

Vehicular Emissions in Review

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ABSTRACT

This review paper summarizes major and representative developments in vehicular emissions regulations and technologies from 2015. The paper starts with the key regulatory advancements in the field, including newly proposed Euro 6 type regulations for Beijing, China, and India in the 2017-20 timeframe. Europe is continuing developments towards real driving emissions (RDE) standards with the conformity factors for light-duty diesel NOx ramping down to 1.5X by 2021. The California heavy duty (HD) low-NOx regulation is advancing and may be proposed in 2017/18 for implementation in 2023+.

LD (light duty) and HD engine technology continues showing marked improvements in engine efficiency. Key developments are summarized for gasoline and diesel engines to meet both the emerging criteria and greenhouse gas regulations. LD gasoline concepts are achieving 45% BTE (brake thermal efficiency or net amount of fuel energy going to the crankshaft) and closing the gap with diesel. Projections indicate tight CO₂ regulations will require some degree of hybridization and/or high-performing diesel engines. HD engines are demonstrating more than 50% (BTE) using methods that can reasonably be commercialized; and proposals are developed for reaching 55% BTE.

Lean NOx control technologies are summarized, including SCR (selective catalytic reduction), SCR filters, and combination systems. Emphasis is on durability, N₂O, and greatly reduced emissions. Diesel PM (particulate matter) reductions are evolving around the nature of soot and the distribution in the filters. Gasoline direct injection (GDI) particulates carry PAHs (polycyclic aromatic hydrocarbons) through the three way catalyst, but filters can remove most of them. Gasoline particulate filter regeneration is now better understood. Improved understanding of oxidation catalyst formulations are reported with further quantification of the impact of precious metal formulations. Finally, the paper discusses some key developments in three-way catalysts, with improved understanding of the catalyst-support interactions, and the introduction of a low-mass cellular substrate that improves TWC cold start performance.

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INTRODUCTION

Hundreds of papers and presentations are provided annually on the emissions and fuel efficiency of engines for vehicular applications. The challenges on both fronts continue with tightening criteria pollutant and greenhouse gas regulations in all major markets of the world.

This paper focuses on key developments in 2015 related to emissions and technologies for both diesel and gasoline engines in the automotive and heavy-duty markets. As in reviews from previous years [1], it begins with an overview of the major regulatory developments covering criteria pollutants and CO₂. Then, a high-level review is provided of engine technologies, starting with light-duty gasoline and diesel engines, and then heavy-duty diesel engines. In this section, only broad developments are covered with the intent of summarizing the directions and emissions challenges for exhaust technologies. Next, the paper covers lean NOx control, oxidation catalysts, diesel and gasoline PM filters, and closes with representative papers on gasoline emission control.

This review is not intended to be all-encompassing and comprehensive. Representative papers and presentations were chosen that provide examples of new, key developments and direction.

REGULATIONS

Regulatory activities in 2015 that will affect vehicular emissions technologies are mainly proposals that will be finalized in 2016:

- Beijing 6/VI LD/HD and China 6 LD regulations proposed.
- Light-Duty (LD) Real-Driving Emissions (RDE) NOx conformity factors proposed.
- US Phase 2 HD greenhouse gas regulations for 2021-2027
- Other - Indian Bharat 6/VI proposed timing, EU HD In-Service Conformity tightening, California HD NOx program, real world CO₂

Chinese Emissions Regulations

After a couple years of discussion, two rather significant vehicle regulatory developments occurred in China in 2015- Amendments to the Chinese air pollution law; and proposals for Beijing 6 and China 6 LD and HD vehicle tailpipe pollution limits. Both are summarized here.

Amendments to the Clean Air Law

Amendments to China's 15-year-old air pollution law were finalized that grant the state new powers to punish offenders and create a legal framework for moving forward [2]. Most vehicle provisions cover compliance to regulations and enforcement, the latter of which is similar to the US model wherein manufacturers self-report and regulators at various levels provide back-up testing.

Still other provisions are unique. Vehicles cannot idle for more than 3 minutes. Local governments can designate zones where only clean non-road equipment can be used. Diesel engines need to conform to the applicable emissions regulations at time of manufacture, and be repaired or retrofit with emissions equipment. Non-repairable engines need to be destroyed and documented as such. Retrofit implementation has started already, with perhaps 3X more engines being fit in China in 2015 than in all of the US for the same period.

Beijing 6 and China 6

Beijing has been implementing the same tailpipe regulations as the national government, but on a somewhat earlier timeframe [3]. For the first time there is a departure of protocols as indicated by separate proposals that were issued late in 2015.

The Beijing Environmental Protection Board is soliciting comments for "Beijing 6" LD regulations that, beginning in December 2017, follow California's LEV III protocols, but at the ULEV 70 maximum emissions level (70 mg/mi NMOG+NO_x; non-methane organic gases). This is about 30% tighter than the 2015 fleet average requirement in California, and 1/3 the numeric levels of Euro 6 (different test cycle). California attains this level as a fleet average requirement in 2019, so for one to two years Beijing will have the tightest standards in the world. The proposal stipulates the US FTP-75 (Federal Test Procedure) test cycle and also adopts the US supplemental test cycles with specific limit values identical to ULEV 70. Contrary to California, the PM (particle mass) limit of 3 mg/mi is phased in later, through 2021. There is no PN (particle number) limit. Also unique is the 200,000 km durability requirement (California is 240,000 km), and a PEMS-based in-use test requirement with a conformity factor of 1.2X the test cycle limit values. Beijing is proposing to maintain the ban on light-duty diesels.

On the other hand, in December the national Ministry of Environmental Protection published a discussion proposal for moving forward. China 5 (essentially Euro 5) implementation is proposed in 2017, as well as China 6a (Euro 6 but on the World-harmonized Light-duty Transient Cycle, WLTC) and China 6b, which is 1/3 the emission level of Euro 6 (or China 6a). Figure 1 summarizes the key features. Implementation dates for China 6a and b are yet to be proposed, but 2019 was floated for China 6a. As in Europe but contrary to the Beijing 6 proposal, there is a PN limit value of 6 X

10¹¹/km, in China 6a, but it is for all vehicles except natural gas. China is proposing implementing RDE (Real-Driving Emissions) regulations after a two year monitoring period. After that, the diesel NO_x conformity factor is proposed at 2.1X the limit value. A PN conformity factor is still to be determined.

	China 5 (2017)	China 6a (~2019, TBD)	China 6b (TBD)
Emissions	Eu5	NMHC: 68 mg/km, NO _x : 60 mg/km	~LEV III ULEV 50/70 ~1/3 of Eu6; NMHC: 22 mg/km, NO _x : 20 mg/km
Drive Cycle	NEDC	WLTC+RDE	WLTC+RDE
PM/PN Limit	PM < 4.5mg/km	PM < 4.5 mg/km PN < 6x10 ¹¹ #/km	PM < 3.0 mg/km PN < 6x10 ¹¹ #/km
Durability	160,000km	160,000km	160,000km

Figure 1. Summary of the China 5 and 6 light-duty emissions proposal.

Beijing also proposed Beijing VI HD standards for December 2017 [3]. There are two sets of requirements in parallel: Euro VI equivalent engine-based emissions limits; and a set of full-vehicle based emissions limits. The full-vehicle emissions standard includes chassis dynamometer testing method and emissions limits as 1.2 times the Euro VI WHTC limits. Beijing also adopted CARB's newly released defeat device screening test requirements using PEMS testing. In addition, Beijing requires remote OBD testing as part of the in-use conformity requirements.

European Real Driving Emissions

In two separate votes in the Technical Committee on Motor Vehicles (TCMV), the European Commission and the member states approved RDE test methods (May) and light-duty diesel NO_x conformity factors (October) with implementation timing [4, 5].

The two RDE test methods, which are still being evaluated and monitored, are described in detail by Vlachos, et al. [6]. The methods are used to verify that a sufficient coverage of normal dynamic driving conditions is achieved during tests, and then to calculate the RDE emissions for valid tests.

The moving averaging window ("MAW") method uses a CO₂ moving averaging window during on-road testing to identify valid windows and determine, based on these windows, the RDE emissions result. The window width is 50% of WLTP total CO₂ emissions in kilograms; the window moves about once per second. Tests which cover sufficiently the prescribed dynamic boundary conditions are used for emissions calculations. Weighted emissions are calculated as follows. If the associated CO₂ value of the emission window lies outside the WLTP CO₂ reference curve for the associated average speed by more than ±50%, the window is rejected. Values within ±25% are given a weighting of one, and those between ±25 and ±50% of the average have a reduced proportionate weighting. Windows are categorized into speed bins according to their average vehicle speed, and weighted average values for urban, rural, and motorway driving are determined. The final RDE emissions value is calculated assigning an equal weight for each of these three categories. Figure 2 illustrates the approach.

The second approach, called “Power Binning”, categorizes the road emissions according to the instantaneous power delivered to the wheels. The method checks that a sufficient number of events fall within each power bin and ensures that the resulting power distribution lies within the prescribed tolerances around the normalized power distribution defined on the basis of WLTP database. Average values, for valid trips, are computed per power bin and weighted by the normalized power distribution for calculating the final RDE emissions value.

RDE emissions using both the MAW and the Power Binning approaches need to be reported as part of the certification package for monitoring purposes. This will allow minor changes to be made to the final method that is chosen for conformity.

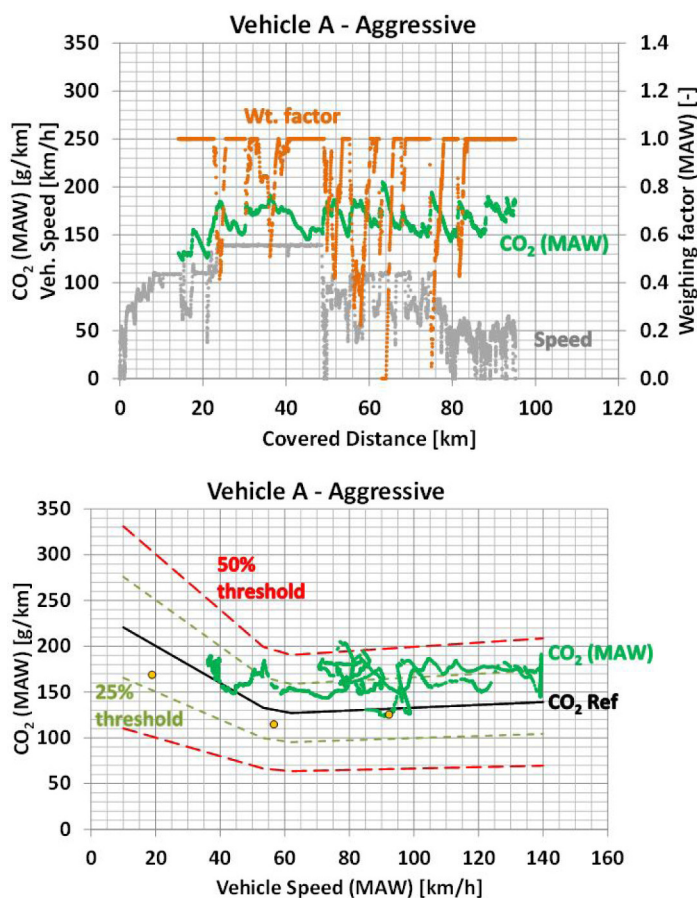


Figure 2. Illustration of the Moving Average Window (MAW) method for RDE analysis. Raw CO₂ and speed data (from moving CO₂ window) are shown in the top figure. CO₂ is then binned by speed on the left to determine point weighting relative to a reference CO₂ curve (bottom). Emission weighting factors that come from this are transposed in the top figure. [6]

In a case study [6], the calculated RDE NO_x value using the MAW method was within 1% of the actual value measured on the course. The Power Binning approach underestimated the actual NO_x value by 15% using the same data set. It was also much more discriminatory on which tests were valid.

In an October TCMV meeting, LDD NO_x conformity factors and the timing of implementation were agreed upon: A conformity factor of 2.1X was approved for implementation in September 2017/19 (new/all

platforms), with tightening to 1.5X in September 2020/21. Although the European Parliament Environmental Committee thought the factors were too loose, the European Parliament approved these values in February 2016, but upon agreement that the conformity factors will be reviewed for future tightening. The GDI (gasoline direct injection) PN conformity factors are yet to be proposed.

US Phase 2 Heavy-Duty Greenhouse Gas Proposal

The final stage of the Phase 1 HD greenhouse proposal starts in 2017. The EPA (Environmental Protection Agency) published a proposed rule that will build upon this and be phased in from 2021 through 2027 [7]. The main features of the proposed rule are:

- Maintain separate engine and vehicle standards, but reweight test cycles to better-reflect real-world operation
- Regulate trailers using a computer model of technology options such as aerodynamics, rolling resistance, and weight reduction.
- Include transmissions using modeling or integrated powertrain testing.
- Improved vehicle simulation model to regulate vehicle technologies.
- 18 vocational vehicle categories
- Chassis dyno confirmation of reductions for some classifications
- Regulate natural gas emissions from the crankcase and LNG (liquid natural gas) tanks.

Natural gas engines will need to be classified according to their intended application, and will continue to be regulated under their respective base engine designation (spark ignition - gasoline engine category, compression ignition - diesel). Figure 3 shows a summary of the reduction levels and sources for several classes of vehicles [8].

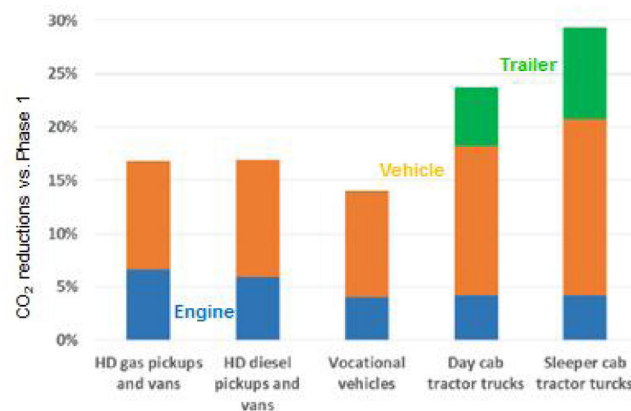


Figure 3. CO₂ reductions from the proposed US HD GHG Phase 2 regulation, showing the separate engine, vehicle, and trailer standards for different vehicle classes. [8].

A final rulemaking is expected by mid-2016.

Other Regulatory Developments

India has been putting together its fuel and emissions roadmap for several years. It is all coming to a final point but a formal regulatory proposal is not yet available. Press releases are stating that the

Transportation Minister, the lead authority on tailpipe regulations, will leapfrog from Bharat Standard (BS) IV tailpipe standards (country-wide in April 2017) directly to BS-VI (essentially the same as Euro 6/VI LD/HD standards) standards in April 2020 [9], and the vehicle manufacturers have apparently agreed [10]. The government's first roadmap had proposed implementing BS-V norms in 2020, and BS-VI norms four years later, from April 2024, with the most-recent agreement coming after one intermediate step.

The European Commission is exploring methods to improve the HD in-service conformity requirements [11]. The method is based on a work-based or CO₂ moving average window method for NO_x in-use conformity. There are various exclusions in the PEMS on-road testing that are being considered - cold start, low power (windows <20% rated power), and the 90th percentile window pass threshold. Closing the exclusions generally caused issues only for the N1 and N2 vehicle classes (goods transport with <12,000 kg gross vehicle weight). Of the 29 tested vehicles in this class, 40% that passed would have failed a tighter power exclusion, 15% (of 13 vehicles tested) more would have failed cold start if it was included, and 24% more would have failed by increasing the window percentile threshold above 90%.

California estimated the implementation timing for its HD low-NO_x program [12]. California already has an optional HD NO_x certification level down to 20 mg NO_x/bhp-hr, 90% lower than the mandatory federal level. The timeline for tightening the mandatory level further is to have a proposed rule in 2017-19, with a final rule by 2019, and implementation in 2023-2027. Technical work is being conducted now to determine the feasibility of tightening down to 20 mg/bhp-hr. On a related note, the US EPA finalized their National Ambient Air Quality Standard for ozone, tightening it from 75 to 70 ppb. They estimate that only a few areas outside of California will be out of attainment with the new standard in 2025, implying that further HD NO_x tightening will not be needed. However, regional air quality districts contest this implication, and are calling for the EPA to follow California to help out.

Perhaps one of the most surprising regulatory reports of the year compares European real-world CO₂ emissions to certification values measured on the NEDC (New European Drive Cycle) [13]. The database includes 600,000 vehicles from 11 data sources from six European countries. The study found that in 2001 cars were emitting about 8% more CO₂ than indicated on the test cycle. In 2014 this gap increased to 40% more. Put another way, the certification test data implies that CO₂ dropped 28% over this time frame, but the real-world fuel CO₂ emission decreased only 7% over the 14 years. This improvement is only 0.5% per year, less than the yearly improvement before CO₂ regulations of about 1% per year. The researchers attribute 75% of the 2014 gap to testing vehicles on the favorable end of the allowable tolerances and procedures.

Finally, VW acknowledged use of a cheat device on diesel vehicles that increased NO_x emissions in real-world driving versus when the vehicle was being tested on the dynamometer for emissions compliance. As with the HD experience in the late 1990s, wherein elevated in-use NO_x emissions of US trucks in the 1990s led to the

EPA NTE (Not-to-Exceed) in-use regulations, the VW disclosure is already having regulatory implications. For example the discussed EU RDE NO_x conformity factors tightened after the disclosure.

ENGINE TECHNOLOGIES FOR CO₂ REDUCTIONS

Engine technology is evolving very rapidly, primarily to meet the tight CO₂ regulations in all the major markets. In light-duty applications the future choice to meeting customer demands and GHG regulations will continue to drive the most economical choices, which so far, are engine-based approaches rather than battery-electric or fuel cell vehicles. In heavy-duty applications the range of choices to do the same are limited to the range of fossil fuel types, with diesel fuel developments still holding an advantage. This section will provide the latest examples of new engine technologies reported in 2015. Many of the promising approaches from previous years are advancing more incrementally, so are not within the scope of this overview.

Light-Duty Engine Developments

Reese [14] provided some interesting analyses on total vehicle requirements to attain the US 2025 GHG regulations. He analyzed model year 2015 US EPA certification data by comparing fuel energy used in the test and the calculated vehicle demand energy (VDE; based on weight, rolling resistance, aerodynamics, etc.). He concluded that to meet the 2025 regulations the vehicle Propulsion System Efficiency (PSE = VDE/used energy), which accounts for engine, transmission, and driveline efficiencies, will need to be about 35% if the size and VDE (energy demand) remain the same. Figure 4 shows the PSE spectrum of model year 2015 vehicle certifications as a function of certification test load factor (as % of rated power). If all this PSE improvement comes from engines, the best gasoline engine needs 30% more total fuel reductions and the best diesel engine needs 11%. Some full hybrid vehicles are already there. Reese showed a couple gasoline engines targeted for about 30% fuel reductions, and one diesel platform targeted for 15% by 2025. In practice, the improvements will be a mix of all the opportunities on the vehicle and powertrain. For example, recent improvements to two gasoline vehicles dropped fuel consumption 17 and 30% by improving VDE (vehicle demand) 7 and 18% and PSE (propulsion) by 13 and 17% respectively.

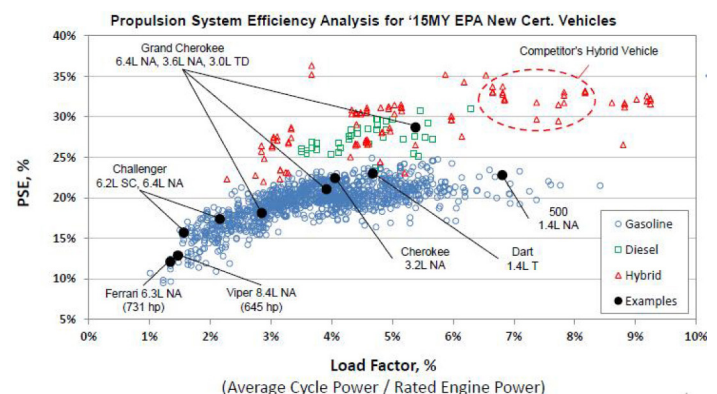


Figure 4. The propulsion system efficiency (intake to wheels) for model year 2015 US vehicles as a function of test load factor. With current technology changes, a PSE ~35% is needed to meet 2025 GHG regulations. [14]

temperatures result in more NO₂ based regeneration of the DPF, and when all the factors are added in, the estimated fuel consumption savings is on the order of 3-5% at medium and high loads.

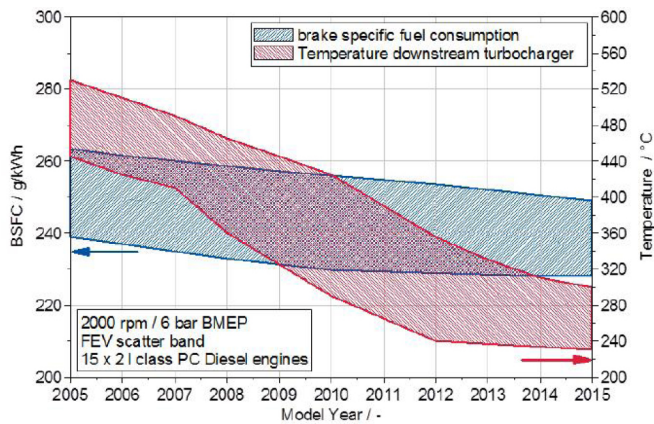


Figure 6. Relationship between fuel consumption, exhaust gas temperature over the last decade for surveyed diesel engines in the 2 liter class. Fuel consumption dropped about 5% from 2006 to 2015, but exhaust temperatures dropped 220°C at a medium load point. [25].

HD Engine Directions

The US EPA Phase 2 HD GHG proposal [7] lists some potential engine technologies and implementation timing needed to meet the regulation. Table 1 shows the projected technologies and GHG reductions for the largest truck engines. Technologies that will be implemented at the highest rate by 2024 are reducing parasitics like friction and pumps, improved aftertreatment, reduced pumping losses, and improved combustion. These total about 4.2% reductions relative to a 2017 engine, which will be ~6% lower than a 2010 engine to meet the Phase 1 rule. The incremental hardware cost relative to 2017 levels associated with these items is only about \$400, but assumes costs on the flat part of the learning curve (mature).

Meszler, et al. [27] did a cost-benefit analyses for a variety of technologies using a range of assumptions. Engine-based approaches generally provide a payback period of less than a year, but range from about 1.5 years for waste heat recovery down to a few months for incremental technologies. Generally the engine technologies are very cost effective, so will be implemented earlier than required by the regulations.

To help move these engine technologies forward, the five to six year US Department of Energy SuperTruck Program is winding down [28]. Both Daimler and Cummins achieved the program goals of building a 13 liter class engine that will achieve 50% BTE at highway cruise load. Volvo and Navistar started later or were delayed, and both are on track for completing these goals as well. Part of the program was also to build a Class 8 truck that would increase freight fuel efficiency (ton-miles/gallon) by 50% (or -33% fuel consumption). This goal was exceeded by impressive margins: -46% and -53% load-specific fuel consumption. About 26-44% of this fuel consumption reduction came from the engine; the balance from decreasing power demand. The Appendix has a comprehensive summary of the general technologies used by the participants to achieve 50% BTE.

Table 1. Projected large truck engine fuel consumption reductions (relative to 2017 engines) and penetration rates for various technologies to meet the US EPA Phase 2 HD greenhouse gas rule (proposed). [7]

Supplemental Emissions Test (SET) Mode	SET Weighted Reduction (%) (2020-2027)	Market Penetration (2021)	Market Penetration (2024)	Market Penetration (2027)
Turbo compound with clutch	1.8%	5%	10%	10%
WHR (Rankine cycle)	3.6%	1%	5%	15%
Parasitic/Friction (Cyl kits, pumps, FIE), lubrication	1.4%	45%	95%	100%
Aftertreatment (lower dP)	0.6%	45%	95%	100%
EGR Intake & exhaust manifolds/Turbo/VVT/Ports	1.1%	45%	95%	100%
Combustion/FI/Control	1.1%	45%	95%	100%
Downsizing	0.3%	10%	20%	30%
Weighted reduction (%)		1.5%	3.7%	4.2%

A third goal of the program is to identify a pathway to achieve 55% BTE. Given this aggressive goal, all efficiency improvements are given consideration, so there are many common improvements.

Cummins [29], Daimler [30], and Navistar [31] are considering dual-fuel low-temperature combustion (LTC) approaches using gasoline/ethanol (Cummins and Navistar) or natural gas (Daimler). All are counting on waste-heat recovery and further combustion improvements.

There are also some unique approaches under consideration. Cummins is projecting 1.7% BTE improvements from piston crown thermal barriers. (Separately, Uchida [32] estimates 1.1%.) Navistar is exploring variable valve actuation and very high compression ratios, and Daimler is doing a lot on predictive engine controls. Only Volvo [33] is downsizing and downspeeding, although Daimler already did this to help attain 50% BTE.

Rankine cycle waste heat recovery is one of the key technologies to attain 55% BTE. Although it was used by all the participants to get to 50% BTE, unforeseen advances in more traditional technologies since the start of the program could have been used instead. Eckerle [34], who has been reporting on WHR (waste heat recovery) advances for more than five years, projected that the Super Truck fuel consumption impacts will be maintained (+3% BTE), and recent architecture and cost reduction improvements can deliver a line-haul truck customer payback period of about 24-30 months, with potential to get to 18 months on the horizon.

Eckerle also broadly addressed CO₂ trade-offs versus tailpipe NO_x levels in the California low-NO_x program. Figure 7 shows a summary of projected CO₂ improvements for today's diesel and spark ignition natural gas engines with a three-way catalyst for a range of tailpipe NO_x levels. Assuming a 95% deNO_x efficiency for the SCR system, future diesel engine CO₂ emissions could increase 5% if the tailpipe NO_x is dropped from about 70 to 30 mg/bhp-hr. Natural gas CO₂ emissions might increase 1-2% going down to 20 mg/bhp-hr NO_x.