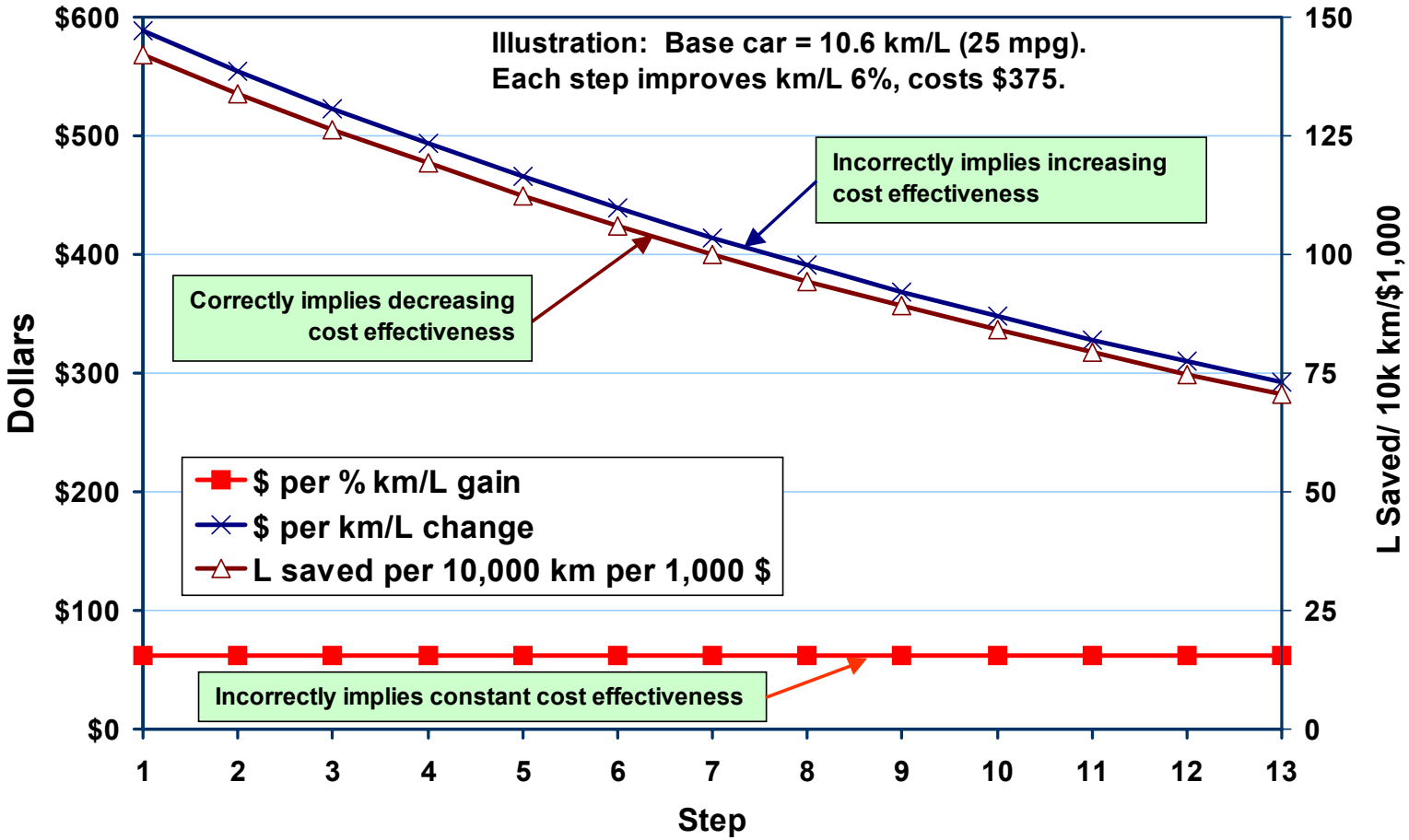


A Sample Constant U.S. Cost Effectiveness Metric Gives a Negative Slope if Repeatedly Applied



Constant 6% mpg gain per $375, applied 13 times: four typical U.S. cost effectiveness plots

The Common [% km/l gain per $] Cost-effectiveness Metric Used Can Give False Implications



Properties of cost effectiveness estimate vs. order of technology implementation (same real savings for each measure)

Several "Degrees" of ICE Hybridization are Examined

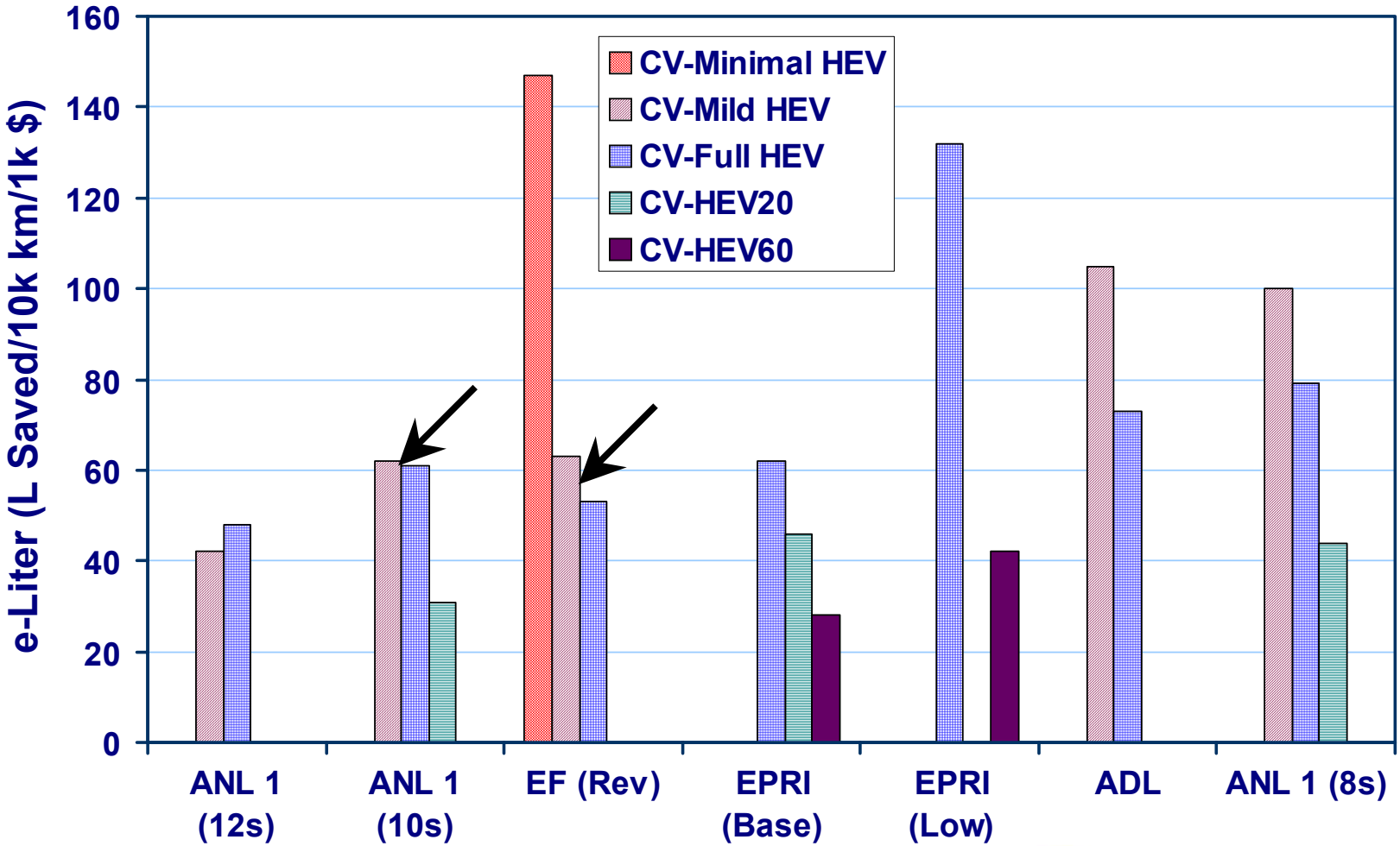
Charge-sustaining Hybrids

- Minimal hybrid = idle off, perhaps some degree of regenerative braking (ISG), no grid connection
- Mild hybrid = between minimal (or nothing) and full, in any given study, no grid connection
- Full hybrid = idle off, considerable regenerative braking, electric launch, no grid connection

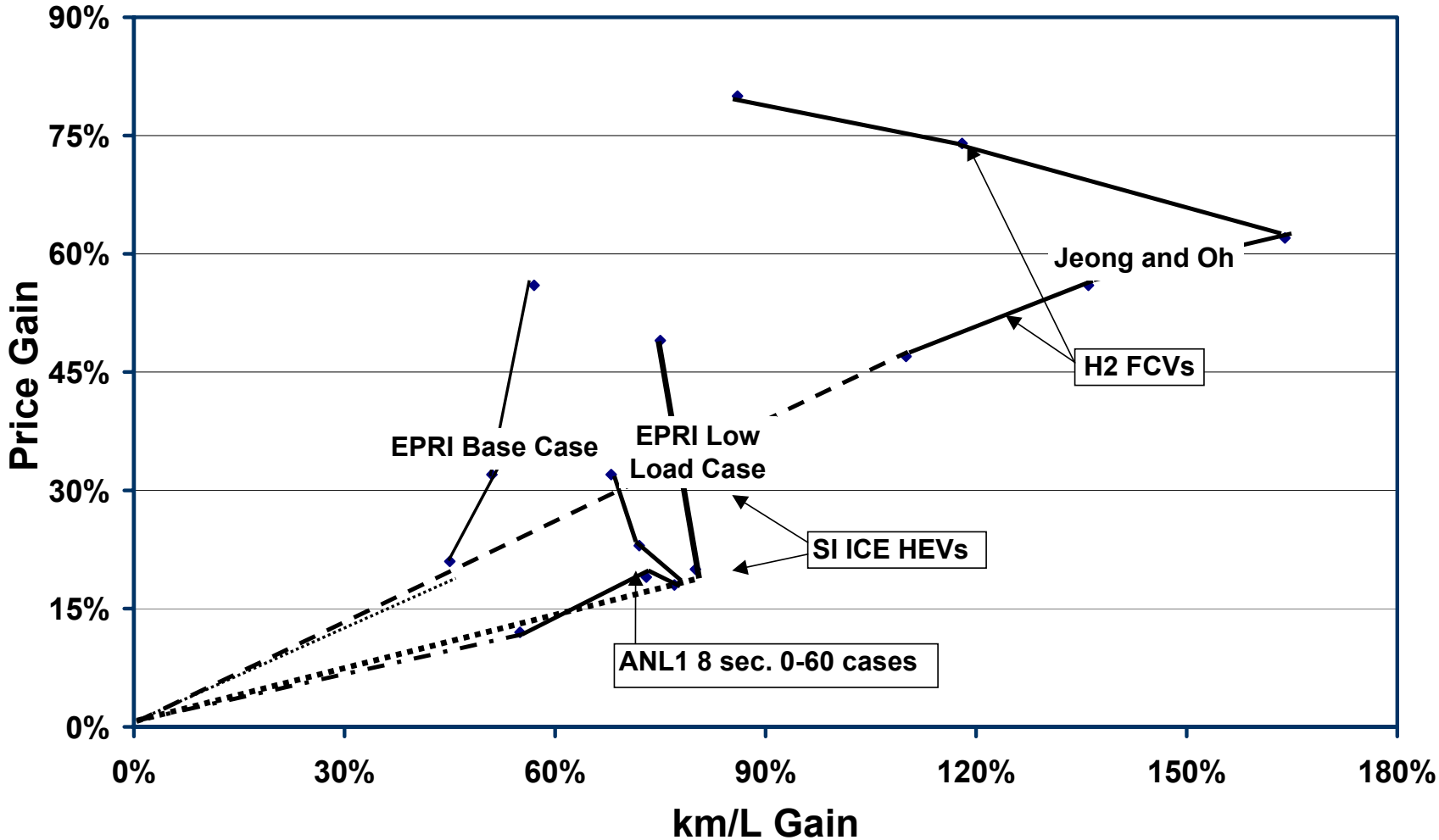
Charge-depleting (and Sustaining) Hybrids

- HEV## = a grid connectable hybrid with ## miles of electric range

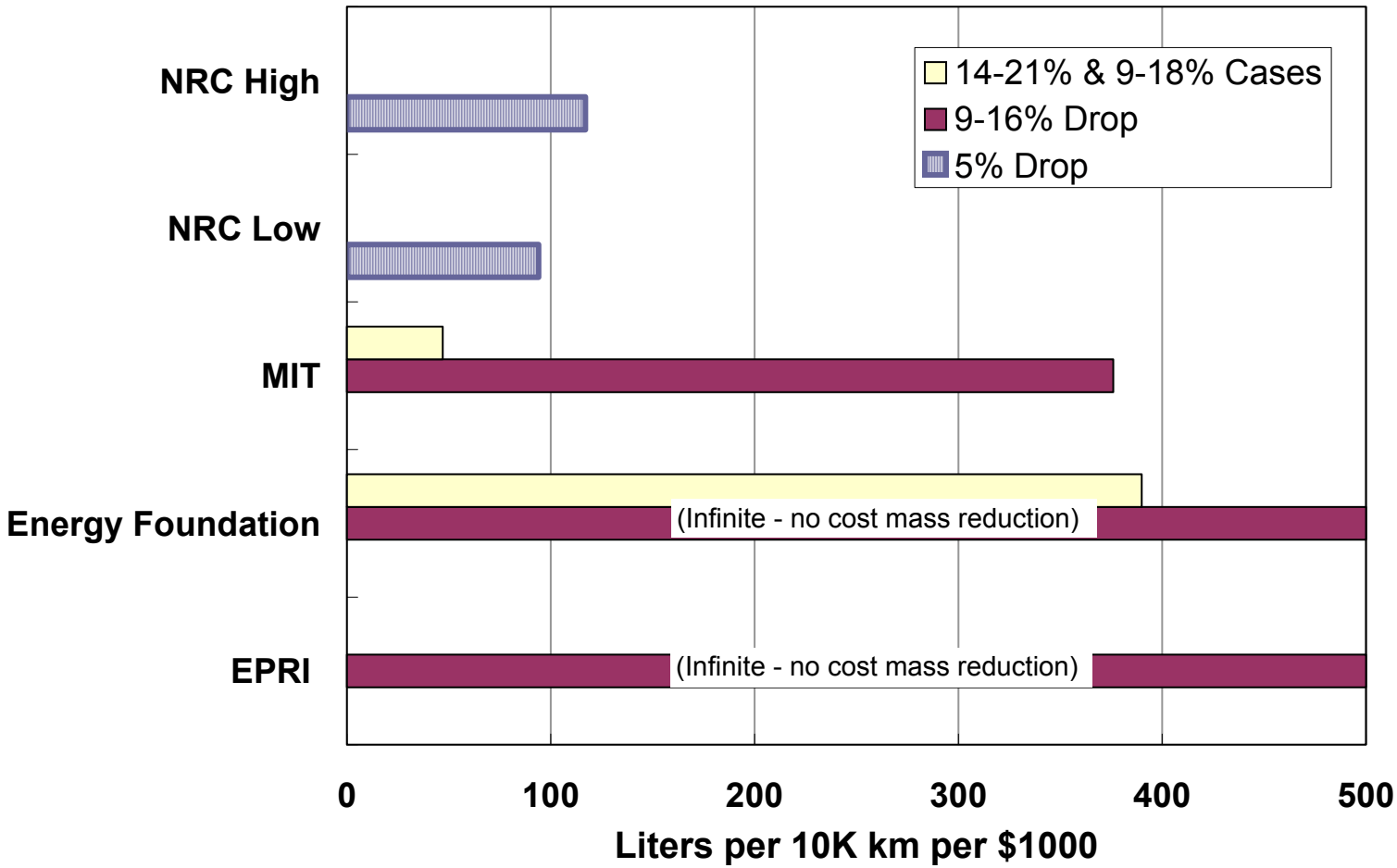
Fuel Saved per km per $ Metric Indicated Inconsistent Results With "U.S. Method"



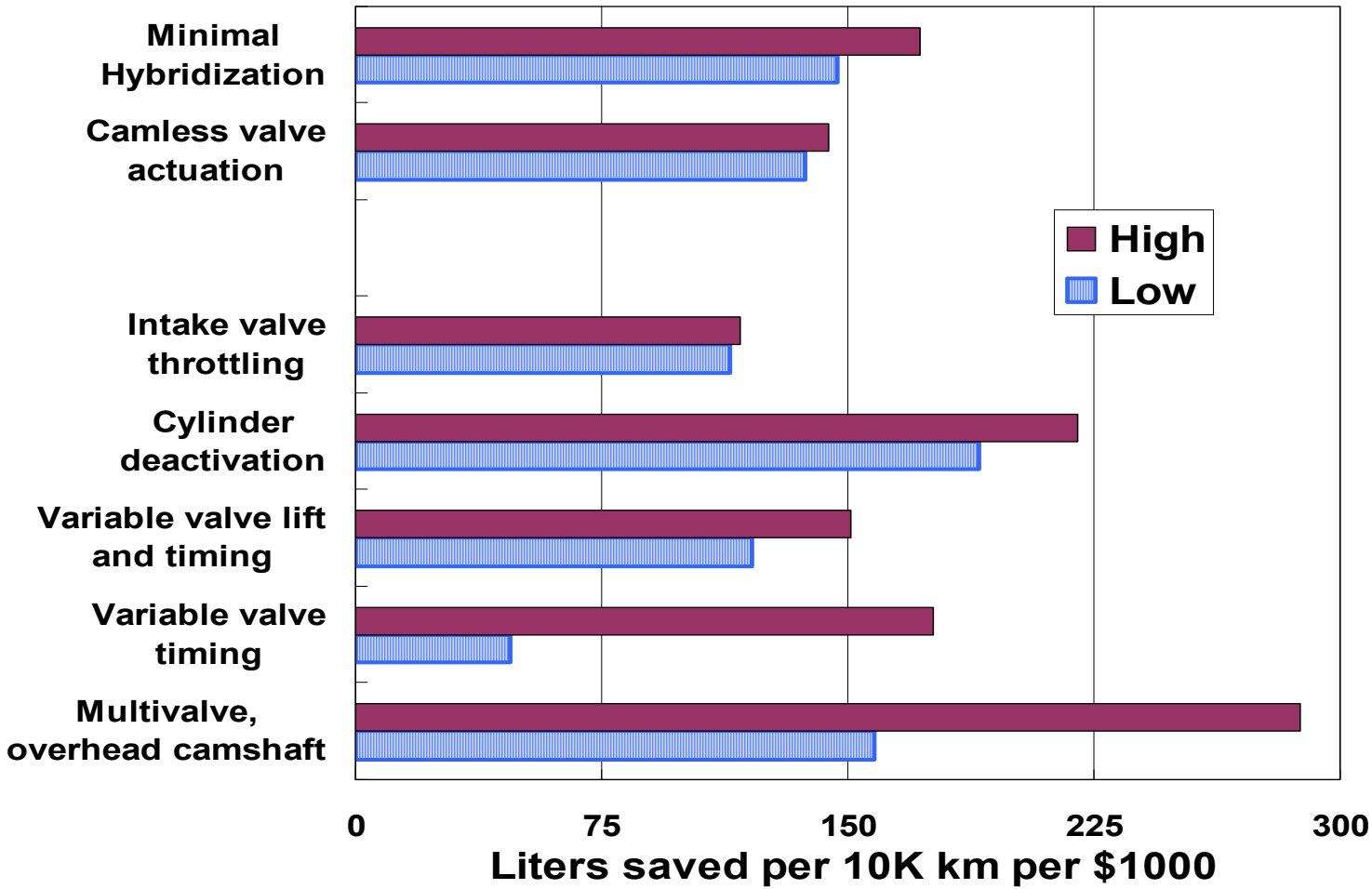
Many Studies Indicate Adding Battery Pack & Motor Diminish km/L Gain Rate



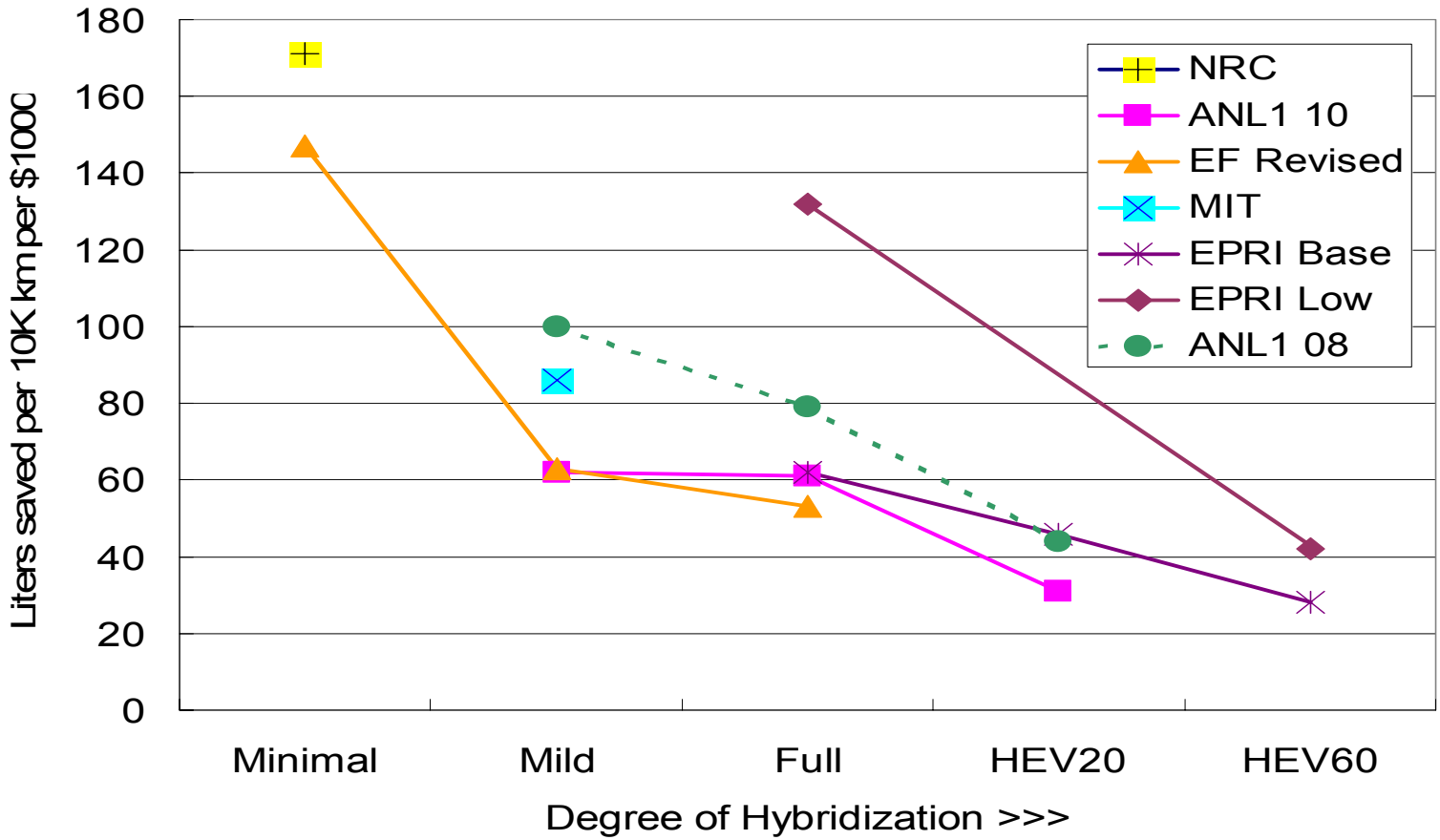
Predictions of Mass Reduction Effectiveness Are Highly Variable



Cost-effectiveness Implies Minimal Hybridization Competes with High-Tech Valve Actuation

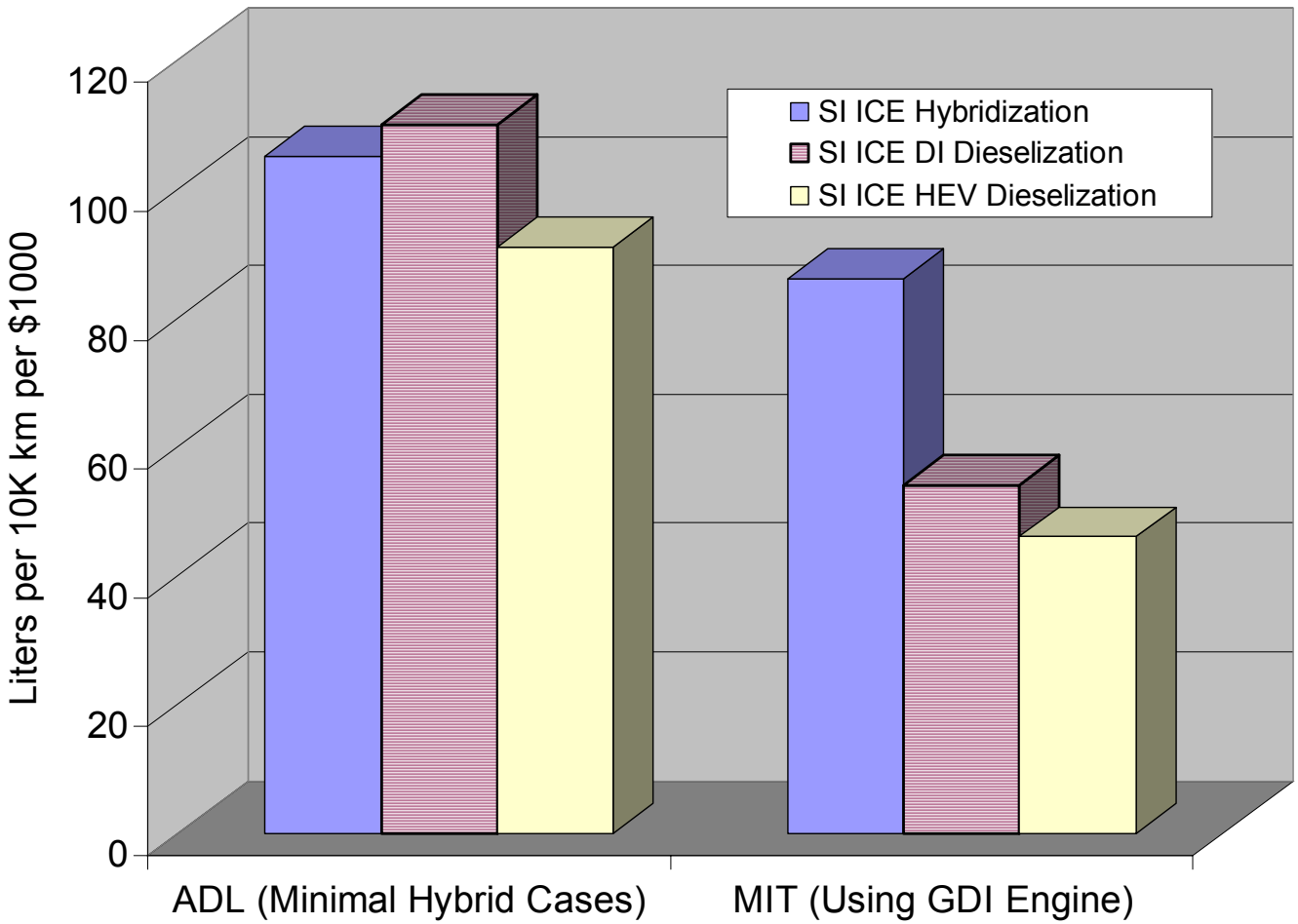


Studies With Increasing ICE Hybridization Indicate Decreasing Cost Effectiveness

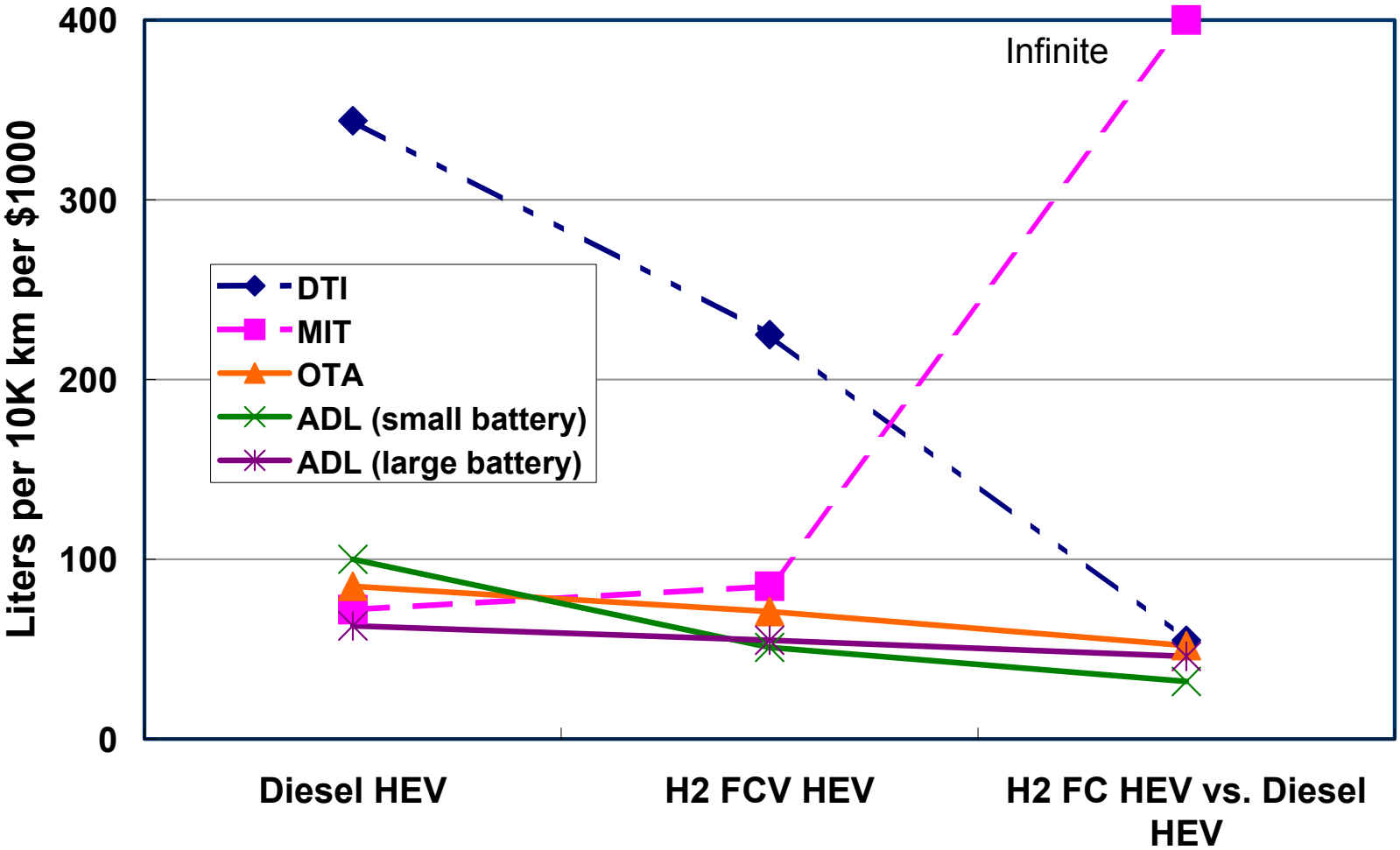


Cost effectiveness of increasing hybridization for HEVs with 0-97 km/h acceleration in 8 to 10 seconds

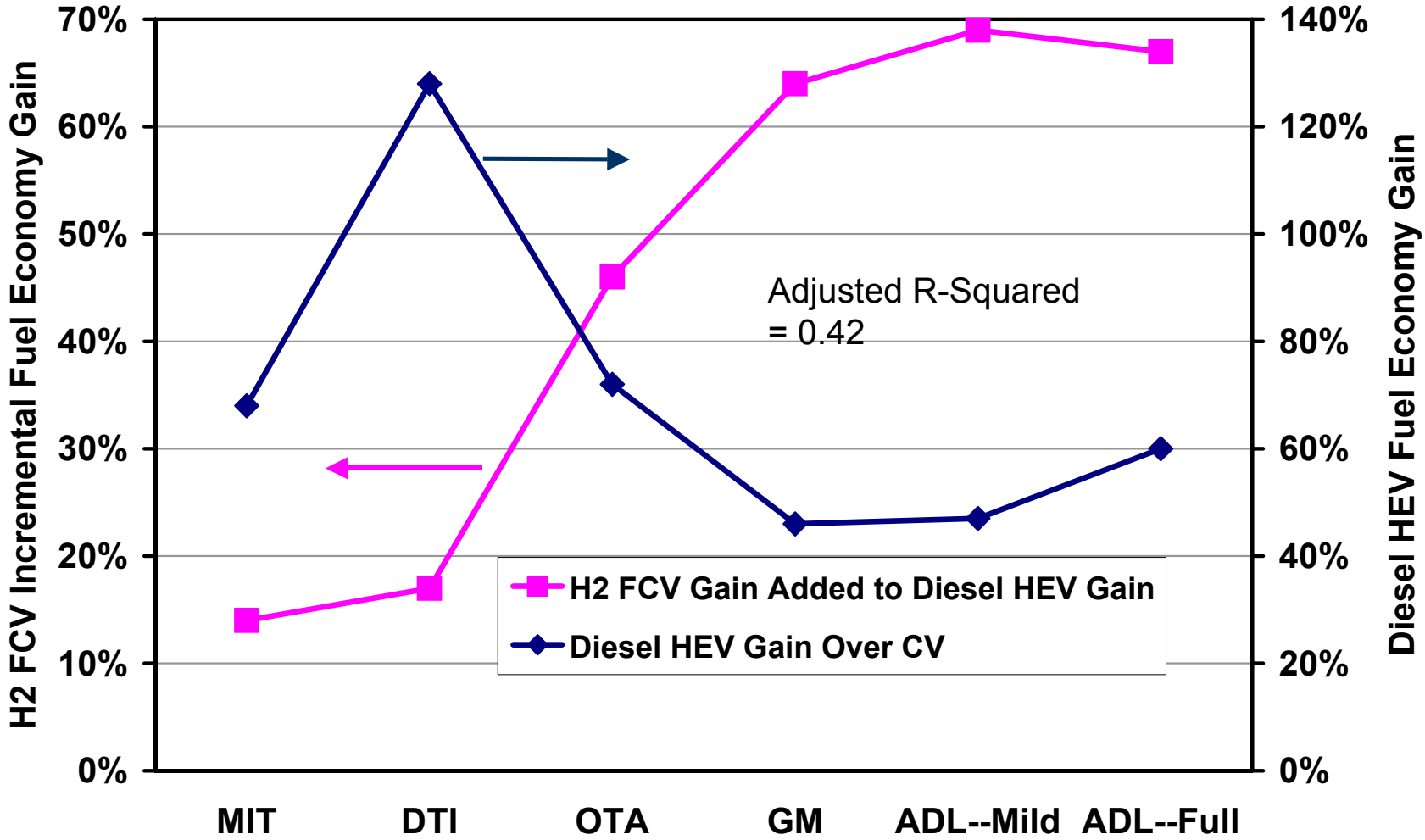
Cost Effectiveness of Dieselization vs. Minimal Hybridization is Uncertain



Aside From MIT, Studies Have Estimated Diesel HEVs to be More Cost Effective Than H2 FCVs



If a Study Estimated a Higher Diesel HEV Gain, It Likely Estimated Lower Added H2 FCV Gain



Themes Across Studies

- Cost Effectiveness Estimates for Value of Mass Reduction Vary Greatly
- Series Hybrids are Less Effective than Parallel Hybrids – Parallel Hybrids were Evaluated
- Minimal Hybridization is Competitive with Sophisticated Valve Actuation
- If Diesel Fuel and Gasoline are Similarly Priced (U.S.), Dieselization and Minimal Hybridization Compete
- If Diesel Fuel is Much Cheaper than Gasoline (Europe), Dieselization is Superior to Hybridization
- After Minimal to Mild ICE Hybridization, Dieselization is Less Cost Effective than Before (2 studies)

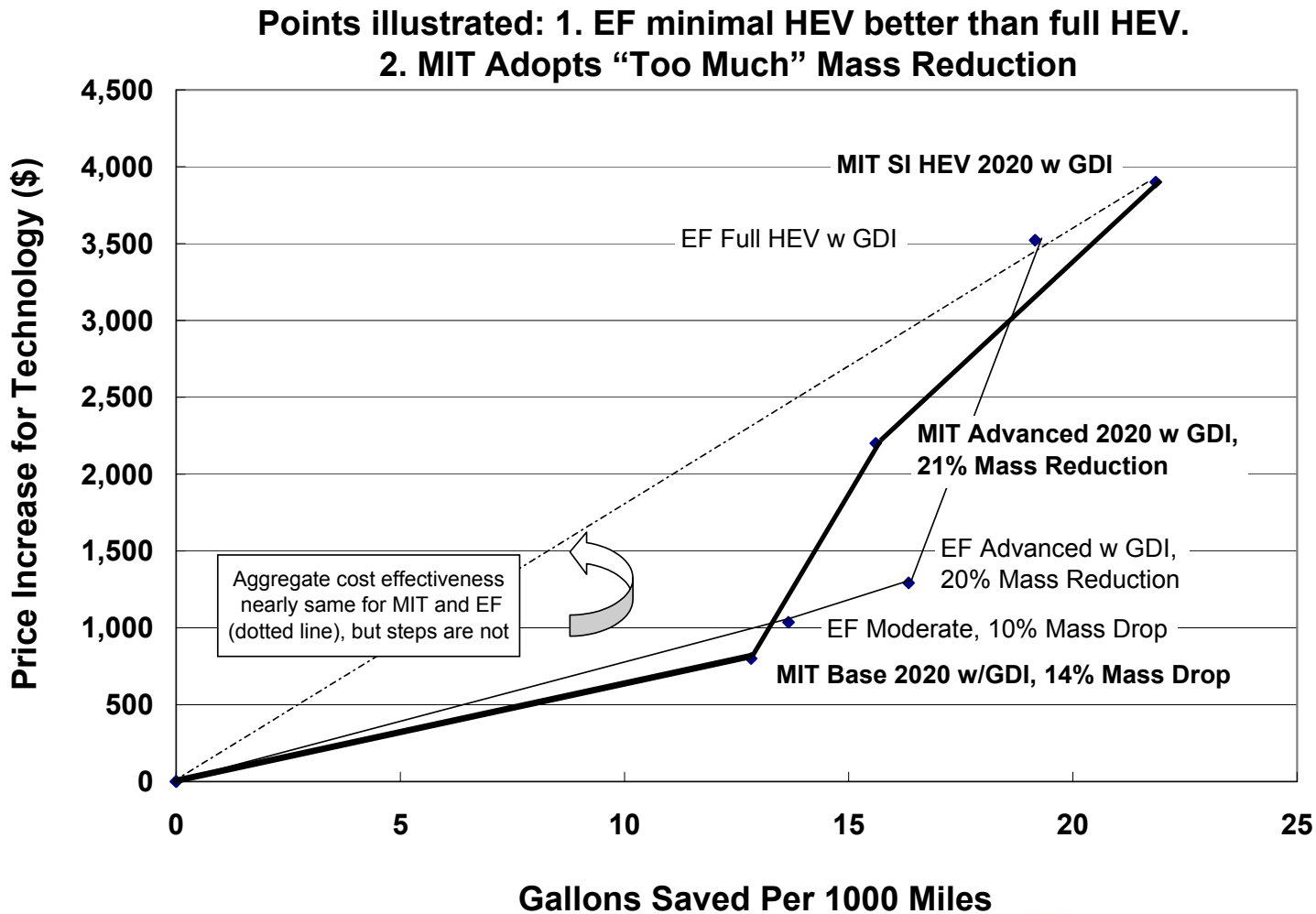
Common Themes (Continued)

- The Cost Effectiveness of Increasing Hybridization Diminishes Considerably (but use of grid is possible)
- Minimal to Full Hybridization vs. Minimal Hybridization to Dieselization Has Not Been Evaluated
- Diesel Hybrids Were Estimated to be More Cost Effective than H2 FCVs (but see caveats)
- Studies Optimistic About Diesel HEVs L/km are Less Optimistic About Incremental Benefit of H2 FCVs
- ICE HEVs Offer the Next Big Reduction in L/km, and H2 FCVs Another Big Reduction <u>with</u> Fuel Switching

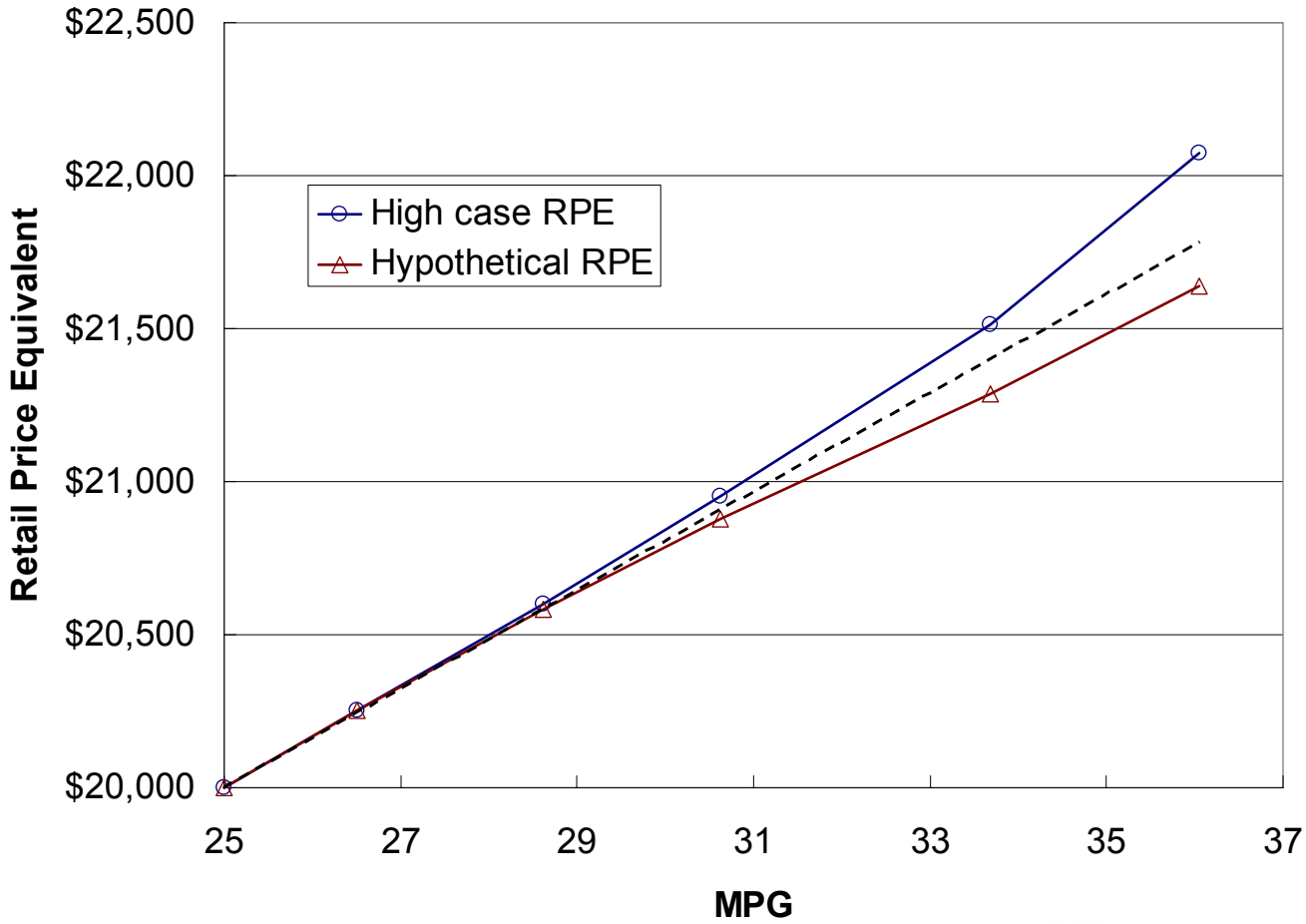
<u>Caveats:</u> Full fuel cycle emissions differences and oil replacement are not valued, fuel costs when switching (or alternating) fuels are very important. Cost effectiveness is not net present value!

Supplemental Supporting Slides Not Used in Presentation

Plots of the Sequence of Steps Show MIT Not Following the Theoretical Approach



Hypothetical Costs Within the NRC Range With Increasing Fuel Saved per $ Could Lead to Declining Slope



Several NRC Technologies Indicated that Multiple Technology Opportunities Exist at About 6% km/L gain for $375

	km/L	Retail Price Equivalent $	
	% Improvement	Low	High
Base Vehicle			
Cylinder Deactivation	3 to 6	$112	$252
Continuously Variable Transmission	4 to 8	$140	$350
Integrated Starter Generator	4 to 7	$210	$350
Camless Valve Actuation	5 to 10	$280	$560
Intake Valve Throttling	3 to 6	$210	$420
Engine Supercharging and Downsizing	5 to 7	$350	$560
Mean	4 to 7.3	217	415

High and Low Price for Technology Opportunities Allowing 6% Gain According to U.S. NRC 2001