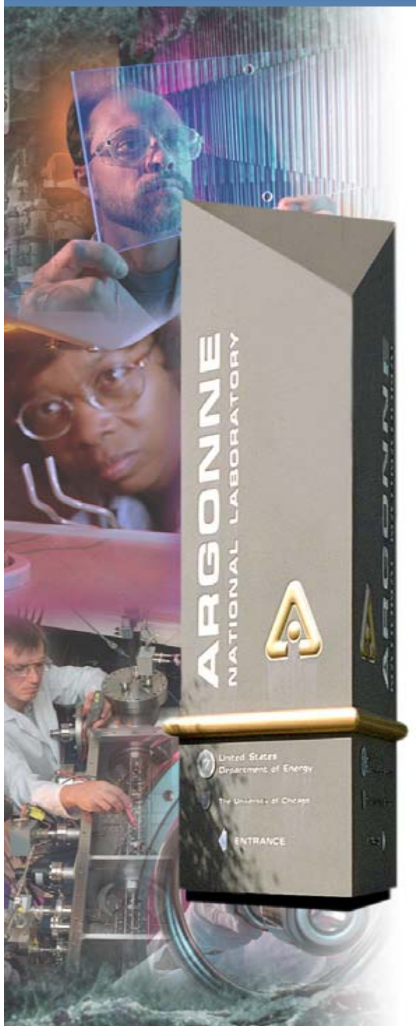
EVS 21 MONACO
2 - 5 April 2005



An Examination of the Potential for Regenerative Braking for a Range of Driving Cycles and Two Vehicle Configurations

D.J. Santini, F. An, S. Plotkin,
and J. Anderson

Center for Transportation Research

Sponsors:
E. Wall and T. Duong
Office of Freedom Car and Vehicle Technologies
U.S. Department of Energy

Argonne National Laboratory
Transportation Technology R&D Center

Born to be clean

A Simple Conclusion Has a Complex Set of Causes. Those Causes are Examined.

- ***<u>Conclusion:</u>***
- ***Potential fuel consumption reductions from hybridization of the biggest U.S. commercial trucks – Class 8 combination trucks (C8CTs) - are <u>far</u> lower than for front wheel drive cars***

- ***<u>Observation:</u>***
- ***By examining two ends of the spectrum – most favorable to least favorable – we can later better understand important vehicles in between, such as:***
  - ***Rear wheel drive passenger cars***
  - ***Front wheel drive passenger trucks***
  - ***Rear wheel drive passenger trucks***
  - ***Rear wheel drive straight trucks for urban delivery***

Two Ends of the U.S. Highway Vehicle Market – a Mid-Size Car and Large Commercial Truck - are Examined

	Mid-size Car (sedan)	C8CT (heavy truck)
Input/Test Mass (kg)	1648	31,818
Engine kW	115	320
Peak W/kg	70	10
Engine size (L)	3.0	12.0
Transmission	Auto (4)	Manual(10)
Frontal Area (m^2)	2.20	8.66
Drag Coefficient	0.32	0.70
Rolling Resistance C0 (C1)	0.009 (0.000115)	0.0065 (0.00000145)

The Theoretical Mid-Size Car is Slightly Larger than a Toyota Prius Hybrid

2005 Toyota Prius – Classified as Mid-Size by the U.S. Government

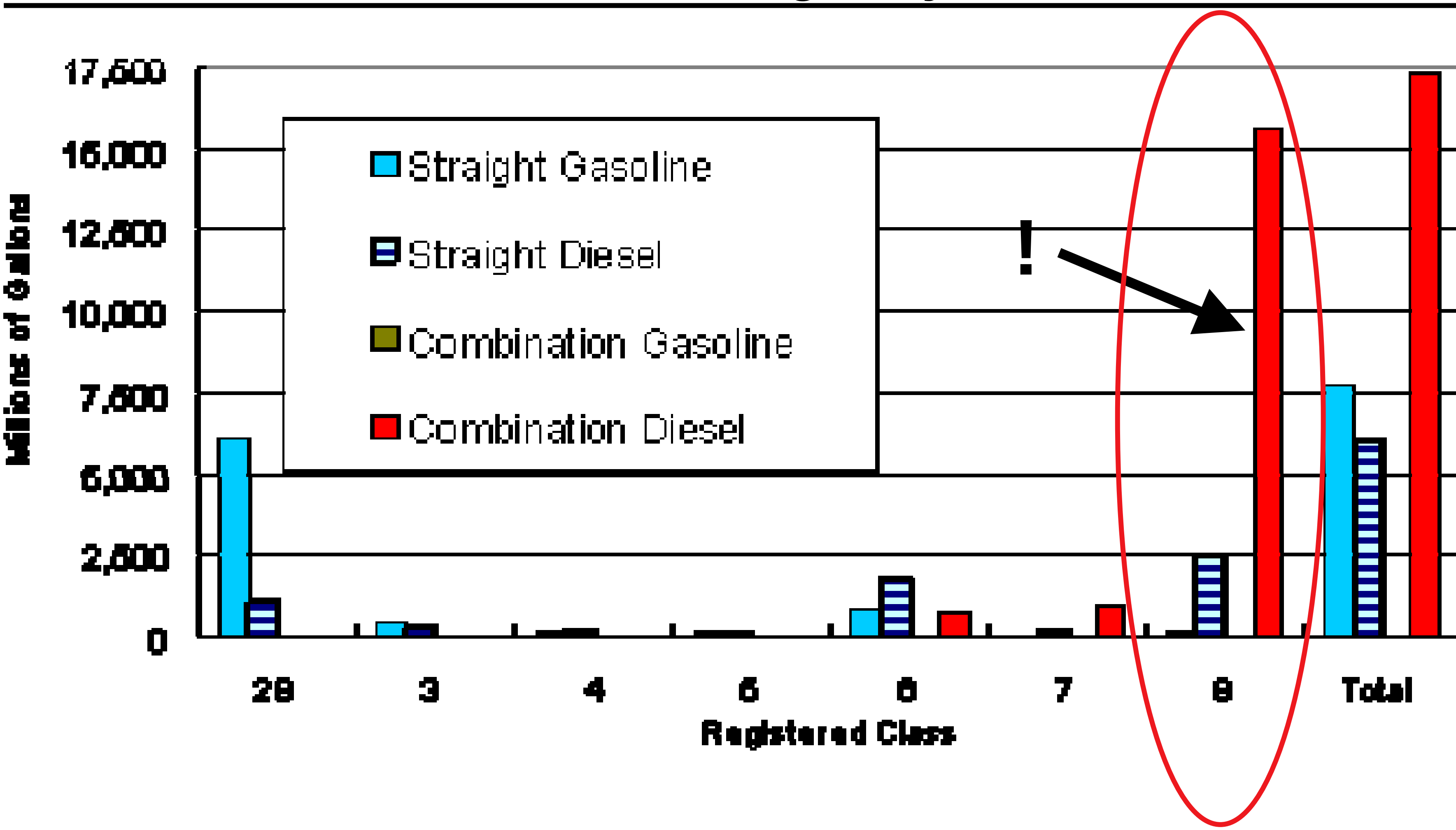
U.S. Class 8 Combination Truck (C8CT) Tractors Use Aerodynamic Features, Trailers do Not

Experimental Trailer **Commercial Tractor**

U.S. C8CT With an Experimental Aerodynamic Trailer (5 axles typical)

(Straight trucks [not shown] have an integral storage box on 2-3 axles)

C8CTs Dominate the U.S. Consumption of Commercial Truck Highway Diesel Fuel

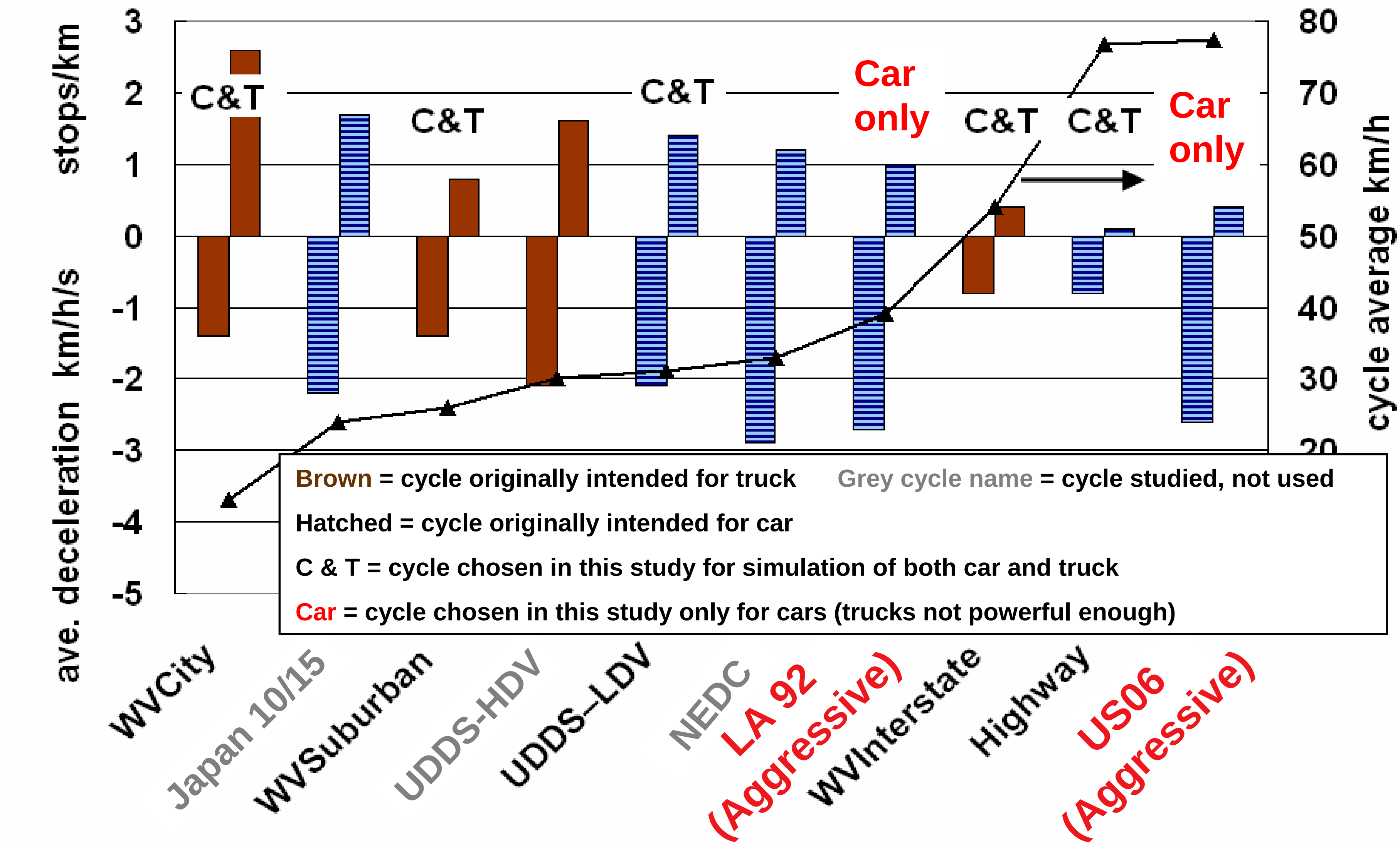


U.S. Fuel Use Patterns by Weight Class and Type of Commercial Truck, 1997

How are Fuel Consumption Reductions from Use of Regenerative Braking Energy Achieved?

- **Note: Fuel energy suffers high losses before becoming useful.**
- **Useful energy is defined here as positive tractive energy *plus* accessory energy! Negative tractive energy accomplishes deceleration. It has the potential to become useful energy via regeneration. Many losses occur before a small amount of useful energy is made available.**
- **Friction braking energy, which is less than negative tractive energy, must be converted to electrical energy by a generator, stored, used by a motor to eliminate engine use and losses.**
  - **Issue 1: How much of the engine's useful (and wasted) energy can be replaced by a motor via generated and stored electrical energy?**
  - **Issue 2: Since the stored energy can be used flexibly in time, when are the most effective times to replace useful energy to enhance efficiency?**
  - **Issue 3: Does the motor power allow substitution of more efficient engine technology in a manner acceptable to the consumer and society?**
    - Atkinson cycle can be used despite low power density
    - Diesels may be enabled by hybrid powertrain emissions reduction benefits

Cycles Studied = 7 for Cars, 5 for C8CTs. Stop Frequency and Deceleration Affect Regeneration Energy Totals.



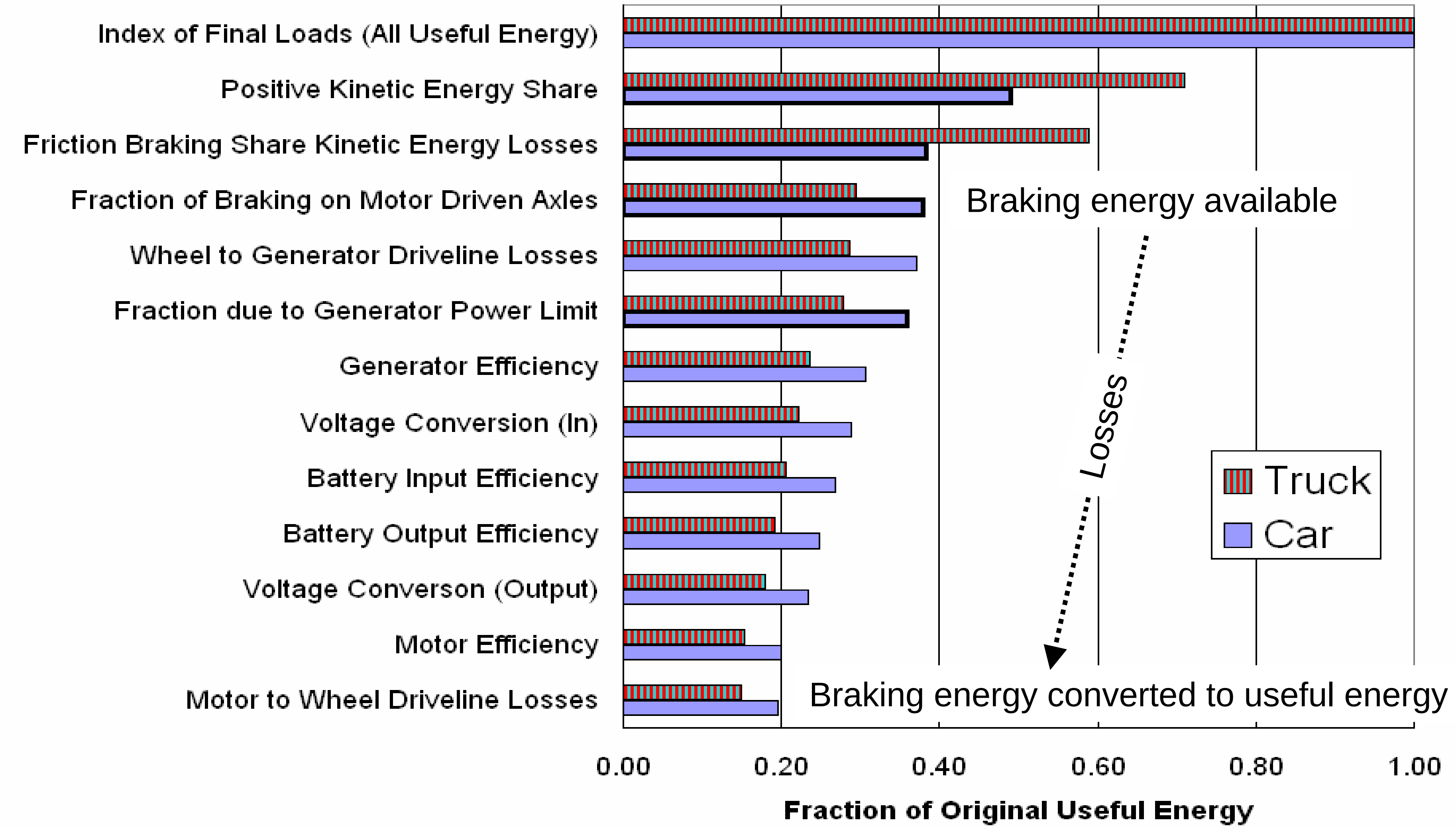
 Some Attributes of Driving Cycles Examined and Used

Some Fundamentals are Difficult.

- **All prior losses to aerodynamic drag and rolling resistance before deceleration starts are irretrievable losses. Kinetic energy is theoretically retrievable, but retrieval is practically limited.**
- **Positive inertia kinetic energy = negative inertia kinetic energy over a stop-start sequence and over a driving cycle**
- **Only a small portion of negative inertia kinetic energy can be converted via regenerative braking to positive useful energy.**
- **Deceleration is caused in a conventional vehicle by four forces:**
  - Aerodynamic drag (causing further irretrievable losses, unless the hybrid is altered)
  - Rolling resistance (causing further irretrievable losses unless the hybrid is altered)
  - Driveline friction (which may be different in a hybrid than conventional powertrain)
  - Friction braking
- **Regenerative brakes convert energy otherwise lost to friction brakes**
- **Hybrid regenerative brakes cannot entirely replace friction brakes**
- **Numerous losses occur after generation of electricity by regenerative braking, before useful energy is created by the motor**

Capture, Storage and Use of Braking Energy Involves Many Losses. A Small Share of Useful Energy Can be Replaced

Stepwise Losses up to Braking Energy and After to Replace Useful Energy

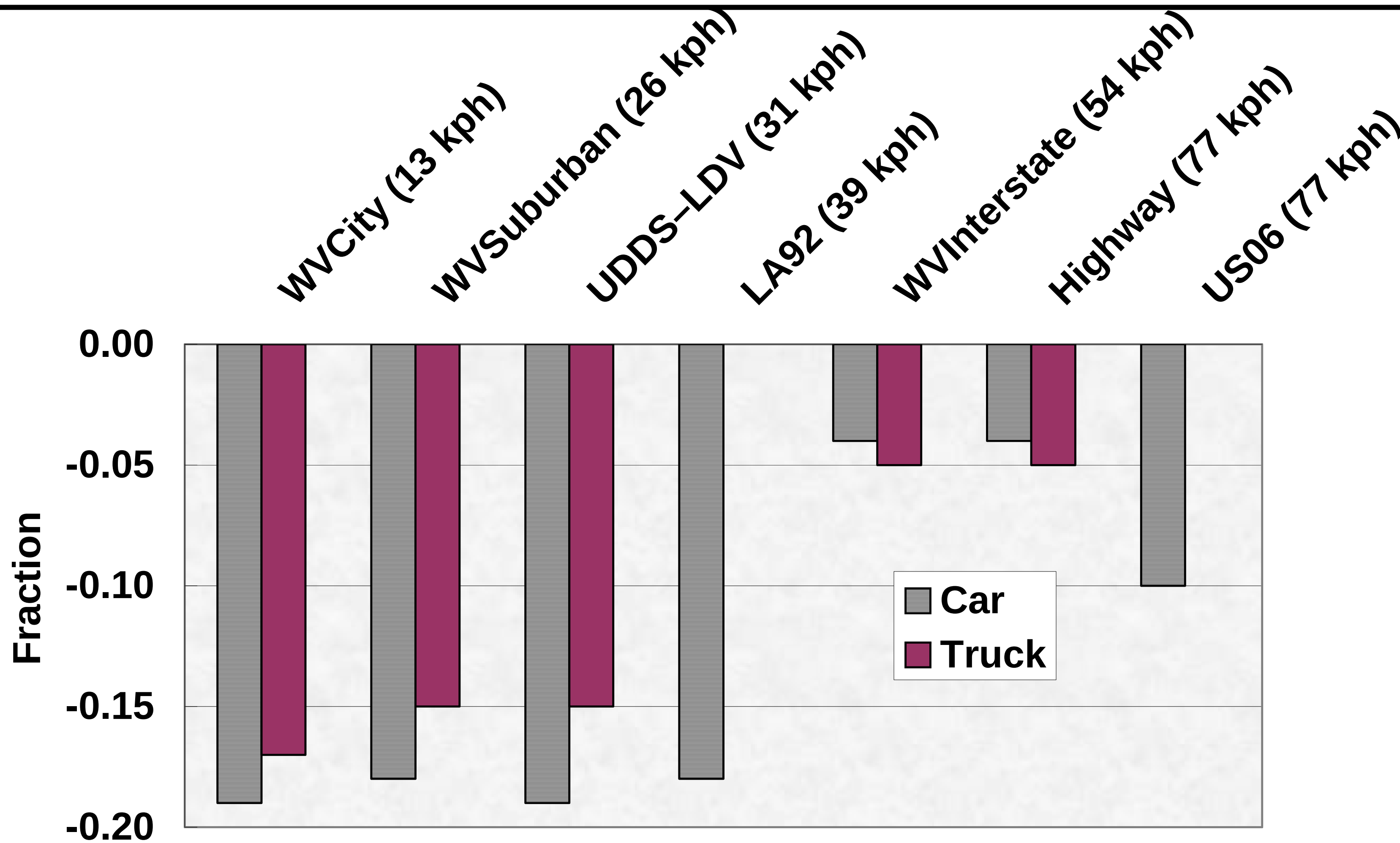


Example: UDDS-LDV Cycle – Results Vary Significantly by Cycle

3 Fuel Consumption Reduction Effects via Use of Captured Braking Energy are Possible, and are Separately Examined

- **Partial *engine (energy) replacement* (reduction in amount of useful energy originating from the engine and from fuel)**
  - **using the motor and battery instead of engine and fuel holding modal distribution of energy use ~ constant**
- ***Efficiency enhancement* (improvement in efficiency of an unaltered engine during times that it continues to operate)**
  - ***selectively* using motor and battery instead of engine, differing mode shares for fuel and electric energy**
- ***Engine substitution* (altering the engine used)**
  - **downsizing the engine, using motor power to maintain total power and comparable acceleration**
  - **adopting more efficient engine technology**
    - Atkinson cycle spark ignition gasoline
    - Direct injection compression ignition diesel

Engine (Energy) Replacement Benefits are Computed - Car for 7 Cycles, C8CT 5



Fractional Reduction in Tractive Load + Accessory Load

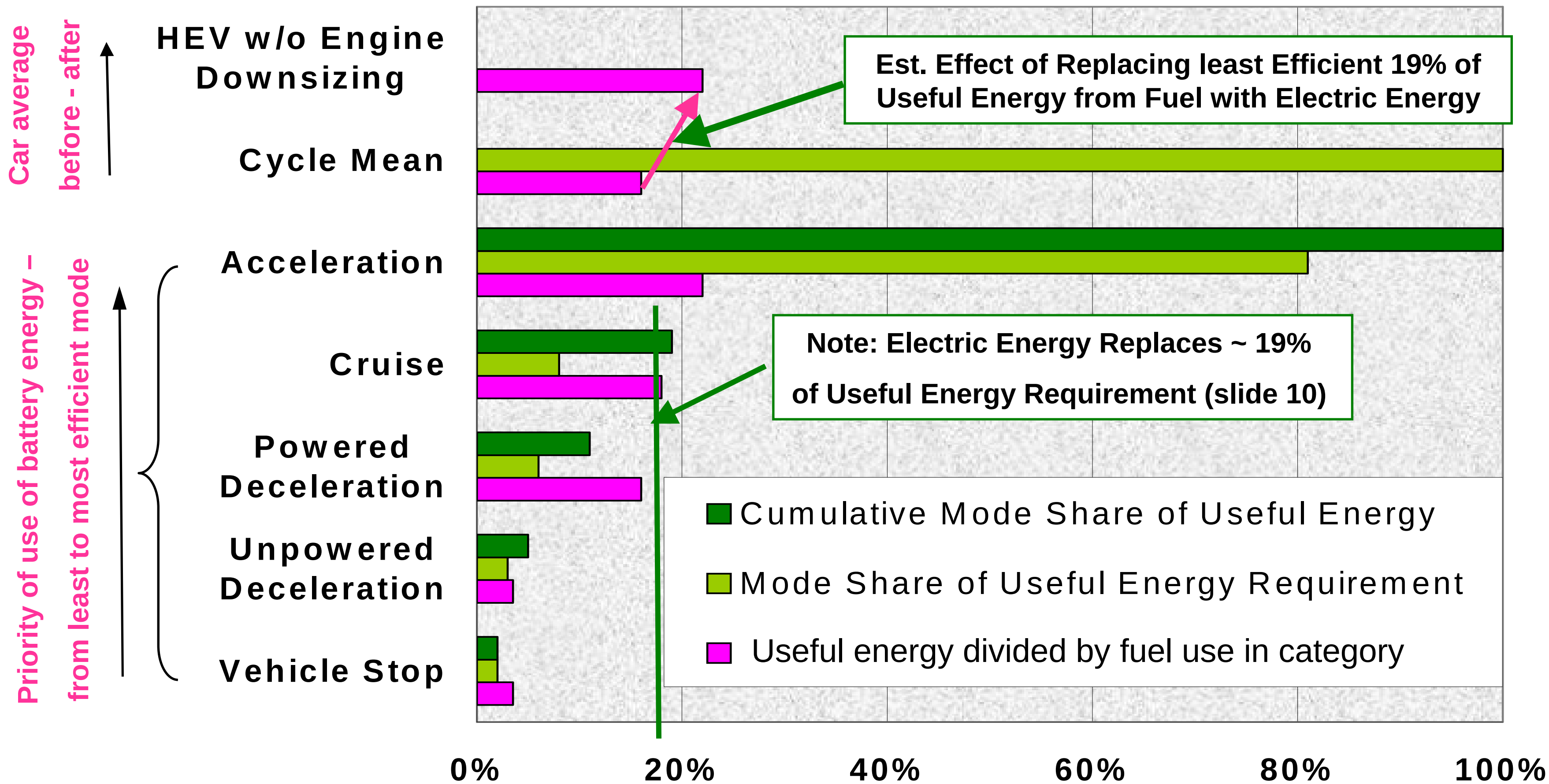
Useful energy reduction from regenerative braking, divided by original useful energy requirement

An Important Accounting Concept is Average Modal Energy Use and Efficiency Over the Cycle

Modes of Operation (conventional vehicle efficiency)

- **Vehicle stop** (very low)
- **Acceleration** (highest)
- **Cruise** (intermediate)
- **Powered Deceleration** (intermediate)
- **Unpowered Deceleration** (very low)

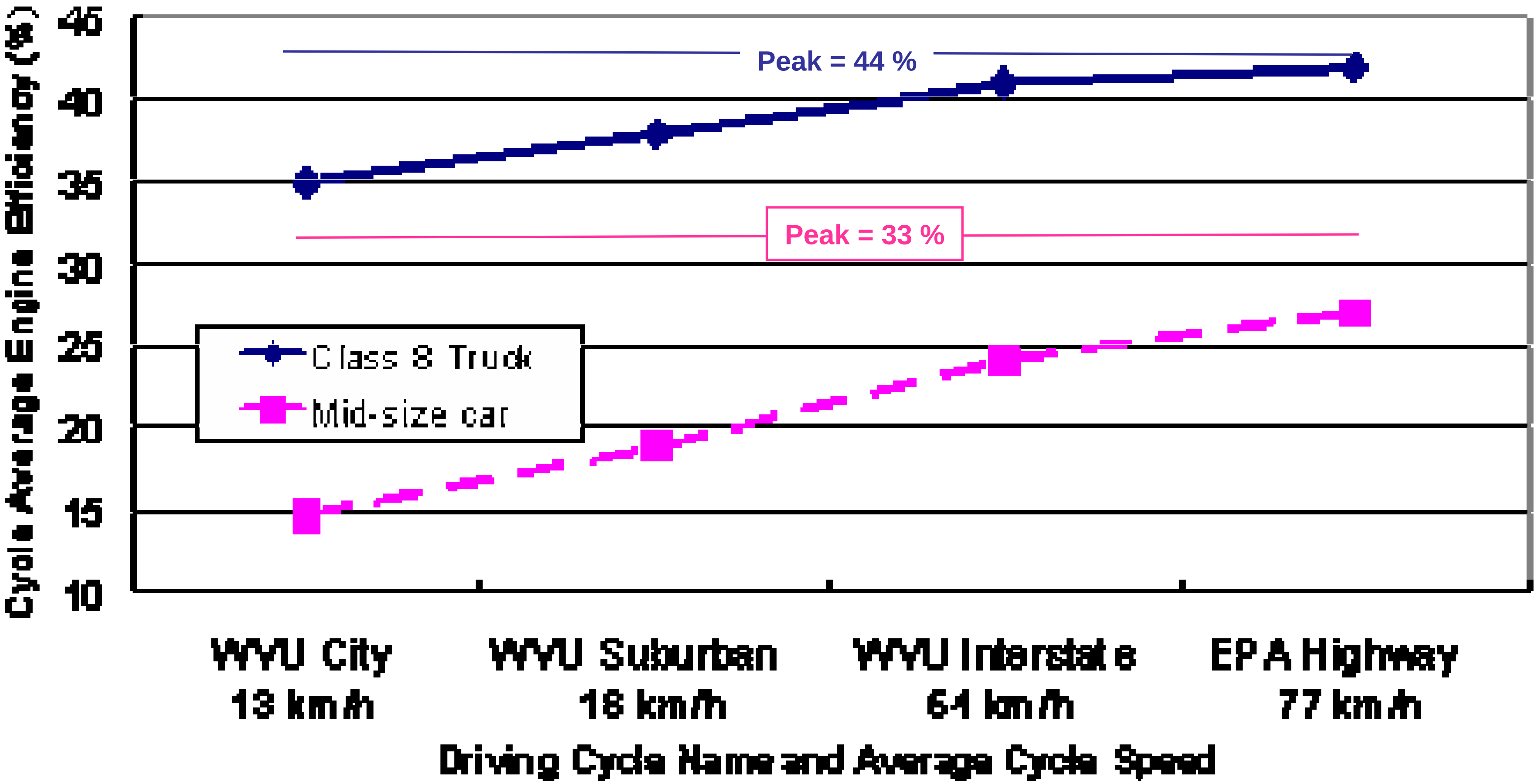
Efficiency Enhancement - Uses Electric Energy to Replace Least Fuel-Efficient Modes



Example – Energy Attributes by Mode for Mid-Size Car for UDDS-LDV

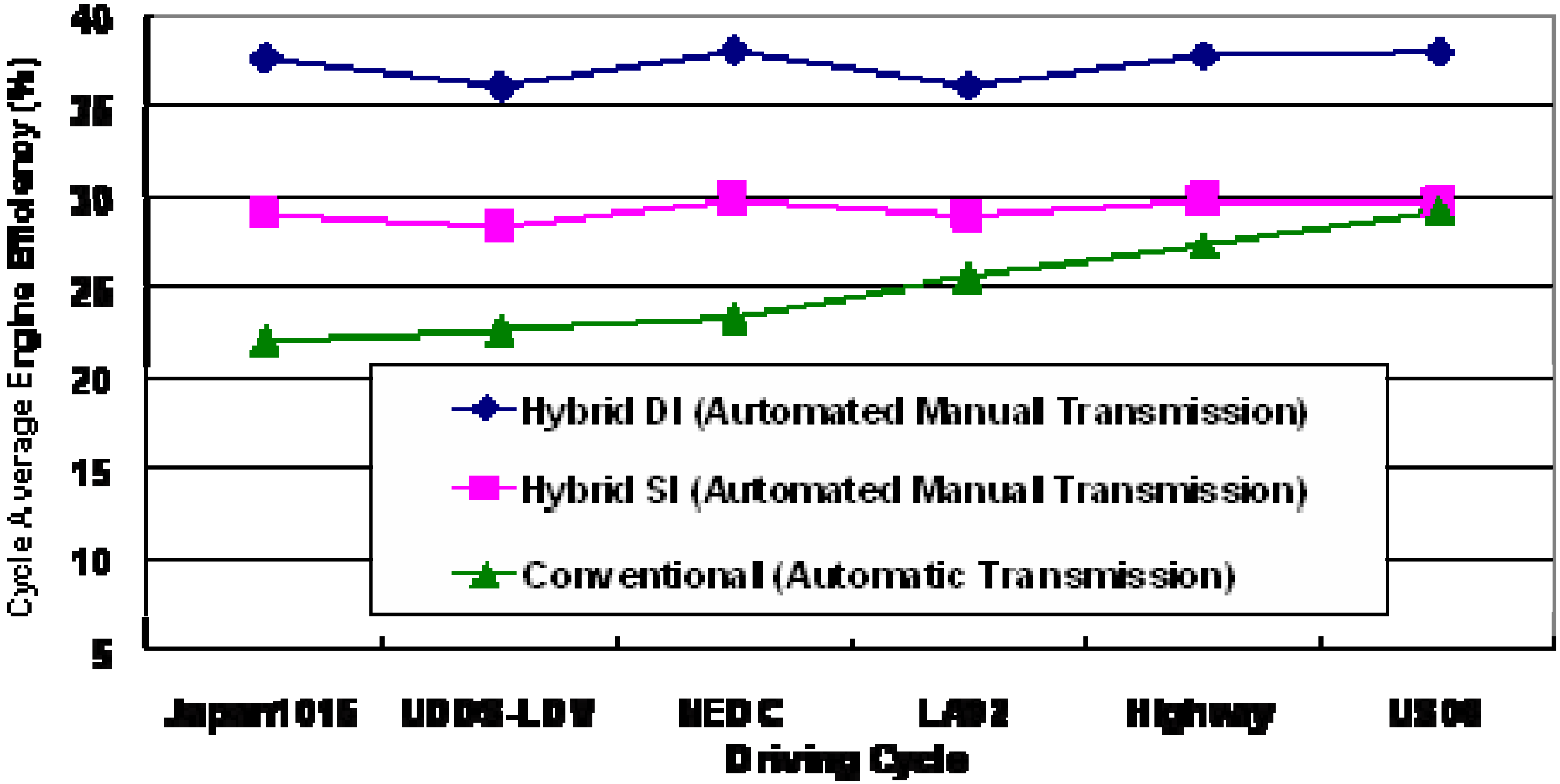
Driving Cycle: No Engine Downsizing (Achieves 22% Efficiency: Peak is 33%)

Engine Substitution: Extreme Downsizing Flattens The Engine Efficiency Curve vs. Speed and Moves the Curve Closer to the Peak. DI Diesel Causes a Jump vs. ICE



Simulated Engine Efficiencies, by Driving Cycle: Mid-Size Car with SI ICE and C8CT with Direct Injection Diesel

Rousseau et al's EVS-21 R&D Implies Near Constant Engine Efficiencies Are Achieved by "Full" HEVs

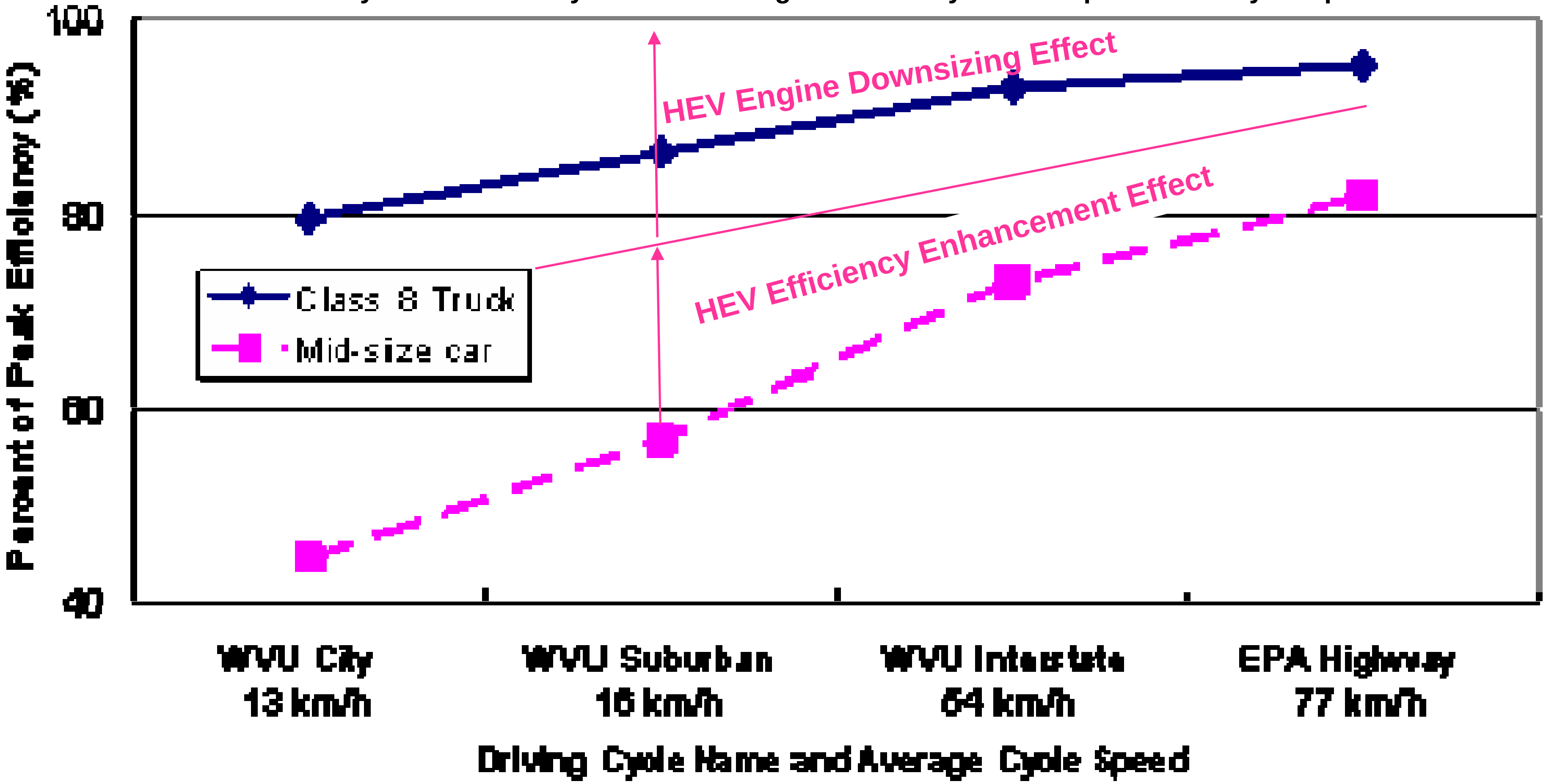


Sequence of Engine Efficiencies, by Driving Cycle, for "Full" Parallel Hybridization of a Light Duty Vehicle with an SI ICE, then with a Direct Injection Diesel

Even Extreme Downsizing in a Conventional Powertrain Does Not Achieve Flat Engine Efficiencies vs. Cycle Speed

Note that there is much less remaining efficiency to "squeeze out" by means of hybrid electric energy in the C8CT

Implications of last few slides is that both efficiency enhancing control strategy and engine downsizing are necessary to obtain flat hybrid vehicle engine efficiency near the peak for all cycle speeds.

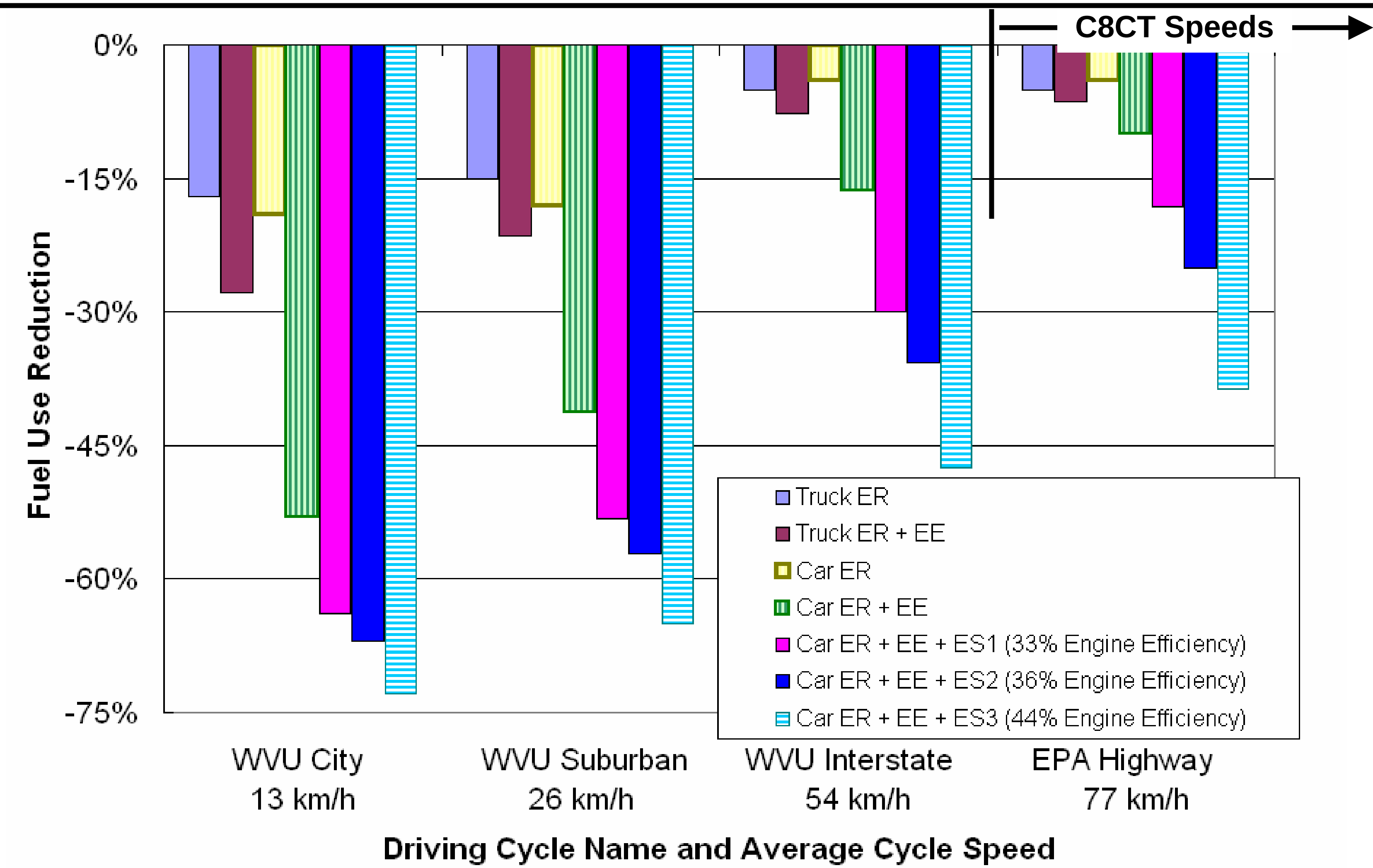


Percent Peak Engine Efficiency in a Mid-Sized Car and C8CT

The Passenger Car Has Five Ways to Increase Efficiency When Hybridized; The C8CT Only Two.

Opportunity Associated with Hybridization	Car	C8CT Truck
Engine (Energy) Replacement (Electric for Tractive & Accessory Energy) [ER]	X	X
Efficiency Enhancement (Control Strategy) [EE]	X	X (less effective)
Engine Substitution – Downsizing [ES1]	X	Done
Engine Substitution - Improved SI Technology (Atkinson) [ES2]	X	Not Applicable
Engine Substitution - Switch to Advanced Diesel [ES3]	X	Done

C8CT's Have Less HEV Potential on a Given Cycle and are Used on Unfavorable Cycles



~ Maximum Reductions in Fuel Use via Hybridization for the Mid-Size Car vs. C8CT, by Driving Cycle and Possible Step

Potential Benefits of Hybridization of C8CTs are Far Lower than for Front Wheel Drive Cars

- **C8CTs are used on high speed, limited access highways. Stop/start is infrequent. Share of kinetic energy is small**
- **Extreme engine downsizing is already used by C8CTs**
- **Highly efficient diesel engines are already used by C8CTs**
- **Two points discussed in the paper, not in the presentation**
  - **Generator-motors on two driven axles (of five) for C8CTs can probably accomplish a much smaller share of regenerative braking**
  - **kW ratings of generators with comparable ability (vs. car) to recover braking energy would be very large relative to the kW ratings of engines presently in C8CTs**

Thus: Spin-off of on-highway fuel saving benefits from light duty hybrid powertrain R&D to C8CTs will be small.