Truck Technology Assessment Workshop Handout

California Environmental Protection Agency

AIR RESOURCES BOARD

- Phase 1 Standards
- Technology Summaries

Phase 1 Standards

Final Phase 1HD Diesel Engine Standards (gCO2/bhp-hr)					
	LHD(2b-5)	MHD(Class 6-7)		HHD(Class 8)	
			Tractors	Vocational	
	630	630	518	584	490
2014-2016 MY	600	600	502	567	475
			487	555	460

Final Phase 1 HD Combination Tractor Vehicle Standards (gCO2/ton-mile)									
	Baseline (2010)			2014-2016			2017+		
	Class 7	Class8		Class 7	Class8		Class 7	Class8	
		Day	Sleeper		Day	Sleeper		Day	Sleeper
Low Roof	116	88	80	107	81	68	104	80	66
Mid Roof	128	93	89	119	88	76	115	86	73
Hi Roof	138	103	94	124	92	75	120	89	72

Final Phase 1 Vocational Vehicle CO2 Standard (gCO2/ton-mile)			
	LHD Class 2b-5	MHD Class 6-7	HHD Class 8
Baseline (2010)	408	247	236
2014 2016 MY	388	234	226
2017 MY and beyond	373	225	222

Engine/Powerplant and Drivetrain Optimization: Technology Summaries

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Advanced Transmissions / Engine Downspeeding

Potential FCR Improvement: 0 to 9.5% [2010] (1,2)

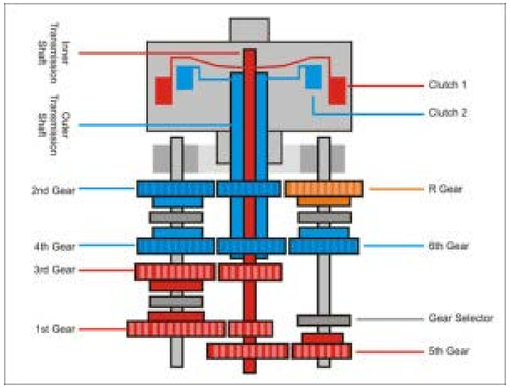
Cost: $500 – $15,000 (1,2)

Technology Readiness Level: Commercial

Applicability:

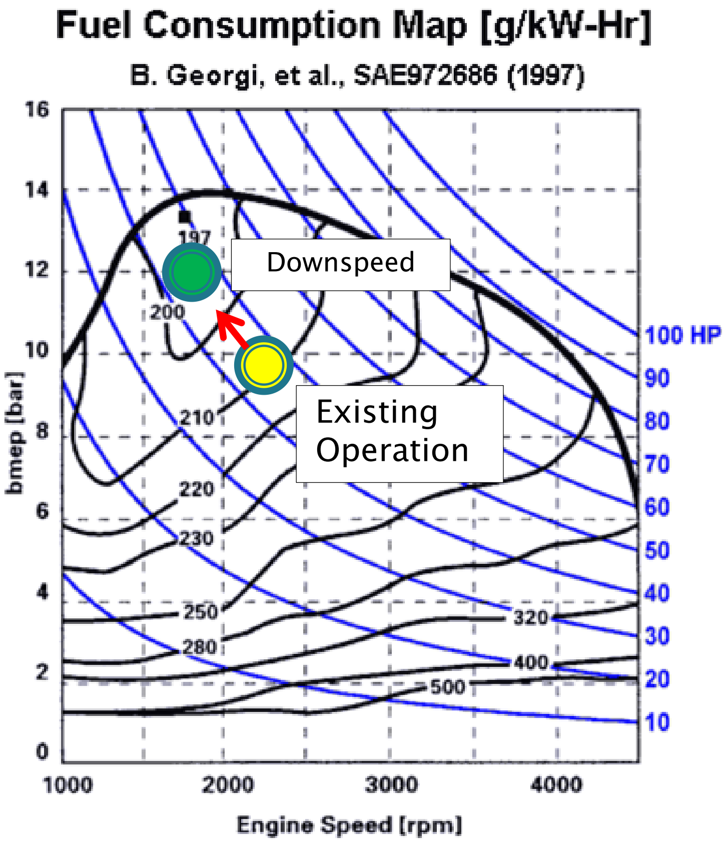
HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
AMT: 4-8% FCR $4,000-$7,500 DCT: FCR and Cost Unknown	AT: 0-5% FCR $15,000 DCT: FCR and Cost Unknown	AT: 2-3% FCR $1,000-$2,600 DCT: Unknown			AT: 2.7-4.1% FCR $500-1,650 AMT: 5.5-9.5% FCR $700-$1,400

- Automatic Transmission (AT)
  - Torque converter
- Automated Manual Transmission (AMT)
  - Manual with control module taking over shifting
- Dual-Clutch Transmission (DCT)
  - Two power paths from engine to axle



Advanced Transmissions / Engine Downspeeding

- Downspeeding=Efficiency
  - Same power at lower speeds
  - Less engine friction
- Facilitated by transmission



Waste Heat Recovery

Potential FCR Improvement: 2.5-10% [2010] (2,3)

Cost: $7,000 – $15,000 Bottoming Cycle (2)
$2,000 – $7,000 Turbocompound (2)

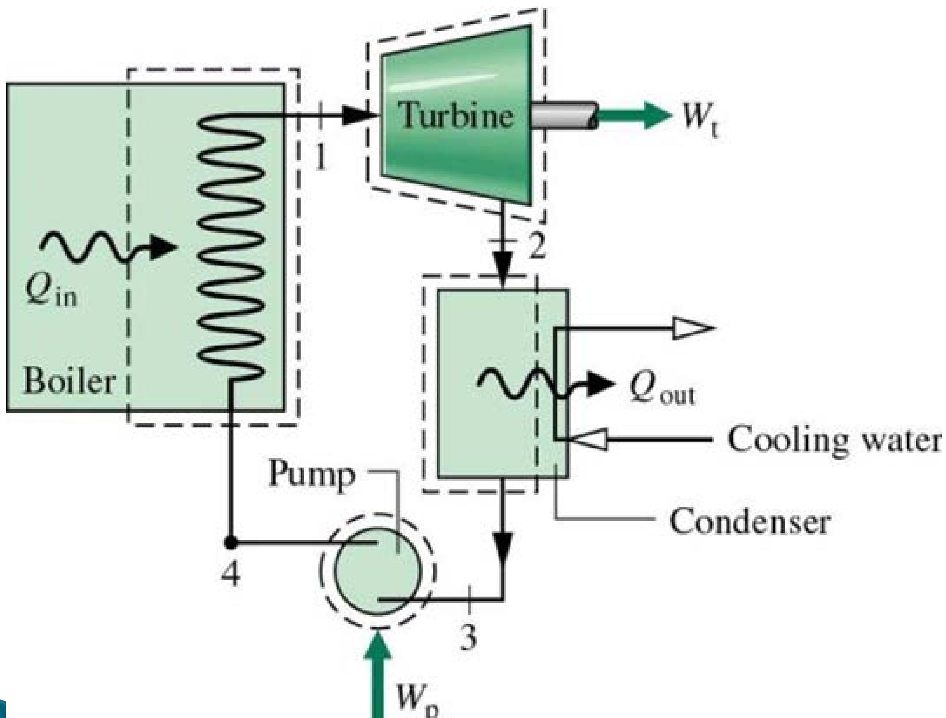
Technology Readiness Level: Bottoming: Pilot
Turbocompound:Commercial

Applicability

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X					

- Two Different Approaches
  - Bottoming Cycle:
    6-10% FCR, $7,200-$15,000
  - Turbocompound
    Mechanical: 2.5-3% FCR, $2,000-$3,000
    Electric: 4-5% FCR, $6,000-$7,000

Waste Heat Recovery (Bottoming Cycle)



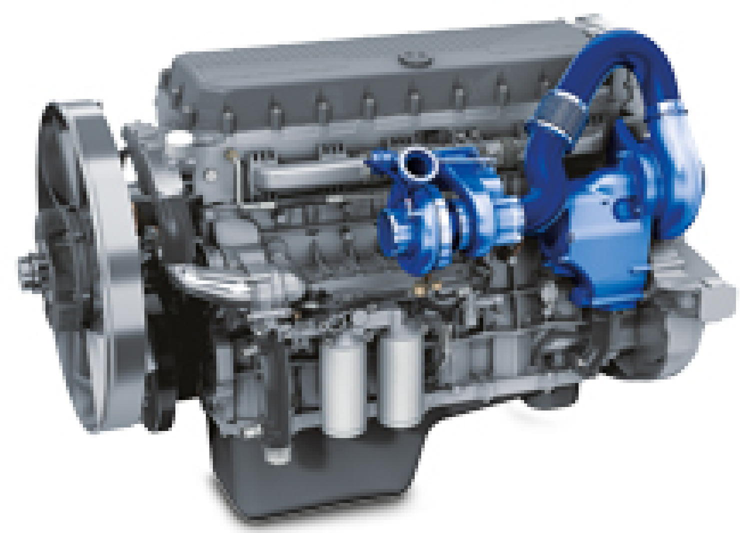
Rankine Bottoming Cycle:

1. A working fluid is pumped from low to high pressure by a pump (3 to 4).
2. The pressurized liquid is heated at constant pressure by an external heat source (in this case, the exhaust gas) to become a superheated vapor (4 to 1).
3. The superheated vapor expands through a turbine to generate power output. Electrical or Mechanical (1 to 2).
4. The vapor then enters a condenser where it is cooled to become a saturated liquid (2 to 3).

Waste Heat Recovery (Turbocompounding)

- Base turbocharged engine remains the same and a second power turbine is added to the exhaust stream
- <u>Mechanical turbocompounding</u>: Connected to crankshaft
  - (2.5-3% FCR)
- <u>Electric turbocompounding</u>: Drives electrical generator
  - (4-5% FCR, including electrified accessories)

<u>Turbocompound</u>



Combustion and Fuel Injection Optimization

Potential FCR Improvement: 1 to 6% [2010] (1)

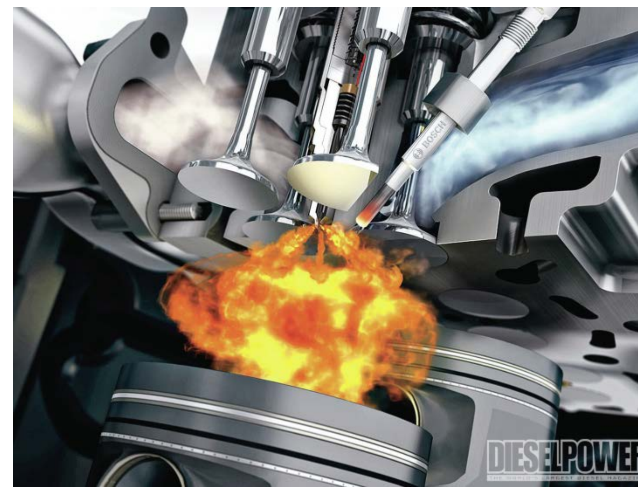
Cost: $500-2,000 (2009 Dollars) (2)

Technology Readiness Level: Commercial

Applicability:

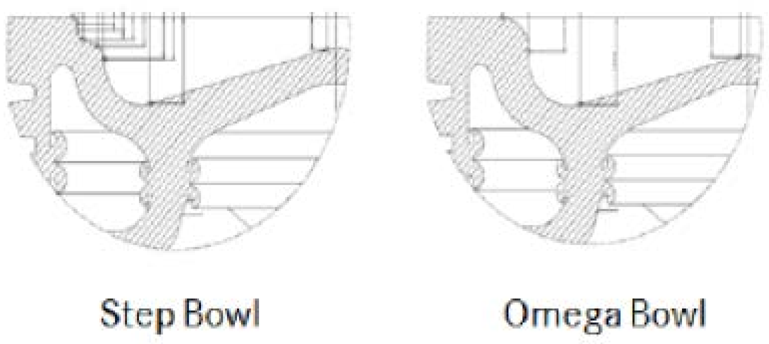
HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
x	x	x	x	x	x

- Combustion Chamber design
- High pressure or high flow injectors
- Modifying injection spray pattern

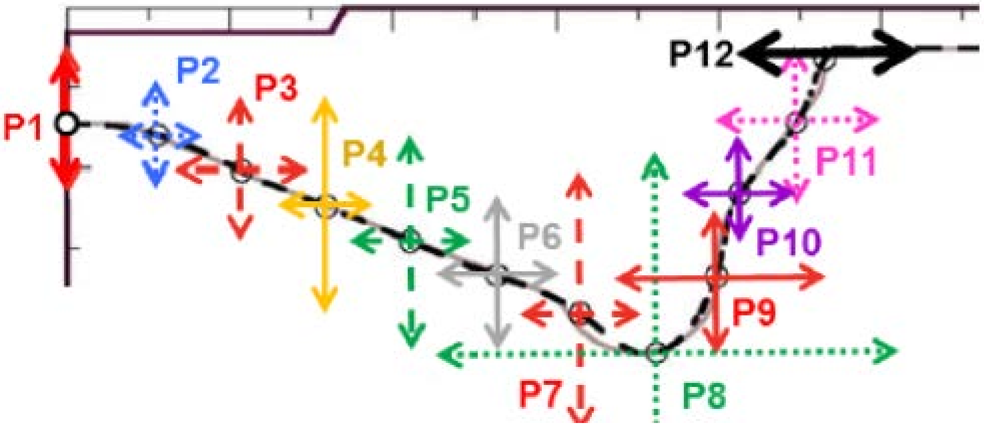


Combustion and Fuel Injection Optimization

- Combustion Chamber design
  - May require more advanced materials and structural design
  - Allows for improved air management and mixing



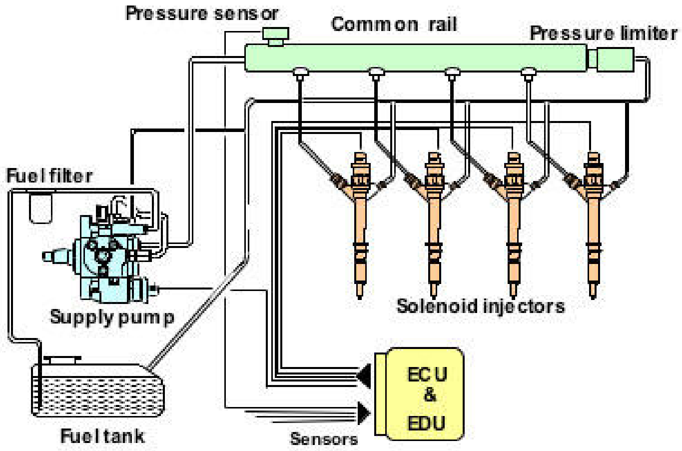
(Daimler SuperTruck)



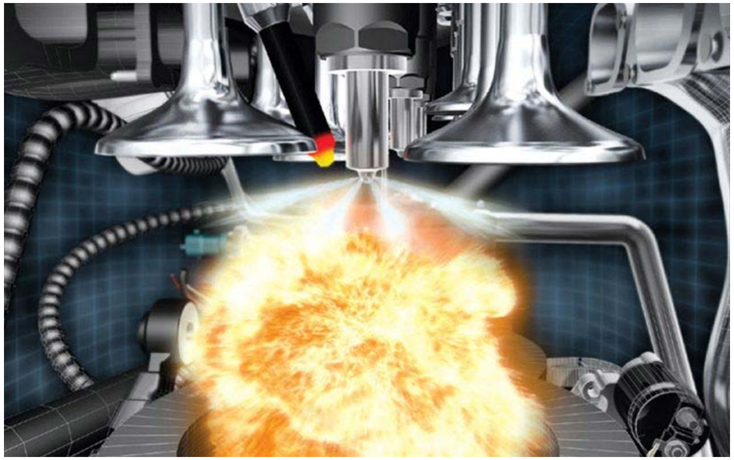
(Cummins SuperTruck)

Combustion and Fuel Injection Optimization

- High pressure or high flow injectors
  - Common Rail Systems
  - Variable spray; piezoelectric replace solenoid
  - Up to 4,000 bar (~2020)



- Modifying injection spray pattern
  - Controls combustion heat release rate



Air Handling Improvements

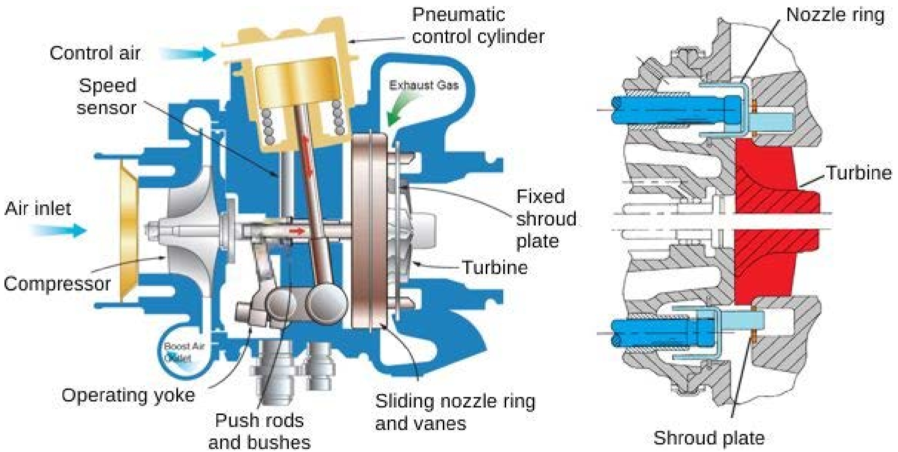
Potential FCR Improvement: 1-2% [2010] (3)

Cost: n/a

Applicability

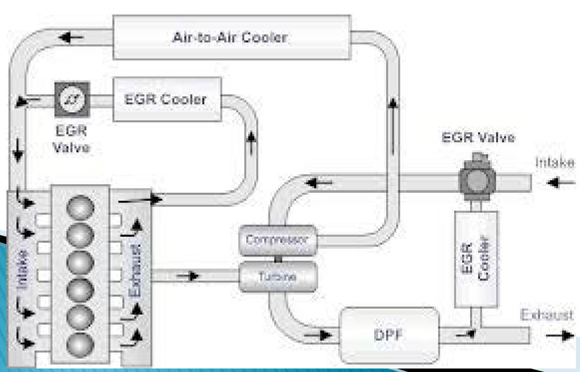
HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X	X	X	X	X	X

- Optimize efficiency of air and exhaust transport
  - Intake
    - Turbo Design Optimization
      - Variable Geometry Turbo (VGT)
      - Twin Compressor
  - Exhaust
    - Higher Efficiency Exhaust Recirculation (EGR)



Basic Components of Moving Wall VGT
Right: Turbine nozzle closed (top) and open (bottom)

(Cummins)



Schematic of a Hybrid High Pressure Loop EGR Configuration (Dieselnet)

Higher Efficiency Aftertreatment

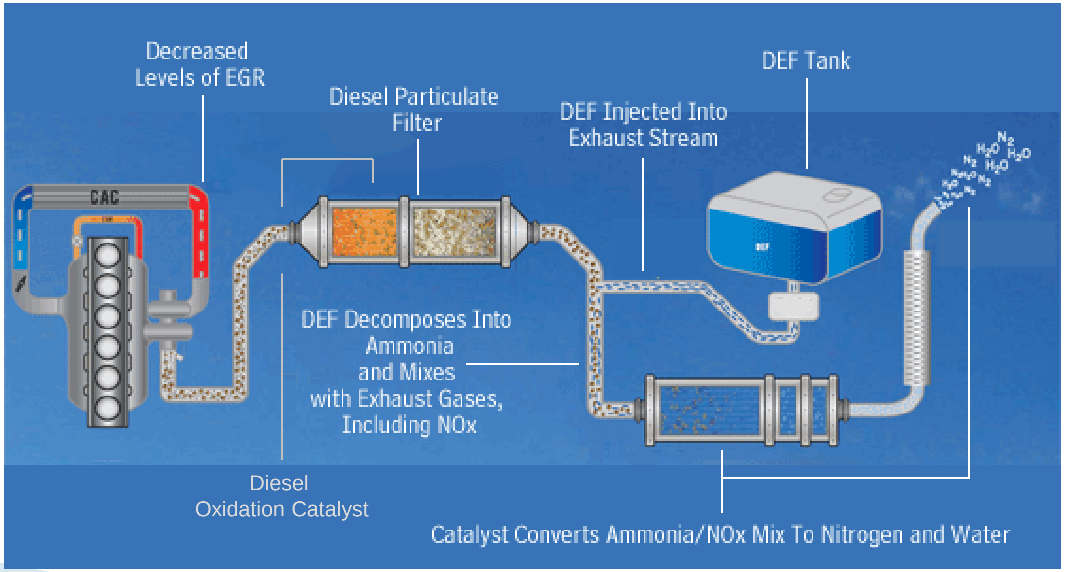
Potential FCR Improvement: 0.5 to 1.5% [2010] (3)

Cost: n/a

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
x	x				

- Lower backpressure SCR/DPF devices to reduce pumping loses.
- High performance SCR catalyst, thin wall DPF, high flow DEF doser.
- Insulated exhaust manifold and aftertreatment system.
- Higher NOx conversion rate.



Advanced Combustion Cycles

Potential FCR Improvement: 1-20%* [2010] (2,7)

Cost: Up to $10,000 (2009) (2)

Technology Readiness Level: Research & Development

Applicability

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X	x	x	x	x	x

Low Temperature Combustion (LTC) Strategies

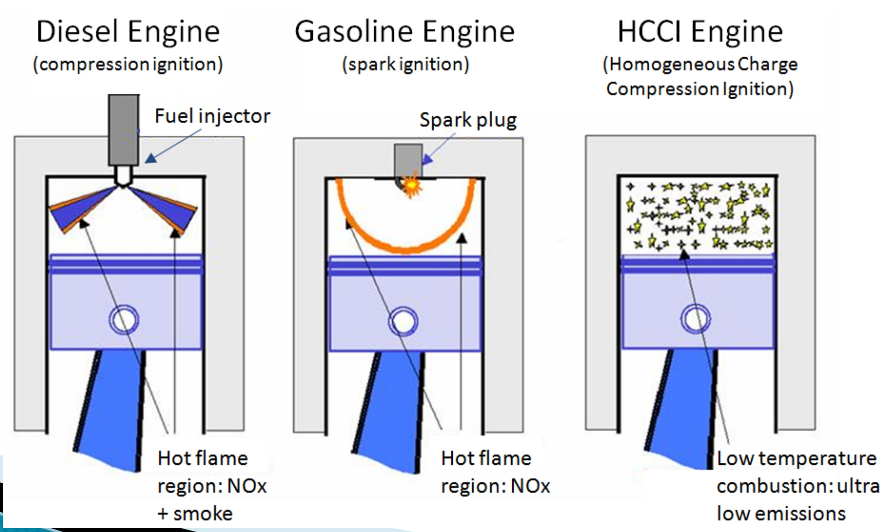
- More complete combustion at lower temperatures results in lower NOx and PM emissions, as well as reduced fuel consumption
- Three LTC strategies:
  - Homogeneous Charge Compression Ignition (HCCI)
  - Premixed Charge Compression Ignition (PCCI)
  - Reactivity Controlled Compression Ignition (RCCI)

* Technologies are still in developmental stages, therefore; FCR improvement and costs are rough estimates and subject to change. Values listed above include all technologies listed.

Advanced Combustion Cycles

Homogeneous Charge Compression Ignition (HCCI)

- Fuel is homogeneously mixed with air
- Air/fuel mixture injected into combustion chamber prior to ignition
- Very high air/fuel ratio (lean)
- Thermal efficiencies as high as compression-ignition (CI) engines.
- Significantly reducing NOx and particulate emissions due to lean homogenous fuel/air mixture combined with low combustion temperatures.
- Efficiency improved due to the elimination of throttling losses, the use of high compression ratios, and a short combustion duration.



Advanced Combustion Cycles

Homogeneous Charge Compression Ignition (HCCI)

Implementation Issues

- Ignition Timing Control

  Research is needed to improve methods for maintaining proper ignition timing as load and speed are varied. Poor timing can result in Low Specific Power Output and HC/CO emissions.

- Extending the Operating Range to High Loads

  Difficulties with rapid and intense combustion at high loads has led to unacceptable noise, NOx levels, and potential engine damage.

- Cold Start Capability

  Potential use of glow plugs or spark ignition may be necessary.

Advanced Combustion Cycles

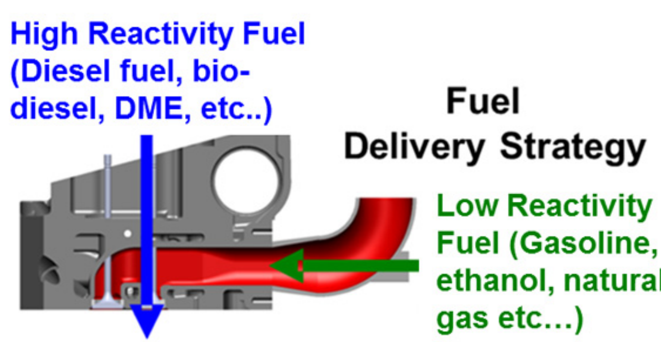
Premixed Charge Compression Ignition (PCCI)

- Intake air is premixed with fuel creating HCCI-like conditions as compression stroke nears top-dead center (TDC).
- Near TDC, late fuel pulse is injected and burns before the initial premixed homogenous fuel/air mixture.
- Lengthens burn duration, allowing engine to operate at a higher specific power.
- Late fuel injection allows for more direct control over where and how the combustion sequence begins.
- Implementation Issues
  - Fuel stratification may produces higher emissions of NOx and PM.

Advanced Combustion Cycles

Reactivity Charge Compression Ignition (RCCI)

- Uses a blend of two fuels of different reactivity, and multiple injections during the engine cycle, to better optimize and control combustion phasing, duration, and magnitude at varying engine loads and speeds.
- Examples of fuel pairings include gasoline (low reactivity)/diesel (high reactivity), and ethanol (low)/diesel (high).
- By tailoring the relative amount of fuel charge and combustion timing, RCCI offers enhanced thermal efficiency helping to reduce CO_2 emissions, while at the same time, lowering emissions of NOx and PM.



*Images obtained from University of Wisconsin, http://www.warf.org/technologies/summary/P100054US01.cmsx

Advanced Combustion Cycles

Potential Future Impacts

Fuel Consumption Benefits				
Technology	Engine Type	FCR	Price*	Reference
Gasoline HCCI	5-8 L	10-12%	$685	2
PCCI @ low/med load	6-9 L diesel	1-2%	$8,000	2
PCCI @ low/med load	11-15L diesel	1-2%	$10,000	2
RCCI	Multiple classes	8-15%, up to 20%	Unknown	6

*Prices in 2009 dollars

Engine Downsizing

Potential FCR Improvement: 2% [2010] (1,2)

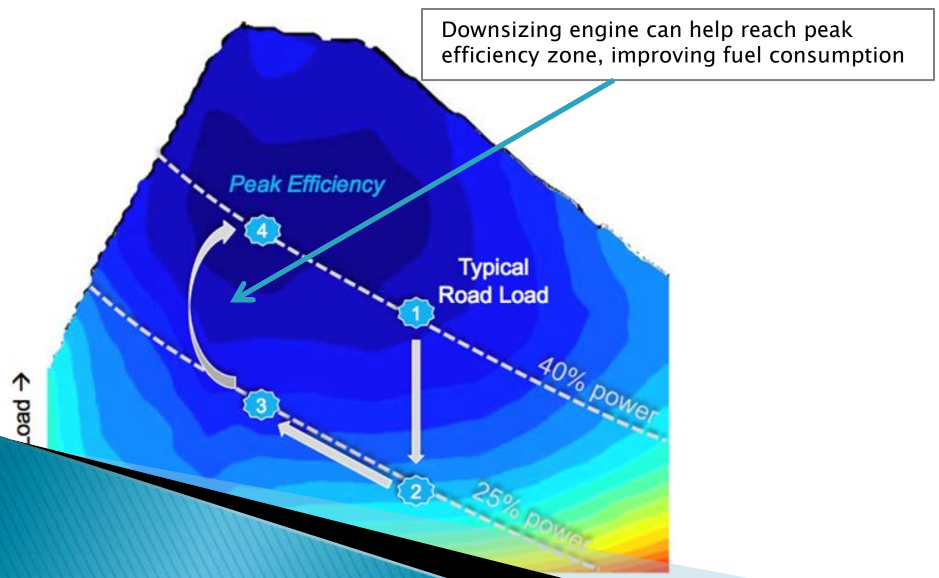
Cost: $1,229 (2009 Dollars) (1,2)

Technology Readiness Level: Commercial

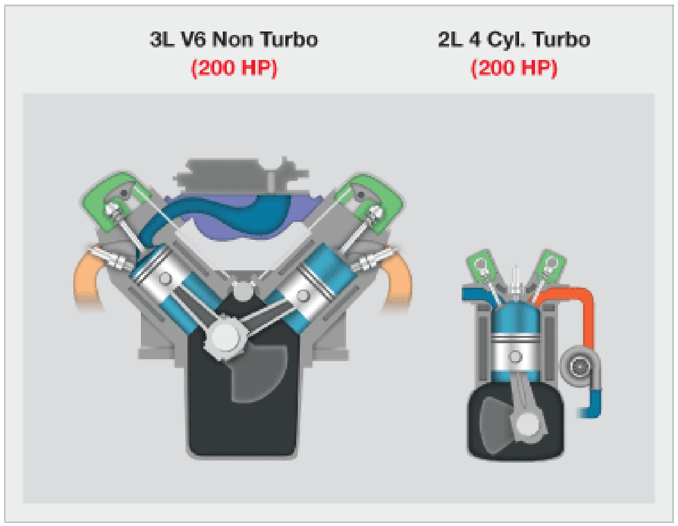
Applicability

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
x	x	x	x	x	x

- A smaller engine equipped with a turbocharger can produce the same power density as a larger engine without a turbocharger.
- The reduced weight and friction losses as a result of the smaller engine enable a reduction in fuel consumption for the same amount of power.



Turbo + Small Engine = Fuel Economy



By harnessing the energy from exhaust gas otherwise wasted, turbocharger helps a smaller engine to perform like a bigger one with better fuel efficiency.

Frictional Energy Loss/Auxiliary Load Reduction

Potential FCR Improvement: 0.5-4% [2010] (1,7,8)

Cost: $0-$500 (2009 dollars) (2)

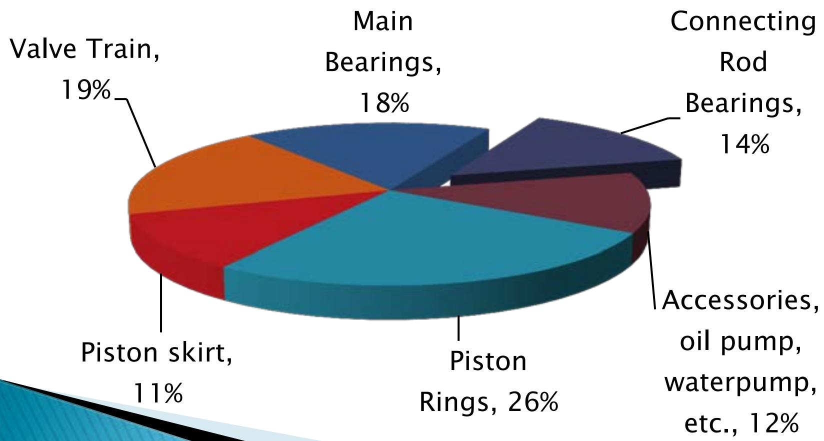
Technology Readiness Level: Commercial

Applicability

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X	x	x	x	x	x

- 6% - 15% of the energy produced by an engine is lost due to friction.
- EPA estimates that frictional energy losses are responsible for the consumption of 1 million barrels of oil each day in the transportation sector.

Engine Losses due to Friction



Techniques to Reduce Frictional Losses

Low Viscosity Synthetic lubricants

Anti-Friction Coatings

Optimized Component Geometries

Frictional Energy Loss/Auxiliary Load Reduction

Low Viscosity Synthetic Lubricants

- Provide less resistance than conventional vehicle lubricants reducing the amount of work necessary for pumps/gears/shafts to move the oil around.
- Improved temperature range, better protection against oxidation, and longer lifetime relative to conventional lubricants.
- Extended oil change intervals due to longer lifetime lead to monetary savings and less downtime .

Statistics

Cost: 2-3 times more than conventional models.

Fuel Consumption Reduction: 0.5% - 2%

ROI: US EPA estimates truck owners can save more than $1,680 per year in fuel by switching to low viscosity oil bases.

Frictional Energy Loss/Auxiliary Load Reduction

- Anti-Friction Coatings
  - Smoother, harder surfaces make them less susceptible to abrasion and wear while reducing frictional losses.
  - Coating technologies include magnesium phosphate deposition, molybdenum nickel chromium plating, nitride coating, and high-luster polishing.

- Optimized Component Geometries
  - More precise pattern designs can reduce friction by removing unwanted sources of roughness and abrasion.

Fuel consumption improvements of 3% -4% are estimated when combining low viscosity lubricants with low friction surfaces.

Frictional Energy Loss/Auxiliary Load Reduction

Auxiliary Electrification

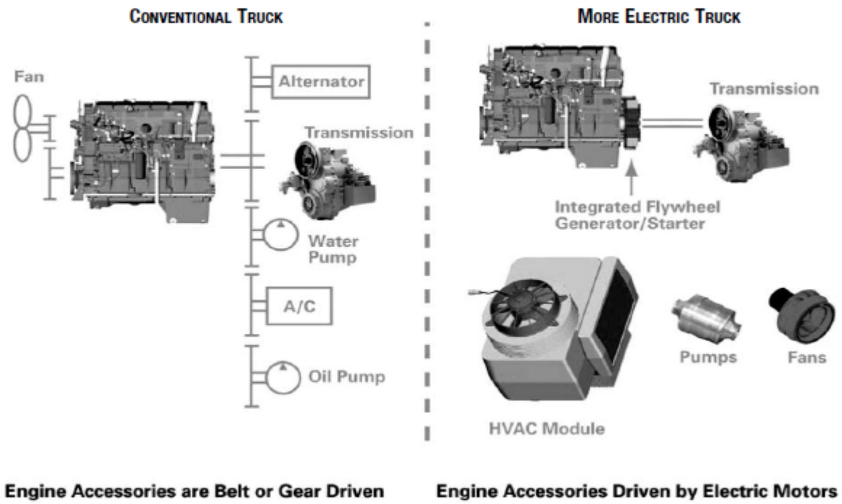
Potential FCR Improvement: 1-3% [2010] (2)

Cost: $1,000-$2,000 (2009 Dollars) (2)

Technology Readiness: Demonstration

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X	x	x	x	x	x



- Conversion of accessories to electric power is still in the demonstration stage for non-hybrid vehicles.

- Reductions will be <u>duty-cycle dependent</u> with a more pronounced effect in short-haul/urban applications than in long-haul trucking applications.

Frictional Energy Loss/Auxiliary Load Reduction

Auxiliary Electrification

Electrification significantly reduces parasitic fuel consumption of accessories, lowering fuel demand.

- Belt/Gear Drive
  - Belts/gears require a constant fuel source even when accessory is not in operation.

- Electrified
  - More efficient as parasitic loads can be run on an "as needed" basis
  - Accessories can run at speeds independent of engine speed.
  - Potential sources of electricity
    - Waste Heat Recovery
    - Hybrid system

Variable Valve Actuation

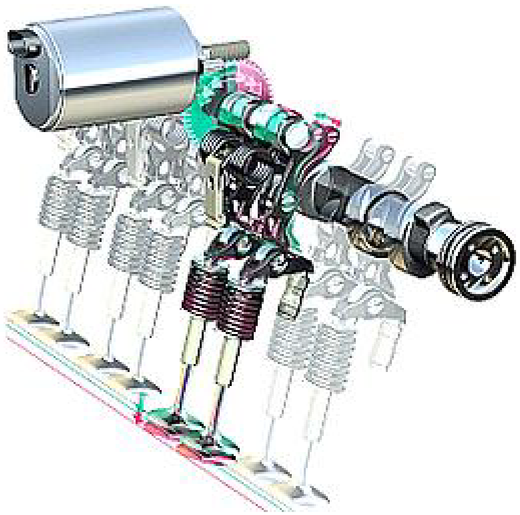
Potential FCR Improvement: 1% [2010] (9)

Cost: \$50/cylinder, ≈\$300 total (2009 Dollars) (2,9)

Technology Readiness: Commercial

Applicability

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
		x	x	x	x



- Advanced control of engine valves to improve efficiency, power, and emissions.
- Allows the valve actuation/timing to be adjusted independent of the camshaft angle.
- Intake and exhaust valve timing typically adjusted through the use of cam phasers.

Cylinder Deactivation

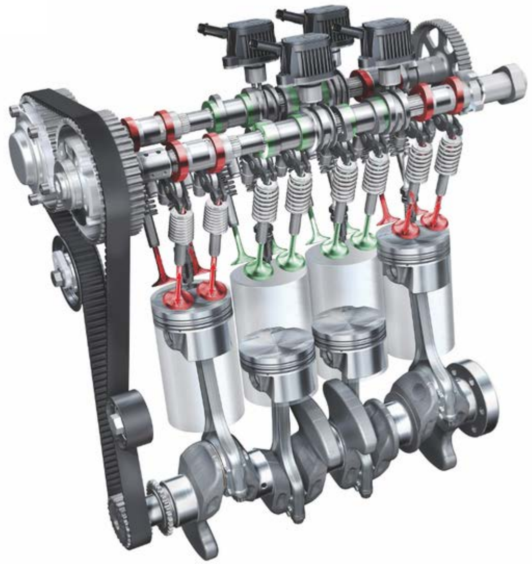
Potential FCR Improvement: 2.5-3% GDI [2010] (2)

Cost: $75 (2009 dollars) (2)

Technology Readiness Level: Commercial

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
					x



- Typical light-load driving uses only around 30% of engine's maximum power.
- Deactivating a cylinder during light loads allows the remaining cylinders to run at higher specific load levels, minimizing pumping losses to improve efficiency.
- Cylinder deactivation is not a highly implemented fuel reduction technology in turbocharged diesel engines due to turbocharger surge problems.

Stop-Start

Potential FCR Improvement: 5%-10% [2010] (22)

Cost: $600-900 (2012) (22)

Technology Readiness Level: Commercial

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
	X	X		X	X

- Automatically shuts down engine during periods of idle.
- The time between idle shut down and restart will vary based on manufacturers' preprogramed settings that include:
  - Applying the brake pedal
  - Depressing clutch / releasing the clutch
  - Interior vehicle temperature sensor
  - Movement of the steering wheel
  - Battery or / auxiliary power demand

<u>Limitations of SST</u>

- Highly dependent on duty cycle
- System requires more durable starter and longer lasting/powerful battery.

Automatic Neutral Idle

Potential FCR Improvement: n/a

Cost: n/a

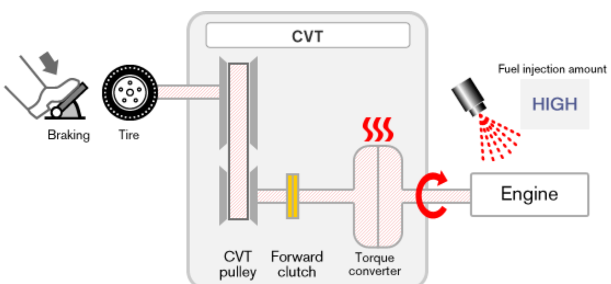
Technology Readiness Level: Commercial

Applicability:

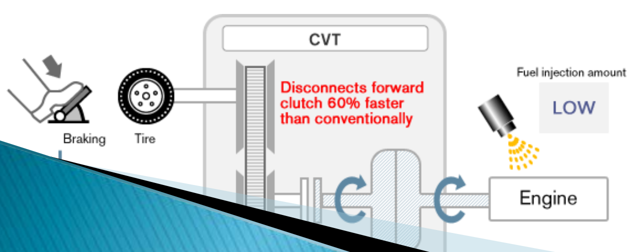
HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
		x	x	x	x

Alternative FCR technology for automatic transmission vehicles with duty cycles not compatible to start/stop technology.

Traditional



Neutral-Idle



- Losses associated with the torque converter in automatic transmissions are most significant when stopped in drive mode.
- Transmission will automatically shift to neutral at a stop when operator's foot is on brake, and then automatically re-engage drive when brake is released.
- Provides parasitic load reduction and reduces torque converter clutch slip speed improving fuel consumption losses.
- Not as effective for FCR as start/stop.

Class 2b/3 Stoichiometric GDI

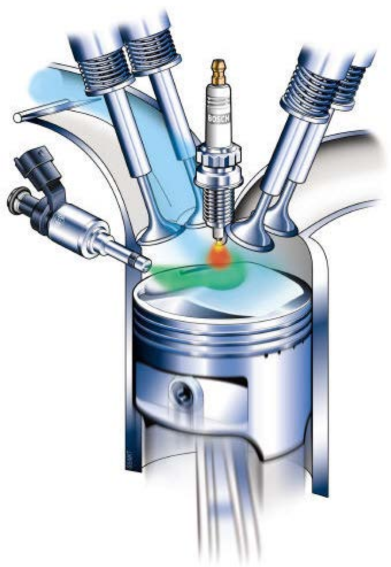
Potential FCR Improvement: 2-3%* [2010] (1)

Cost: $512-$930 (2009 dollars) (2)

Technology Readiness Level: Commercial

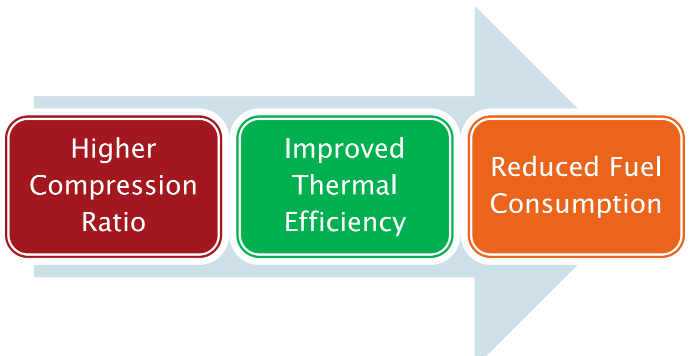
Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
					x



- Gasoline Direct Injection: Injects fuel directly into cylinder while maintaining proper air/fuel ratio to allow use of 3-way catalytic converter.
- Engine must still be throttled to maintain proper air/fuel ratio.
- Internal cooling of cylinder from fuel vaporization results in higher knock margin allowing greater compression ratios.

* FCR improvement relative to a port injected engine.



Class 2b/3 Lean Burn GDI

Potential FCR Improvement: 10-14%* (2010) (1)

Cost: $750 (2009 dollars) (1)

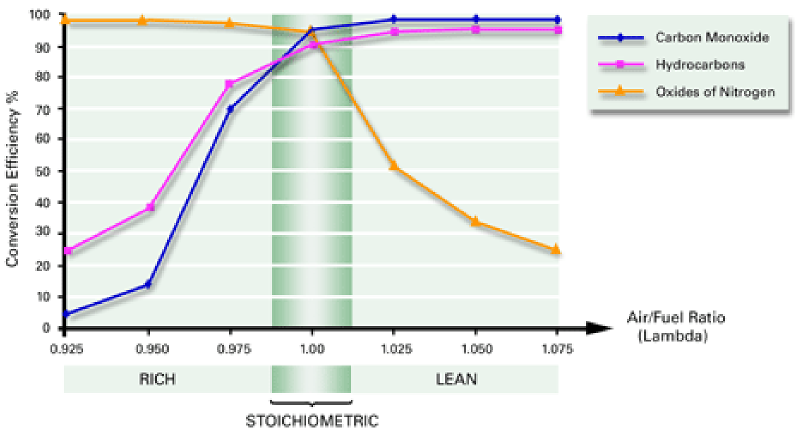
* FCR and cost increments relative to stoichiometric GDI engine.

Technology Readiness Level: Commercial

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
					x

Operating "lean" results less efficient NOx conversion for 3-way catalyst



- Gasoline Direct Injection engine that varies air/fuel ratio based on load to minimize throttling loses.
- Reduction in fuel consumption due to reduced pumping losses, increased compression ratios, and higher efficiency due to lean-burning mixture.
- Typically equipped with turbochargers.
- Aftertreatment similar to diesel (e.g. SCR, EGR) is required to meet emission standards.

Camless Engines

Potential FCR Improvement: n/a

Cost: n/a

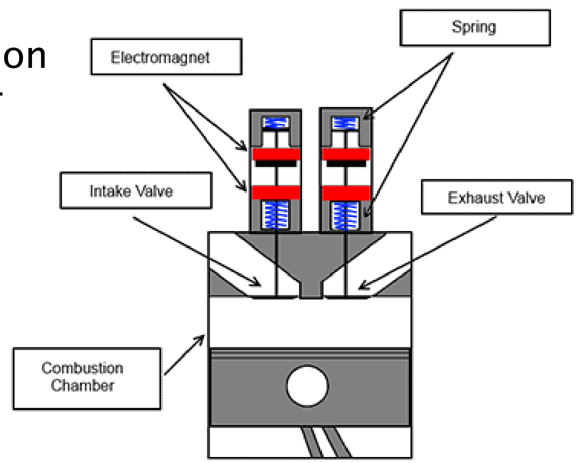
Technology Readiness Level: Research and Development

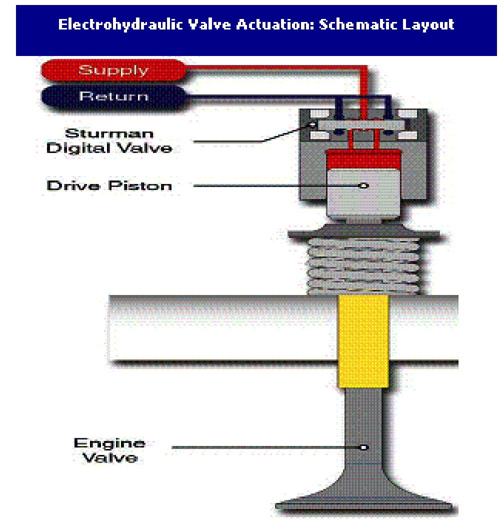
Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
x	x	x	x	x	x

- Allows for independent control of valve lift, valve velocity and timing, and selective valve deactivation/activation.
- Optimizing all parameters of valve motion will result in fuel consumption reduction, higher torque and power output, lower exhaust emissions.
- Currently in prototype stage of development.

Electromagnetic Systems





Electrohydraulic Systems

- Use combination of a high-pressure hydraulic source and fast-actuating solenoid values to control valve opening/closing.
- Current hydraulic systems require large power consumptions to function
- Most applicable to diesel engine design.

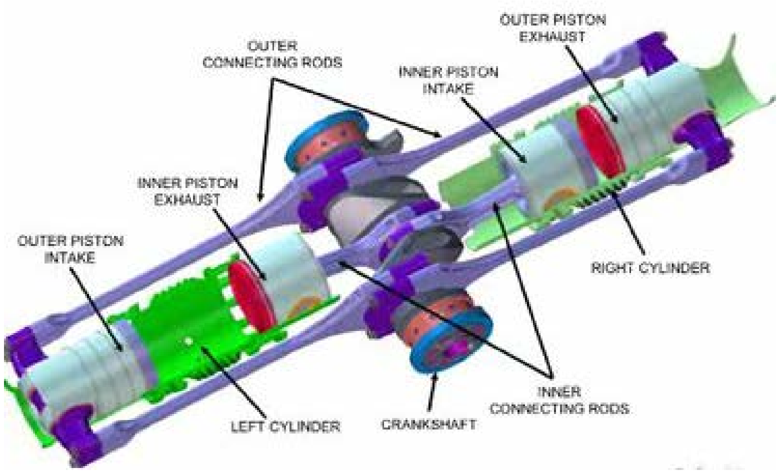
Opposed Piston Engine

Potential FCR Improvement: n/a
Cost: n/a

Technology Readiness Level: Research and Development

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X	x	x	x	x	x



- Eliminates the cylinder head and valve train of traditional engines resulting in a smaller, lighter weight engine that reduces heat and friction loss.
- Greater surface area/volume and power/weight ratios.
- Leaner air/fuel ratio requirements and shorter combustion duration result in enhanced thermal efficiencies.

- Potential 15-24% lower cycle-average brake-specific fuel consumption depending on application. (10)
- Currently in developmental R&D and prototype stages. Automakers see opposed piston engines as a post-2020 technology.

Free Piston Engine

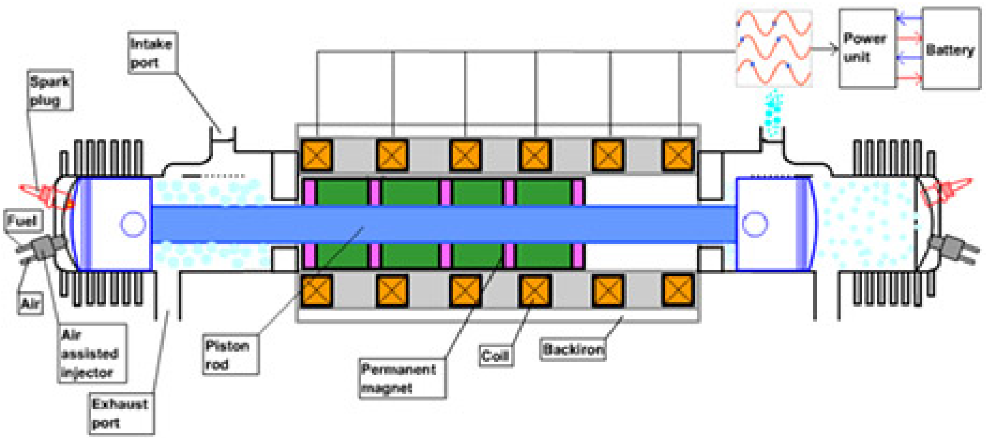
Potential FCR Improvement: estimated up to 20% (2009) (11)

Cost: n/a

Technology Readiness Level: Research and Development

Applicability

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X	x	x	x	x	x



- Piston motion not restricted by a rotating crankshaft.
- Elimination of crankshaft mechanism reduces the number of parts and complexity of the engine design.
- Results in reduced frictional losses, lowered manufacturing costs, and a longer engine lifetime.

- Linear alternator converts mechanical work to electricity as piston moves through the permanent magnet/electromagnetic coil system.
- Variable compression ratios optimize combustion leading to higher part load efficiencies.
- Fuel consumption reduced by about 20% relative to conventional engine designs and up to 50% during light load applications.
- Free piston engines have been demonstrated to run on different fuels such as gasoline, diesel, crude oil, and vegetable oil.

Vehicle/Trailer Efficiency

Table of Contents

Aerodynamics (Long-Haul)

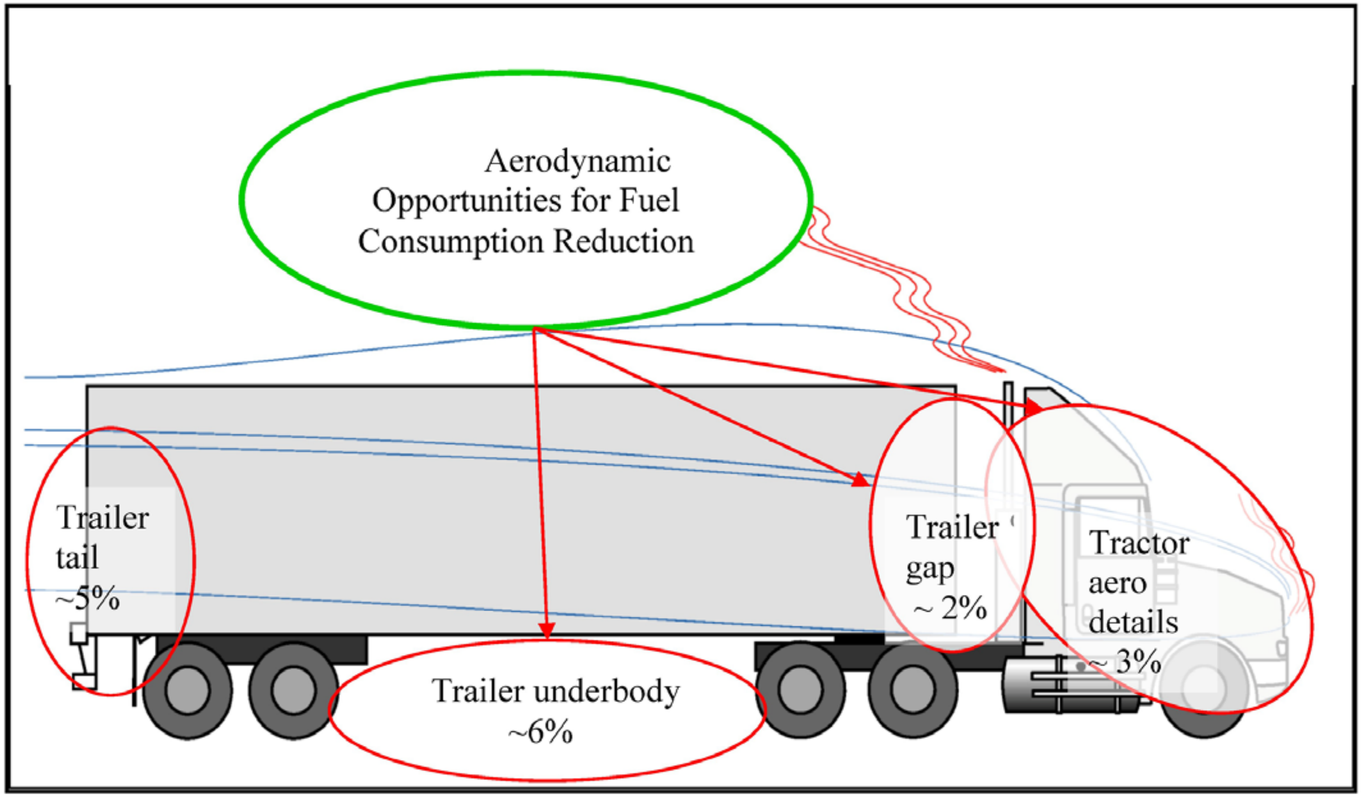
Potential FCR Improvement: 9-16% [2010](1)

Cost: Trailer $700-$4,800 (2013) (5)

Tractor $2,700-$6,250 (2009) (2)

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
x					



SOURCE: NRC, 2014, Figure 6-3 (4)

Aerodynamics(Long-Haul): Tractor

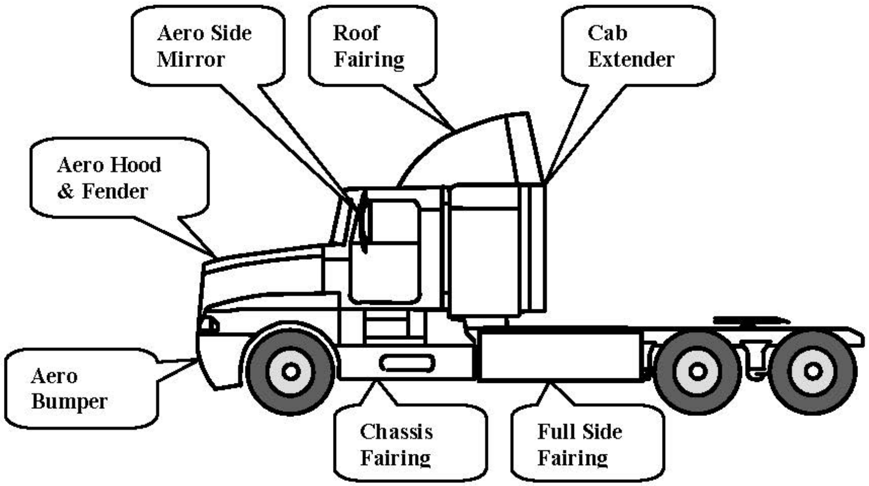


FIGURE 6-4 Sleeper tractor with aerodynamic features identified. SOURCE: NRC, 2010, Figure 5-5.

Classic Tractor

"SmartWay" Aerodynamic Tractor

"Next Generation"

Aerodynamics(Long-Haul): Trailer

Trailer Technologies include:

Side Skirts

Boat tails

Gap reducers

Underbody Devices

Aerodynamics(Long-Haul): Trailer

Table 6: Summary of interview responses on trailer technology costs and level of adoption

Technology	Fuel Savings	Cost to End User		Typical Payback Time	Adoption in New Trailer Sales
		High	Low		
Side skirts – average	3%	$1,100	$700	1–2 years	40%
Side skirts – best	7%			< 1 year	
Boat tails – average	3%	$1,600	$1,000	2–3 years	3%
Boat tails – best	5%			1–2 years	
Gap reducers	1%–2%	$1,000	$700	2–5 years	Minimal
Underbody devices	2%–5%	$2,200	$1,500	2–5 years	3%

Low-Rolling Resistance Tires

Potential FCR Improvement: 2-14% (2010)(2)

Cost: $30-$225 per tire (2009 Dollars) (2)

Technology Readiness Level: Commercial

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X	x	x	x	x	x

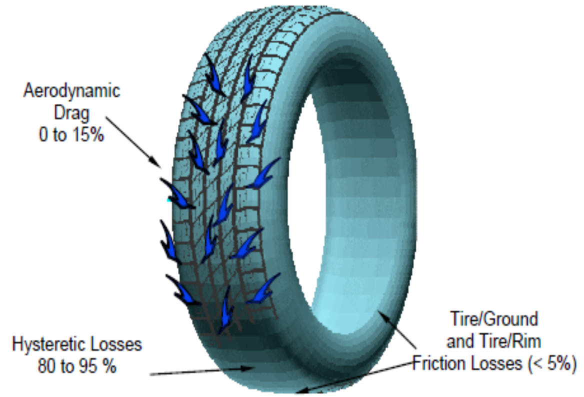
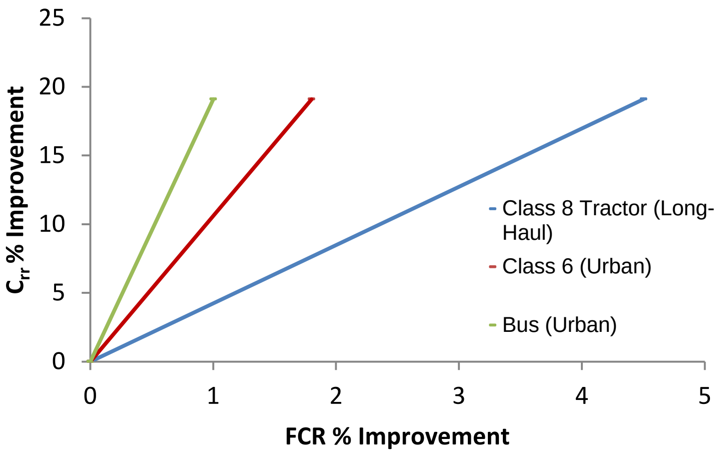


Figure IX-6: Contributors to Rolling Resistance (Michelin, 2002)

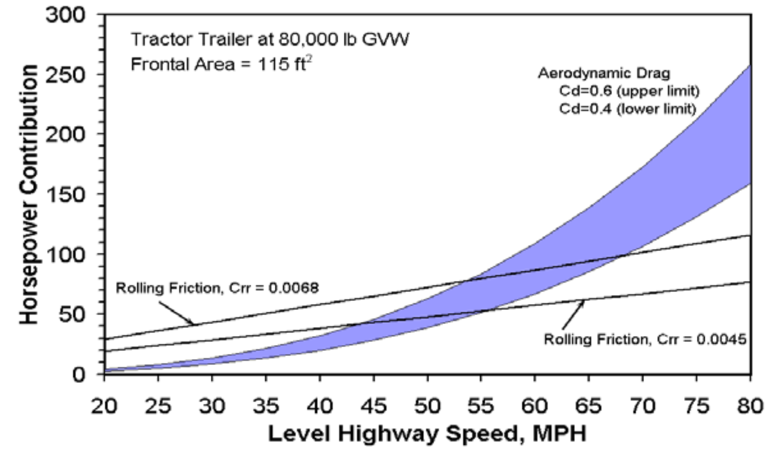
- Tire rolling resistance accounts for roughly 1/3 of power required to propel a line-haul truck at highway speeds.
- Characteristics of low rolling resistance tires include reduced sidewall flexing, tire rubber material, and tread design/thickness.

Low-Rolling Resistance Tires



Truck Class	Ratio of (*) $(C_{rr}\%)/(FCR\ \%)$
Class 8 Long Haul	≈ 4
Class 6 Urban	≈ 10
Bus Urban	≈ 20

* Numbers generated using rolling resistance data from sources TIAX, 2009 and NAS, 2010 (1,2).



- From graph, rolling resistance can be seen to have greater impacts at increased speeds.
- Fuel consumption reduction in relation to rolling resistance is highly duty cycle dependent.
- Potential savings much greater for fast moving line-haul sector than for stop-and-go urban sector.

Low-Rolling Resistance Tires

Wide Base Single Tires vs. Dual Tires

- Wide base single (WBS) tires can provide both rolling resistance improvements and weight improvements relative to dual tires

- Eliminating two sidewalls and bead areas by switching to wide base singles can cut flex-related rolling resistance in half.

- Weight savings on a combination truck ranges from 800-1000 pounds when applied to drive and trailer axles. (23)

- Additional cost for purchase of new wheels if transitioning from dual tires to a single wide tire. (about $1,200 per trailer for aluminum wheel/WBS tire combination). (2)

Longer Combination Vehicles (LCVs)

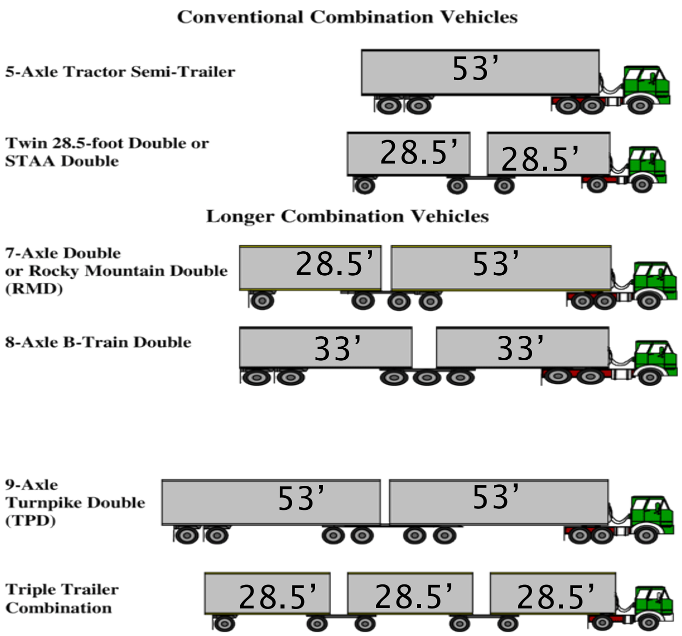
Potential FCR Improvement: 13-21% (2010) (12)

Cost: n/a

Technology Readiness Level: Commercial

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X					



- Increased cargo capacity enhances fleet productivity.
- Lowers shipping costs, reduces fuel consumption, reduces traffic congestion.
- Annual fuel cost savings of $8000 – $13,000* (12).
- GHG Reduction: up to 34 metric tons per year nationally.
- Will require changes to current laws and regulations.

- Values assume fuel prices of $3.80 per gallon, 2166 gallons of fuel saved with Rocky Mountain Doubles and 3500 gallons of fuel saved with Turnpike Doubles and Triples.

Longer Combination Vehicles (LCVs)

Implementation Issues

Safety Issues	Remedies
- Potential increase in passenger vehicle safety and higher risk of rollover due to increased instability.	- Analyze safety records of states which currently allow LCVs
- Wider off-tracking during turns and potential trailer swaying.	- Likely requires extensive operator training
- Enhanced road wear due to heavier weights.	- Mitigated by increasing number of axles. - Studies suggest some combinations generate less road damage when normalized for tons transported.

Axle Efficiency (6x2 Design)

Potential FCR Improvement: 2.5% (2010) (13)

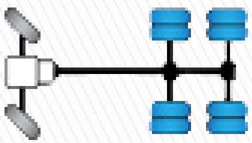
Cost: $1000-$2000, ROI: 20 months (13)

Technology Readiness Level: Commercial

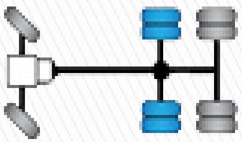
Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X	x	x	x	x	

Current Technology 6x4	Suggested Technology 6x2



* blue represents drive wheels



1 steer, 2 drive axles: equivalent to 4 drive wheel positions

1 steer, 1 drive axle, 1 dead axle: equivalent to 2 drive wheels positions

- 6x2 offers weight reduction of 400-450 lbs.
- Lack of internal gearing on 6x2 rear dead axle decreases parasitic losses from internal friction.
- 2.5% benefit in fuel consumption reduction leads to reductions in GHG

Axle Efficiency (6x2 Design)

6x2 Market Analysis

Current Market Penetration: 2.3%

- Estimated to account for 18% of new class 8 tractor sales in 5 years.

Costs

- Approximately $1000-2000 more expensive than 6x4 design.
- Suppliers expect costs of 6x2 to approach 6x4 design within a few years.

Resale Costs

- Currently, resale value of 6x2 configuration is about $4000 less than 6x4 design.
- With increased demand for 6x2 design in future, this resale penalty is expected to evaporate by the time a fleet is ready to sell.

Axle Efficiency (6x2 Design)

Concerns with 6x2 Implementation

- Reduced traction?
  - 6x2 configuration is readily used in Europe
  - US fleets which have switched to 6x2s report no significant issues with reduced traction.

- Increased tire ware on single drive axle
  - Useable 6x2 drive tire lifetime about 1/3 lifetime of 6x4 drive tire.
  - Tires on additional dead axle are less expensive, last longer, and have lower rolling resistance.

Overall payback period estimated to be around 20 months

Automatic Tire Inflation (ATI)

Potential FCR Improvement: 1% (2017) (17)

Cost: $700 – $1,000 (17)

Technology Readiness Level: Commercial

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X	x	x	x	x	x

- Tires represent the second largest financial expense for most fleets.
- Continuously monitors and adjusts air pressure within tires to insure proper inflation.
- Inspectors have found that only about 50% of tires checked during roadside surveys are within 5% of their recommended pressure.
- ATIs will improve fuel economy, extend tire lifetime, and improve safety.

<u>Payback recouped in 1-2 years.</u>

Speed Limiters

Potential FCR Improvement: 0.7-1%/mph reduction (2010) (1)

Cost: n/a

Technology Readiness Level: Commercial

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X					

- EU, Japan, Canada, and Australia have all implemented national regulations to limit the speed of heavy duty trucks.

- Fuel savings of 0.7% - 1% per mph speed reduction for an aerodynamically optimized tractor/trailer assuming a 65 mph baseline.

- 3.5% - 5% fuel benefit for a fleet lowering governed speed from 65 mph to 60 mph.

- 7% -10% fuel benefit for a fleet lowering governed speed from 70 mph to 60 mph.

Speed Limiters

Advantages

- Lower speeds may result in improved safety on roadways.
- Reduced GHG emissions due to improved fuel economy.

Disadvantages

- Reduced productivity and longer trip times might require more trucks on the road and increase shipping costs.
- Potential increase in traffic congestion due to longer commute time.
- Fleets lose flexibility of determining balance between fuel cost and trip time.
- Potential changes to rear axle ratio might be necessary to match new, lower cruise speeds.

Lightweighting

Potential FCR Improvement: 0.75–3.2% (2010) (1)

Cost: $600–$13,500 (2009 dollars) (1)

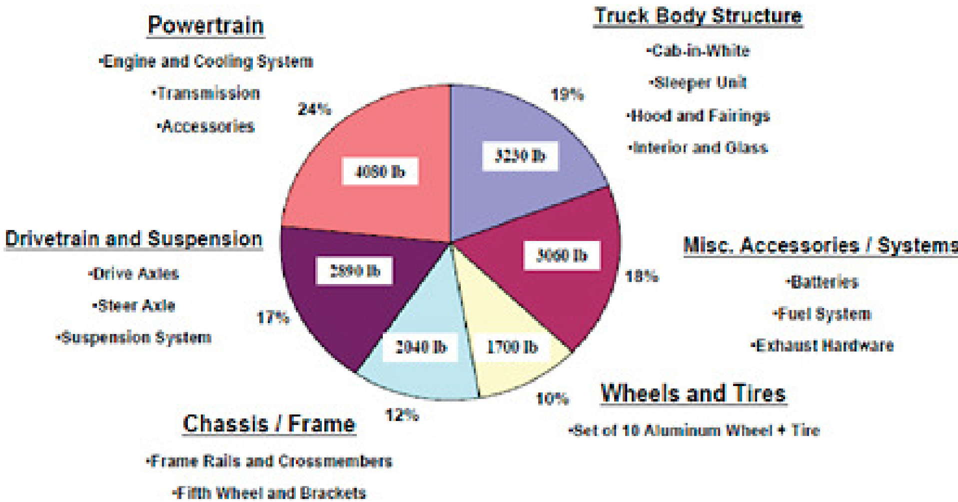
Technology Readiness Level: Commercial

Applicability:

HD Tractors		Class 3–8 Vocational			Class 2b–3
Long Haul	Short haul	Urban	Rural	WorkSite	
x	x	x	x	x	x

- Reducing a vehicle's mass decreases the fuel consumption by lowering the energy demands needed to overcome rolling resistance, climbing grades, and acceleration.
- Reduction in overall vehicle weight also improves freight transportation efficiency as more freight can be delivered on a ton-mile basis in a capped out vehicle.
- Cost ranges between $2-10/lb. with initial lightweighting features costing less (2).

Class	FCR (%)	Weight Reduction (lbs).	Cost: 2009 dollars
8	1.25	2500	$13,500
3–6	3.2	1000	$4,770
2B/3	0.75	300	$600
	1%	500	$3000



Lightweighting

Mass Reduction Methods

Material Substitution

- Lower density/higher strength materials such as high-strength steel, aluminum, magnesium alloys, carbon fiber, titanium, plastics.

Smart Design

- Optimize structural design to reduce total amount of materials

Reduced Powertrain Requirements

- With overall vehicle weight reduction, smaller, lighter engines/transmissions/ drivetrains with reduced torque requirements can be used to reduce weight even further.

Connected Vehicles

Predictive Cruise Control

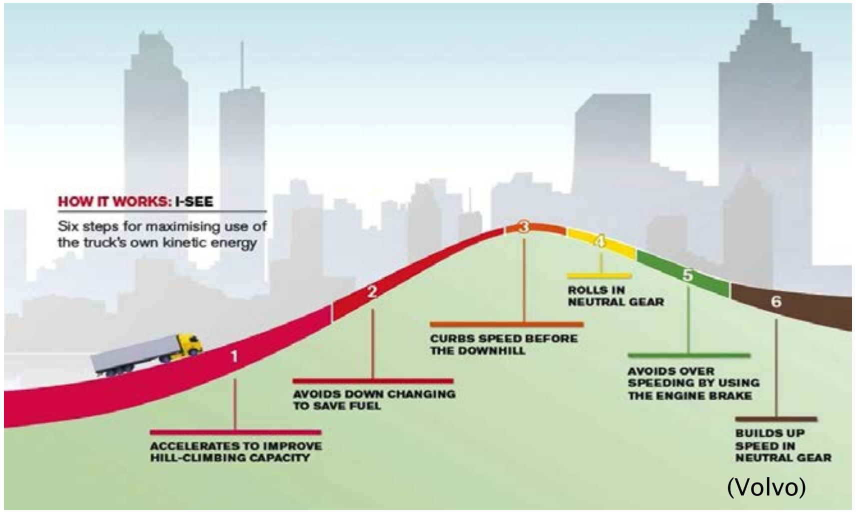
Potential FCR Improvement: 1–3% (2010) (1,2)

Cost: $850 – $1,561 (2009 Dollars) (1)

Technology Readiness Level: Demonstration

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X					



(Volvo)

- PCC not only controls vehicle speed and gap length, but also adjusts transmission and gear settings to maximize fuel economy.
- System primarily intervenes when negotiating uphill and downhill stretches.
- Uses maps and GPS to predict upcoming route terrain and adjusts engine output accordingly to maximize fuel economy.
- Fuel consumption reduction will be dependent on road topography.
  - In hilly conditions, fuel savings will accrue because there is less need to accelerate on uphill climbs and less time spent in lower gears.

Connected Vehicles

Potential FCR Improvement: 10–21% (2010) (1,20)

Cost: $500–$2,600 (2009 dollars) (1)

Technology Readiness Level: Demonstration

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X					

Platooning

"Computer Monitored Drafting"

- Vehicles travel closely together (drafting) resulting in a lower drag coefficient improving fuel economy, while reducing both emissions and traffic congestion.
- Spacing between vehicles can range from 7 - 30 feet with larger vehicles (class 8 trucks) having wider gaps.
- Inter-vehicle communication systems and cooperative cruise control technology allows speed updates to vehicles every 20 msec, allowing the "convoy train" to automatically make adjustments to speed and gap space.

Connected Vehicles

Platooning

Fuel/GHG Savings and Implementation

- Pilot studies have shown fuel consumption/GHG savings ranging from about 10-21% in trial trucks to 3-10% fuel consumption savings in the lead truck(1). Anticipated costs cover additional safety features and sensors.

- Large scale testing of platooning possible on public roads by 2015 with goals of developing a reliable self-driving system within 5 years and implementing the technology sometime within the next decade.

Implementation Challenges

- Public Acceptance: Driver Discomfort, Safety Issues
- What happens during an unforeseen emergency?
- Joining/Leaving Platoon
- Will new traffic regulations be warranted?
- How to keep platoons from hindering ability of other vehicles to merge onto highways?

Idle Reduction Technologies

Potential FCR Improvement: 1.3–9% (2010) (1,2)

Diesel APU = 5 grams CO_2/ton-mile

Battery/Electric = 6 g CO_2/ton mile (Ph 1)

Cost: $900 – $12,000 (21)

Technology Readiness Level: Commercial

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X					

- US fleets use 3 billion gallons of diesel fuel yearly while idling, approximately 8% of total fuel burned.
- Fuel consumed while idling costs the national trucking industry about $8 billion dollars annually.

Main Engine Speed (Revs/Minute)	Average Fuel Consumption
650 RPM	≈ 0.5 gallons/hour
1000 RPM	≈ 1.0 gallons/hour
1200 RPM	≈ 1.2 gallons/hour (21)

*All cost values obtained from NACFE, (2014). Confidence Report: Idle Reduction Solutions (21).

Idle Reduction Technologies

Technologies Discussed

- Fuel Operated Air Heaters
- Diesel Auxiliary Power Units (APUs)
- Battery HVAC/APUs
- Automatic Engine Start/Stop Systems
- Truck Stop Electrification
- Solar Energy Capture

*All cost values obtained from NACFE, (2014). Confidence Report: Idle Reduction Solutions (21).

Idle Reduction Technologies

Fuel Operated Air Heaters

- Fuel consumption as low as 0.02 – 0.13 gallons/hour (about 1 gallon during 24 hour period).
- Installed units range from $900 – $1500.
- Only provide bunk heating to the cab, does not provide air conditioning or AC power for hotel loads.
- Can drain truck's main batteries with long term use.

Idle Reduction Technologies

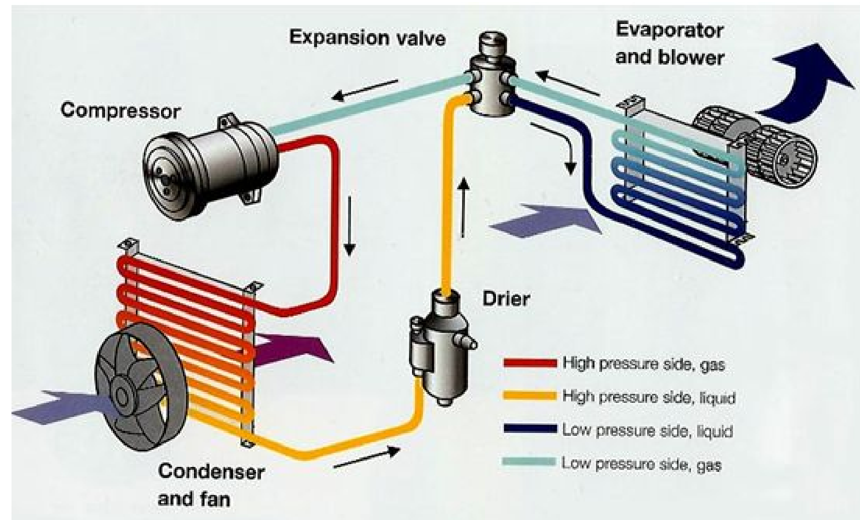
Diesel APUs

- Burn between 0.1 – 0.5 gallons of fuel/hour.
- Can provide a complete solution for cab cooling, heating, AC power for hotel loads, block heating and battery charging.
- Weigh between 400 and 550 pounds.
- Require periodic maintenance such as oil and filter changes.
- Installed prices range from $8,000– $12,000.

Idle Reduction Technologies

Battery HVAC/APUs

- Units can provide 8-10 hours of cooling capacity.
- System's batteries are recharged during main engine running or through off-shore power.
- Produce zero emissions while in operation, however, charging during main engine operation does require some fuel consumption (Typically recharges in 1 -3 hours).
- Weigh between 400 -500 pounds.
- Prices range from $4,500 - $6,000 ($8,500 - $8,800 including installation).
- Replacement batteries typically $180 - $260.



Idle Reduction Technologies

Automatic Engine Start/Stop Systems

- Continuously monitors cabin temperatures when occupied and automatically turns engine on/off as needed to maintain a desired temperature.
- New models focus on monitoring state of charge of batteries to maintain interior cabin temperatures. System comes on to recharge batteries when battery life is low.
- Drawback of system is that main engine must idle during recharge periods.
- In California, system must be combined with a “Clean Idle” engine to meet idling regulations.
- Adds little weigh to the vehicle
- Prices range from $1,500 – $2,500.

Idle Reduction Technologies

Solar Energy Capture

- Roof mounted solar panels capture energy to run and recharge the battery HVAC system.
- Daylight breaks can be extended to a minimum of 14 hours when captured on-vehicle solar energy provides most of the battery HVAC's power.
- Zero emission technology: requires no engine load to recharge batteries.
- New products contain low-adhesion polycarbonate covering allowing for easy dirt removal from panels.
- Estimated annual savings of about $6,000 due to reduction in engine idling.

Idle Reduction Technologies

Truck Stop Electrification

- Removable window adapter to provide long term, idle-free AC power.
- Typical cost about $2.00/hour.
- Significant investment in infrastructure must be undertaken to make this a viable idling reduction solution for fleets.

- Lack of coverage and limited number of electrified parking spaces across United States means fleets must rely on alternate idle reduction technologies during trips.

Air Conditioning Improvements

Potential FCR Improvement: 0%*

Cost: $70 (2007 dollars) (18)

Technology Readiness Level: Demonstration

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X	x	x	x	x	x

HVAC Refrigerant

Current Refrigerant

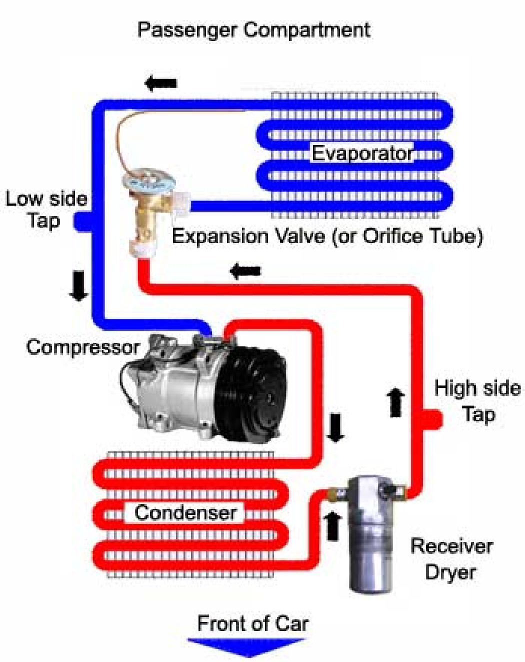
HFC-134a : GWP of 1300

Alternative Refrigerants

HFC-152a : GWP of 120

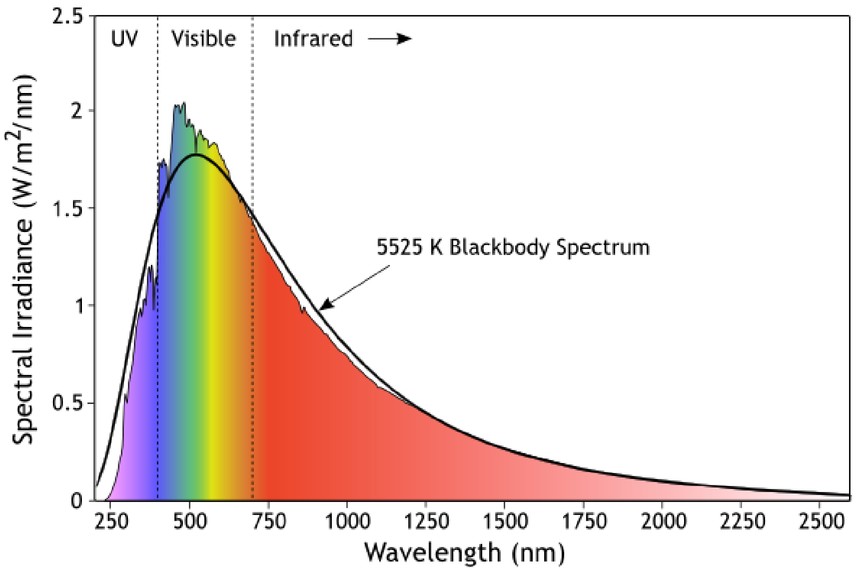
R-744 (CO_2) : GWP of 1

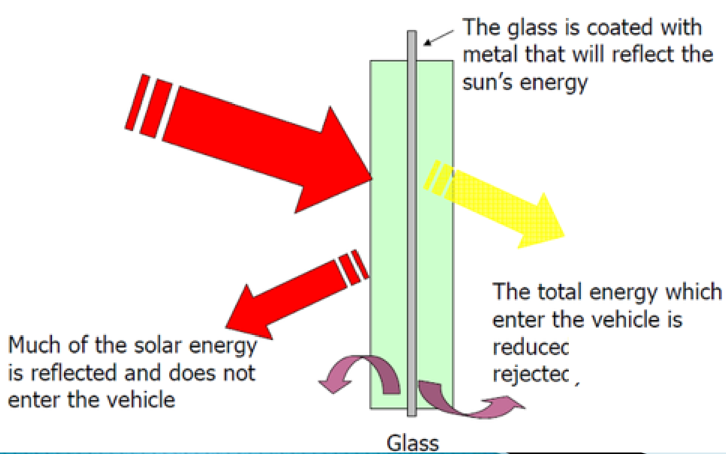
- ≈2.5% reduction in GHG(19) Assuming constant leak rates, alternative refrigerants offer 1-2 orders of magnitude less GWP emissions.
- Estimated cost of about $70 to upgrade to lower GWP refrigerants.
- Potential flammability concerns with reduced GWP refrigerants.



* Not a fuel saving technique. Reduction in GHG comes via limiting the amount of high greenhouse warming potential (GWP) molecules into the atmosphere.

Air Conditioning Improvements





IR Reflective Glazing

Potential FCR Improvement: ≈1% (2010) (14)

Cost: $15–$110 (2009 dollars) (15)

Technology Readiness Level: Commercial

Applicability

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X	x	x	x	x	x

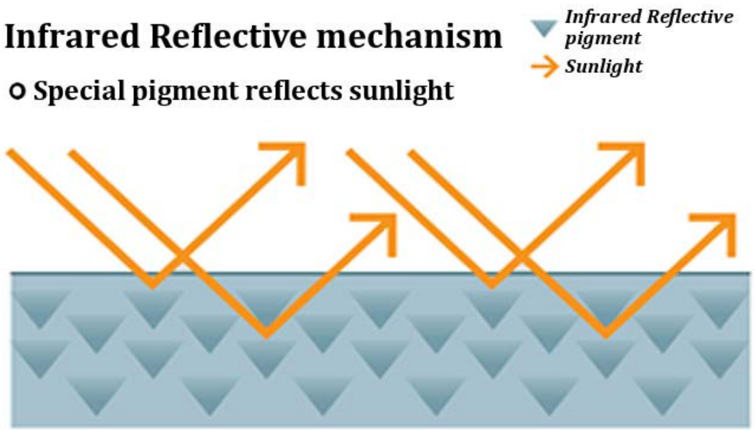
- 70% of all solar radiation is emitted through vehicular window surfaces.
- About 50% of solar radiation reaching Earth's surface is in the Infrared region.
- Limiting IR wavelengths from entering the vehicle lowers interior cabin temperatures without affecting operator visibility.
- Reduced interior temps lower workload and fuel consumption of HVAC systems.

Air Conditioning Improvements

Glazing Costs

- Estimated direct cost to consumers of about $\$1.50/ft^2$ to add reflective glazing to laminated surfaces.
- Estimated cost of $\$2.50/ft^2$ to switch from tempered glass to reflective laminated glass.
- Estimated 1% improvement in fuel consumption reduction.

Air Conditioning Improvements



IR Reflective Paints

Potential FCR Improvement: ≈1% (2010) (16)

Cost: $70 (2009 dollars) (24)

Technology Readiness Level: Commercial

Applicability

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X	x	x	x	x	x

- Current reflective paints can reflect up to 30% of incoming solar radiation.
- Estimated increased cost up to $70 for reflective paints relative to traditional paint bases.
- Potential to reduce fuel consumption/reduce emissions up to 1%.
- Current research shows growth in the replication of darker color schemes.

Air Conditioning Improvements

Improved Cabin Insulation

Potential FCR Improvement: n/a

Cost: n/a

Technology Readiness Level: Commercial

Sleeper cab insulation

Applicability

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X	x	x	x	x	x

- Minimizes energy transfer between the interior cabin and outside environment.
- Less work is required of the HVAC to maintain a specific temperature.
- Benefits limited: Difficult to eliminate energy transfer areas near supporting structures within the vehicle.

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