Technology to Meet Future FE and GHG Requirements

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Improving Vehicle Fuel Economy

- Methods to improve vehicle fuel economy are well understood from knowledge of energy loss
- General methods are
  - improve engine peak efficiency potential
  - reduce losses at light load from throttling
  - reduce weight, drag and rolling resistance
  - reduce accessory load and eliminate idle

ICF Methodology

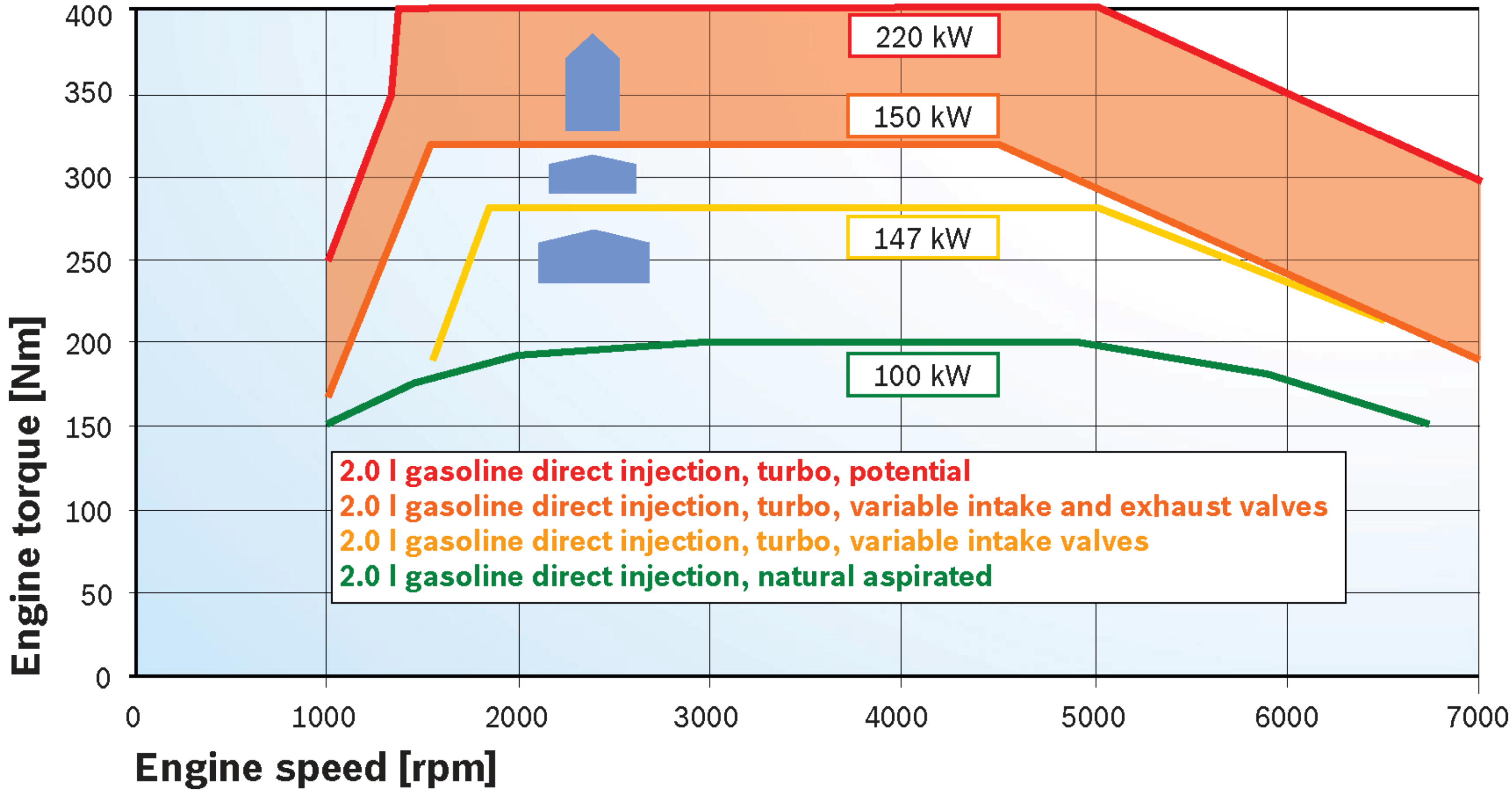
- ICF monitors technology developments worldwide through the trade press and key international conferences.
- Preliminary analysis of potential based on research papers and prototype data.
- Extensive follow up on technology attributes and lead time with manufacturers and Tier I suppliers.
- All cost data obtained from high level contacts at Tier I suppliers, who are now major technology developers.

Short Term Engine Technologies

- Technologies in the pipeline now
  - Variable Valve Lift (2-step/ continuous)
  - Gasoline Direct Injection with CR increased by ~2 points (lean burn longer term for US, used in Europe)
  - Cylinder cutout (V6/8 only)
  - Turbo- GDI- VVT combination
  - Reduced Engine Friction

More Torque

by Means of Direct Injection, Cam Phasing and Turbo Charging



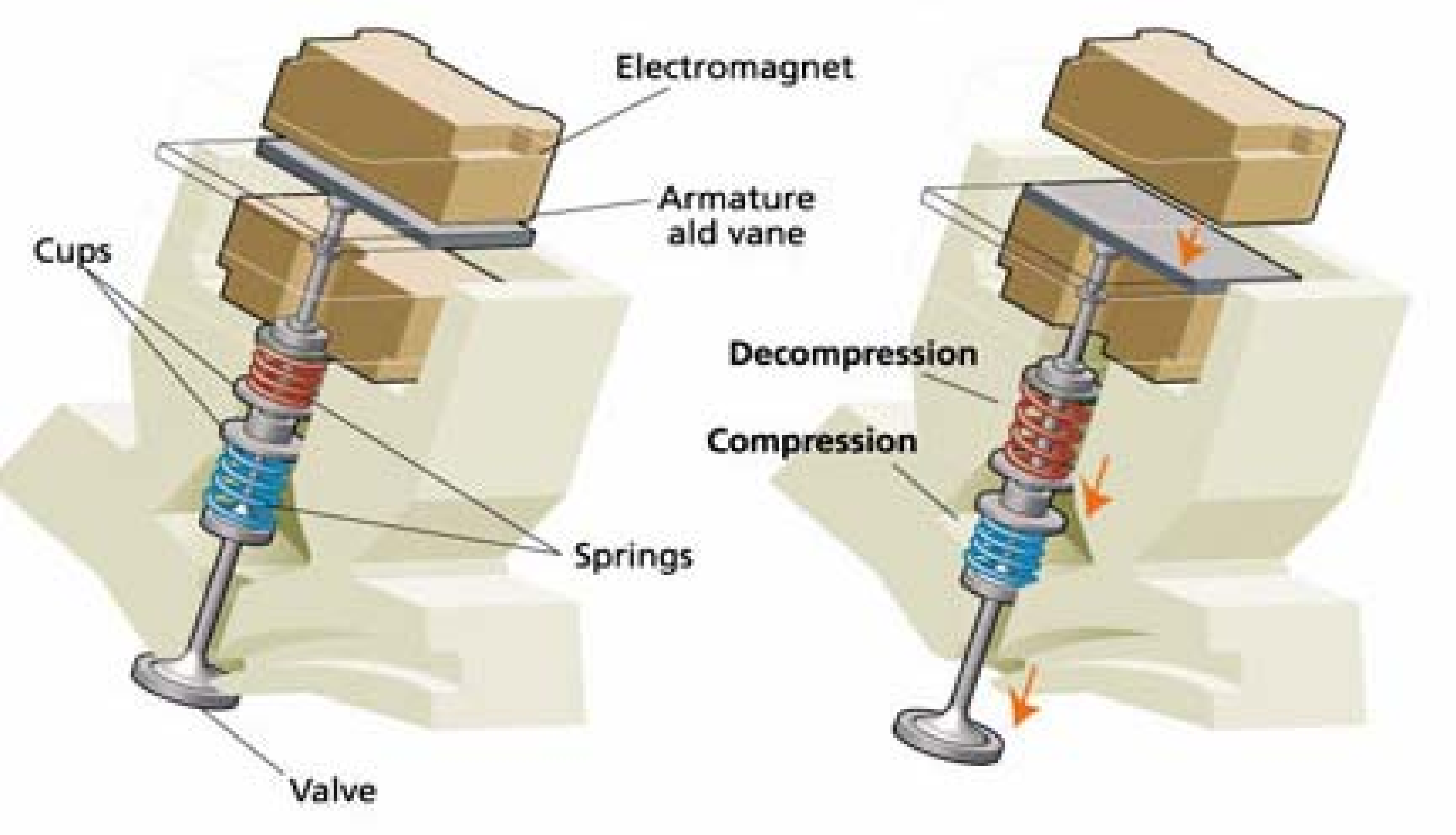
2015 Engine Technology Potential

2 –step valve lift		4 to 5%	$125 -175
Continuous valve lift		7 to 8%	$300 -400
Gasoline Direct Injection (GDI)		3 to 4%	$160 – 250
Turbo – GDI		13 to 15%	$ 0 to 650
Friction Reduction		2 to 4%	$30 to 70

Mid-term Engine Technology

- Most promising development is cam-less valve actuation which offers potential to reduce throttling loss to near zero, and make Atkinson cycle possible at light load.
- Cam-less engine will be key enabler for gasoline HCCI in longer term
- "Half cam-less" engine will enter production in 2014/2015 in luxury cars with about 15%+ FE improvement at a cost of $500 to $700.
- More advanced valve strategies may allow mixed mode 2-stroke/ 4-stroke engines by 2020.

Valeo Electromagnetic Camless Valve Actuation Schematic



2030 Engine Technology Potential

"Half cam-less" engine		15 – 16%	$400 to 600
Full cam-less HCCI with GDI		19 – 22%	$1000 to 1500
Advanced friction reduction		4 to 6 %	~$100
GDI lean burn		17 to 19 %	$1000 to 1500
Combination with turbo		~ 25% ?	~ $1500

Transmission Technology

- While more gear ratios and wider ratio range allows better matching of engine to load, reduction of internal losses (especially in the torque converter) is also important.
- Future transmission options seem to be shaping up as follows:

  - Six/Seven speed automatics for RWD and larger FWD cars

  - CVT for smaller FWD cars and small trucks

  - AMT (6-/ 7-speed) for sporty cars.

Transmission Technology Benefits

Six speed automatic		4 to 5 %	$100 to 150
CVT (small cars)		6 to 8 %	$150 to 200
AMT (sports cars)		7 to 8 %	$150 to 200
Torque converter elimination		3 to 4 %	~ 0

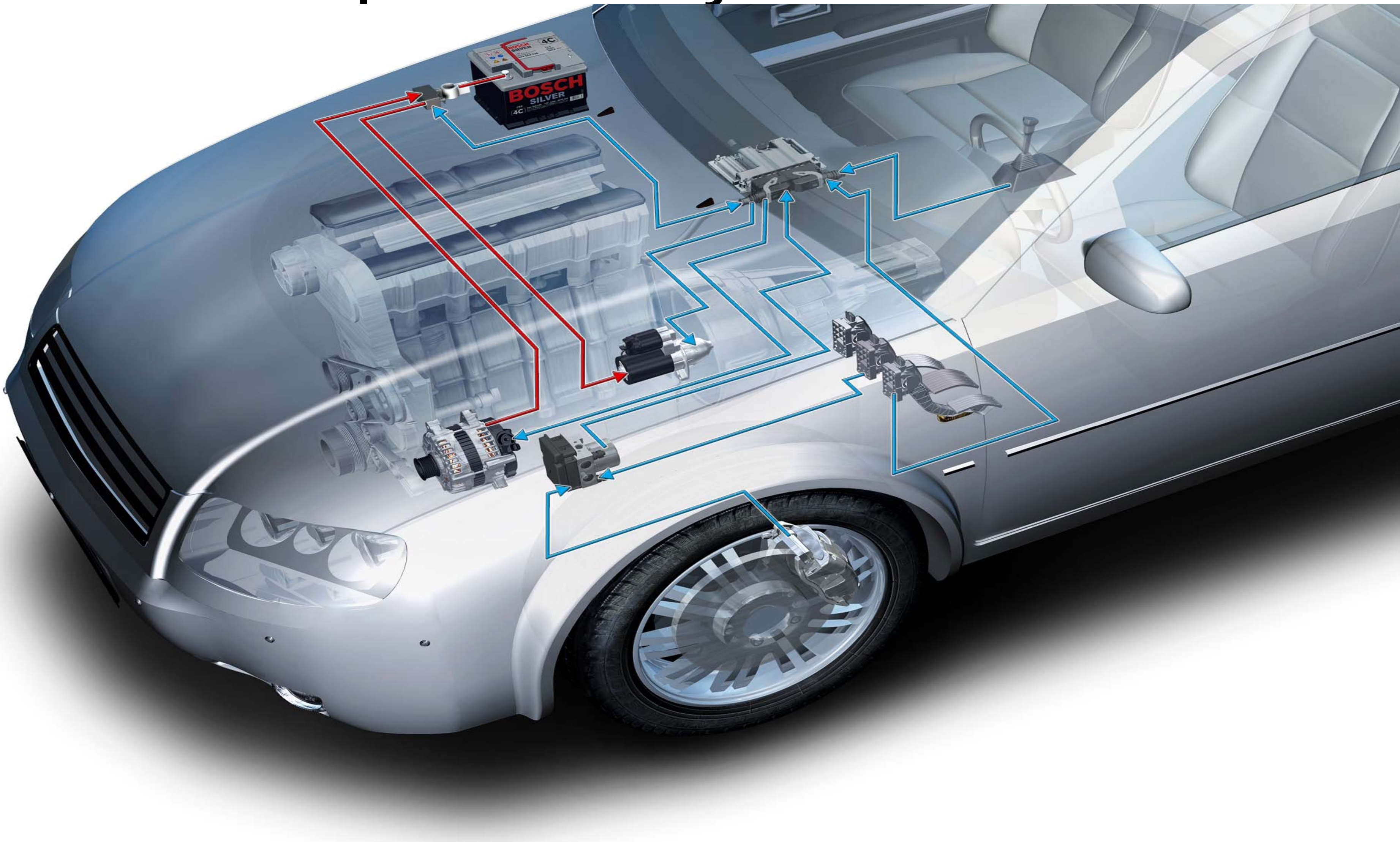
Reducing Vehicle Energy Demand

- Weight reduction is possible but quite expensive. While up to 20% weight reduction is technically possible, only 5 to 10% may be practical at reasonable cost ~ $60 per percent
- Drag and rolling resistance reductions of 10 to 20% can be achieved by 2020.
- Driving the accessories electrically is more efficient than belt drive, since accessories can be used ‘on-demand’. Electric Power Steering and Water Pump are the most effective.

Idle Stop- Start

- New “intelligent” starter motor design pre engages engine when stopped, resulting in faster, quieter start, even with 14V system.
- Electrical system must be upgraded with additional battery to withstand start cycles.
- System will also require electrical AC drive and transmission pump + “hill holder” for automatic transmissions.
- Electrical upgrades will facilitate electric accessories such as power steering and water pump, with additional FE benefit.

Idle Stop Start System



Maximum Potential of Conventional Technology (FE Increase)

		2006 – 2016	2016 – 2030
Engine & Transmission		15 – 19 %	22 – 28 %
Weight, drag and tire loss reduction		7– 11 %	11 – 16 %
Accessories		2 – 3 %	3 – 5 %
Idle Stop		3 – 4 %	2 - 3 %

Summary of Conventional Technology Potential

- Overall, the sum of all conventional technologies can lead to a 33 ± 3% FE increase by 2020 and possibly, up to 50 ± 5 % FE increase by 2030.
- The inability of manufacturers to change technology rapidly will limit the reduction actually attainable to lower values.
- Major conclusion is that hybrids and diesels are required to meet the ~40% improvement goal for 2016 and will require a market penetration of 15% to 20%% combined.
- Of course, consumer preference changes to 2016 can help or hurt these values.

Types of Hybrids

- Meeting the 40+% 2016 requirement and future requirements will require relatively rapid transition to electric drive -100% by 2030?
- A large number of “hybrid” designs have been unveiled, each with unique attributes.
- Four types that will be in the US market and span the range of designs
  - Belt drive Alternator Starter (BAS)
  - Crankshaft mounted single motor (IMA)
  - Dual Motor “full” hybrids (Prius/Escape)
  - Plug-in hybrid vehicles.

Common Attributes of Hybrids

- Hybrids must fully exploit all synergies with drive train and accessories to provide large improvements in fuel economy.
- Hybrids provide large fuel economy gains only in stop-and go driving.
- Benefits deteriorate in very hot/cold weather due to space conditioning needs.
- Hybrids not suited for cargo hauling or high continuous load operation.
- Different geographies and densities provide different opportunities for different designs.

Hybrid System Benefits

- BAS systems using existing 14V electrical system can be cheap but it will provide limited FC reduction, ~ 15%
- The Toyota system can be very efficient with FC reduction approaching 45% but has the disadvantages of high price, ~US$5000-7000
- One- motor systems of the Honda IMA type could be more cost effective than other types while offering significant FC reduction, ~30%.
- Different manufacturers have very different assesements of what will ultimately succeed.

Plug-in Hybrids

- Definition of PHEV varies on vehicle capability in all-electric mode.
- Type, range in (semi) EV mode and battery cost issues dominate technical debate.
- However, consumer acceptance and likely level of electricity use issues are probably more important than technical issues.
- At present, difficult to make any economic case for purchase even with off-peak electricity.
- GHG benefits are currently quite small in the US relative to a hybrid, and de-carbonization of the electric sector needs to occur first.

Electric Vehicles

- Li-Ion Battery technology has now advanced to the point where 200+km range is possible, but cost is still high.
- EV costs are associated with the idea that they should replace rather complement typical cars and offer all their attributes.
- City car type EV designs can be inexpensive and very efficient, and can serve urban commuters or be a rental vehicle.
- However, ideal applications mirror those situations well served by mass transit. Hence, City EVs may have unintended consequences of shifting people away from mass transit!

Diesel Issues

- Unlike a hybrid, the diesel’s fuel efficiency benefit is more robust across all driving conditions and under load.
- Cost and benefit on cycle comparable to IMA hybrid, but GHG benefit is lower due to higher carbon content of fuel.
- Terrific low-end torque makes it well suited to cargo hauling and towing .
- Diesel fuel subsidy in EU and some developing countries creates incorrect incentives for light vehicle dieselization. Schipper and Fulton claim diesels in EU have double the VMT of gasoline!

Diesel Costs and Benefits

- Current diesel engines add $1500 (4 cyl.) to 3000 (V-8) for the engine alone and another $700 to $1200 for emissions after-treatment.
- FE can be increased by 30 to 35% in combination with other changes.
- Significant additional improvement is possible with a diesel- hybrid combination, with some cost reduction in emission control.
- Diesel market in the US seems to be fading with rapidly rising diesel fuel prices.

$/Percent FC Reduction: Midsize Car with 25mpg On-road Base

		2015	2025
Conventional Tech		35 to 50	30 to 40
Advanced Conventional		NA	50 to 60
IMA Hybrid/ Diesel		100- 110	75 – 80
Full Hybrid		140 – 160	100 – 120
PHEV		200+	~150

Analysis Implications

- Costs of hybrid, diesel, PHEV and EV per unit of fuel consumption are much higher than those of conventional technology.
- With increased efficiency from conventional technology, marginal value of HEV,PHEV and diesel keep getting worse.
- As the developed world embarks on serious conservation, fuel prices cannot be expected to rise significantly by 2030 so consumer incentives continue to drop.
- Possibility of a consumer and political revolt against “excessive conservation”.

Consumer Expectations

- Most analysis based on some constant attribute assumption, held to current levels
- Why should the 2030 vehicle have attributes similar to current vehicles?
- Vehicles could continue to become more luxurious and in 2030 most vehicles could offer
  - Wide range of power accessories
  - Ultra-safe bodies and radar collision avoidance
  - 120 mph cruise capability
  - Four wheel drive, four wheel steering
  - Self driving and self parking capability

Fearless Forecast

- Vehicle FE rises to 35 mpg (EPA test) by 2018 and then stay flat to 2040- history repeats itself!
- Speed limits are raised to 125 mph by 2030 on special toll ways.
- On road fuel economy starts declining in 2018 and goes back to 20 mpg by 2040!
- President Sarah Palin repeals EPCA.