Truck Technology Assessment Workshop
Trucks and TRU Session
September 2, 2014

Engine/Powerplant and Drivetrain Optimization

Vehicle /Trailer Efficiency

Presentation Outline

- Background
  - Phase 1 and Phase 2 Standards
  - Potential for Further GHG Reduction
- Key Engine and Vehicle Technologies for Various Vehicle Classes
- Key Technology Descriptions
- GHG/NOx Tradeoff
- Conclusions and Next Steps
- Contacts

Background

Background

- Technologies being evaluated to set stringency of Phase 2 standards.

- Phase 1 GHG standards serve as the baseline for the technology assessment.
  - Handout contains tables of Phase 1 engine and vehicle standards.

National Academy of Sciences Estimated Potential GHG/Fuel Consumption Reduction (FCR) per Vehicle from Applying Engine/Vehicle Technologies

Category	Phase 1 Technology Reductions from 2010 baseline	Potential from 2010 baseline (based on NAS*)	Difference
HD Tractor-Trailer (Class 7-8)	Up to 23%	48%	25%
HD Vocational (Class 3-8)	6-9%	19-33%	13-24%
HD Pick-ups and vans (Class 2b)	12-17%	32%	15-20%

* Does not include Hybrid or Electric (covered in Hybrid Technology Assessment category)

Key Engine and Vehicle Technologies for Various Vehicle Classes

What are the Key Technologies Being Evaluated?

DIESEL ENGINE TECHNOLOGIES

1. Advanced Transmissions/Engine Downspeeding
2. Advanced Combustion Cycles
3. Waste Heat Recovery
4. Engine Downsizing
5. Stop-Start
6. Automatic Neutral Idle
7. Combustion and Fuel Injection Optimization
8. Higher-Efficiency Aftertreatment
9. Reduced Friction and Auxiliary Load Reduction
10. Air Handling Improvements
11. Variable Valve Actuation/ Cylinder De-activation

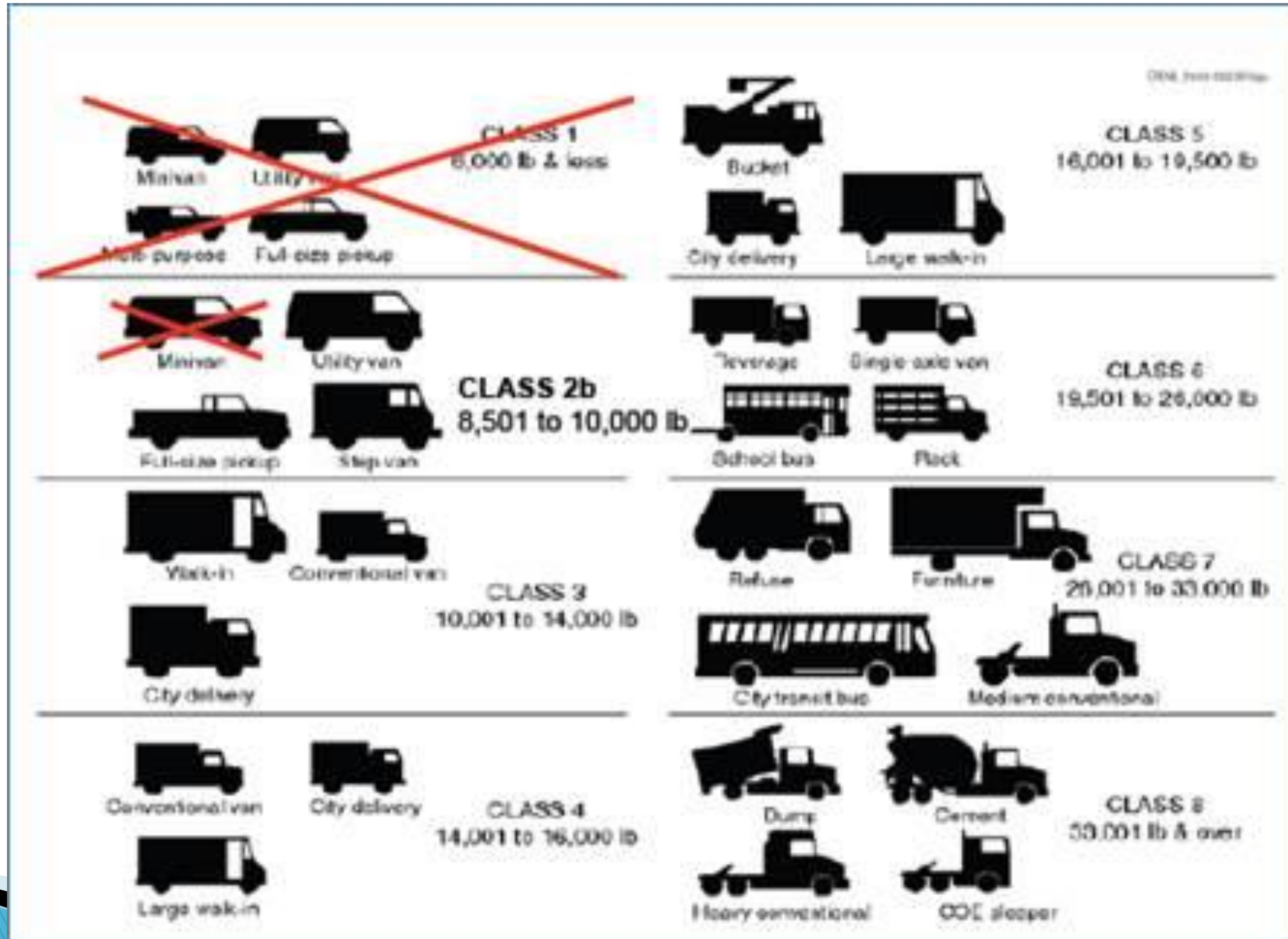
VEHICLE EFFICIENCY TECHNOLOGIES

1. Aerodynamics
2. Lightweighting
3. Low-Rolling Resistance Tires
4. Automatic Tire Inflation System
5. Vehicle Speed Limiters
6. Connected Vehicles (Platooning, predictive cruise control)
7. Axle Efficiency
8. Idle Reduction
9. Improved Air Conditioning System

GASOLINE ENGINE TECHNOLOGIES (Class 2b and 3)

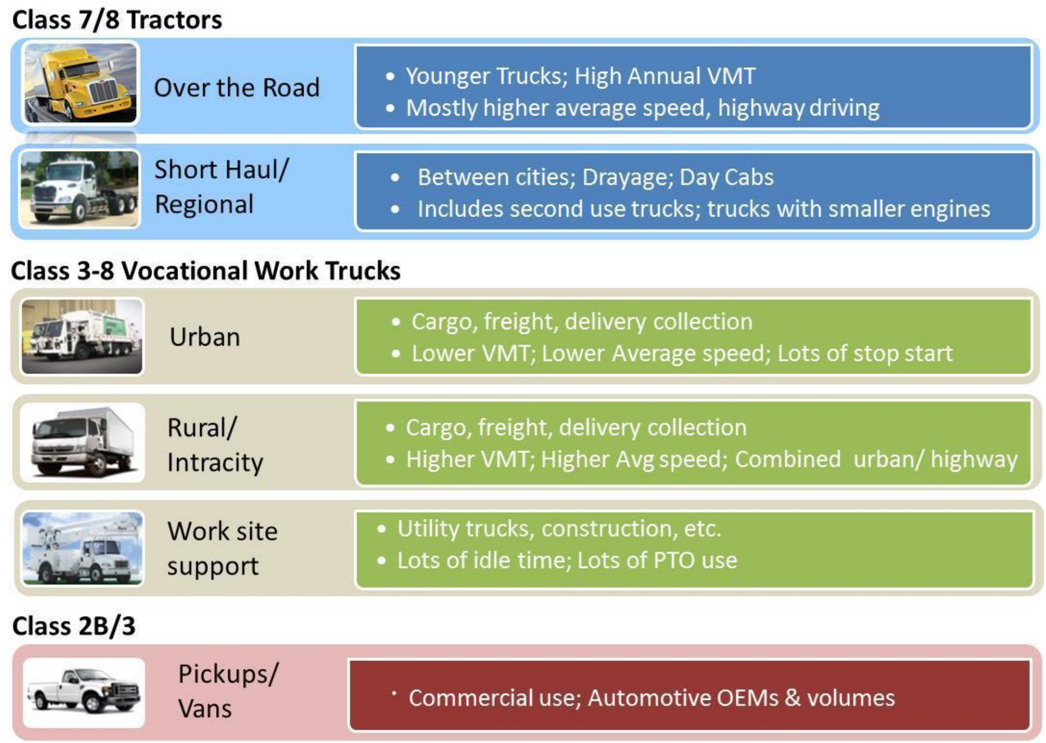
1. Lean Burn Gas Direct injection (GDI)
2. Stoichiometric GDI

What Classes of Trucks are Addressed in Technology Assessment?

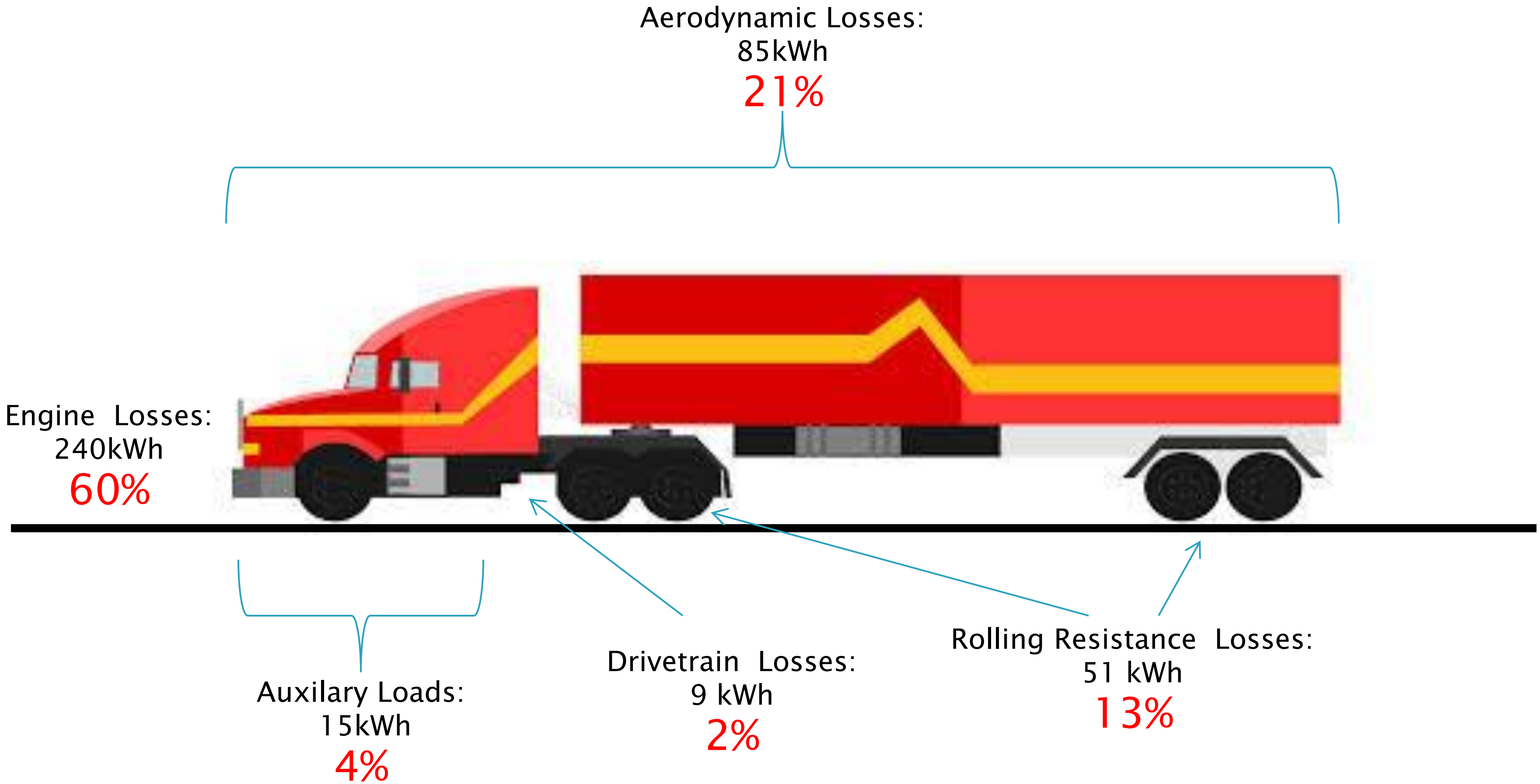


Key Engine and Vehicle Technologies: Heavy Duty Class 7-8 Tractors

- Three main categories:
  - Heavy Duty Tractors (Class 7-8)
  - Heavy Duty Vocational (Class 3-8)
  - Heavy-Duty Pick-ups and Vans (Class 2b-3)



Key Technologies Address Main Sources of Energy Losses



Based on Data from U.S. DOE (21st Century Truck Partnership). 2006

Heavy Duty Class 7-8 Tractors Key Technologies

	KEY TECHNOLOGIES	Potential GHG/FC Reduction (per Vehicle) from 2017 baseline
Engine/ Drivetrain	• Combustion and Fuel Injection Optimization • Air Handling Improvements • Reduced Friction and Auxiliary Load Reduction • Higher efficiency aftertreatment (SCR/DPF packaging) • Waste Heat Recovery • Advanced Transmissions /Engine Downspeeding (AMT)	• Up to 35%
Vehicle	• Aerodynamics* • Lightweighting • Low-Rolling Resistance Tires • Automatic Tire Inflation System • Vehicle Speed Limiters • Connected Vehicle • Axle Efficiency • Idle Reduction*	

* Most applicable to over-the road operations

DOE SuperTruck Program Shows Potential for Class 8 Tractor Trailers

- Project sponsored by the United States Department of Energy (DOE)
- $115 million in DOE funding awarded to private contractors under Supertruck Program
- Engine Efficiency Goal: By 2015, demonstrate 50% Brake Thermal Efficiency (BTE)
- Vehicle Efficiency Goal: By 2015, demonstrate 50% improvement in freight efficiency (ton-miles/gallon), which is equivalent to a **33%** reduction in load specific fuel consumption **(gallons/ton-mile)**
- Baseline is a 2009 MY tractor

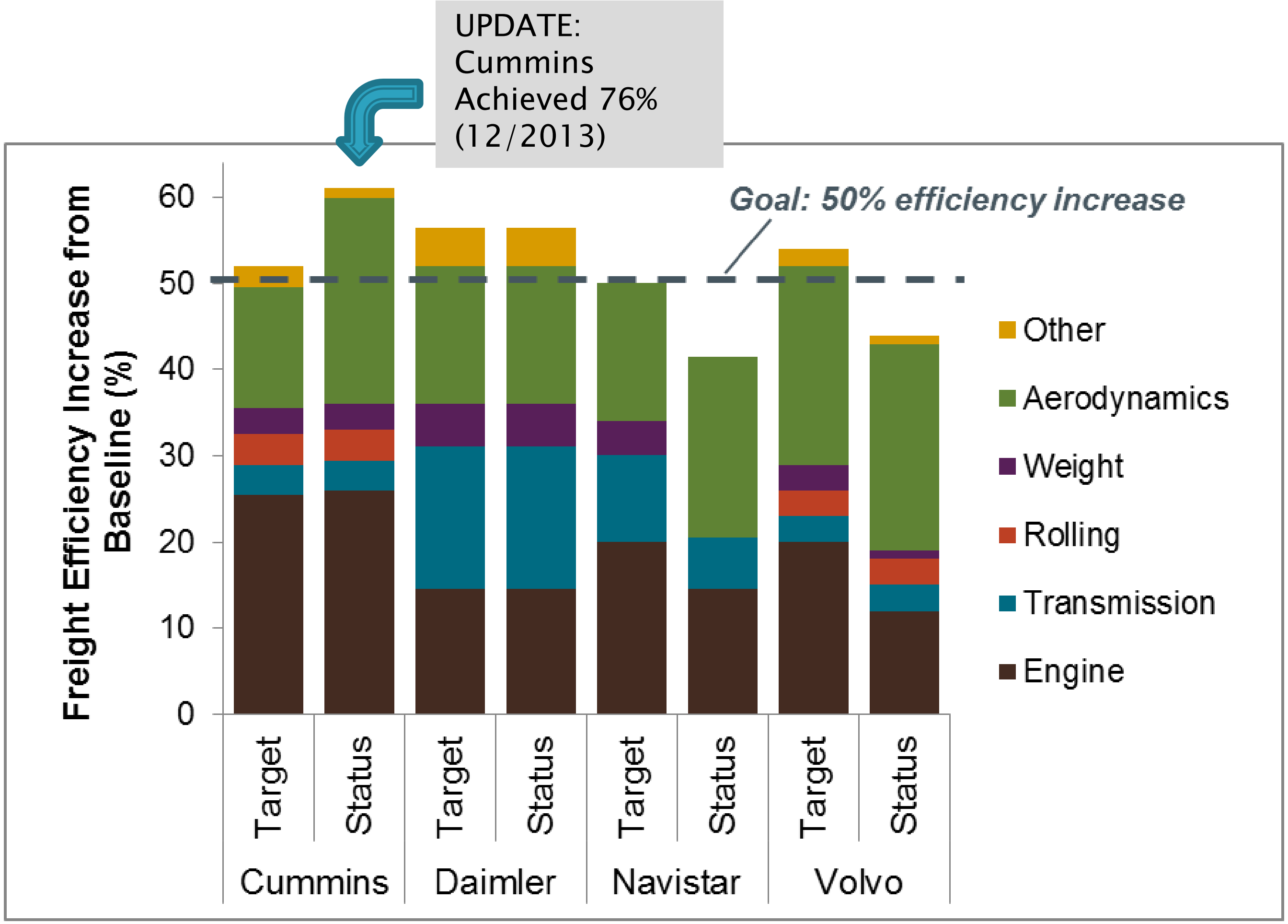
The Four SuperTruck Teams have Differing Strategies to meet the Same Goals

Strategy	Cummins	Daimler	Navistar*	Volvo
Engine Downsize	NO	YES	NO	YES
Engine Down-speeding	YES	YES	NO	YES
Transmission	AMT	AMT	Dual-Mode Hybrid	DCT
Hybridization	NO	Mild	Full (series/parallel)	NO
Waste Heat Recovery	YES (mechanical)	YES (electric)	NO	YES
Turbocompounding	NO	NO	YES (electric)	YES (mechanical)

(ICCT, 2014)

* Navistar program suspended since 2013

The Four SuperTruck Teams have Made Significant Progress in Meeting Goals



Comparison of US SuperTruck targets and 2013 status for tractor-trailer freight efficiency in miles/ton-gal. (ICCT, 2014)

Cummins/Peterbilt SuperTruck Technologies

ENGINE TECHNOLOGIES

1. Advanced Transmissions/Engine Downspeeding (AMT)
2. Advanced Combustion Cycles (LTC)
3. Waste Heat Recovery (Bottoming Cycle)
4. ~~Engine Downsizing~~
5. ~~Stop-Start~~
6. ~~Automatic Neutral Idle~~
7. Combustion and Fuel Injection Optimization (Calibration Optimization; Piston Bowl Geometry, Peak Cylinder Pressure)
8. Higher efficiency aftertreatment (Advanced Catalyst Coating)
9. Reduced Friction (Seals, oil viscosity) Auxiliary Load Reduction (More efficient lube and H2O pumps)
10. EGR/Turbo/Air Handling Improvements
11. ~~Variable Valve Actuation/ Cylinder De-activation (Variable Valve Actuation)~~

VEHICLE EFFICIENCY TECHNOLOGIES

1. Aerodynamics
2. Lightweighting
3. Low-Rolling Resistance Tires (Single-wide)
4. ~~Automatic Tire Inflation System~~
5. ~~Vehicle Speed Limiters~~
6. Predictive Cruise Control (GPS Route Manager)
7. Axle Efficiency (6x2)
8. Idle Reduction (Li Ion Battery APU)
9. Improved Air Conditioning System

Comparison of NAS Estimated Potential GHG/FCR (per Vehicle) from Applying Engine/Vehicle Technologies to Cummins SuperTruck

Category	Phase 1 Technology Reductions from 2010 baseline	Potential from 2010 baseline (based on NAS*)	Cummins/Super Truck from 2009 baseline
HD Tractor-Trailer (Class 7-8)	Up to 23%	48%	43%

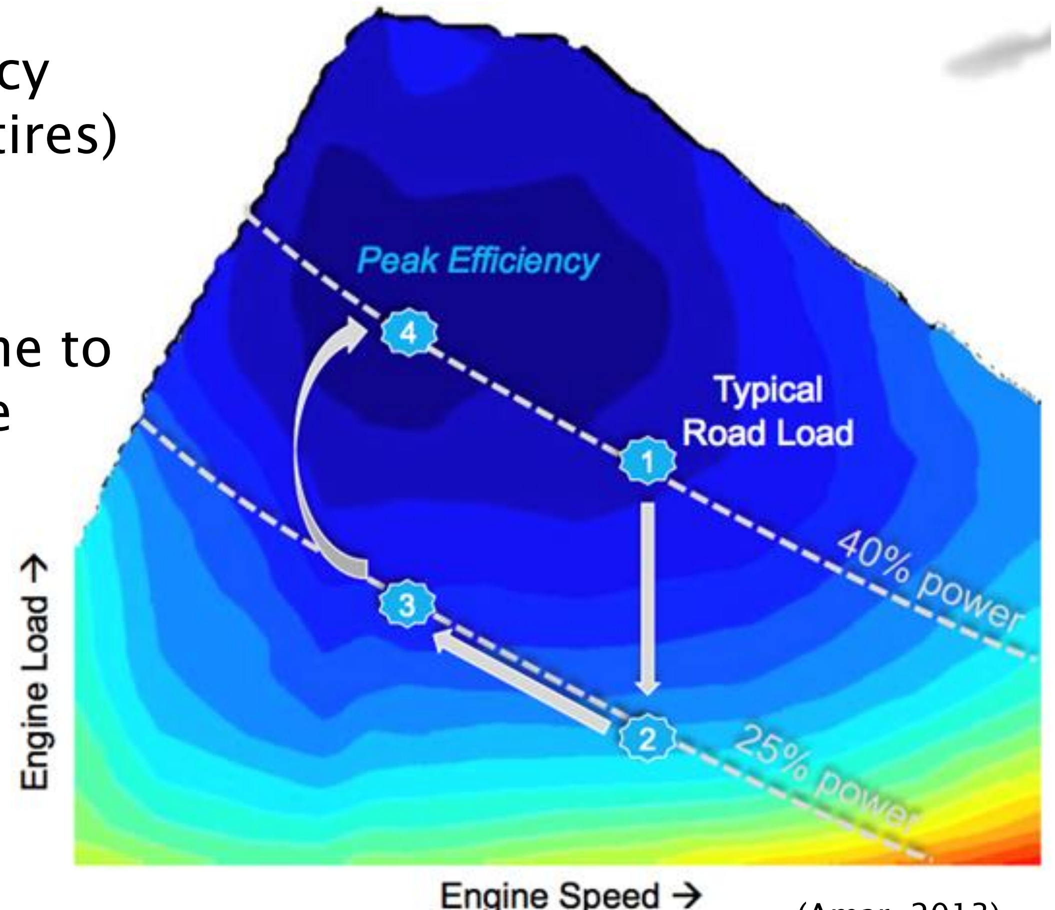
* Does not include Hybrid or Electric (covered in another Tech assessment category)

Cummins Demo 2 SuperTruck Recently Demonstrated 10.7 mpg

- 312 mile roundtrip from Fort Worth to Vernon, Texas
- Typical 2009 tractor fuel economy: 5.5 – 6.5 mpg
- Also tested over a 24 hour drive cycle that includes optimized idling
  - 75% improvement in mpg
  - 43% improvement in GHG emissions/fuel consumption rate (gallons/ton-mile)
  - 86% improvement in freight efficiency (ton-miles/gallon).

Daimler and Volvo use Down-sizing/Downspeeding Approach

- 1. ⇒ 2. = Vehicle Efficiency Improvements (aero, LRR tires)
- 2. ⇒ 3. = Downspeed (transmission)
- 3. ⇒ 4. = Downsize engine to get in Peak Efficiency zone



(Amar, 2013)

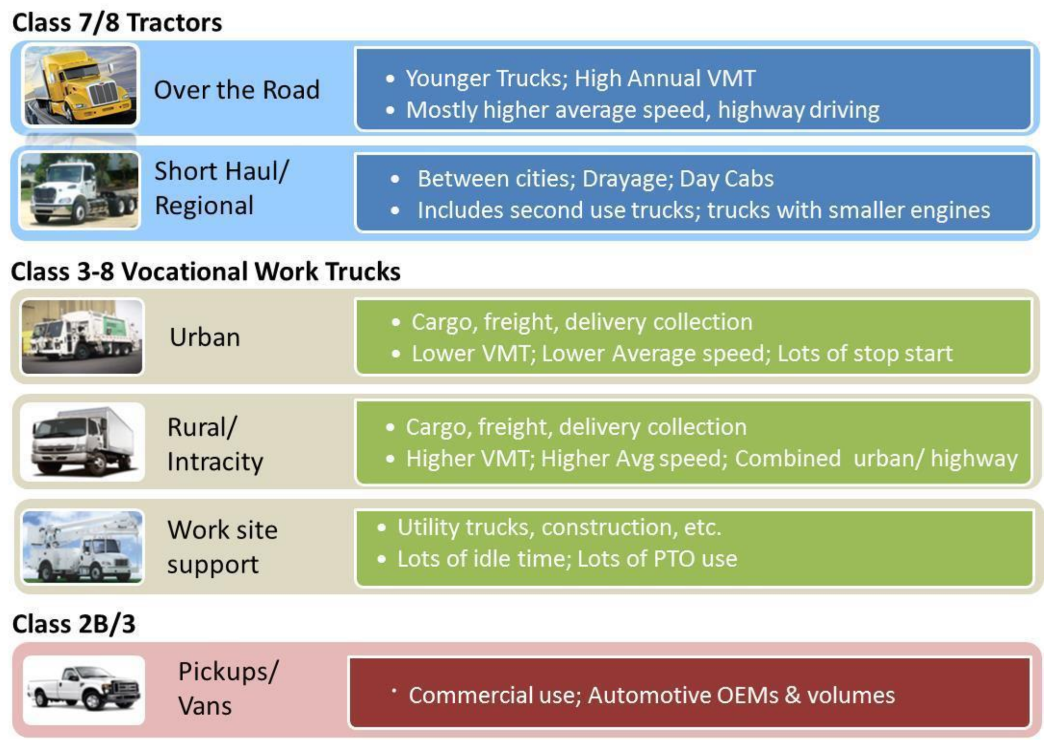
Volvo's Aerodynamic Concept

(Amar, 2013)

- No mirrors
- Low ride height
- Integrated trailer aerodynamics
- Small tractor-trailer gap
- Steeply -Raked Windshield

Key Engine and Vehicle Technologies: Heavy Duty Vocational Vehicles Class 3-8

- Three main categories:
  - Heavy Duty Tractors (Class 7-8)
  - Heavy Duty Vocational (Class 3-8)
  - Heavy-Duty Pick-ups and Vans (Class 2b-3)



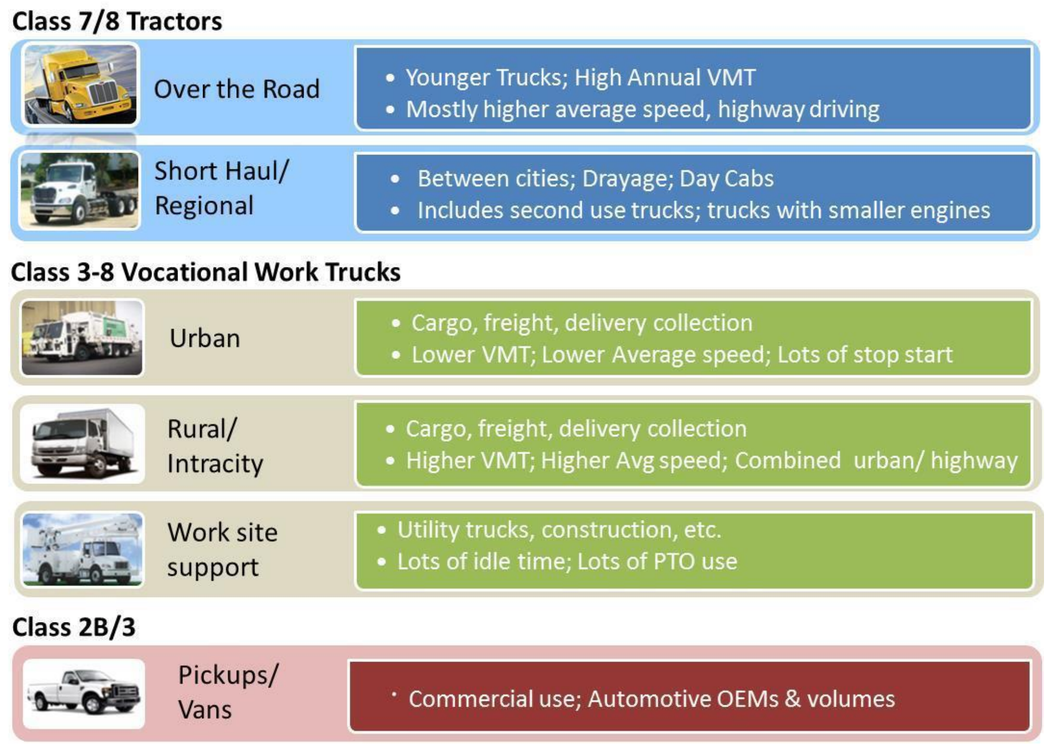
Heavy Duty Vocational Class 3-8 Key Technologies

	KEY TECHNOLOGIES	Potential GHG/FCR per Vehicle Reduction (%) from 2017 baseline
Engine/ Drivetrain	• Combustion and Fuel Injection Optimization • Air Handling Improvements • Reduced Friction and Auxiliary Load Reduction • Higher efficiency aftertreatment Advanced Transmissions /Engine Downspeeding (AT,DCT) • Stop-Start • Automatic Neutral Idle • Engine Downsizing	• Up To 35%
Vehicle	• Aerodynamics* • Lightweighting • Low-Rolling Resistance Tires • Automatic Tire Inflation System *(Electrification of Accessories included in Hybrid Technology Assessment)*	

* Applicable to Rural Intercity Straight Trucks

Key Engine and Vehicle Technologies: Heavy Duty Pick-ups and Vans 2b-3

- Three main categories:
  - Heavy Duty Tractors (Class 7-8)
  - Heavy Duty Vocational (Class 3-8)
  - Heavy Duty Pick-ups and Vans (Class 2b-3)



Heavy Duty Pick-ups and Vans (Class 2b-3)

	KEY TECHNOLOGIES	Potential GHG/FCR per Vehicle Reduction (%) from 2017 baseline
Engine/ Drivetrain	• Combustion and Fuel Injection Optimization • Air Handling Improvements • Engine Downsizing • Variable Valve Actuation/ Cylinder De-activation • Reduced Friction and Auxilary Load Reduction • Higher efficiency aftertreatment • Advanced Transmissions /Engine Downspeeding (AT,AMT,DCT) • Stop-Start • Automatic Neutral Idle • Gasoline: Stoichiometric GDI	• Up to 23%
Vehicle	• Aerodynamics • Lightweighting • Low-Rolling Resistance Tires • Automatic Tire Inflation System *(Electrification of Accessories included in Hybrid Technology Assessment)*	

Discussion of Specific Technologies

Discussion of Specific Technologies

- Waste Heat Recovery (Bottoming Cycle, Turbocompounding)
- Aerodynamics (Long-Haul)
- Advanced Transmissions/Downspeeding
- Stop-Start
- Automatic Neutral Idle
- Connected Vehicles
- Additional information on most other technologies is contained in Handout

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

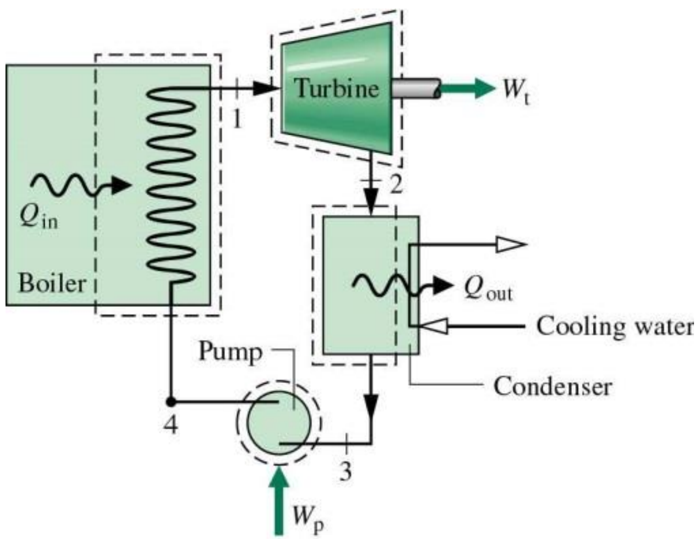
HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
X					

- 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

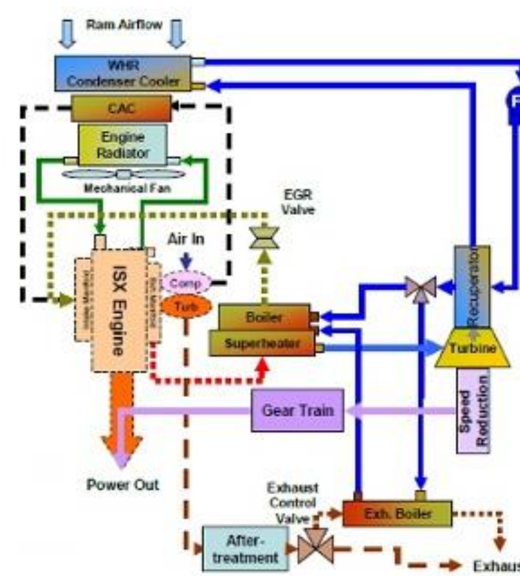
Waste Heat Recovery (Bottoming cycle)

Organic Rankine Bottoming Cycle:

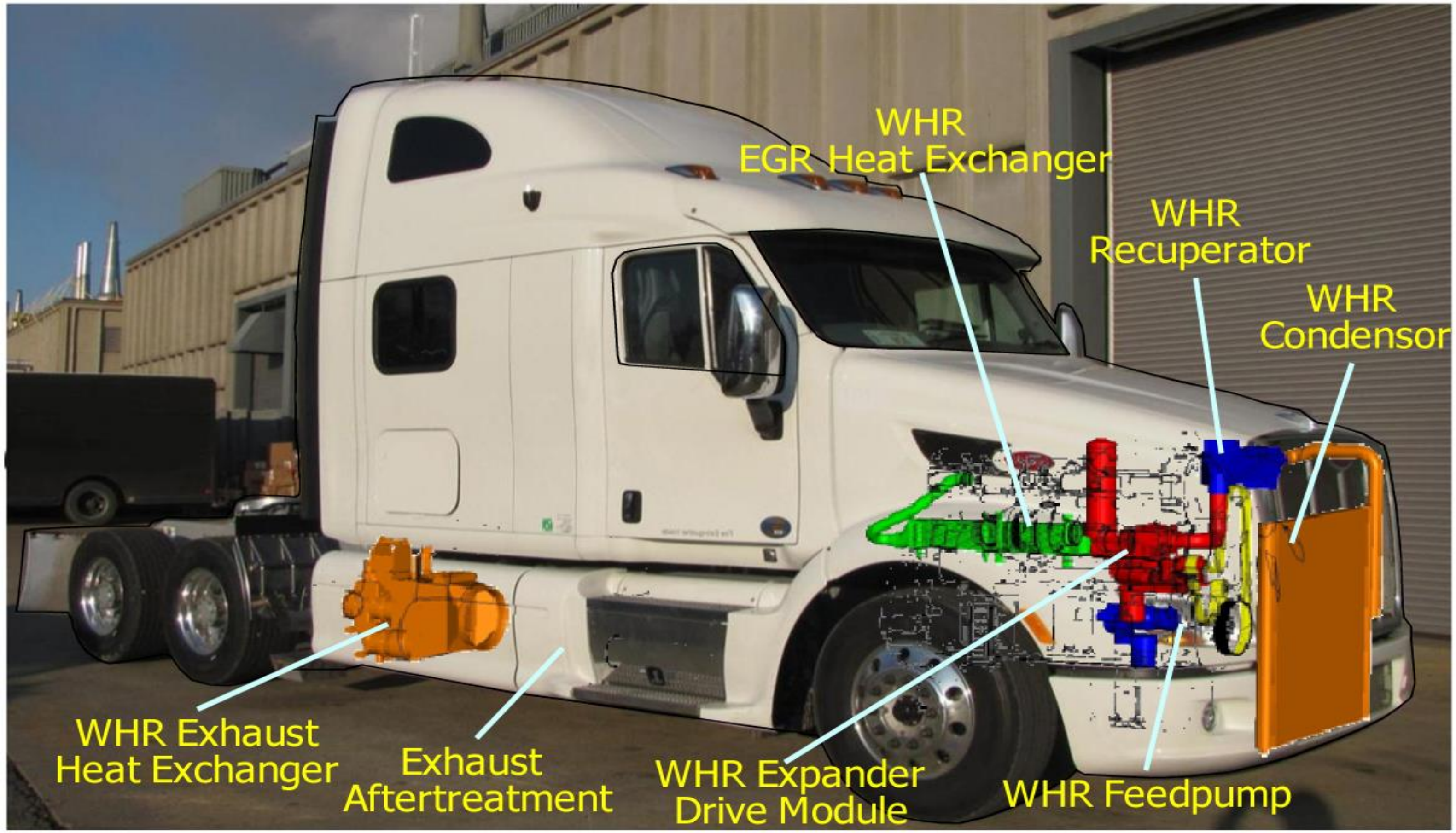
1. A working fluid is pumped from low to high pressure by a pump.
2. The pressurized liquid is heated at constant pressure by an external heat source (in this case, the exhaust gas) to become a superheated vapor.
3. The superheated vapor expands through a turbine to generate power output. Electrical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



SuperTruck Waste Heat Recovery



Waste Heat Recovery (Bottoming cycle)



Cummins waste heat recovery system. (Stanton, 2013)

Waste Heat Recovery (Turbocompounding)

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

Turbocompound

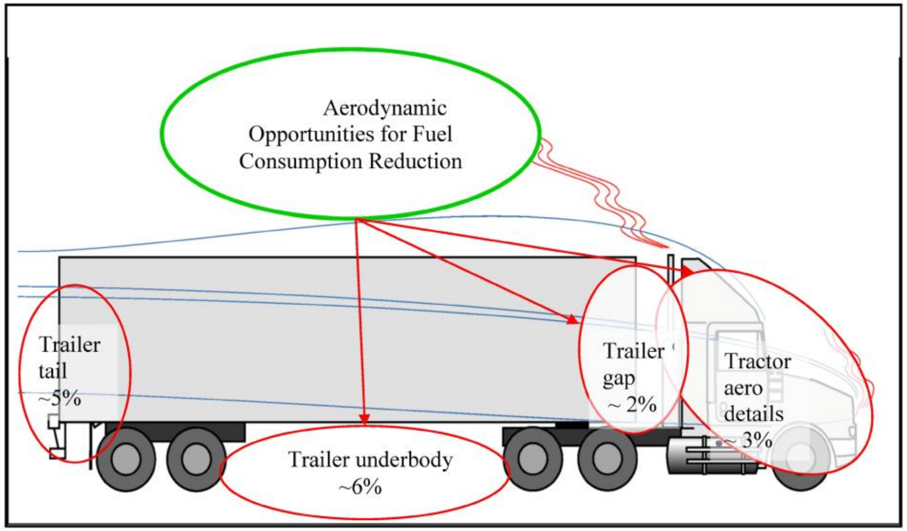
Aerodynamics (Long-Haul)

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

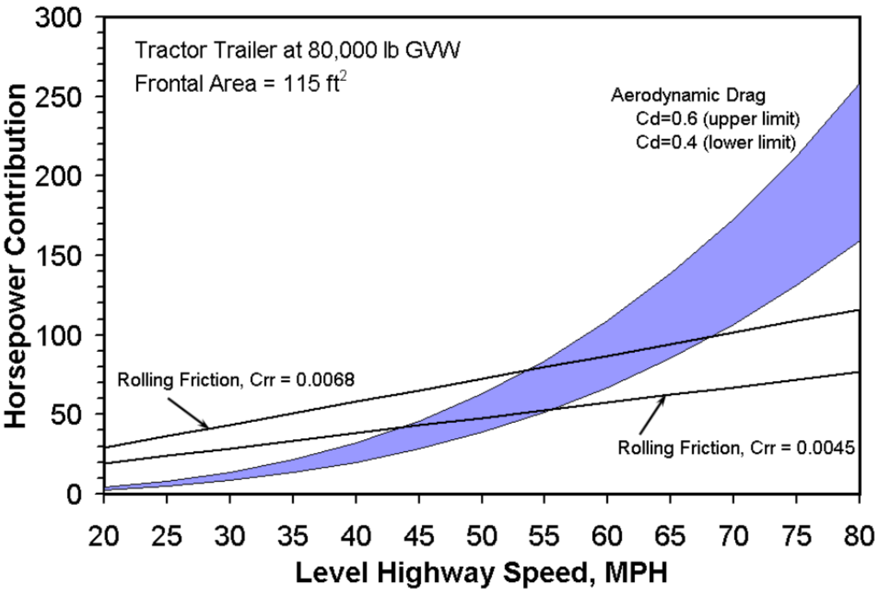
Cost: Trailer $700-$4,800 (2013) (5)
Tractor $2,700-$6,250 (2009) (2)

Applicability:

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



SOURCE: NRC, 2014, Figure 6-3.



Horsepower to overcome Aero Drag= 0.5 Cd A V^3

Aerodynamics(Long-Haul): Tractor

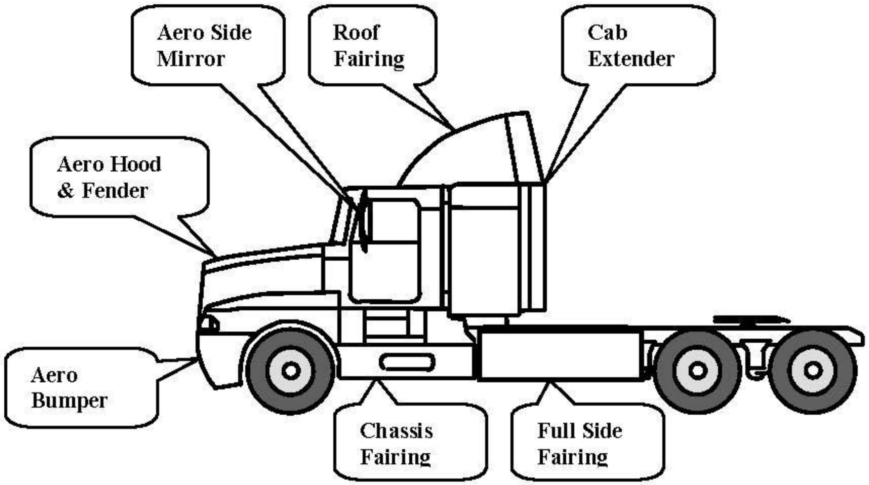


FIGURE 6-4 Sleeper tractor with aerodynamic features identified. SOURCE: NRC, 2010, Figure 5-5.

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%

2014 ICCT Trailer Technologies Report (17)

Advanced Transmissions and Engine Downspeeding

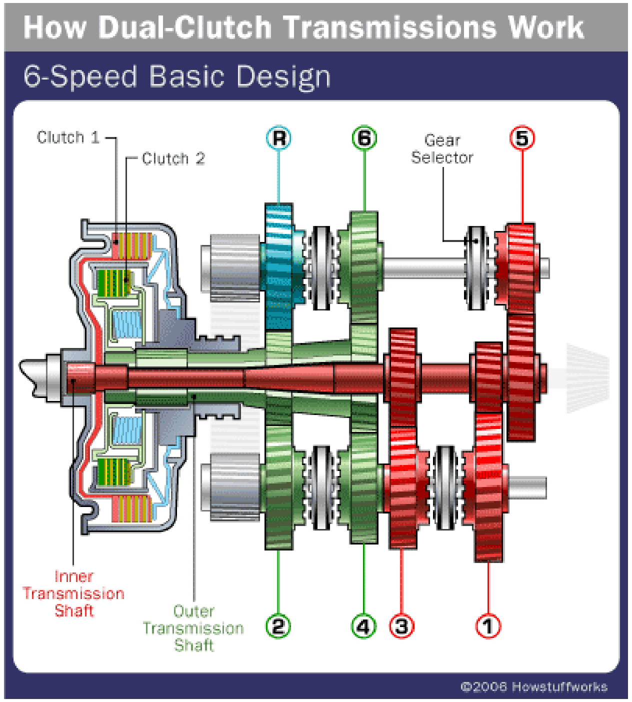
Potential FCR Improvement: 0-9.5% (2010) (1,2)

Cost: $500 – $15,000 [2010](1,2)

Applicability:

HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
AMT,DCT	AT,DCT	AT, DCT	AT, DCT	AT, DCT	AT, DCT

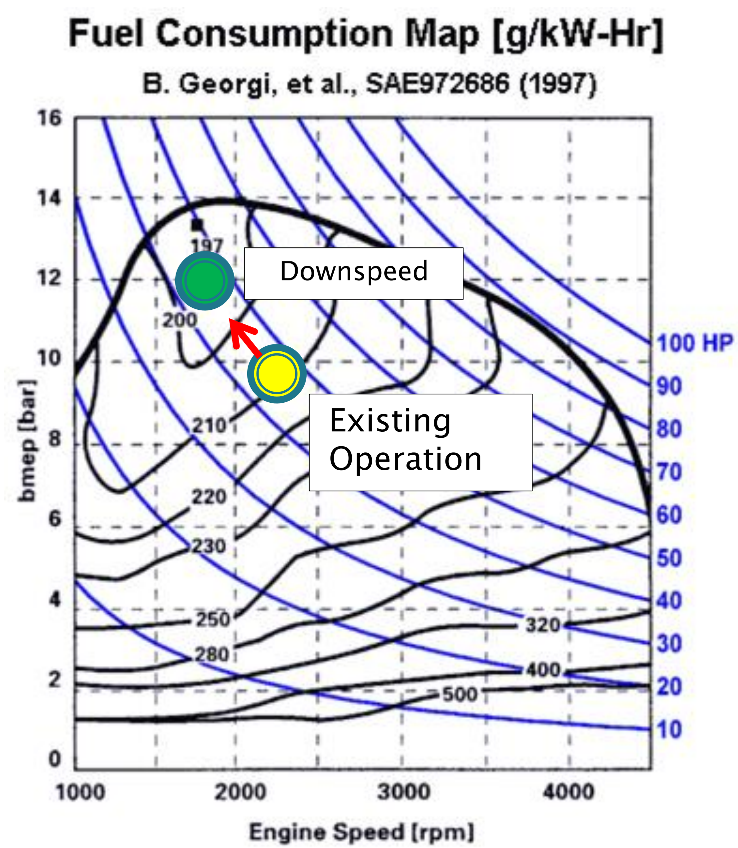
- Automatic Transmission (AT)
  - Torque converter
- Automated Manual Transmission (AMT)
  - Manual with control module taking over shifting
- Dual-Clutch Transmission (DCT)
  - Two power paths from engine to axle



Advanced Transmissions and Engine Downspeeding (continued)

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

- Facilitated by transmission



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

Limitations of Stop-Start

- FCR Benefit 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

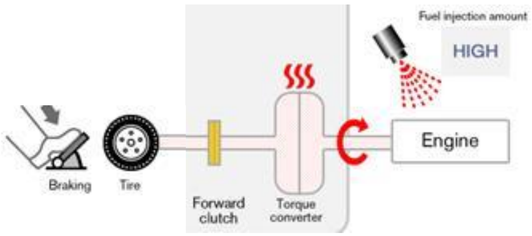
Technology Readiness Level: Commercial

Applicability:

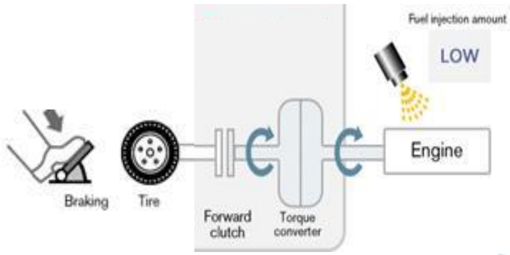
HD Tractors		Class 3-8 Vocational			Class 2b-3
Long Haul	Short haul	Urban	Rural	WorkSite	
		x	x	x	x

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.

Connected Vehicles

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

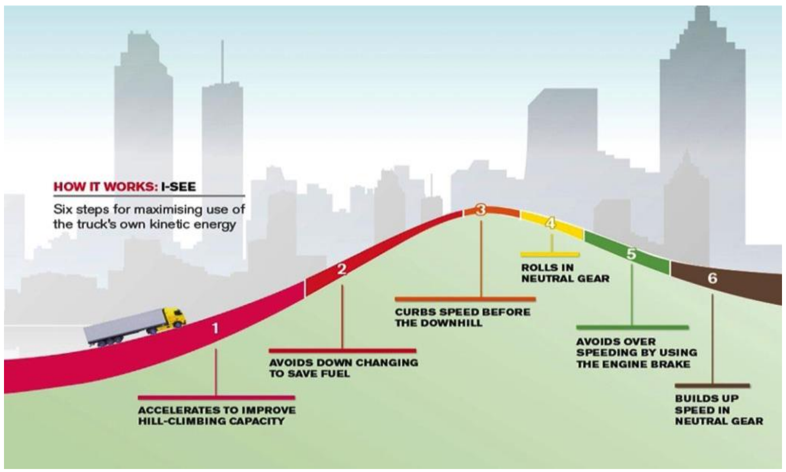
Cost: $850 – $1,560 (2009 Dollars) (1)

Technology Readiness Level: Demonstration

Predictive Cruise Control

Applicability:

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



- 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

Platooning

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					

"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 2 -10 meters 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.
- Would new laws/regulations be required to permit platooning?

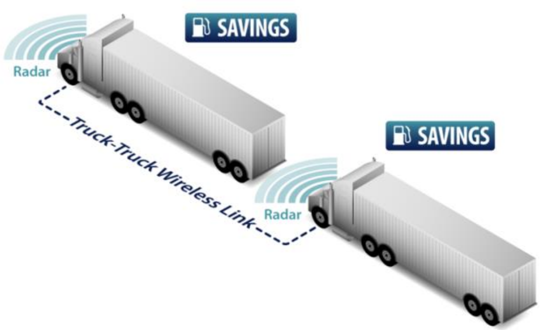
Connected Vehicles

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.

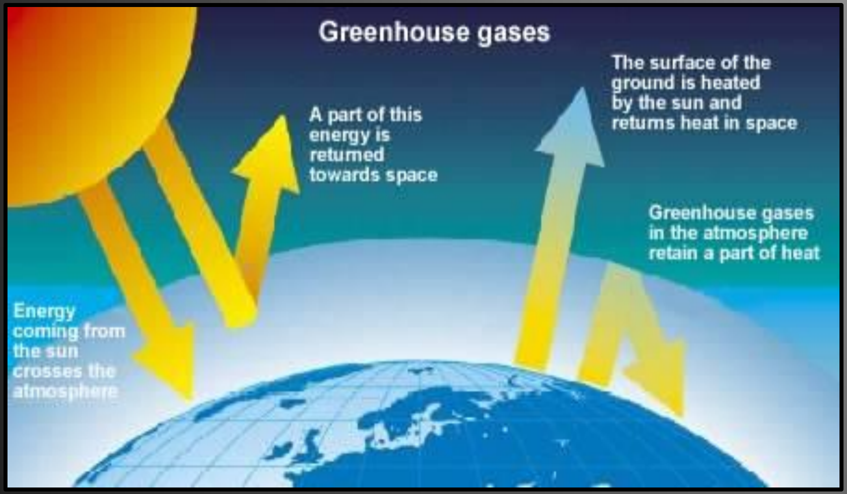
- Large scale testing of platooning possible on public roads by 2015 with goals of developing a reliable self-driving system within 5 years and implementing the technology sometime within the next decade.

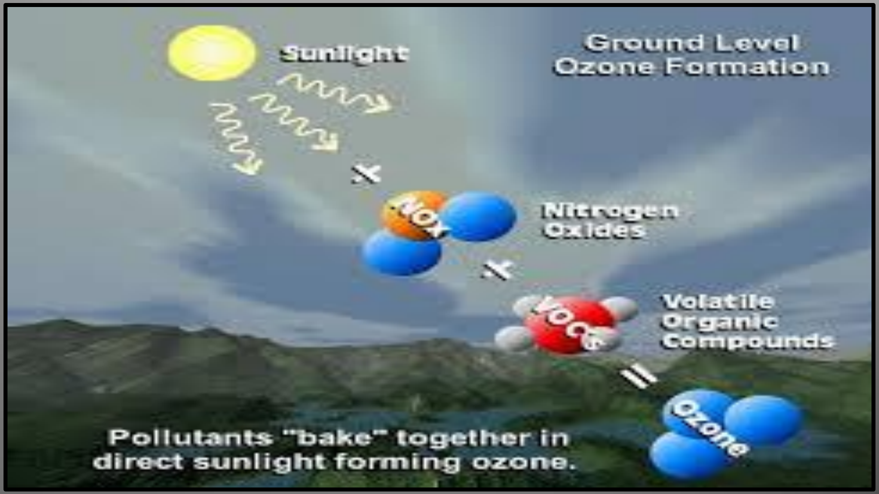


Implementation Challenges

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

GHG/NOx Tradeoff





GHG/NOx Tradeoff

- Need for a balanced approach to maximize both GHG and NOx reductions
  - Systems integration important
  - Engine operation and control strategies must optimize both in-use performance and emission control

- GHG/NOx Tradeoff is solvable!

GHG/NOx Tradeoff Considerations

- Promote technologies/strategies that have both GHG and NOx benefits
  - Improved aerodynamics, reduced friction, idle reduction
  - Connected vehicle technologies
  - Stop-start
  - Advanced combustion strategies

GHG/NOx Tradeoff Considerations

- Ensure GHG technology strategies do not inadvertently increase NOx
  - Impact of waste heat recovery on SCR temperature
  - Impact of load reduction on SCR performance
- GHG/NOx tradeoff options to be discussed in more detail in presentations to follow

Conclusions, Next Steps, and Contacts

Conclusions

- Phase 1 GHG standards dramatically reduced GHG from heavy duty trucks
  - Phasing in now thru 2017
  - 6-23% GHG reduction depending on vehicle application
- Greater GHG reductions possible
  - Stringency options for Phase 2 currently underway
  - Potential for up to 35% additional GHG reduction
- Many promising technologies
  - Waste Heat Recovery, Aerodynamics, Advanced Transmissions/Downspeeding, Stop-Start, Automatic Neutral Idle, Connected Vehicles
- Best options depend on truck class and duty cycle
- CO2/NOx Tradeoff must be taken into account
  - Simultaneous reduction in both pollutants is possible

Next Steps

- Draft Technology Assessment Document Scheduled for Release October 2014

- Related Work
  - ARB Board Update on Heavy-Duty Engine/Vehicle Program – October 2014
  - US EPA Phase 2 NPRM Scheduled for Publication in Federal Register – March 2015

Contacts

- Truck Sector Lead:
  - Kim Heroy-Rogalski kheroyro@arb.ca.gov
  - (916) 327-2200
- Engine/Powerplant and Drivetrain Optimization Lead:
  - Alex Santos asantos@arb.ca.gov
  - (626) 575-6682
- Vehicle/Trailer Efficiency Lead:
  - Jason Hill-Falkenthal jason.hill-falkenthal@arb.ca.gov
  - (626) 350-6746
- Team Members:
  - Krista Fregoso kfregoso@arb.ca.gov
  - Francine Baker fbaker@arb.ca.gov
  - Hung-Li Chang hchang@arb.ca.gov
  - Eloy Florez eflorez@arb.ca.gov
  - Mitzi Magtoto Mitzi.Magtoto@arb.ca.gov
  - Utpala Ramesh uramesh@arb.ca.gov
  - Jeff Lowry jlowry@arb.ca.gov
- Submit comments by Oct. 1 to: http://www.arb.ca.gov/msprog/tech/comments.htm