Workshop on Emerging Technologies for Heavy-Duty Vehicle Fuel Efficiency

Complete Vehicle Efficiency

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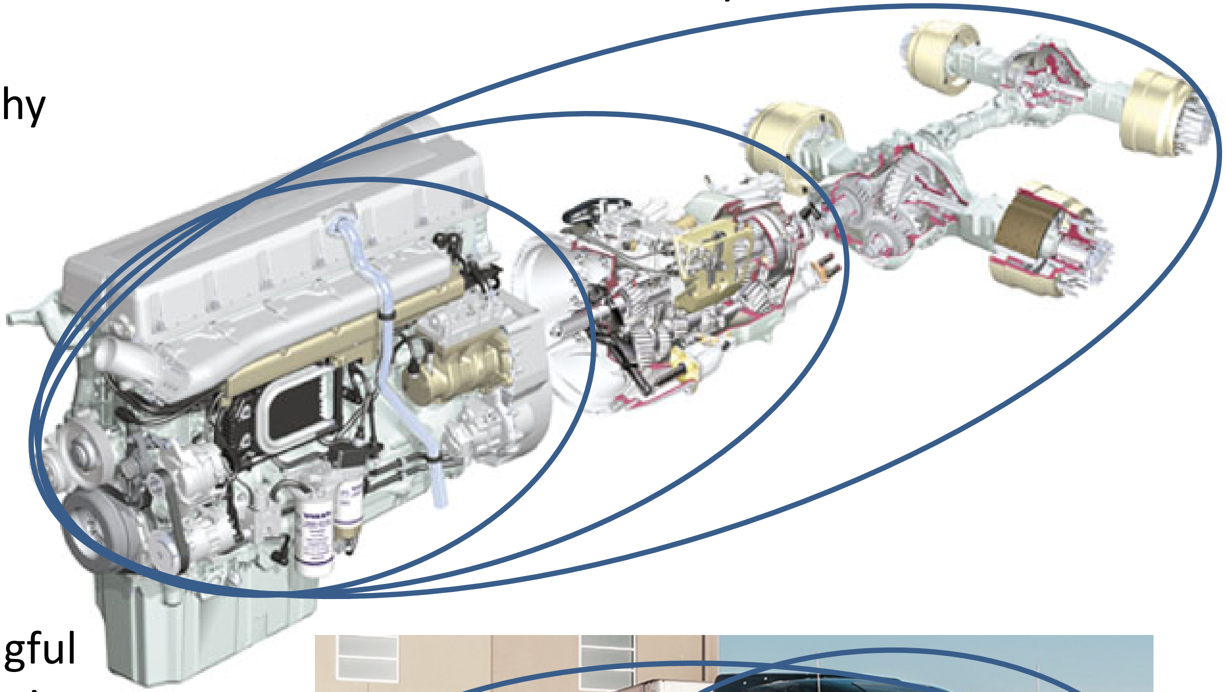
Why Focus on Vehicles?

- It is the vehicle that uses fuel to accomplish work.
- No component does anything apart from it's role within the vehicle system.
- If we want to draw boundaries around components how and why do we choose the boundary?
    - Base engine
    - Engine plus air handling (turbo, coolers)
    - Engine plus after-treatment
    - Engine plus transmission
    - Engine plus complete driveline
    - Tractor
    - Combination

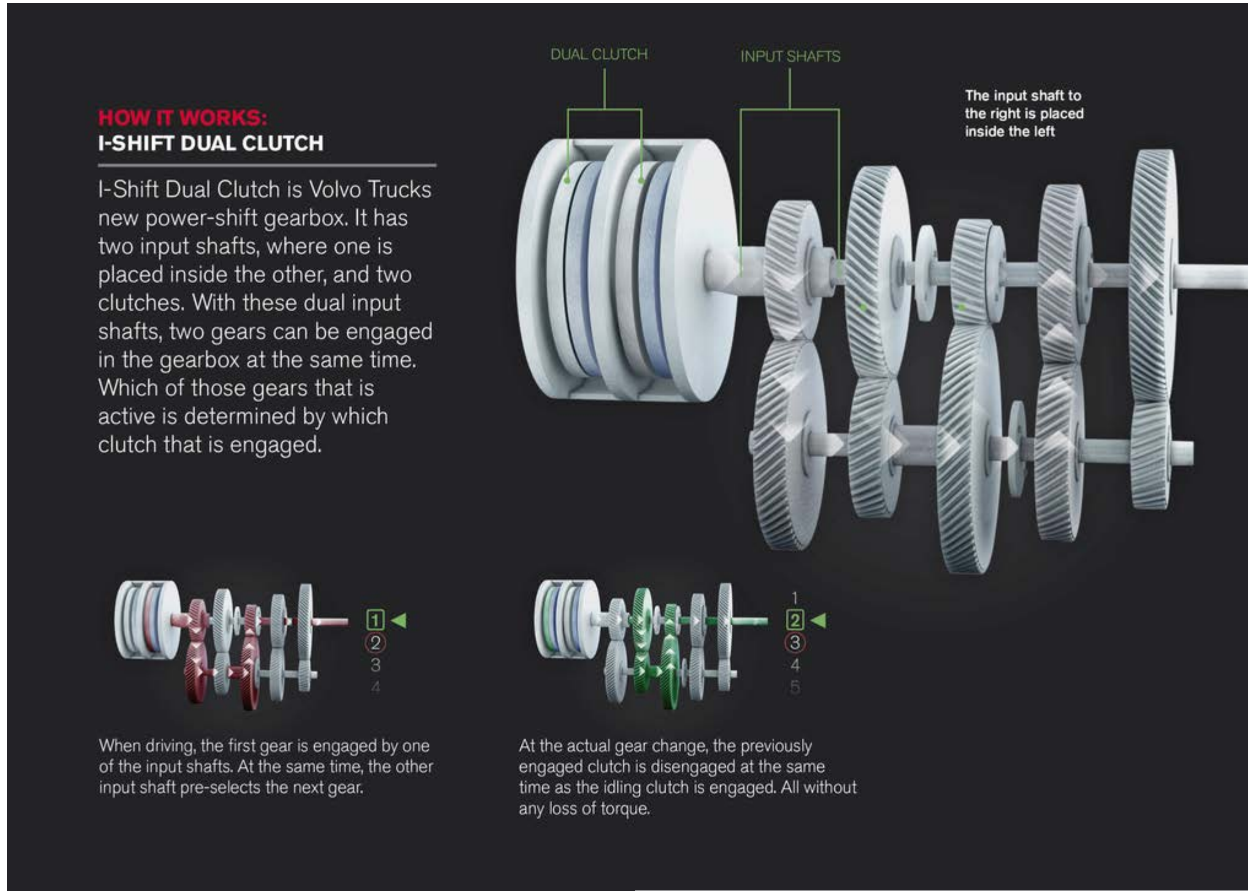


- Engine efficiency is only meaningful in the context of how the engine is deployed. Engine speed and torque output are dictated by
    - Drivetrain set-up
    - Vehicle power demand
    - Control strategies

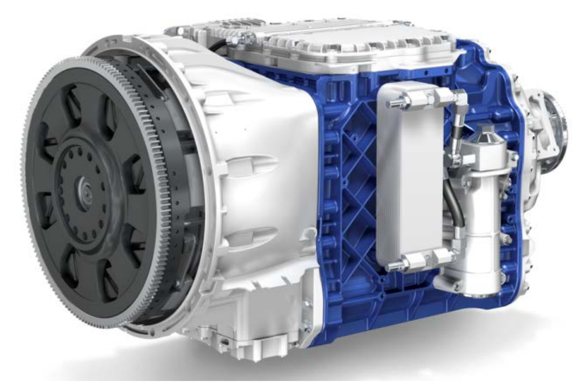
Separate engine regulation is Counterproductive

- Engine will be fully accounted for in vehicle model
- In the real world, the engine does not run on RMC, FTP, or any fixed cycle
  - Load factor varies with engine size
  - Load factor varies with vehicle power demand
  - Operating range is already substantially lower speed than RMC or even reweighted RMC proposal and going even lower
  - Transient characteristics will change dramatically with transmission technology.
- Engines need to be optimized for the expected vehicle duty cycles, not a fixed engine cycle
  - Duty cycles change with engine size, driveline, and vehicle efficiency
  - No fixed engine cycle can adequately deal with changing technology
  - Impacts of engine technology
- Engine efficiency is rating dependent
  - **Typically largest engine at highest power rating has lowest engine cycle BSFC while smallest engine at lowest power rating has lowest vehicle cycle GHG/fuel consumption**
  - **GHG/Efficiency parent engine need only represent 1% of engines sold**
  - Allows gaming- calibrate high efficiency parent sold only in applications that rarely run at high load (e.g. motor homes, coaches)
  - Engine specific efficiency requirement provides no incentive to match engine to vehicle

June 17, 2014
Volvo Trucks is now launching I-Shift Dual Clutch, the first transmission on the market
with a dual clutch system for heavy vehicles. Thanks to power-shift gear changes without any interruption in power delivery, torque is maintained and the truck does not lose any speed during gear changes.



DCT enables the next step toward further down-speeding and down-sizing. Fixed engine test cycles become even less relevant.



Complete vehicle regulation

- EPA has already built on GEM model to add complete vehicle capability
  - Include engine and drivetrain
  - Proposals for gear shifting and accessories
  - Engine mapping
  - Develop realistic drive cycles with grade
- Enhanced aero process with modified coast-down as base
  - Use aero trailer for vehicle drag
- Tire inputs same as phase I
- Add unique vocational duty cycles

Proposed Phase II Vehicle Model:
Run model for each vehicle specification

Engine is fully accounted via map and vehicle characteristics.

Realistic Duty Cycle

Provide pull down menu for standard eco features such as predictive cruise and AMT

OEM inputs:

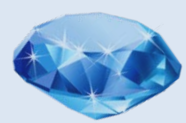
Specific to truck build spec (unique for each sale)

- **Engine fuel map**
- **Transmission ratios & efficiency**
- **Final drive ratio & efficiency**
- **Aero Drag Coefficient** Line haul only
- **Tire Rolling Resistance** Drive and steer
- **Light weight features** Ex: Aluminum wheels
- **5-minute idle shutdown**
- **Vehicle speed limiter**

Agency defined

Aero trailer Cd, RR

EPA Vehicle Simulation



“GEM”

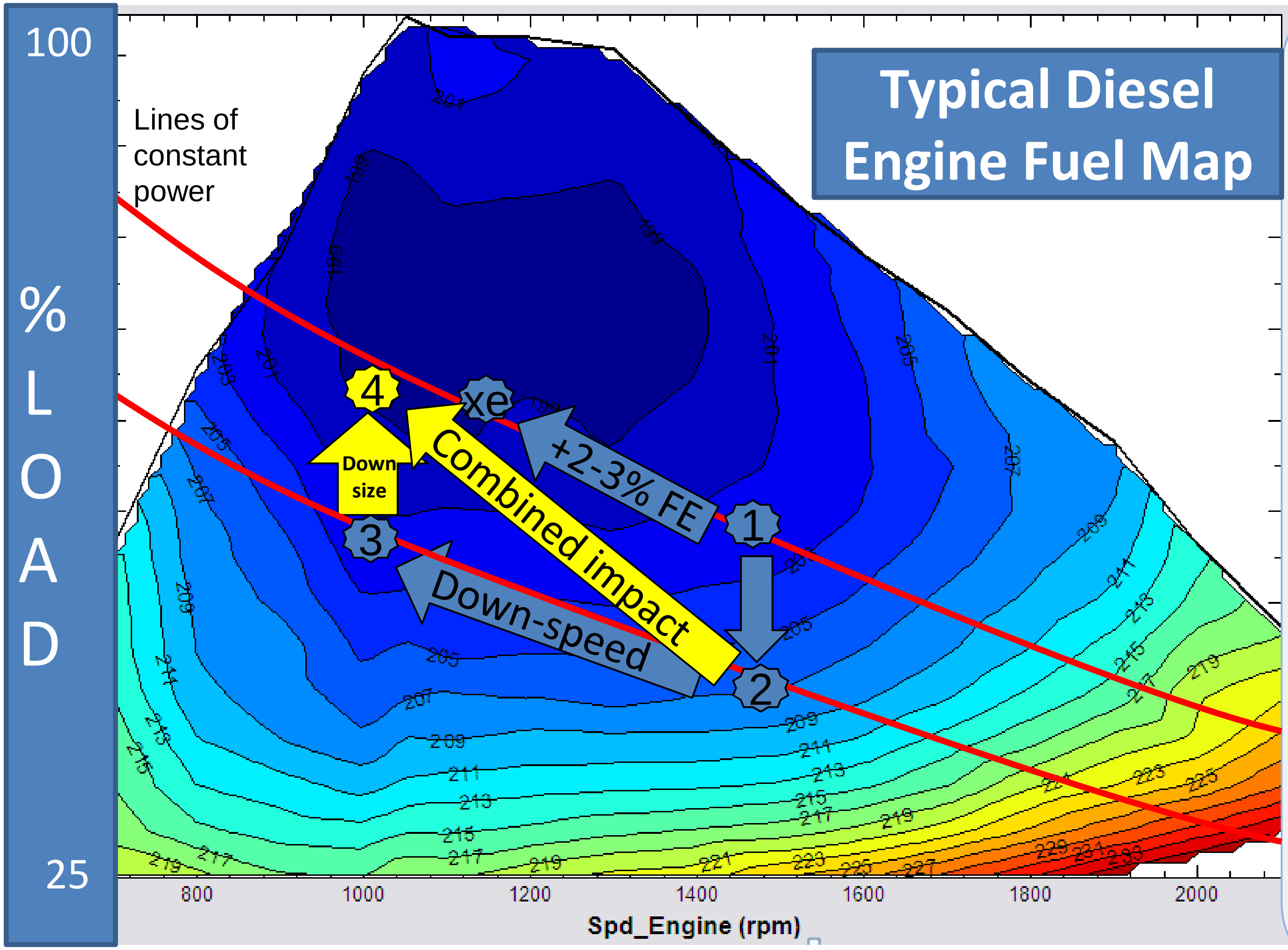
Vehicle CO2 (g/ton-mi)

Phase II - will factor new technology into stringency targets.

Ensuring Benefits with Vehicle Simulation

- Inputs to simulation are all verifiable
  - Certified, auditable engine map
  - Transmission gearing and final drive ratio
  - Aero confirmatory tests
  - Tire data
- Simulated result is evaluated at appropriate vehicle load factor and with actual drivetrain.
- Engine will be fully accounted for in vehicle model
- No need for parent engine or exceptions for de-rated engines
- Compare this to ensuring benefits from engine testing
  - Test cycles miss-represent actual engine operation
  - Impact on in-use efficiency is distorted
  - Only 1% of engines actually need to comply (parent engine ratings)
  - Engines optimized for emissions cycles do not ensure any benefit on vehicle cycles. Optimizing efficiency on emissions test cycles means sub-optimization for vehicle road cycles.

Engine Efficiency Impact of Integration



1. Cruise operating point 2010 Baseline

- Volvo XE13 & Mack Super Econodyne – Down-speeded engine, enabled by integrated AMT & high torque yields 2-3% FE
- 1-2: chassis & trailer improvements reduce load
- 2-3 downspeeding improves efficiency
- 3-4 downsizing increases percent load
- RESULT:
  - Major improvement in vehicle fuel consumption with same engine efficiency

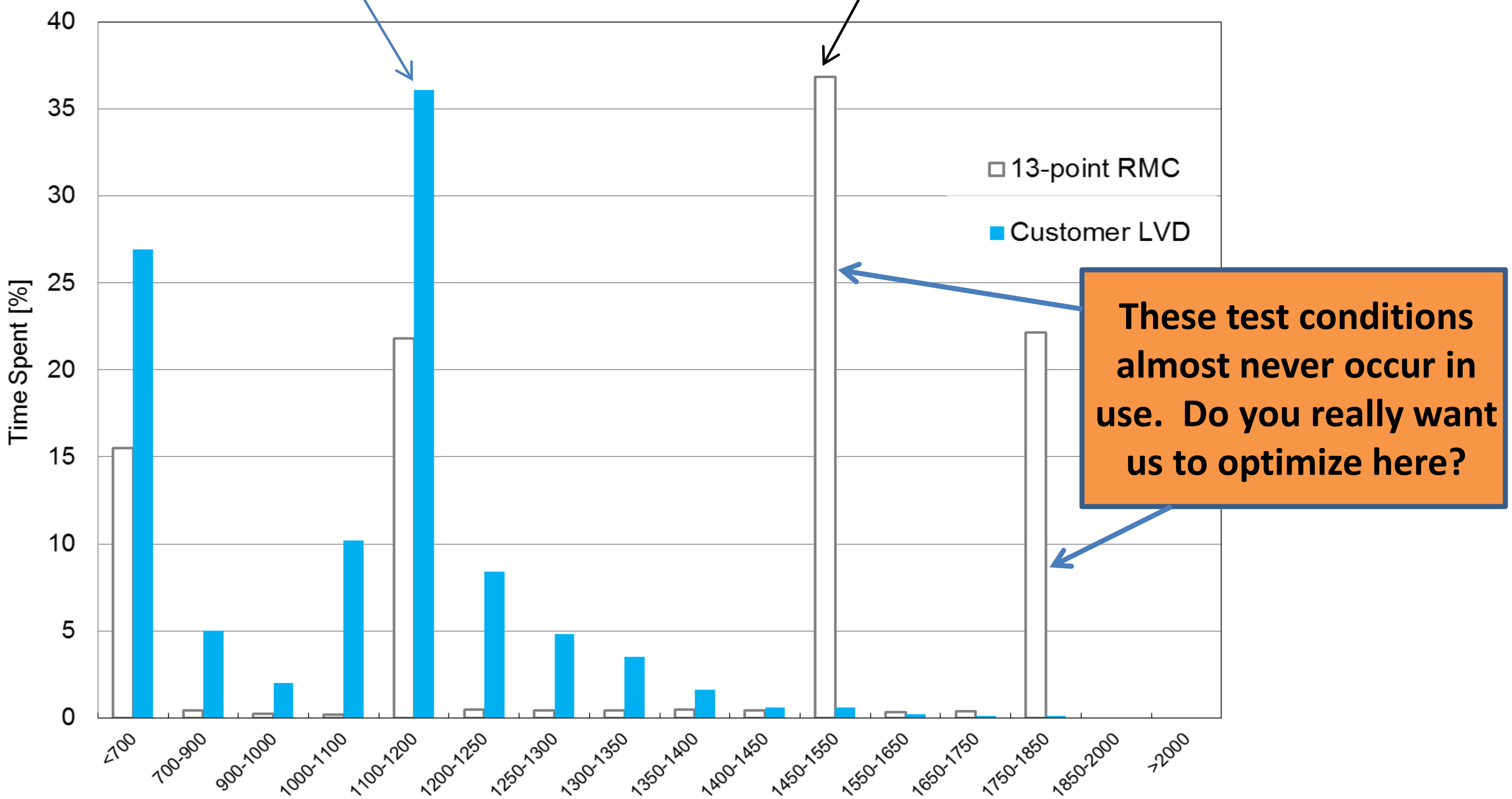
Substantial Fuel Efficiency with same fuel map, enabled by use of AMT and increased low speed torque.

Engine Emissions Duty Cycles are increasingly removed from on-road operating conditions

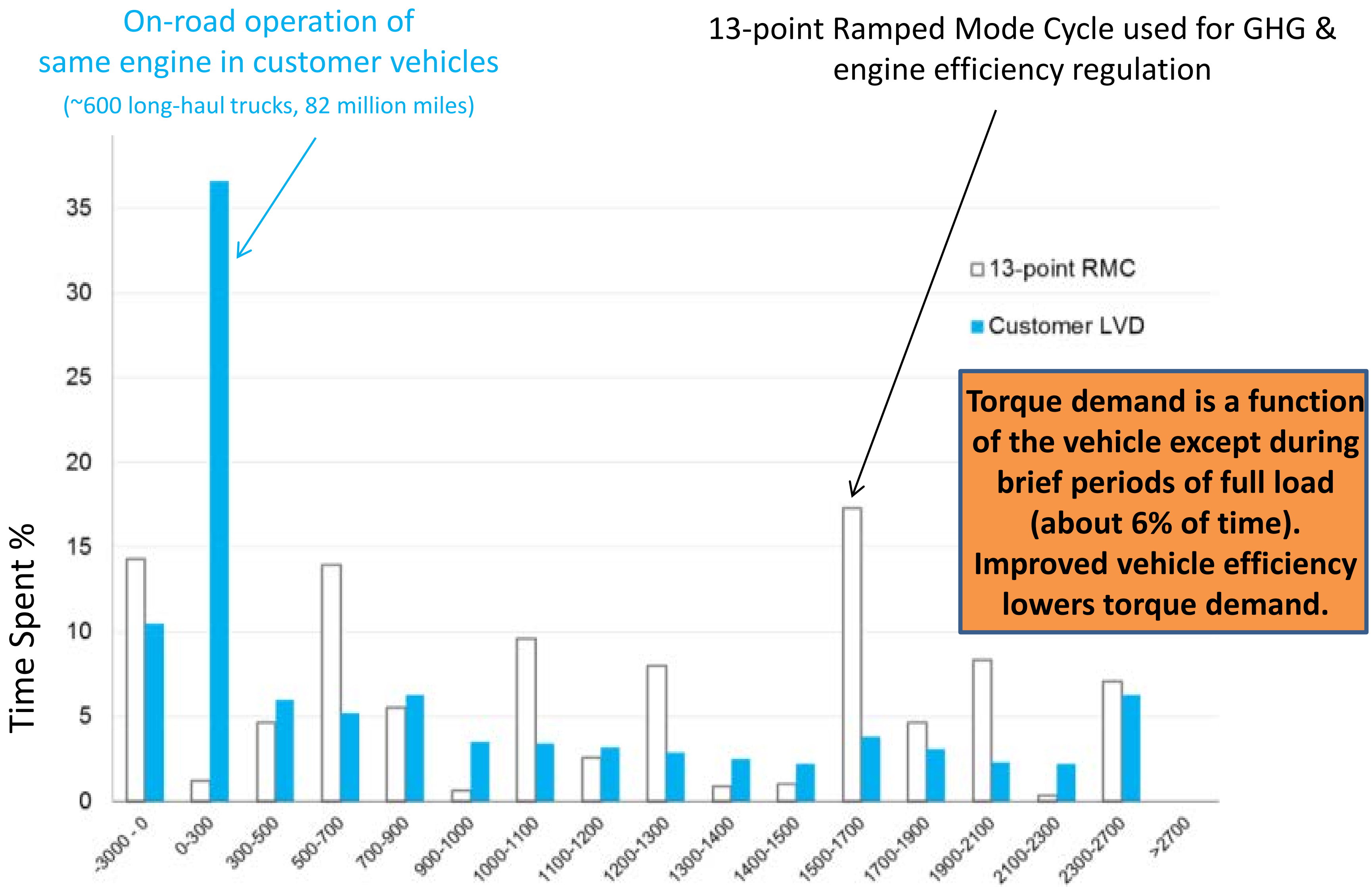
Actual on-road operation of same engine in customer vehicles

(~600 long-haul trucks, 82 million miles)

13-point Ramped Mode Cycle used for GHG & engine efficiency regulation



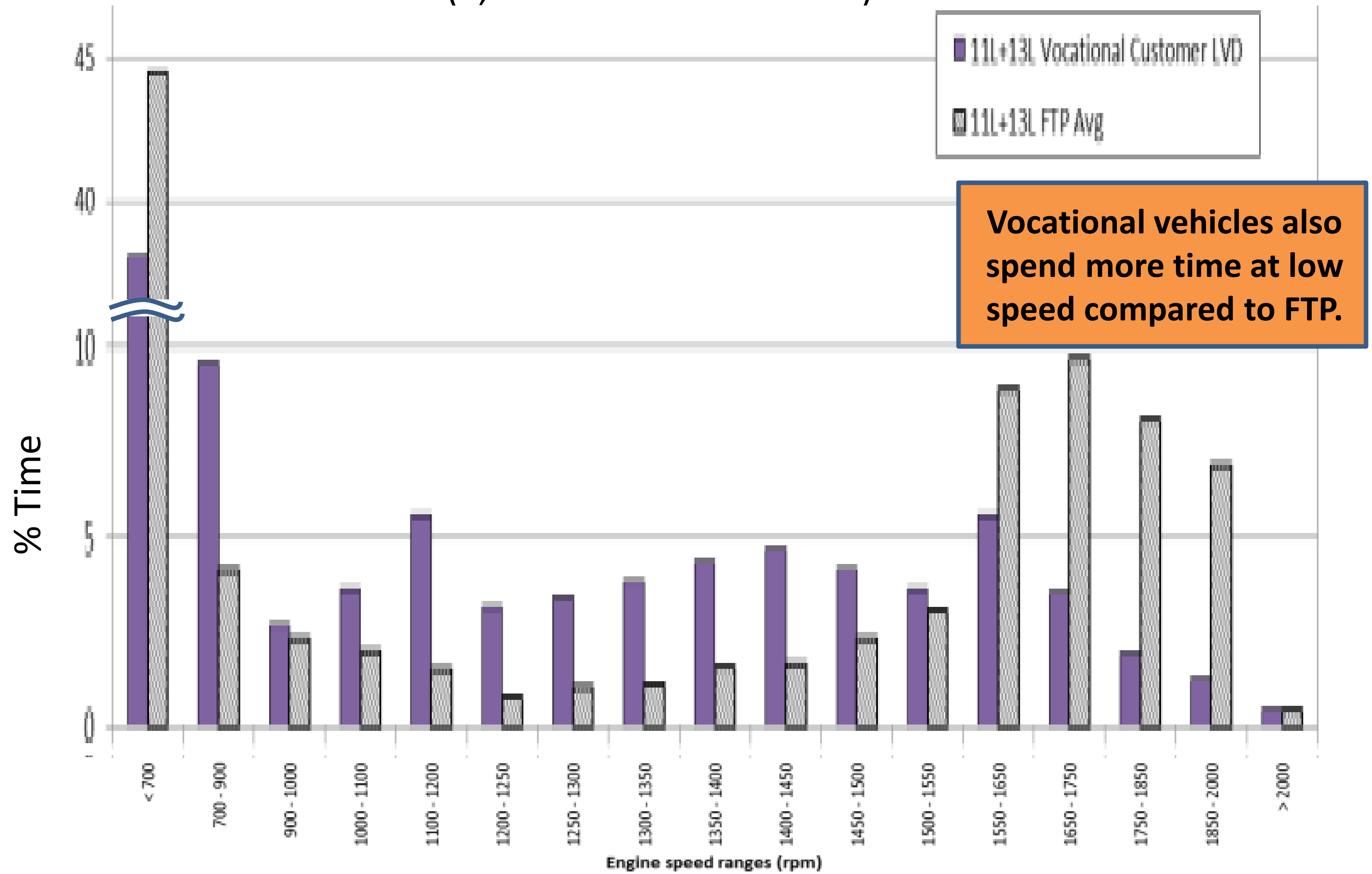
Engine Torque Distribution On-road vs. Emissions Cycle



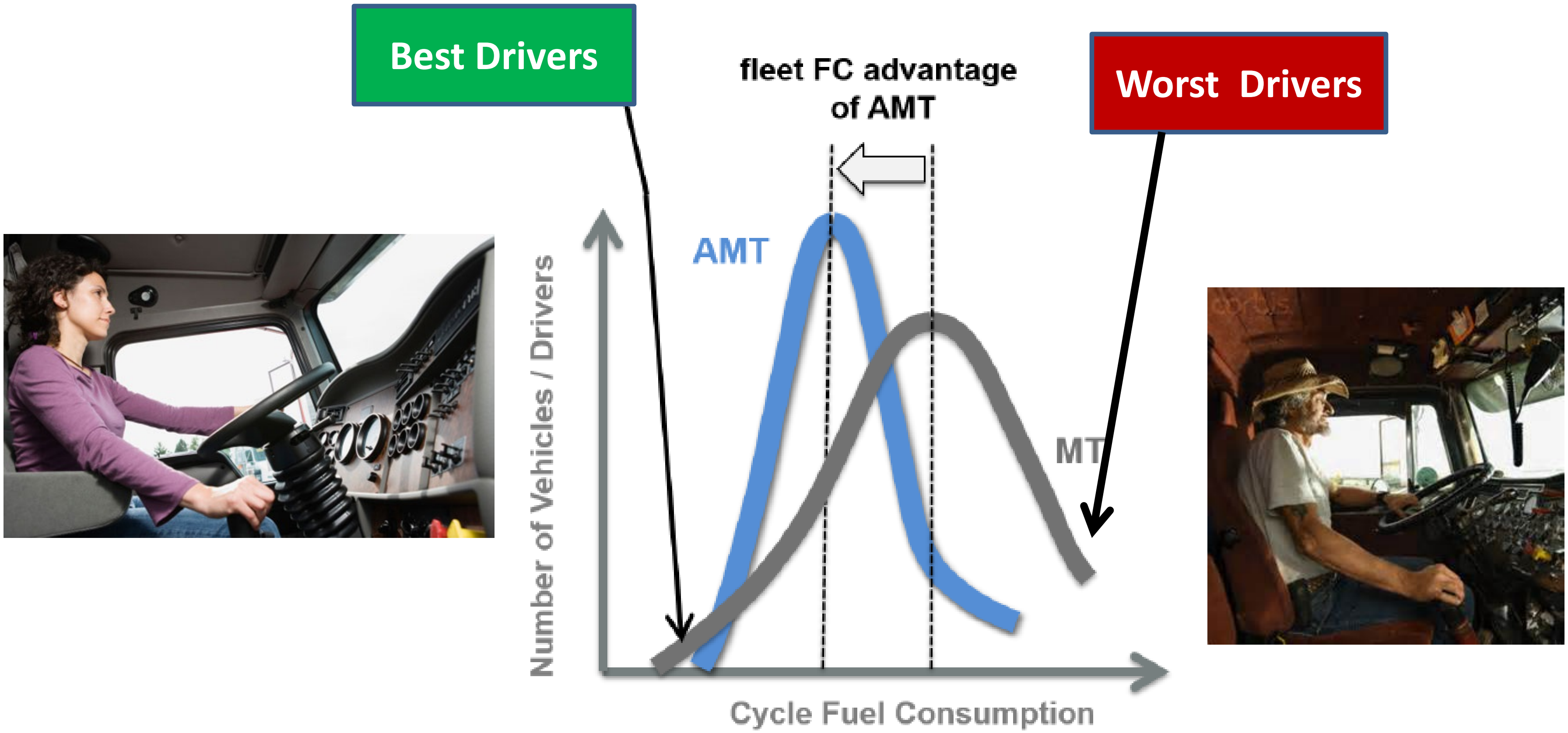
Engine Emissions Duty Cycles are increasingly removed from on-road operating conditions

Engine rpm distribution for FTP & same engine in customer vehicles

(7,500+ vocational trucks)



Driver Impact of Automated Transmissions

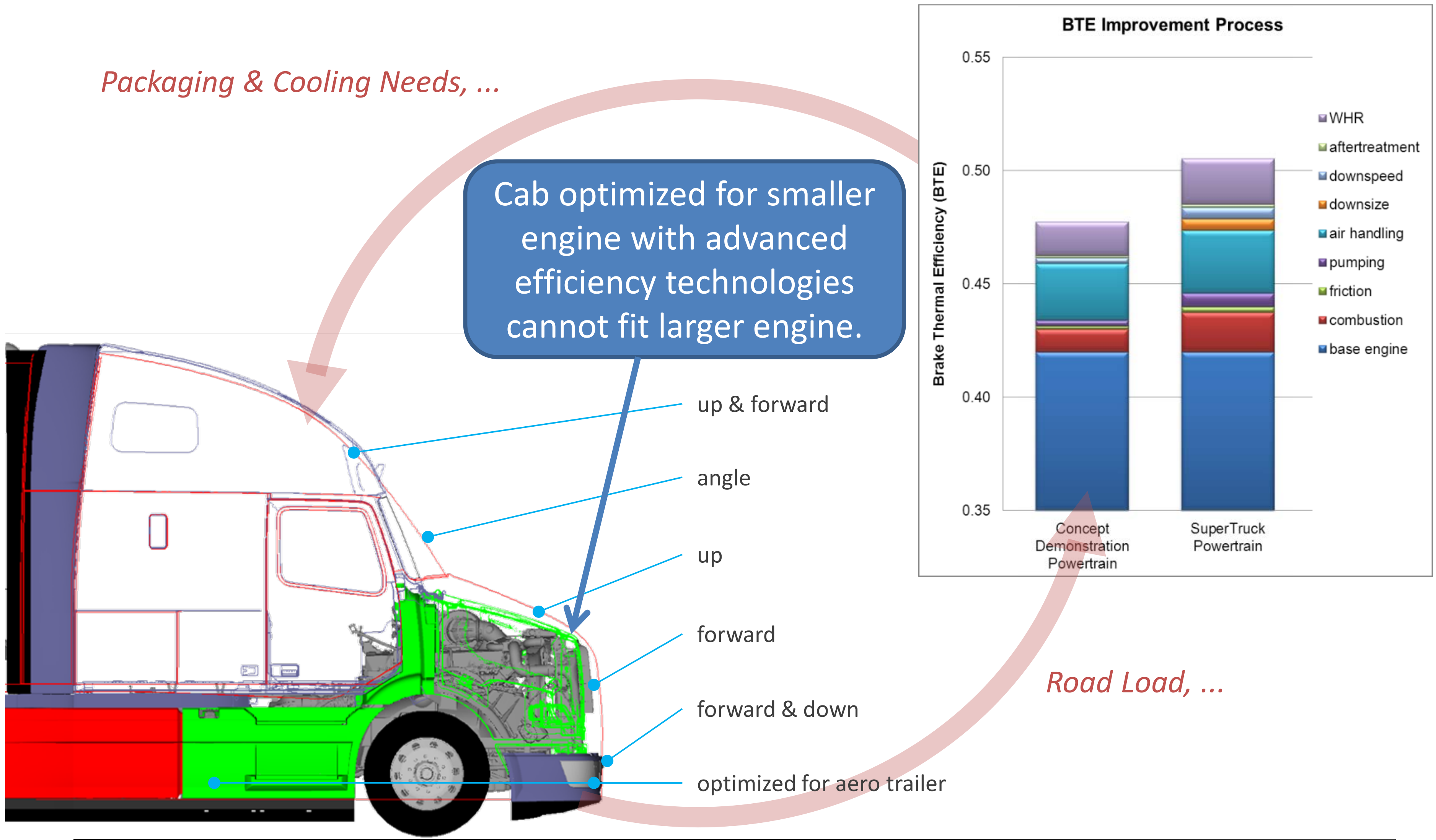


Smart AMT can sense vehicle load and grade to optimize shifting under all driving conditions.

Technology Impact is Distorted by Emissions Test Cycles

- The reason engine operation has moved so far away from RMC is primarily fuel savings.
  - RMC testing ignores this fundamental reality.
  - There is more opportunity for fuel savings on the RMC but it will not result in proportional real-world savings.
- Examples
  - Friction and variable speed pumps
    - Efficiency benefit more than double on RMC compared to engine vehicle cycle
  - Turbocharger efficiency tuned to RMC results in worse FE on engine vehicle cycle
  - Emissions cycles give no credit for down-speeding, whereas effect is significant in vehicles
  - Emissions cycles result in slight negative result for down-sizing (due to engine size impact), whereas down-sizing has positive impact in vehicle owing to higher BMEP and lower friction.
- Developing for emissions cycles will distort technology choices and actual results
  - Cost/benefit choices biased toward achieving test results, especially by component suppliers not responsible for complete vehicle results.
  - Vehicle performance will be significantly less than measured engine reductions.

Aero Improvements in combination with Powertrain Improvements
Importance of Integrated Design



Trailer Potential

- Recognized as biggest potential contributor
- It is essential to model and test tractors with efficient trailers (aero and tires)
  - Efficient trailers can lower vehicle power demand by 10-12%
  - Next generation cabs likely to be in production until beyond 2030
  - Our regulatory design targets need to match future trailers
    - Tractor aero
    - Powertrain power demand
    - Synergistic effect: incorporating aero trailer as standard into the regulation drives aero-compatible tractor designs which pull aero trailers into fleet purchases
- Even if trailers are not federally regulated, tractors should be measured when matched with efficient trailers
  - Efficient trailers should sell themselves when benefits are clearly understood
  - Standards can be developed through voluntary programs like SmartWay to identify and promote trailers with most efficient designs.
  - Tractor manufacturers can advise that tractors are designed for maximum efficiency with trailers meeting efficiency standards
  - California standards already push fleets to adopt efficient trailers.

Total Vehicle Efficiency is the Objective

- **Vehicle stringency targets should be based on all available, reliable, cost-effective technologies, including engine efficiency.**
- **Vehicle manufacturers should be free to innovate and find the most effective ways to achieve target levels.**
- **What if innovative vehicle concepts mean we don't pursue the most expensive and problematic engine technologies deemed costs effective by regulators?**
  - **Customers get efficiency with lower cost and lower risk and will purchase more quickly.**
  - **The innovative vehicle concepts can also be included in the future targets.**

An integrated approach to regulation supports vehicle optimization; benefits everyone :

- **Vehicle Purchasers**
  Cost, reliability
- **Society**
  Faster acceptance
  Innovation
  Global designs
- **Manufacturers**
  Design flexibility
  Global focus
  Implementation

2020 Timeframe Vehicle Efficiency Technologies

Level of improvement potential is application specific.

Need to know baseline, duty cycles and assessment methods before evaluating outcomes.

Engine contribution should not be evaluated apart from vehicle load factors and driveline.

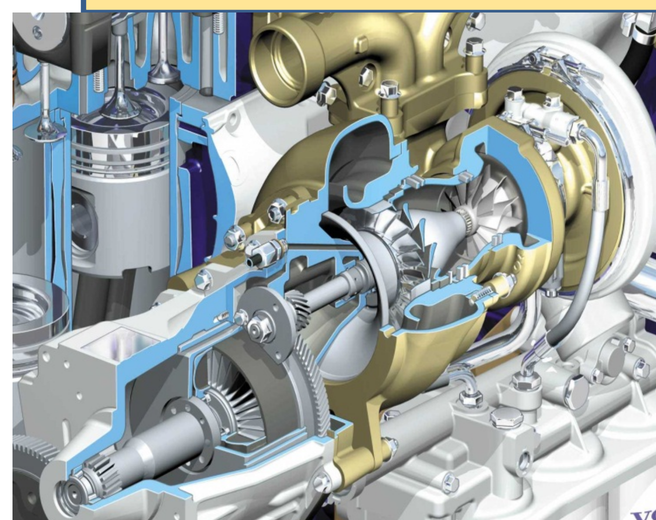
Combined efficiency potential improvements of about 14% for tractor-trailer and 6% for vocational vs. 2017.

Tractor

- Further engine Down speeding and penetration
- Engine down sizing (where applicable)
- Combustion improvements (cylinder pressure, chamber shape, fuel injection)
- Turbo efficiency/Turbo-compound WHR
- Engine friction and fluid pumping
- Predictive Cruise
- 6 x 2 axle
- Low friction axle
- Improved tractor aero matched to aero trailer
- Improved tires
- Smarter accessory management
- Better cab insulation
- Greater penetration of APUs (mainly battery electric)
- High AMT penetration for tractors (vocational?)
- After treatment efficiency

Trailer

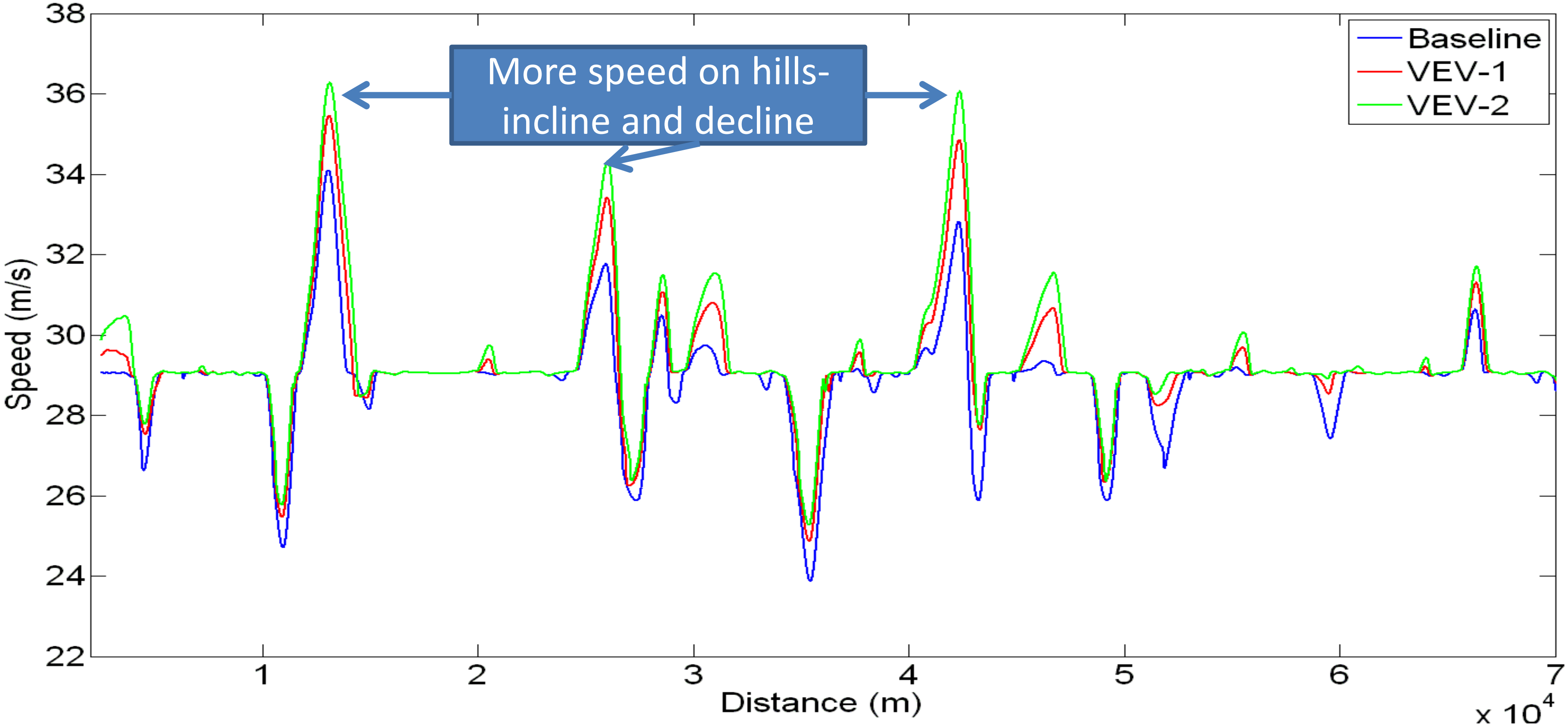
- Improved Trailer skirts
- Improved Boat tail
- Low Crr Tires
- Weight



Predictive Cruise
Intelligent HD Vehicle Energy Management

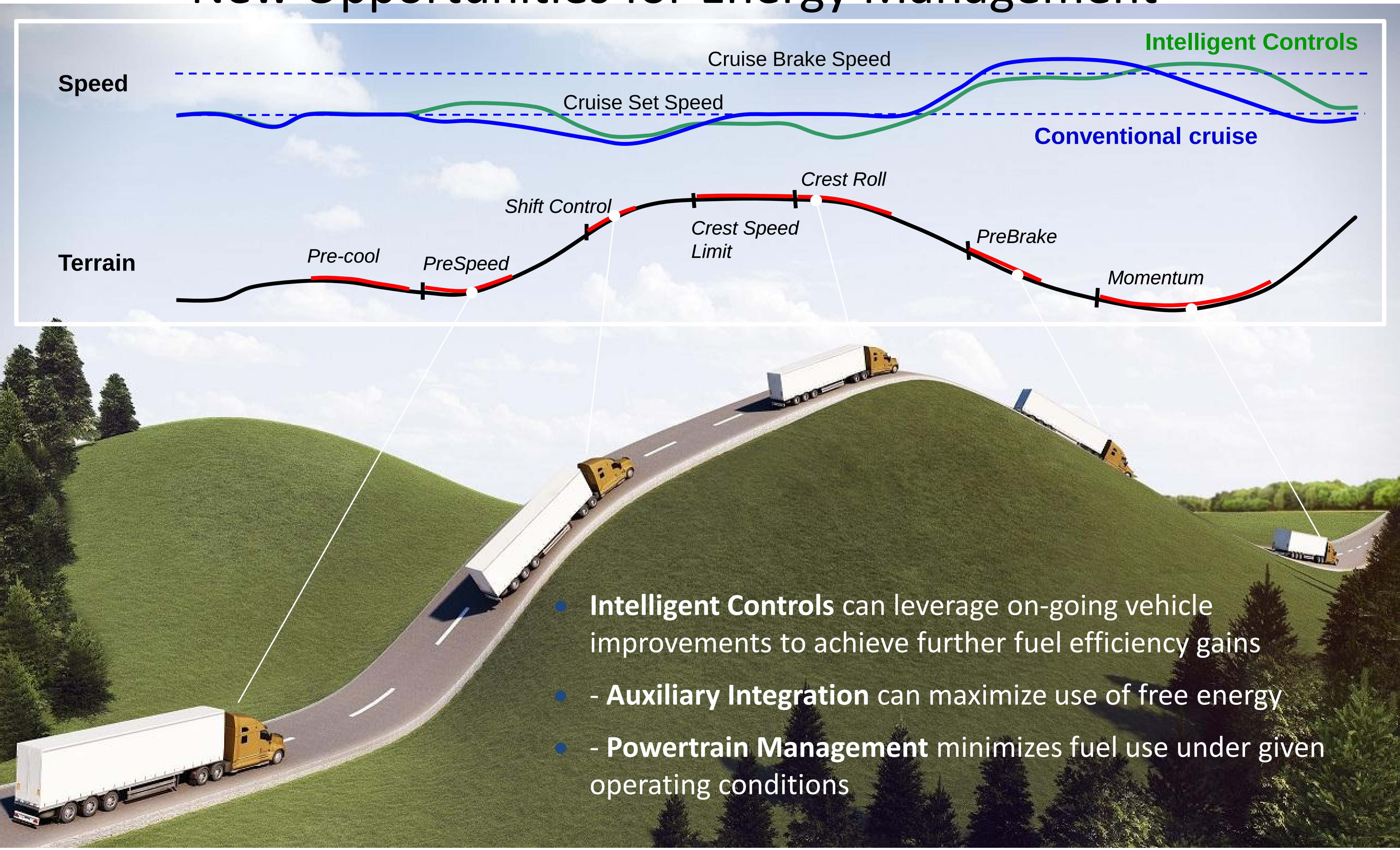
- Intelligent energy management is a growing opportunity that can have considerable real-world fuel saving impact for most customer applications
- Torque management, transmission controls, auxiliaries management require relatively small investments compared to the potential fuel efficiency benefits
- Vehicle efficiency improvements and look-ahead technology are enablers
- Further enhancements can come with V2V communication
- Momentum conservation is effective & affordable

Positive Side effects of vehicle efficiency improvements



- Increased benefit of predictive vehicle controls
- Increased potential for complete vehicle energy management features, e.g. kinetic energy recovery solutions

New Opportunities for Energy Management



- **Intelligent Controls** can leverage on-going vehicle improvements to achieve further fuel efficiency gains
- - **Auxiliary Integration** can maximize use of free energy
- - **Powertrain Management** minimizes fuel use under given operating conditions

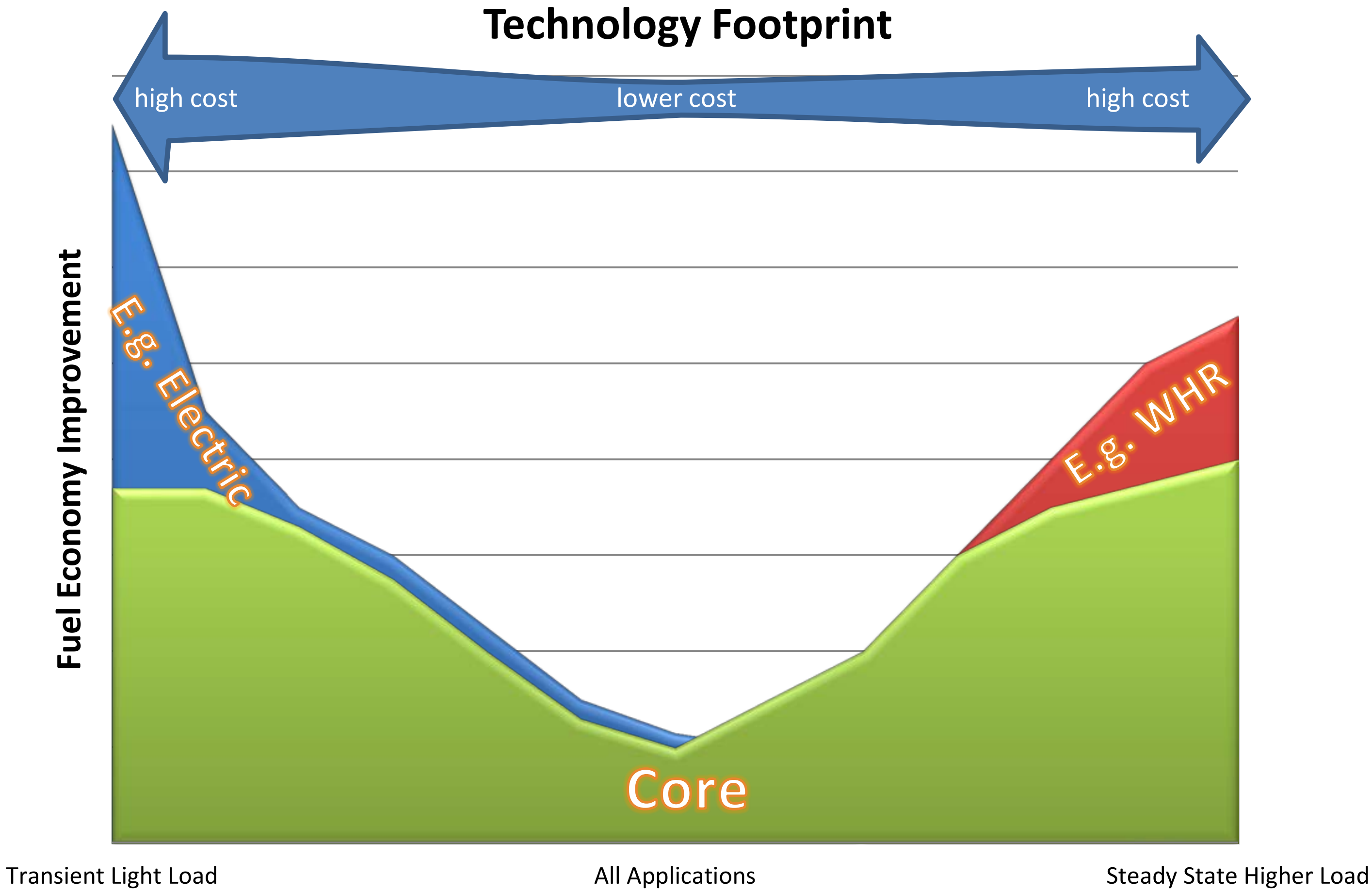
V2V & V2I Enables Other Efficiency Features

- Platooning
- Green Light Optimization Speed Advisory (+ Green Wave for commercial vehicle)
- ecoDriving based on real-time traffic data
- Cooperative Active Cruise Control – based on interaction with other vehicles and infrastructure
- Road work site management (safe and increased throughput)
- Find available parking
- Passing assistance by real-time video information

What Happened to Hybrid?

- US Market for HD hybrid is dead except for a small number of heavily subsidized buses.
- Why?
  - Optimum systems are application dependent, limiting volume opportunities
  - In use efficiency highly driver dependent & much lower than claims
  - Reliability, durability, downtime costs
  - Natural gas competition in urban applications
  - OBD certification requirements drive up cost and create liability concerns for non-integrated systems
  - Weight and space claims
  - Vehicle owners are finding the fuel savings are inadequate to cover initial and operating costs increases (maintenance, downtime, batteries, training)
- Major suppliers dropping hybrid offering due to low sales and high cost
- If forced into the market, expect customers to repair and rebuild old equipment to avoid costs.

Design for application: common vs. application sensitive solutions



Technology viability timeline

2025

Refreshed Platform:

- **Improved predictive control, driver and vehicle management utilizing V2V and V2I**
- **Higher pressure efficient common rail?**
- **Variable valve actuation ??**
- **Cylinder deactivation??**
- **Increased cylinder pressure (~220-240 bar)**
- **Friction Reduction**
- **Marginal turbo improvements**
- **Weight reduction**
- **Improved accessories (alternator, air compressor, …)**
- **Improvements to after-treatment low temp conversion efficiency and ageing**
- **Alternative fuels penetration (NG, DME, ???)**
- **Tractor trailer aero integration**
- **Start/stop engine operation?**
- **Dual Clutch Transmission**

Combined efficiency potential improvements of about 20% for tractor-trailer and 10% for vocational vs. 2017.

Roadblocks to implementation

- **Designing product for all customer applications**
- **Safety and inspection regulations**
- **Noise regulation**
- **CARB NOx mandate**
- **EATS technical progression**
- **Vehicle impacts**
- **Manufacturability**
- **Cost of product**
- **Reliability of product**
- **Weight of product**
- **Payoff time of technology**
- **CERT cycles don’t match usage**
- **Aerodynamics / Vehicle efficiency improvements**

Technology viability timeline

2025+

New Architecture; Highly Questionable Technology
Fuel economy change too difficult to forecast

- Waste Heat Recovery (high risk, low volume)
- Platooning
- Low temperature /high efficiency after-treatment
- High power density (light weight)
- Advanced combustion (zero emission, PPC, HCCI, etc.)
- Alternative fueling (non-diesel, low carbon)
- No EGR
- New architectures (non 4-stroke diesel)
- Heavy electrification (PHEV with electrified major roads)
- Non-conventional hybrid (air, flywheel fluid)
- Longer/Heavier combinations
- Autonomous vehicles
- Electrified urban delivery

Roadblocks to implementation

- Infrastructure changes
- Weight/length regulations
- Regulation for platooning allowance
- Autonomous liability and regulations
- High speed combustion control
- High risk of failure
- New Emission legislations
- EATS technical progression
- Vehicle impacts – major redesign
- Manufacturability – huge investments
- Cost of product
- Reliability of product
- Weight of product
- Payoff time of technology
- Aerodynamics / Vehicle efficiency improvements (cooling)

Summary statements from Volvo Group Trucks Technology

- **Vehicle improvements often negatively impact engine thermal efficiency, and vice-versa (less cooling capacity, load reduction due to vehicle improvements; engine space, weight cooling demand).**
- **An engine is only efficient when properly applied- right size, matched driveline for the application**
- **Core technology (combustion improvement, friction reduction, etc.) improvements apply in nearly all applications.**
- **Many technologies (Hybrid, WHR, Electrification) are application/duty cycle specific and low volume**
- **Big changes require massive investments, are high risk and historically fail**
- **Many technologies are not additive or even counter-productive when added to others (e.g. low temp combustion impact on exhaust after-treatment efficiency and waste heat recovery)**
- **To deliver fuel economy to the customer, GHG certification cycles & methods must reasonably match reality**
- **It is best to define a vehicle efficiency targets and let the most cost effective and reliable solution be found, not to force high engine efficiency, aero Cd, etc.**