ARB Symposium

Technologies for Heavy-Duty Vehicle Fuel Efficiency

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April 22, 2015

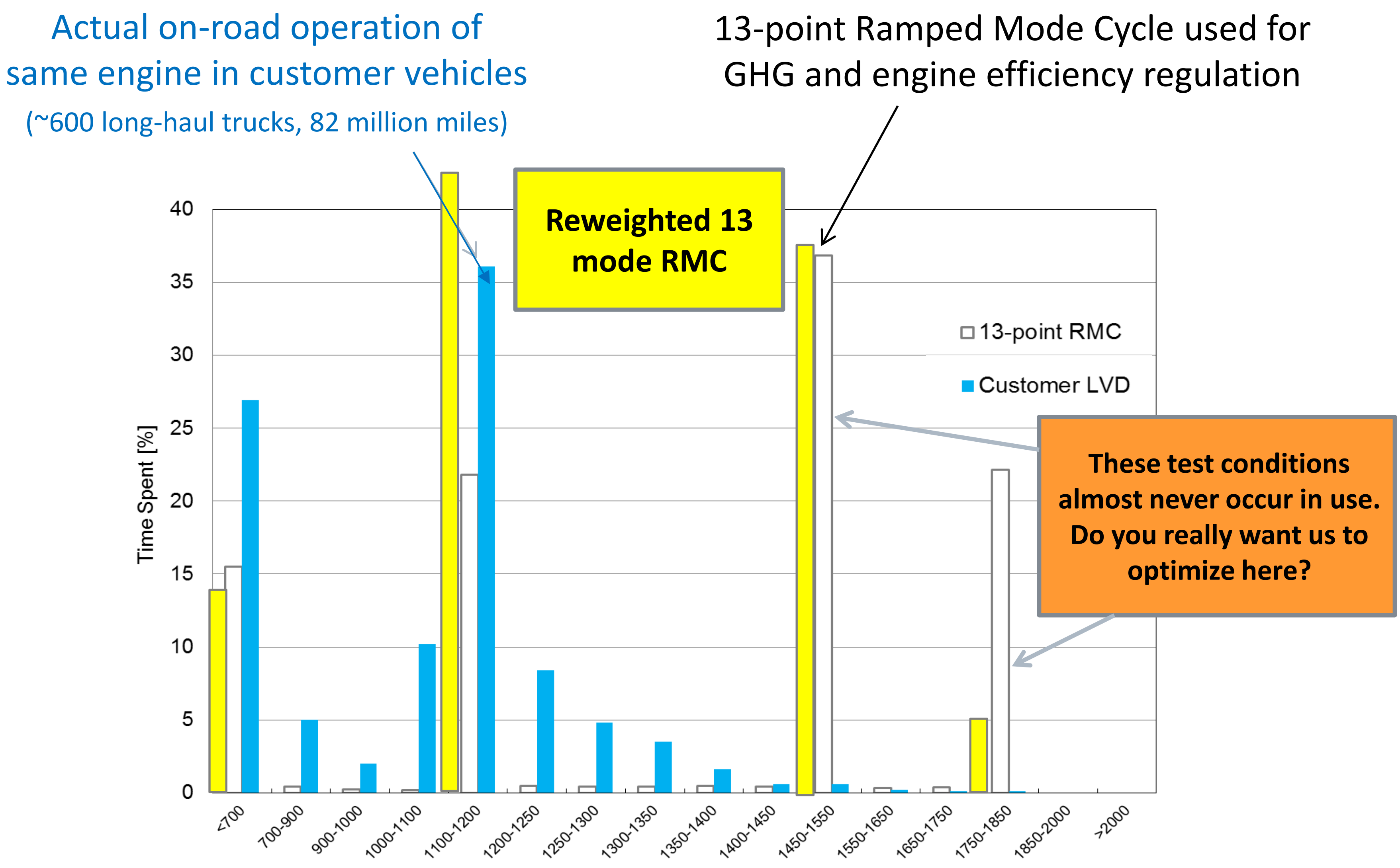
Complete Vehicle Regulation

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

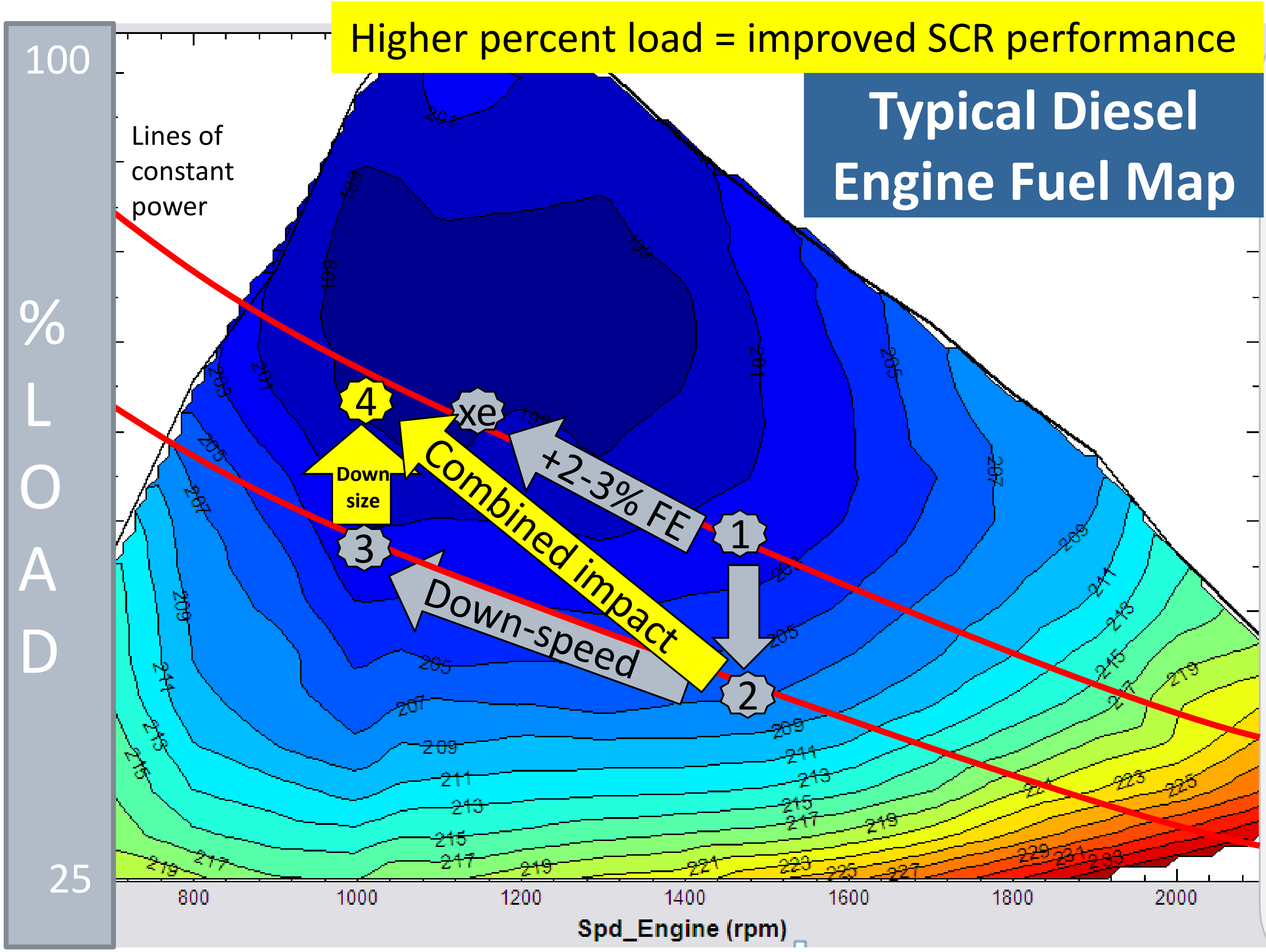
Separate Engine Regulation is Counterproductive

- 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**
  - Engine-specific efficiency requirement provides no incentive to match engine to vehicle

Engine Emissions Duty Cycles: Increasingly Removed from On-road Operating Conditions



Engine Efficiency: Impact of Integration



1. Cruise operating point 2010 Baseline

- Volvo XE13 and Mack Super Econodyne – Down-speeded engine, enabled by integrated AMT and high torque, yields 2-3% FE
- 1-2: chassis and 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.

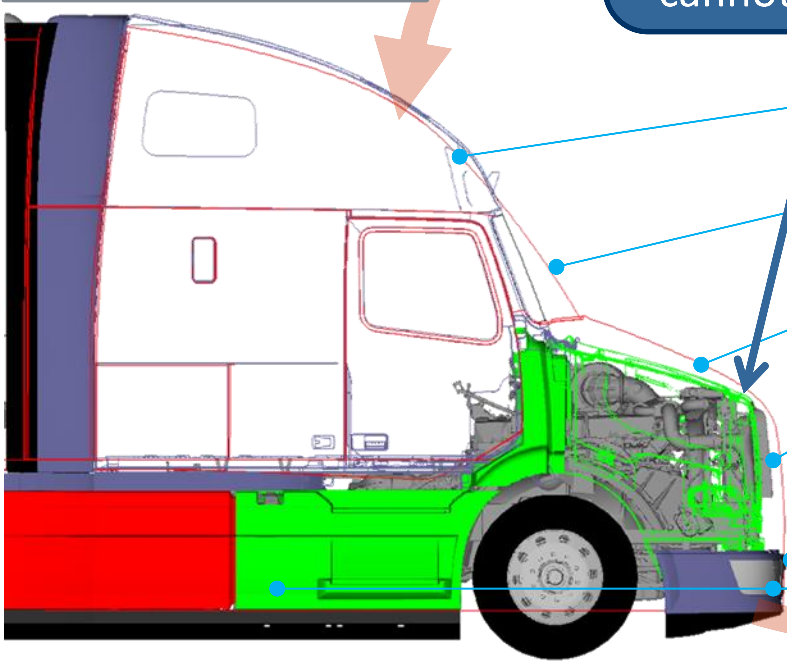
Aero Improvements Plus Powertrain Improvements: Importance of Integrated Design

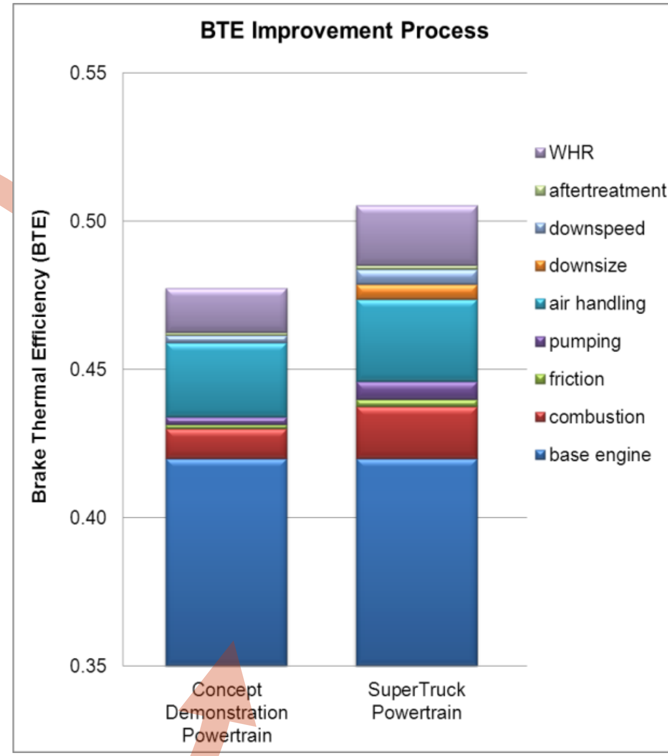
Packaging and cooling needs ...

Example

Rankine waste heat recovery increases cooling demand, resulting in 2% FE loss in aero if new cab is designed to accommodate largest engines with WHR.

Cab optimized for smaller engine with advanced efficiency technologies cannot fit larger engine.





Road load, ...

Trailer Potential

- Recognized as biggest potential contributor to combination efficiency
- 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
    - Regulation must incentivize design optimization with aerodynamic trailers
  - 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

Lower load = less NOx, especially if combined with the right engine and powertrain.

Ongoing Work: Test Facility

- Test planned at Shuttle Landing Facility at Kennedy Space Center
  - Only available facility we could find in entire country

Aerodynamics - Raja Sengupta

2015-04-16

Regulated Efficiency vs. Reality

Regulated efficiency targets can only reflect technologies adequately included in the regulatory structure

- E.G. in phase 1 time frame, the most significant improvements came from introduction of AMTs (automated manual transmissions), which optimize shifting and facilitate down-sizing and down-speeding of engines. (no credit in phase 1)
- Phase 2 measured tractor benefits will potentially be limited by:
  - Very limited aerodynamics on test trailer (no gap reducer? no boat tail?) which may force sub-optimized cab aero design
  - **Potential changes to rule structure could increase GEM results by 10%**
    - Compliance margins on audits for aero and engine mapping without considering production and test variability
    - Changes in aerodynamic test and analysis process
  - Inability to quantify improvements in driver and vehicle management
    - Predictive cruise
    - AMT shifting and coasting
    - V2V and V2I communications and control
    - Platooning
  - No credit for customer programmable idle shutdown and speed limiters
  - Lack of an actual baseline based on real in-use performance
  - Exclusion of well-to-tank GHG impacts from fuels

Efficiency improvements in this presentation are based on what we expect to achieve on average, not what may be measured in the phase 2 regulatory structure.

Existing Regulations Hinder Efficiency

- Trailer rear marker light position (at top of trailer) reduces boat tail efficiency
- Inspection requirements limit skirt effectiveness on tractor and trailer
- Mirror requirements do not allow for substitution with cameras
- NOx control impact on engine efficiency
- Size and weight limits
- Platooning allowance

2021 Timeframe: Vehicle Efficiency Technologies

Tractor

- Engine Down speeding
- Engine down sizing (where applicable)

} Enabled by AMT

- Combustion improvements (cylinder pressure, chamber shape, fuel injection)
- Turbo efficiency/Turbo-compound Waste Heat Recovery
- Engine friction and fluid pumping
- 6 x 2 axle (low penetration)
- Liftable axle
- Improved tractor aero matched to aero trailer
- Improved tires
- Increased AMT penetration for tractors and vocational
- After treatment efficiency (may be used for NOx control)
- Low friction axle
- Predictive Cruise
- Smarter accessory management
- Better cab insulation
- Greater penetration of APUs (mainly battery electric)
- Tire pressure monitor

Trailer

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

Red items not likely to be included in rule provisions

Level of improvement potential is application specific.

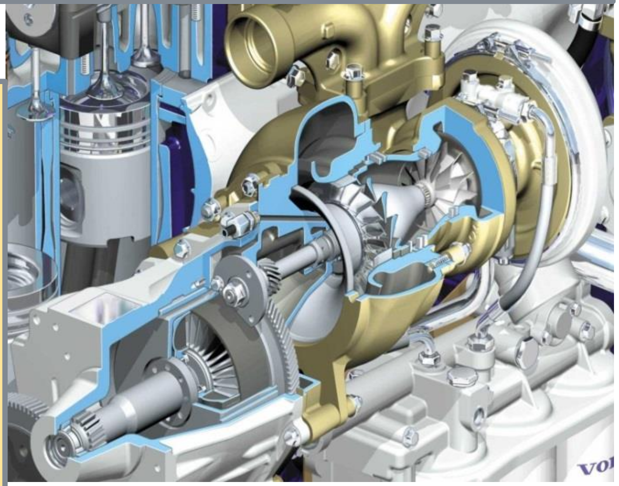
Need to know baseline, duty cycles and assessment methods before evaluating outcomes.

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

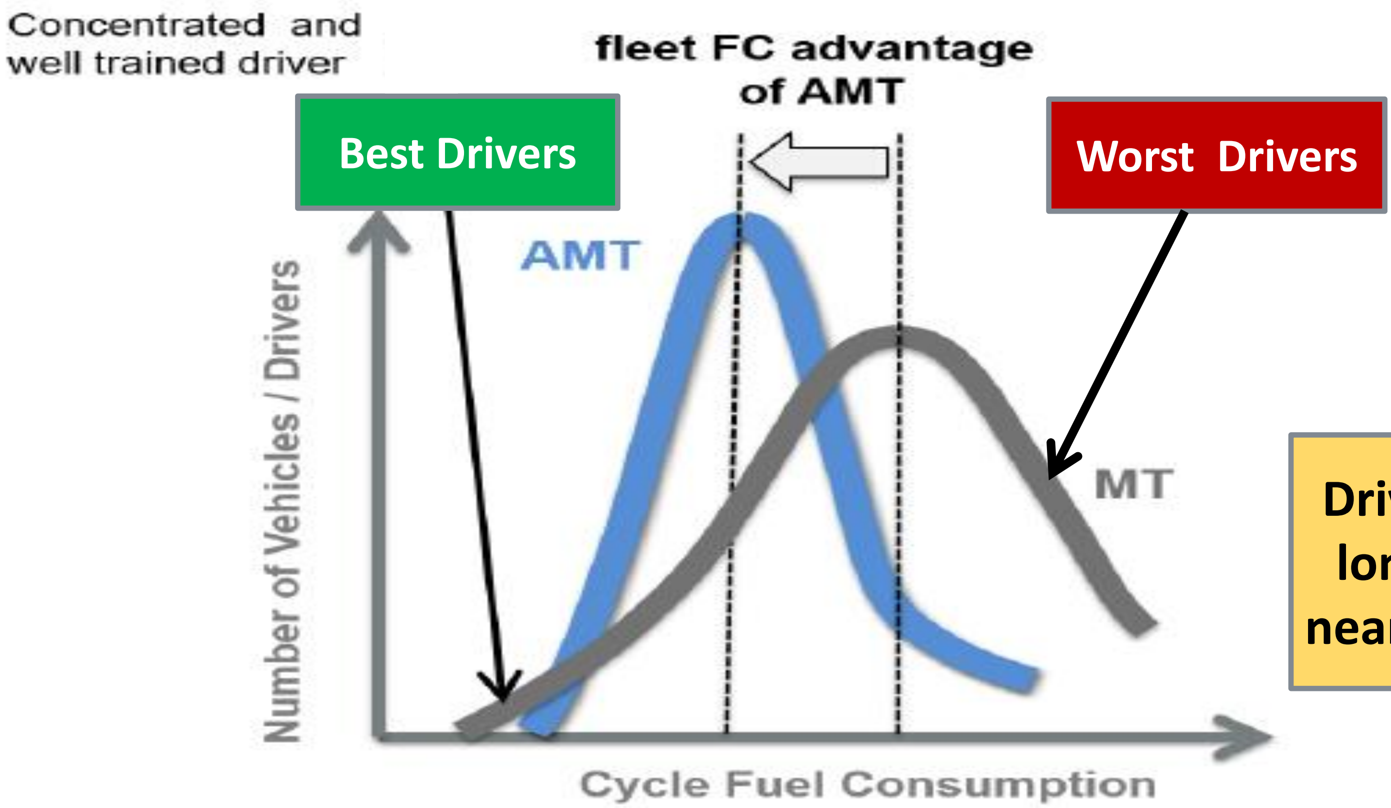
Combined efficiency potential improvements of about 14% for tractor-trailer and 4% for vocational vs. 2017.

Barriers to Implementation

- State and provincial axle weight balance rules (6x2 issue)
- Wheel and brake inspection requirements (skirt optimization)
- Trailer rear light position requirements (boat tail optimization)
- Customer acceptance rate



Driver Impact of Automated Transmissions



Driver turnover for long-haul fleets is near 100% annually!

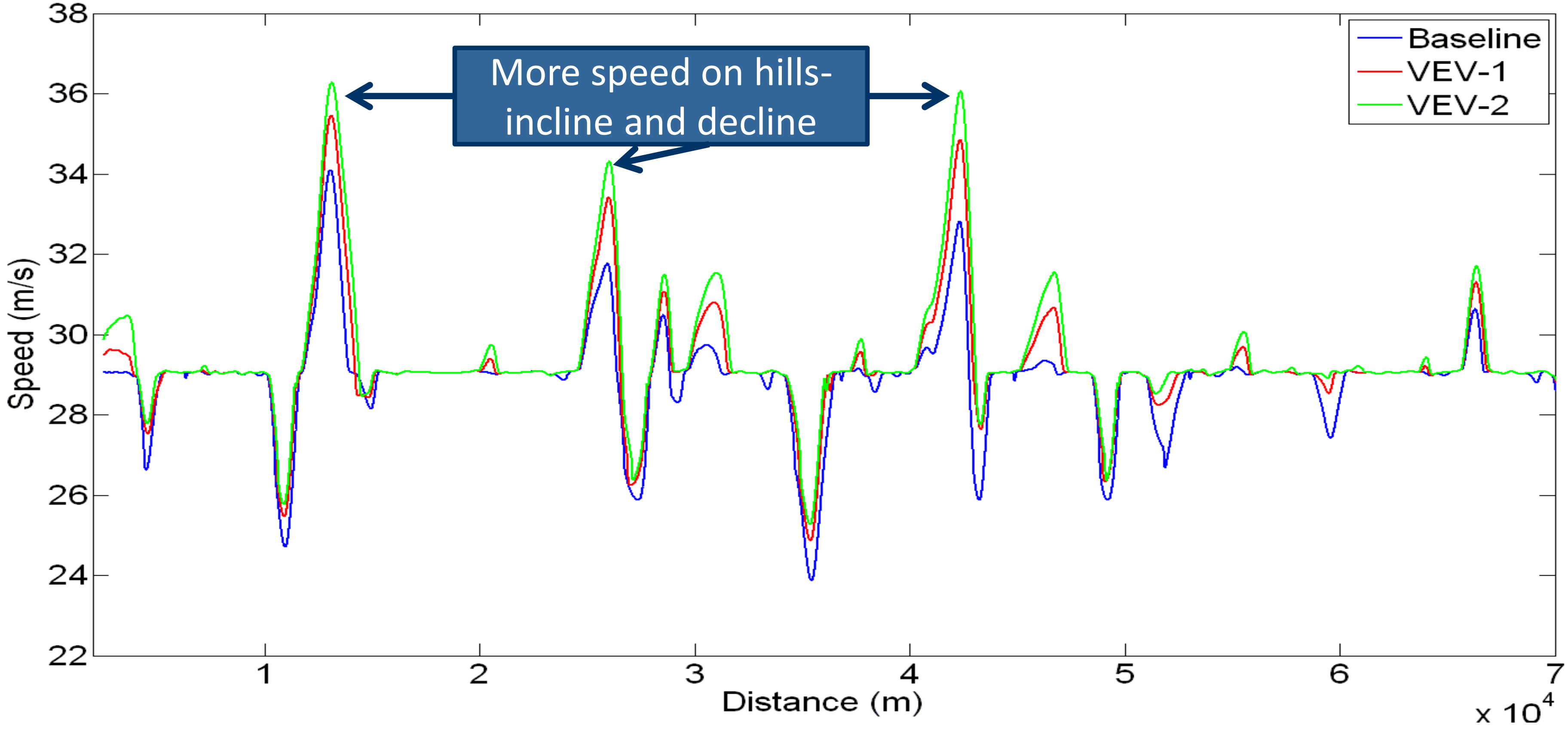
Smart AMTs can sense vehicle load and grade to optimize shifting under all driving conditions.

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 and affordable
- But impact are difficult to quantify in a regulatory structure

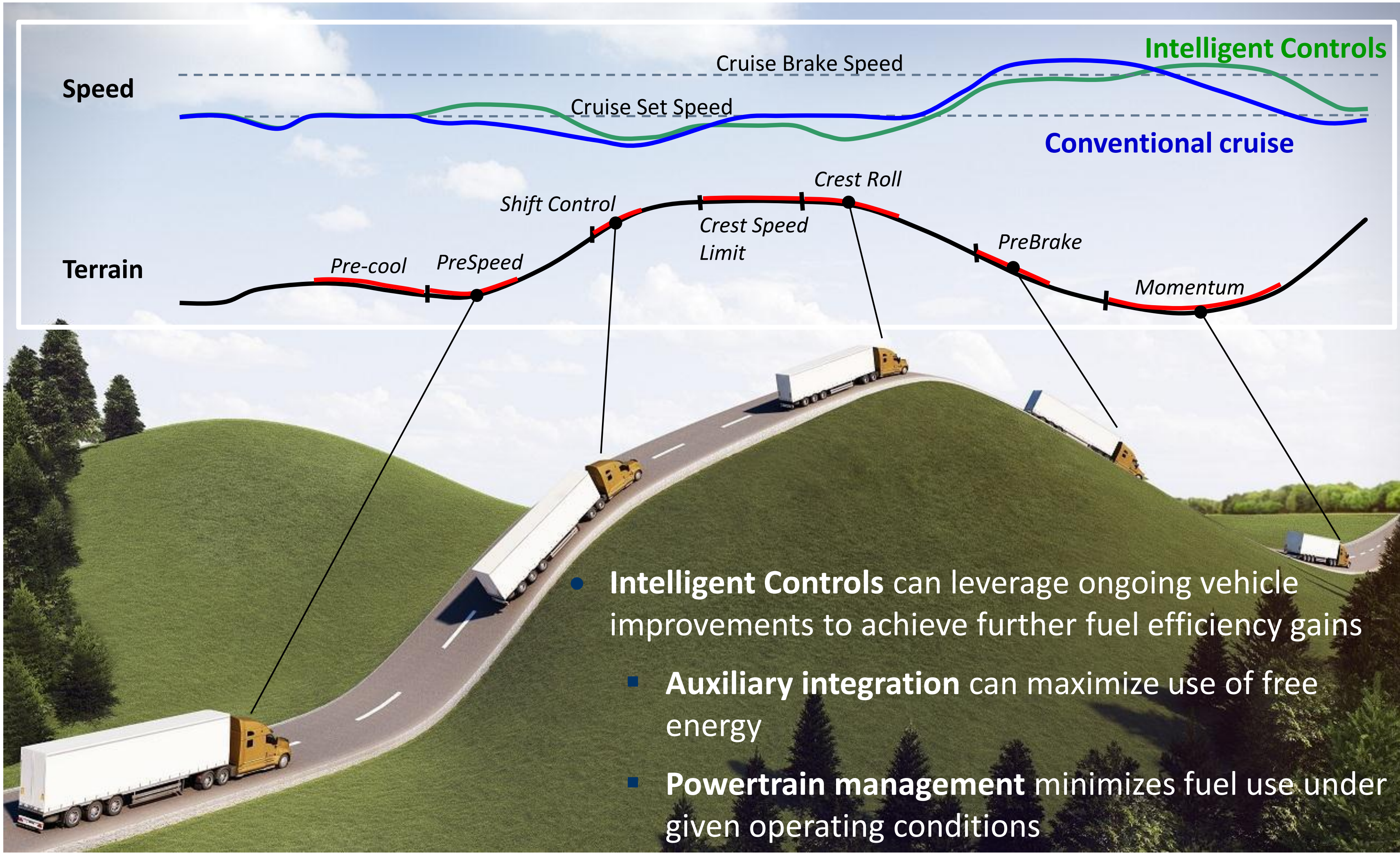
Early results also indicate potential for NOx reduction.

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 ongoing 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

What Happened to Hybrid?

- U.S. 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 and 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 dropped most hybrid offerings due to low sales and high cost
- If forced into the market, expect customers to repair and rebuild old equipment to avoid costs

Technology Viability Timeline: 2024

Tractor

- Improved predictive control, driver and vehicle management utilizing V2V and V2I
- Higher pressure efficient common rail?
- Variable valve actuation ??
- Increased cylinder pressure (~220-240 bar)
- Friction reduction
- Improved accessories (alternator, air compressor, …)
- Improvements to after-treatment low temp conversion efficiency and aging
- Alternative fuels penetration (NG, DME, ???)
- New cab – Tractor-trailer aero integration
- Start/stop engine operation?
- Dual Clutch transmission with further engine down-sizing
- Platooning?

Red items not likely to be included in rule provisions

Trailer

- Boat tail?
- Improved aerodynamics?

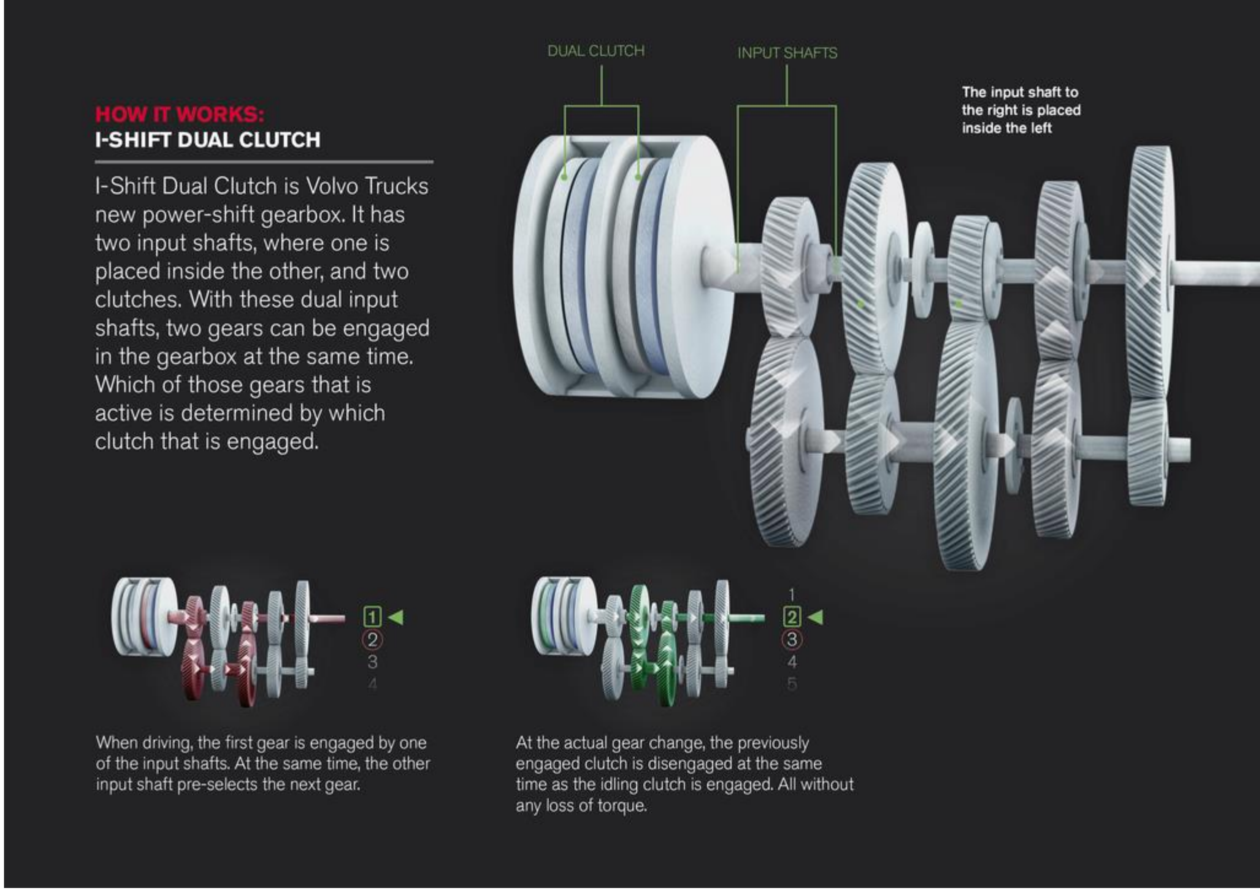
Combined efficiency potential improvements of about 20% for tractor-trailer and 7% for vocational vs. 2017

Roadblocks to implementation

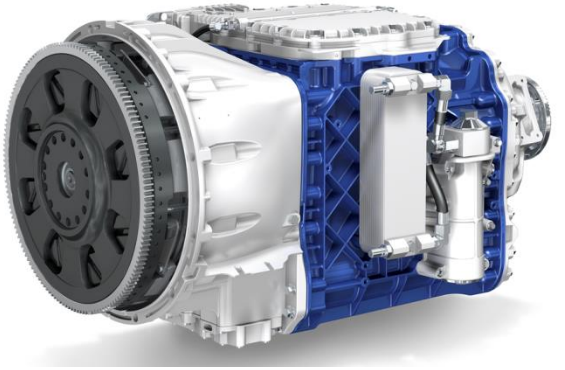
- Designing product for all customer applications
- Safety and inspection regulations
- Noise regulation
- Lower NOx demand
- EATS technical progression
- Vehicle impacts
- Manufacturability
- Cost of product
- Reliability of product
- Weight of product
- Payoff time of technology
- CERT cycles don't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

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.



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

Technology Viability Timeline

2025+ Highly Speculative

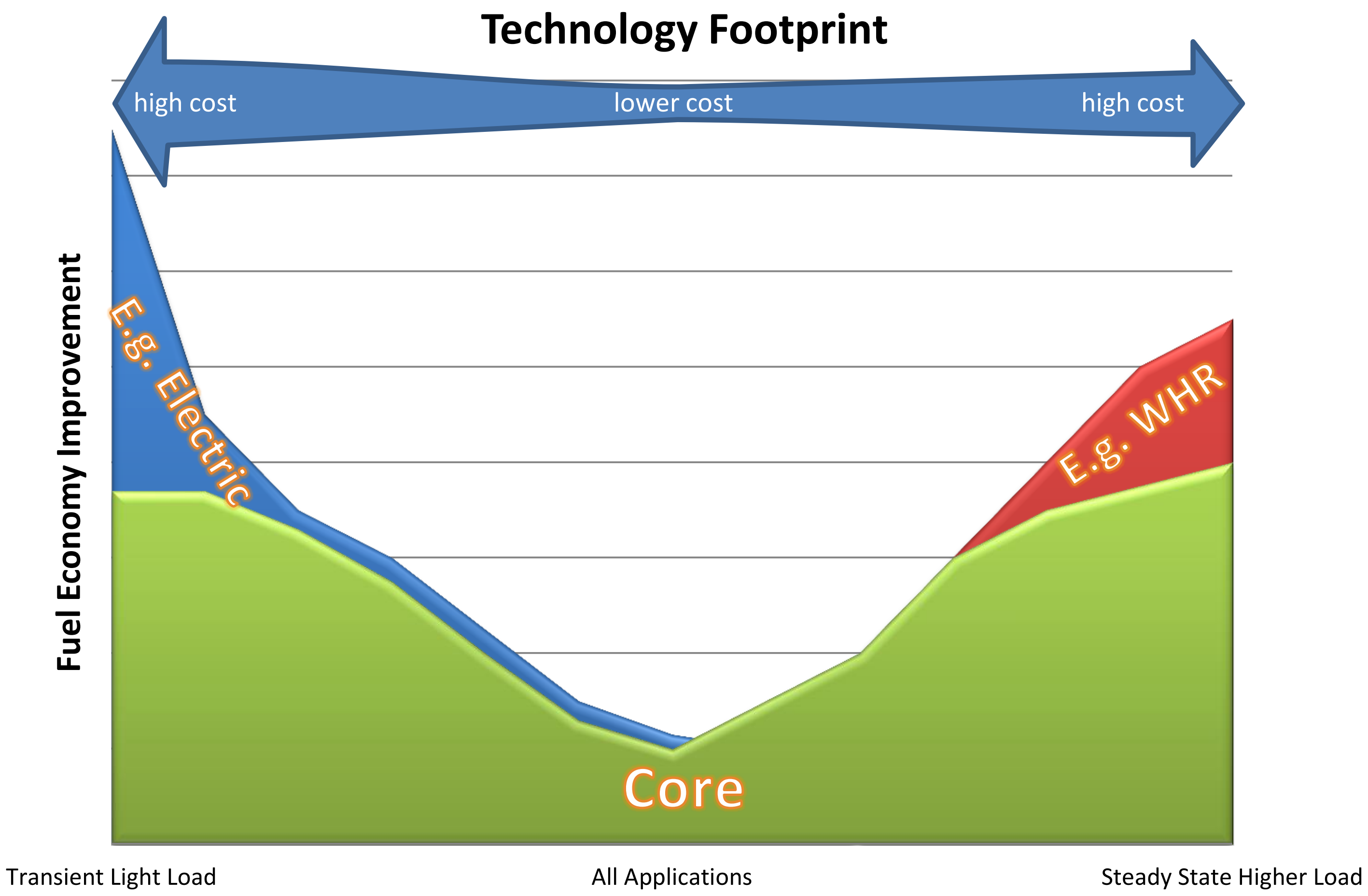
New architecture; highly questionable technology
Fuel economy change too difficult to forecast

- **Waste Heat Recovery (high risk, low volume)**
- **Platooning**
- **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)**

Design for Application: Common vs. Application-Sensitive Solutions



Summary Statements from Volvo Group

- An engine is only efficient when properly applied - right size, matched driveline for the application
- Many technologies (Hybrid, WHR, Electrification) are application-/duty cycle-specific and low volume
- Big changes require massive investments, are high risk and have high development failure rates
- Technologies are not additive and may even be counterproductive when added together (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 and 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.

All estimates of efficiency improvement strongly depend on: regulatory duty cycles; default values in the regulation; audit test margins; what technologies are included in the GEM 2 vehicle model; ability to secure credits for technology not included in the model; other regulations; and much speculation on feasibility beyond 2021 timeframe.