Mobile Source Climate Change Emission Reduction Technologies

Sacramento, California

April 20, 2004

California Environmental Protection Agency

Air Resources Board

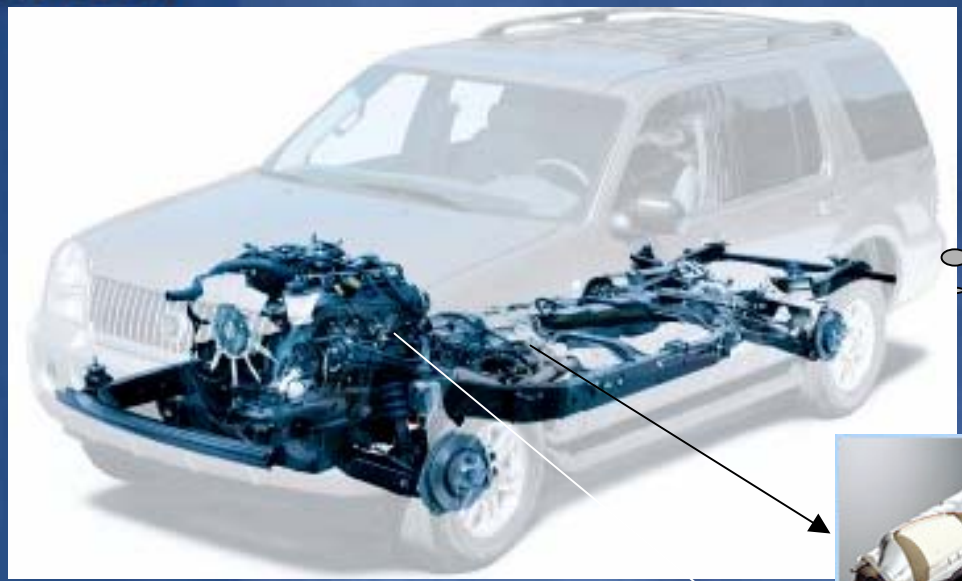
International Vehicle Technology Symposium

- International experts on vehicle climate change emission reduction technologies participated
- Numerous technology areas were covered
  - engine and drivetrain modifications
  - alternatives to reduce methane and nitrous oxide emissions
  - modifications to air conditioning systems
  - alternative fuel vehicles

ARB Technical Review

- Staff investigated technologies that can reduce greenhouse gas emissions from motor vehicles in 2009 and beyond
- Greenhouse gases include:
  - carbon dioxide (CO_2), methane (NH_4), nitrous oxide (N_2O), and hydroflourocarbons (HFC143a)
- Relied primarily on comprehensive technical study initiated by the Northeast States Center for a Clean Air Future (NESCCAF)

Technology Evaluation



Engine

Transmission

A/C compressor

CO_2

Methane

Nitrous Oxide

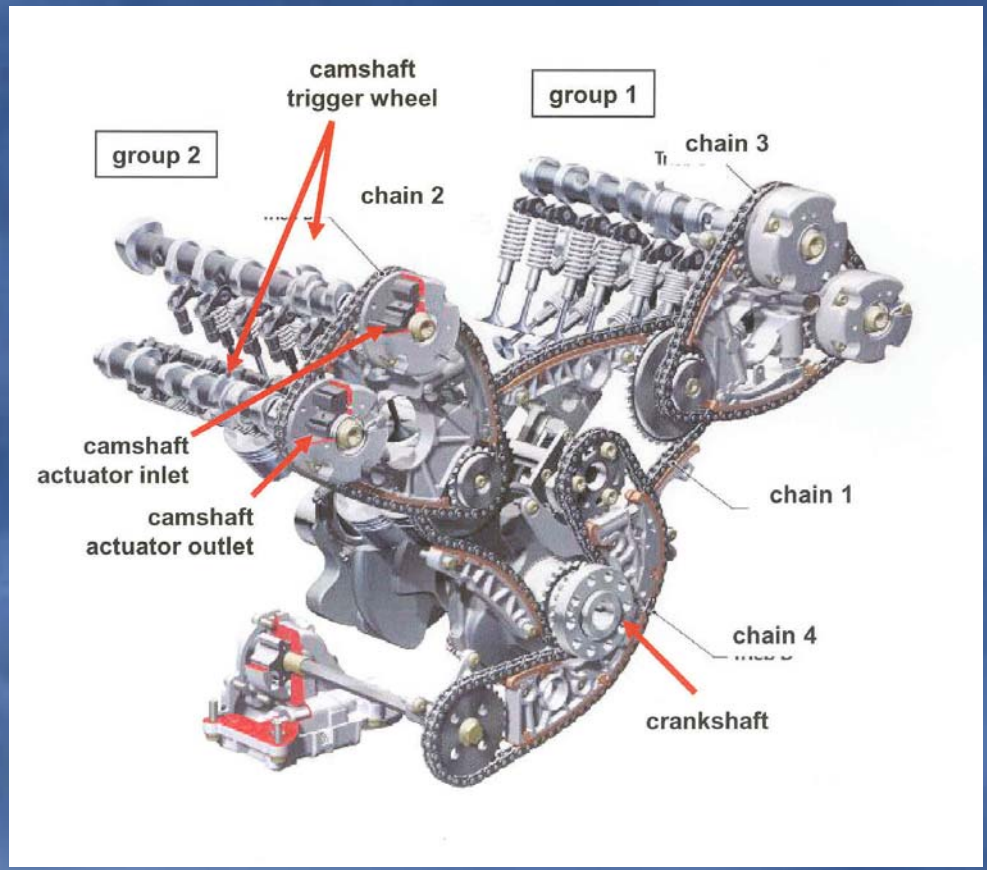
HFC

CO_2

California Environmental Protection Agency
Air Resources Board

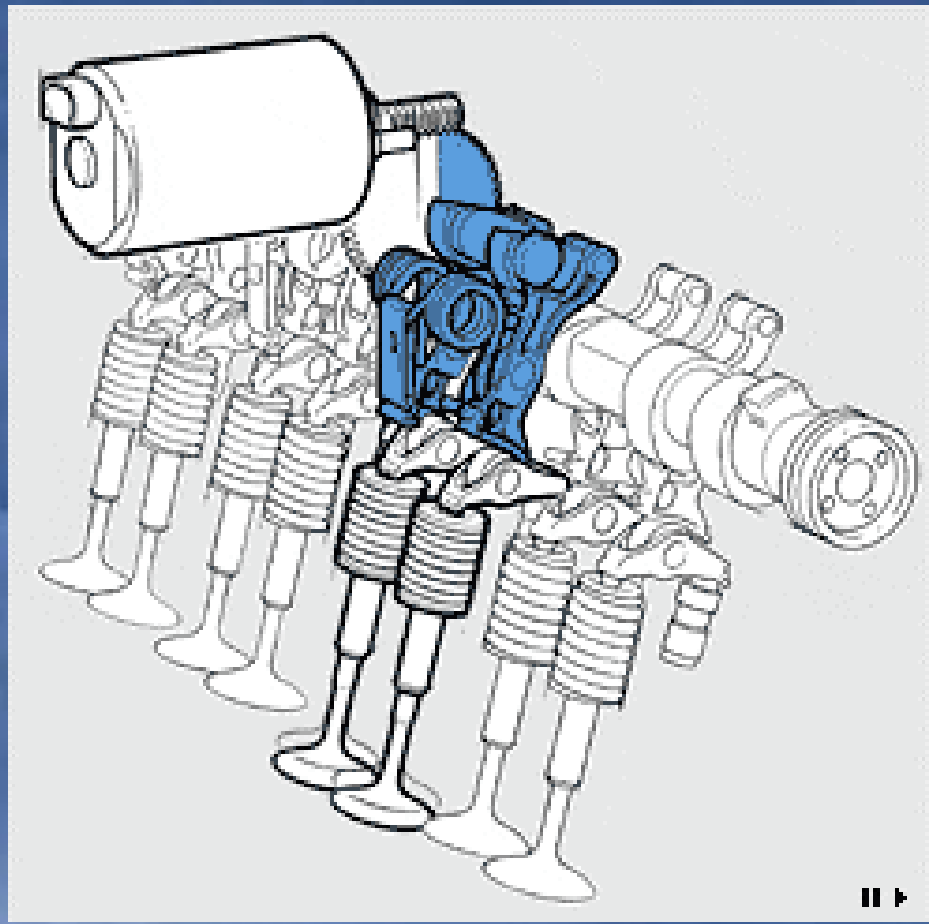
Near Term Technologies 2009-2012

Gasoline Direct Injection Engine w/ Dual Cam Phasers

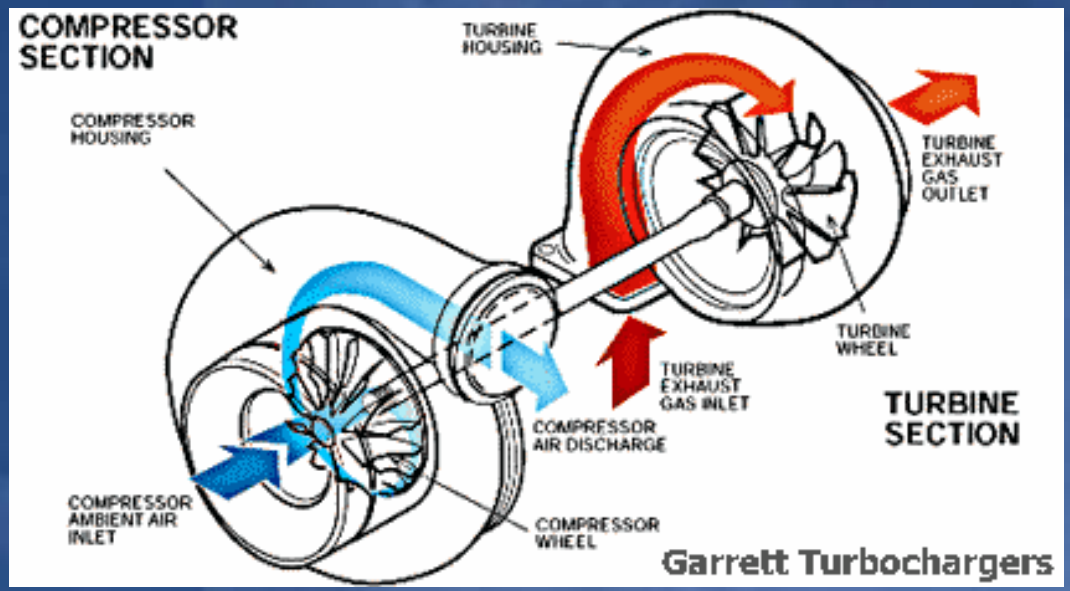


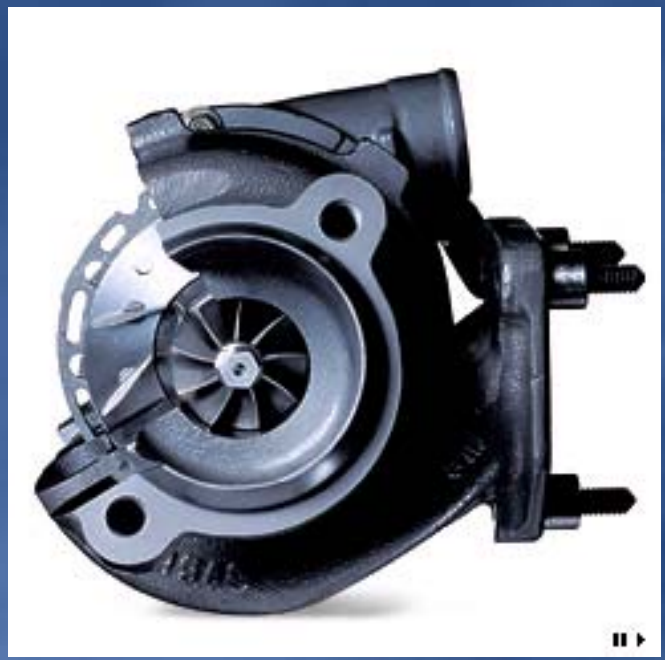
Audi

BMW Valvetronic
(continuous variable valve lift)



Turbocharger



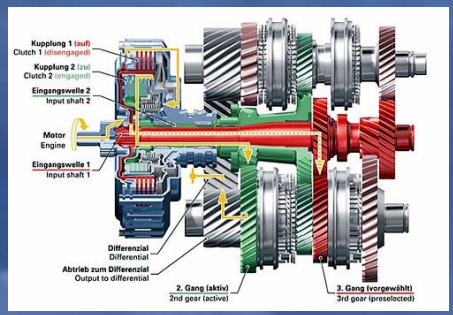


BMW Variable Nozzle Turbo

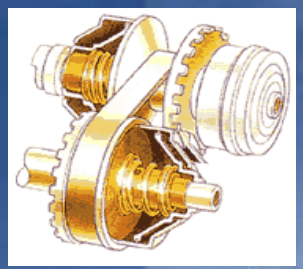
Cylinder Deactivation

Transmissions

6-speed automatic transmission
Lighter, smaller, better performance than 5-speed transmissions.



Automated manual transmission



Continuously variable transmission

Small Car
(Near Term - 2009)

Small Car	Combined Technology Packages	CO_2 (g/mi)	Potential CO_2 reduction from 2002 baseline	Retail Price Equivalent 2002	Potential CO_2 reduction from 2009 baseline	Retail Price Equivalent 2009
Near Term 2009-2012	DVVL,DCP,A5 (2009 baseline)	284	-2.6%	$308	0%	$0
	DCP,CVT,EPS,ImpAlt	270	-7.6%	$570	-5.1%	$262
	DCP,A4,EPS,ImpAlt	269	-7.6%	$360	-5.2%	$52
	DCP,A5,EPS,ImpAlt	260	-10.7%	$494	-8.3%	$186
	DCP,A6	260	-10.8%	$346	-8.4%	$38
	DVVL,DCP,AMT,EPS,ImpAlt	**233**	**-19.9%**	**$465**	**-17.8%**	**$157**
	GDI-S,DCP,Turbo,AMT, EPS, ImpAlt	**215**	**-26.4%**	**$1128**	**-24.4%**	**$820**
Mid Term 2013-2015	gHCCI,DVVL,ICP,AMT,EPS,ImpAlt	229	-21.6%	$673	-28.1%	$365
	CVVL,DCP,AMT,ISG-SS,EPS, ImpAlt	216	-25.7%	$1387	-23.8%	$1079
	gHCCI,DVVL,ICP,AMT,ISG, EPS,eACC	204	-29.9%	$1570	-28.1%	$1262
Long Term 2015-	dHCCI,AMT,ISG,EPS,eACC	217	-25.5%	$2536	-23.5%	$2228
	ModHEV	213	-26.9%	$1937	-25.0%	$1629
	HSDI,AdvHEV	147	-49.5%	$5117	-48.2%	$4809
	AdvHEV	138	-52.6%	$3017	-51.4%	$2709

Near Term Technologies Small Car

- **Small Car - top two packages**
  - Gasoline direct injection-stoichiometric, dual cam phasers, turbo, 6-speed automated manual transmission, electric power steering, improved alternator
    - 24.4% CO_2 reduction - $820 retail price increase
  - Discrete variable valve lift, dual cam phasers, 6-speed automated manual transmission, electric power steering, improved alternator
    - 17.8% CO_2 reduction - $157 retail price increase

Note: Reductions relative to 2009 baseline

Large Car
(Near term - 2009)

Large Car	Combined Technology Packages	CO_2 (g/mi)	Potential CO_2 reduction from 2002 baseline	Retail Price Equivalent 2002	Potential CO_2 reduction from 2009 baseline	Retail Price Equivalent 2009
Near Term 2009-2012	DVVL,DCP,A6 (2009 baseline)	322	-6.6%	$427	0%	$0
	DCP,A6	304	-11.5%	$479	5.6%	$52
	DCP,CVT,EPS,ImpAlt	303	-12.1%	$708	-6.0%	$281
	CVVL,DCP,A6	290	-15.9%	$864	-10.0%	$437
	DCP,DeAct,A6	286	-16.9%	$862	-11.0%	$235
	DCP,Turbo,A6,EPS,ImpAlt	279	-19.2%	$266	-13.5%	-$161
	CVVL,DCP,AMT,EPS,Imp Alt	**265**	**-23.2%**	**$873**	**-17.8%**	**$446**
	GDI-S,DeAct,DCP,AMT, EPS, ImpAlt	**265**	**-23.2%**	**$931**	**-17.8%**	**$504**
	GDI-S,DCP,Turbo,AMT, EPS, ImpAlt	**251**	**-27.2%**	**$369**	**-22.1%**	**-$58**
Mid Term 2013-2015	gHCCI,DVVL,ICP,AMT,EPS,ImpAlt	272	-21.0%	$880	-15.5%	$456
	DeAct,DVVL,CCP,A6,ISG,EPS, eACC	259	-24.7%	$1721	-19.4%	$1294
	ehCVA,AMT,EPS,ImpAlt	250	-27.4%	$929	-22.2%	$502
	ehCVA,GDI-S,AMT,EPS,ImpAlt	242	-29.9%	$1188	-24.9%	$761
	gHCCI,DVVL,ICP,AMT,ISG,EPS, eACC	231	-32.9%	$1796	-28.2%	$1369
	GDI-S,Turbo,DCP,A6,ISG,EPS, eACC	224	-35.1%	$1196	-30.5%	$769
Long Term 2015-	dHCCI,AMT,ISG,EPS,eACC	277	-19.7%	$1978	-14.0%	$1551
	ModHEV	252	-27.0%	$2119	-21.8%	$1692
	AdvHEV	163	-52.6%	$3503	-49.3%	$3076
	HSDI,AdvHEV	157	-54.4%	$4728	-51.1%	$4301

Near Term Technologies Large Car

- Top three packages
  - Gasoline direct injection-stoichiometric, dual cam phasers, turbo, 6-speed automated manual transmission, electric power steering, improved alternator
    - 22.1% CO_2 reduction - $58 retail price savings
  - Gasoline direct injection stoichiometric, cylinder deactivation, dual cam phasers, 6-speed automated manual transmission, electric power steering, improved alternator
    - 17.8% CO_2 reduction - $504 retail price increase
  - Continuous variable valve lift, dual cam phasers, 6-speed automated manual transmission, electric power steering, improved alternator
    - 17.8% CO_2 reduction - $446 retail price increase

Note: Reductions relative to 2009 baseline

Large Truck/SUV
(Near Term - 2009)

Large Truck	Combined Technology Packages	CO_2 (g/mi)	Potential CO_2 reduction from 2002 baseline	Retail Price Equivalent 2002	Potential CO_2 reduction from 2009 baseline	Retail Price Equivalent 2009
Near Term 2009-2012	CCP,A6 (2009 baseline)	484	-5.5%	$126	0%	$0
	DVVL,DCP,A6	442	-13.6%	$549	-8.6%	$423
	CCP,DeAct,A6	433	-15.4%	$550	-10.5%	$424
	DCP,DeAct,A6	**430**	**-15.9%**	**$916**	**-11.0%**	**$790**
	DeAct,DVVL,CCP,A6,EHPS,ImpAlt	**418**	**-18.4%**	**$779**	**-13.6%**	**$653**
	DeAct,DVVL,CCP,AMT,EHPS, ImpAlt	**396**	**-22.6%**	**$667**	**-18.1%**	**$541**
Mid Term 2013-2015	CCP,DeAct,GDI-S, AMT,EHPS,ImpAlt	416	-18.6%	$872	-13.9%	$746
	DeAct,DVVL,CCP,A6,ISG, EPS,eACC	378	-26.2%	$1710	-21.9%	$1584
	ehCVA,GDI-S,AMT,EHPS,ImpAlt	381	-25.5%	$1684	-21.2%	$1558
Long Term 2015-	GDI-L,AMT,EHPS,ImpAlt	354	-30.7%	$1901	-26.7%	$1775
	Mod HEV	372	-27.3%	$2340	-23.1%	$2214
	dHCCI,AMT,ISG,EPS,eACC	362	-29.3%	$3031	-25.2%	$2905
	GDI-L,AMT,ISG,EPS,ImpAlt	354	-30.7%	$2800	-26.7%	$2674
	HSDI,AdvHEV	244	-52.2%	$6821	-49.5%	$6695
	AdvHEV	241	-52.9%	$4091	-50.2%	$3965

Near Term Technologies Large Truck/SUV

- Top two packages
  - Cylinder deactivation, discrete variable valve lift, coupled cam phasers, 6-speed automated manual transmission, electro-hydraulic power steering, improved alternator
    - 18.1% CO_2 reduction - $541 retail price increase
  - Cylinder deactivation, discrete variable valve lift, coupled cam phasers, 6-speed automatic transmission, electro-hydraulic power steering, improved alternator
    - 13.6% CO_2 reduction - $653 retail price increase

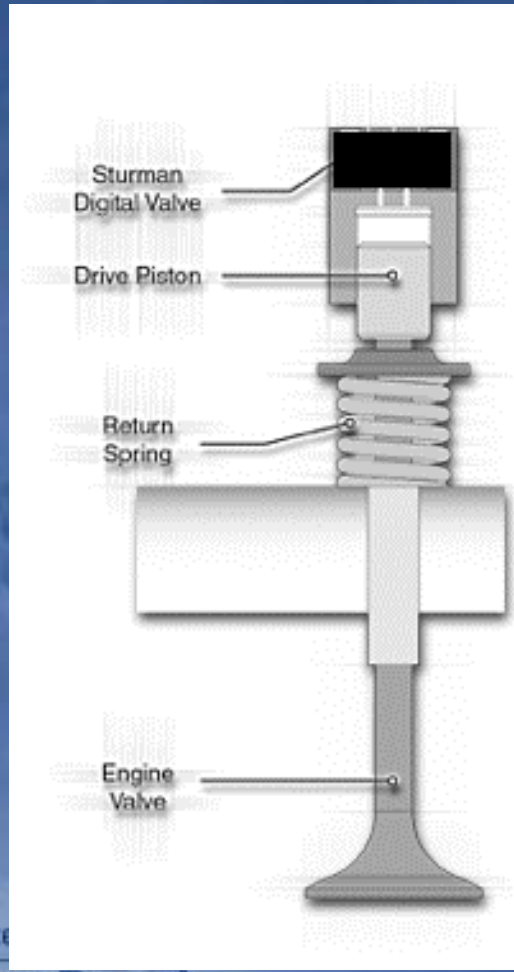
Note: Reductions relative to 2009 baseline

Key Findings--Near Term

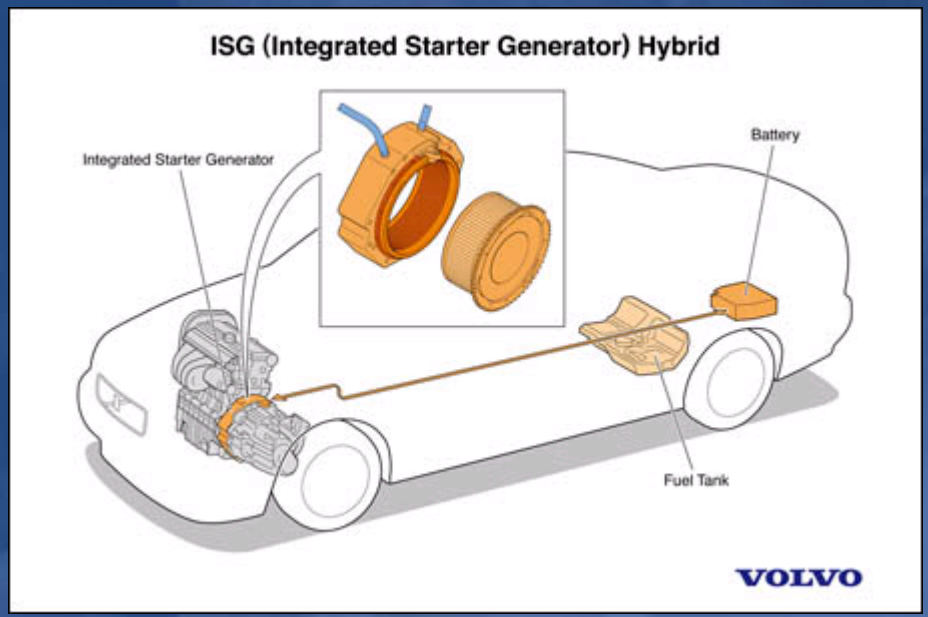
- At least one off-the-shelf or near term package in each vehicle class gives
  - CO_2 reductions of 14-24 percent compared to 2009 baseline
  - Savings of ~$60 to retail price increase of $800
  - Payback 0-5 years
- Best packages generally include
  - Turbochargers w/ engine downsize
  - Variable valve timing
  - Improved transmissions
  - Improved electric accessories
  - Cylinder deactivation

Mid Term Technologies 2013-2015

Electro-hydraulic Camless Valve Actuation



42v Integrated Starter/Generator



Provides stop/start capability and some motor assist

Substantial CO_2 reductions at modest cost

Diesel Engine

Small Car
(Mid Term - 2013)

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	AdvHEV	138	-52.6%	$3017	-51.4%	$2709

Mid Term Technologies Small Car

- **Small Car - top three packages**
  - Gasoline homogeneous charge compression ignition, discrete variable valve lift, intake cam phaser, 6-speed automated manual transmission, integrated starter generator, electric power steering, electric accessories
    - 28.1% CO_2 reduction - $1262 retail price increase
  - Continuous variable valve lift, dual cam phasers, 6-speed automated manual transmission, integrated starter generator - start/stop, electric power steering, improved alternator
    - 23.8% CO_2 reduction - $1079 retail price increase
  - Gasoline homogeneous charge compression ignition, discrete variable valve lift, intake cam phaser, 6-speed automated manual transmission, electric power steering, improved alternator
    - 19.5% CO2 reduction - $365 retail price increase

Note: Reductions relative to 2009 baseline

Large Car
(Mid Term - 2013)

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	GDI-S,DCP,Turbo,AMT,EPS, ImpAlt	251	-27.2%	$369	-22.1%	-$58
Mid Term 2013-2015	gHCCI,DVVL,ICP,AMT,EPS,ImpAlt	272	-21.0%	$880	-15.5%	$453
	DeAct,DVVL,CCP,A6,ISG,EPS, eACC	259	-24.7%	$1721	-19.4%	$1294
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	ehCVA,GDI-S,AMT,EPS,ImpAlt	**242**	**-29.9%**	**$1188**	**-24.9%**	**$761**
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	HSDI,AdvHEV	157	-54.4%	$4728	-51.1%	$4301

Mid Term Technologies Large Car

- Top three packages
  - Gasoline direct injection-stoichiometric, dual cam phasers, turbo, 6-speed automatic transmission, integrated starter generator, electric power steering, electric accessories
    - 30.5% CO_2 reduction - $769 retail price increase
  - Gasoline homogeneous charge compression ignition, discrete variable valve lift, intake cam phasers, 6-speed automated manual transmission, integrated starter generator, electric power steering, electric accessories
    - 28.2% CO_2 reduction - $1369 retail price increase
  - Electro-hydraulic camless valve actuation, gasoline direct injection-stoichiometric, 6-speed automated manual transmission, electric power steering, improved alternator
    - 24.9% CO_2 reduction - $761 retail price increase

Note: Reductions relative to 2009 baseline

Small Truck/SUV
(Mid Term - 2013)

Small Truck	Combined Technology Packages	CO_2 (g/mi)	Potential CO_2 reduction from 2002 baseline	Retail Price Equivalent 2002	Potential CO_2 reduction from 2009 baseline	Retail Price Equivalent 2009
Near Term 2009-2012	DVVL,DCP,A6 (2009 baseline)	404	-9.0%	$427	0%	$0
	DCP,A6	379	-14.7%	$479	-6.3%	$52
	DCP,A6,Turbo,EPS,ImpAlt	371	-16.7%	$283	-8.4%	-$144
	DCP,A6,DeAct	366	-17.7%	$656	-9.5%	$229
	GDI-S,DCP,DeAct,AMT,EPS, ImpAlt	334	-24.9%	$928	-17.5%	$501
	DeAct,DVVL,CCP,AMT,EPS, ImpAlt	330	-26.2%	$736	-18.9%	$309
	GDI-S,DCP,Turbo,AMT,EPS, ImpAlt,DCP-DS	318	-28.4%	$367	-21.3%	-$60
Mid Term 2013-2015	**DeAct,DVVL,CCP,A6,ISG, EPS, eACC**	**316**	**-29.0%**	**$1757**	**-22.0%**	**$1330**
	ehCVA,GDI-S,AMT,EPS, ImpAlt	**309**	**-30.5%**	**$1186**	**-23.6%**	**$759**
	HSDI,AMT,EPS,ImpAlt	**307**	**-31.0%**	**$1585**	**-24.2%**	**$1158**
Long Term 2015-	dHCCI,AMT,EPS,ImpAlt	331	-25.6%	$912	-18.3%	$485
	Mod HEV	325	-27.0%	$2071	-19.7%	$1644
	Adv HEV	210	-52.7%	$3375	-48.0%	$2948

Mid Term Technologies Small Truck/SUV

- Top three packages
  - Diesel high speed direct injection, automated manual transmission, electric power steering, improved alternator
    - 24.2% CO_2 reduction - $1158 retail price increase
  - Electro-hydraulic camless valve actuation, gasoline direct injection - stoichiometric, automated manual transmission, electric power steering, improved alternator
    - 23.6% CO_2 reduction - $759 retail price increase
  - Cylinder deactivation, discrete variable valve lift, coupled cam phaser, 6-speed automatic transmission, integrated starter generator, electric power steering, electric accessories
    - 22.0% CO_2 reduction - $1330 retail price increase

Note: Reductions relative to 2009 baseline

Large Truck/SUV
(Mid Term - 2013)

Large Truck	Combined Technology Packages	CO_2 (g/mi)	Potential CO_2 reduction from 2002 baseline	Retail Price Equivalent 2002	Potential CO_2 reduction from 2009 baseline	Retail Price Equivalent 2009
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	Mod HEV	372	-27.3%	$2340	-23.1%	$2214
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	HSDI,AdvHEV	244	-52.2%	$6821	-49.5%	$6695
	AdvHEV	241	-52.9%	$4091	-50.2%	$3965

Mid Term Technologies Large Truck/SUV

- Top two packages
  - Cylinder deactivation, discrete variable valve lift, coupled cam phasers, 6-speed automatic transmission, integrated starter generator, electro-hydraulic power steering, electric accessories
    - 21.9% CO_2 reduction - $1584 retail price increase
  - Electro-hydraulic camless valve actuation, gasoline direct injection stoichiometric, 6-speed automated manual transmission, electro-hydraulic power steering, improved alternator
    - 21.2% CO_2 reduction - $1558 retail price increase

Note: Reductions relative to 2009 baseline

Key Findings--Mid Term

- Substantially larger CO2 reductions possible
  - Up to 30 percent reduction from 2009 baseline
  - Retail price increase: Typically $400 to <$1600
  - Payback 3-7 years
- Promising technologies
  - Gasoline direct injection
  - Camless valve actuation
  - 42 volt ISG
  - Improved transmissions

Key Findings--Long Term

- Larger CO_2 reductions possible
  - 30-50% reduction possible
  - Retail price increase: $500 to $6700
  - Payback 5 to >16 years
- Promising technologies
  - Moderate HEVs
  - Advanced gasoline and diesel HEVs
  - HEVs available now, but not universal

Hybrid Electric Drive

Honda Civic

Toyota Prius

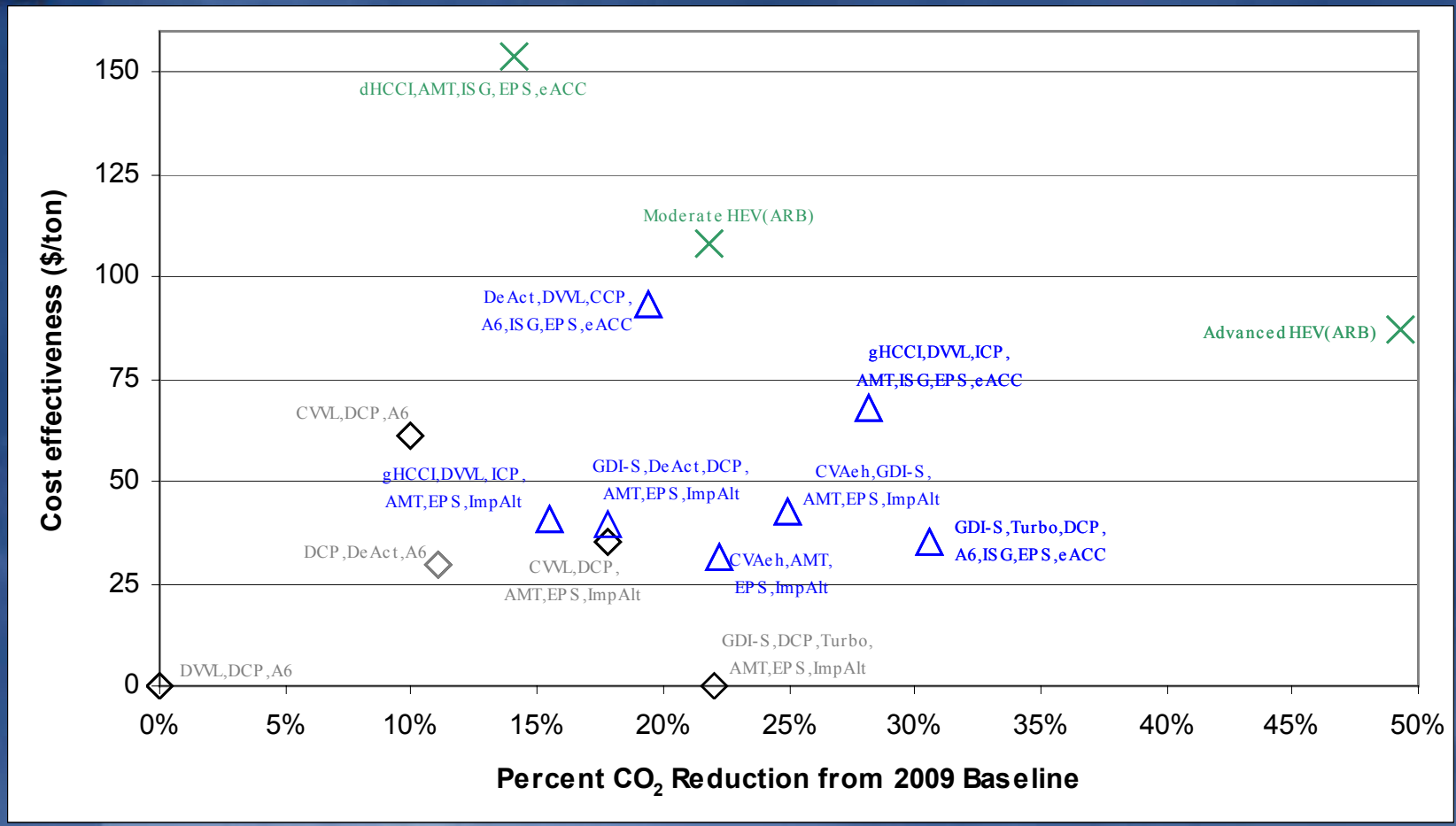
Coming: 2004 Ford Escape, 2005 Lexus SUV, and others

Cost-Effectiveness and Lifetime Cost to Consumer

Cost-Effectiveness

- Cost-effectiveness of emission reductions:
  - Measured as initial technology cost divided by the lifetime reduction of emissions resulting from the technology, in $/ton CO_2
- Assumptions:
  - Vehicle use data (from DMV) on median lifetime:
    - Passenger cars – 219,000 miles, 16.1 years
    - Light trucks (category LDT2) – 224,00 miles, 18.6 years
  - All costs and benefits are in reference to the 2009 baseline
  - Technology cost: retail price equivalent mark-up of 40%

Cost-Effectiveness
(Large Car)



Lifetime Cost to Consumer

- Net present value (NPV) analysis
  - Initial cost of the emission reduction technology (plus 40% retail price mark-up)

$$NPV_0 = -K_0$$

  - Evaluate future net benefits to the vehicle consumer due to the emission reduction technology package
  - Future net benefits are discounted at a 5% discount rate, d

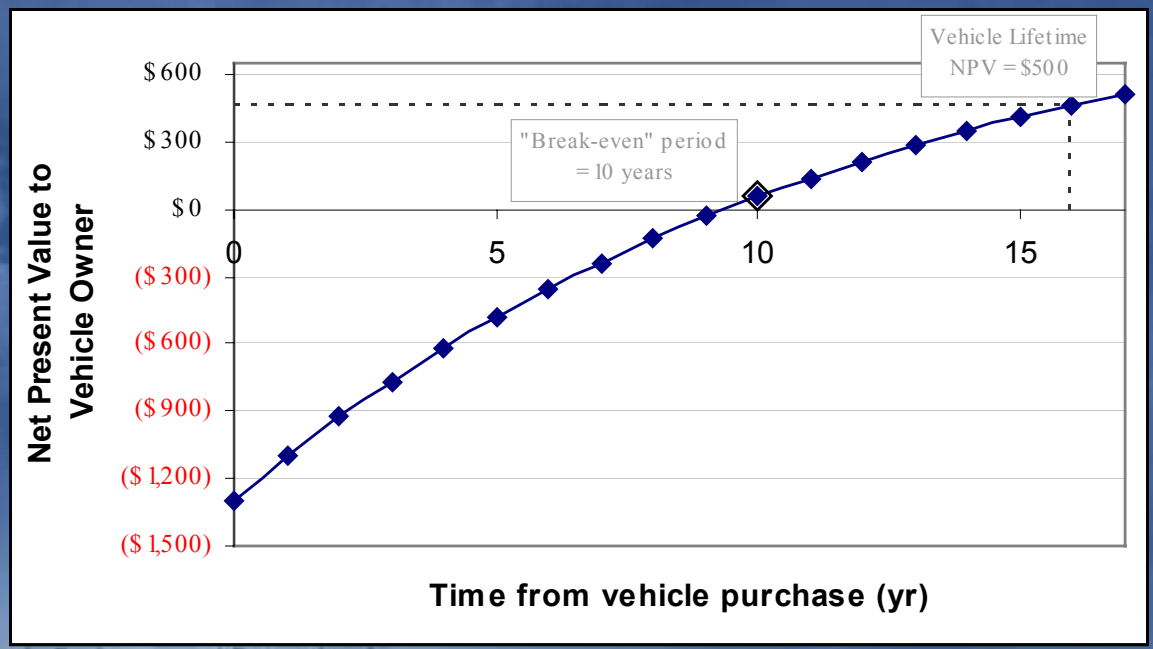
$$NPV_x = NPV_{x-1} + \frac{\sum(Benefits,\ year\ x) - \sum(Costs,\ year\ x)}{(1+d)^x}$$

  - Vehicle use data (from DMV) on vehicle lifetime and miles per year
  - Costs and benefits are in reference to the 2009 baseline

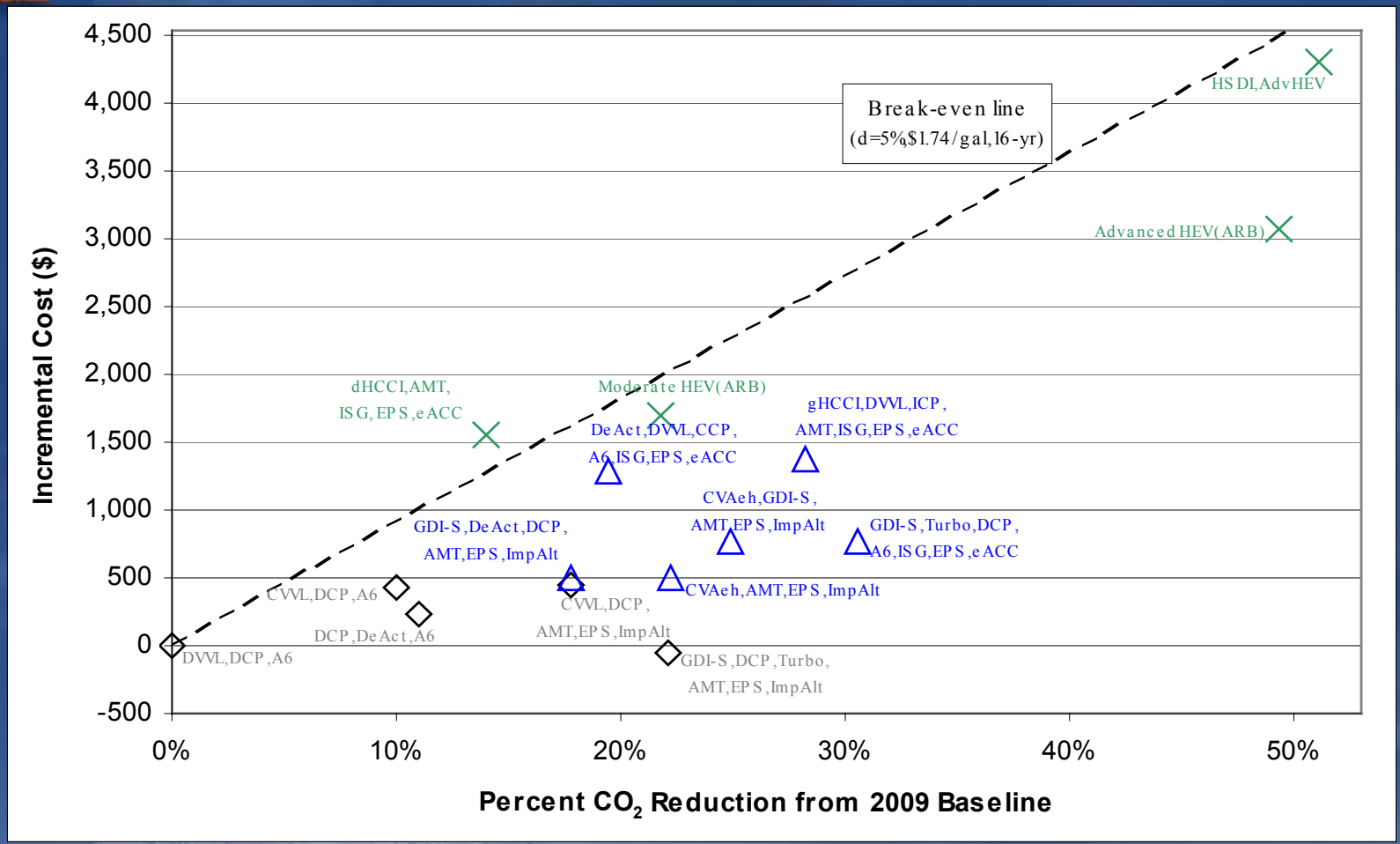
Lifetime Cost to Consumer

(Example for Large Car)

- Technology package: Cylinder deactivation, discrete variable valve lift, coupled cam phasing, 6-speed automatic transmission, integrated starter-generator, electric power steering, electric power steering
- Initial cost from 2009 baseline: $1294
- CO_2 emission reduction from 2009 baseline: 19.4%



Break-even to Consumer
(Large Car)



Cost Assessment

Selected Near-term Results for Cars and Large Trucks

Vehicle Class	Technology Packages	CO_2 emissions (g/mi)	CO_2 change from 2009 baseline	Lifetime CO_2 reduced from 2009 baseline (ton)	Lifetime Net Present Value to Consumer (2004$)	Payback period (yr)	Cost Effectiveness ($/ton)
Small Car	GDI-S,DCP,Turbo, AMT,EPS,ImpAlt	215	-24.4%	15.4	1,133	5	53
	DVVL,DCP, AMT,EPS,ImpAlt	233	-17.8%	11.3	1,267	2	14
Large Car	GDI-S,DCP,Turbo, AMT,EPS,ImpAlt	251	-22.1%	15.8	2,060	0	0
	GDI-S,DeAct,DCP, AMT,EPS,ImpAlt	265	-17.8%	12.8	1,111	4	39
	CVVL,DCP,AMT,E PS,ImpAlt	265	-17.8%	12.7	1,166	3	35
Large Truck	DeAct,DVVL,CCP, AMT,EHPS,ImpAlt	396	-18.1%	21.6	2,106	3	25
	DeAct,DVVL,CCP, A6,EHPS,ImpAlt	418	-13.6%	16.2	1,340	4	40

Summary

- Multiple technology packages to reduce vehicle greenhouse gases have been identified
- These packages have been modeled to determine their potential to reduce greenhouse gases
- Modeling properly accounted for the impact of combining technologies on a vehicle
- The majority of technologies modeled are cost-effective - some provide consumer savings
- Manufacturers have a menu of technologies to choose from
- Significant cost-effective climate change emission reductions are possible in 2009
  - greater reductions possible later