AUGUST 2014

Stakeholder workshop report on tractor-trailer efficiency technology in the 2015-2030 timeframe

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ACKNOWLEDGEMENTS

This project was supported by the Energy Foundation. The authors thank Mallory Werthamer of ACEEE for assistance in administering the July 22, 2014, workshop upon which this report is based. We also thank all the workshop speakers (Ron Graves, Gary Salemme, Don Keski-Hynnila, Tom Stoltz, Tony Greszler, Matt Spears, Jim Tamm, Jamie Scarcelli, Mitch Greenberg, Jim Bruce, Megan Peters, and Mike Roeth), the moderators (Nigel Clark, Therese Langer, Ben Sharpe, and Jason Mathers), and participants for all their insights and contributions throughout the workshop. Finally, we thank Oscar Delgado for his research support on efficiency technologies and Rachel Muncrief for her critical review of this workshop report.

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SUMMARY

Combination tractor-trailers' average fuel economy in the U.S. has remained at approximately six miles per gallon for nearly two decades. As a result, tractor-trailers, though less than 2% of US vehicles, represent about 20% of on-road transportation oil use. These tractor-trailers' overall fuel consumption is projected to increase from 2.0 to over 2.4 million barrels per day over the 2013-2030 period. With the U.S. set to establish heavy-duty vehicle standards for 2020 and beyond, it is an important moment to discuss the emergence of advanced efficiency technologies for tractor-trailers.

The workshop "Emerging Technologies for Heavy-Duty Vehicle Fuel Efficiency" sought to bring together expert stakeholders for a technical exchange on heavy-duty tractor-trailer efficiency. The workshop, held in Washington DC on July 22, 2014, was convened by the American Council for an Energy-Efficient Economy (ACEEE) and the International Council on Clean Transportation (ICCT). The meeting brought together representatives from technology suppliers, original equipment tractor and trailer manufacturers, tractor-trailer fleet users, research groups, non-profit organizations, and government agencies to discuss fuel-saving heavy-duty engine and vehicle technologies.

The focus of the workshop was to discuss emerging tractor-trailer technologies, their timing, and potential to increase tractor-trailer efficiency in the 2015-2030 timeframe. Figure ES-1 summarizes the findings from the workshop regarding the timing of tractor-trailer efficiency technologies entering the fleet and their fuel consumption as a percent from a 2010 baseline. The figure is based on technical research literature, materials from industry presenters, and feedback solicited from the workshop participants.

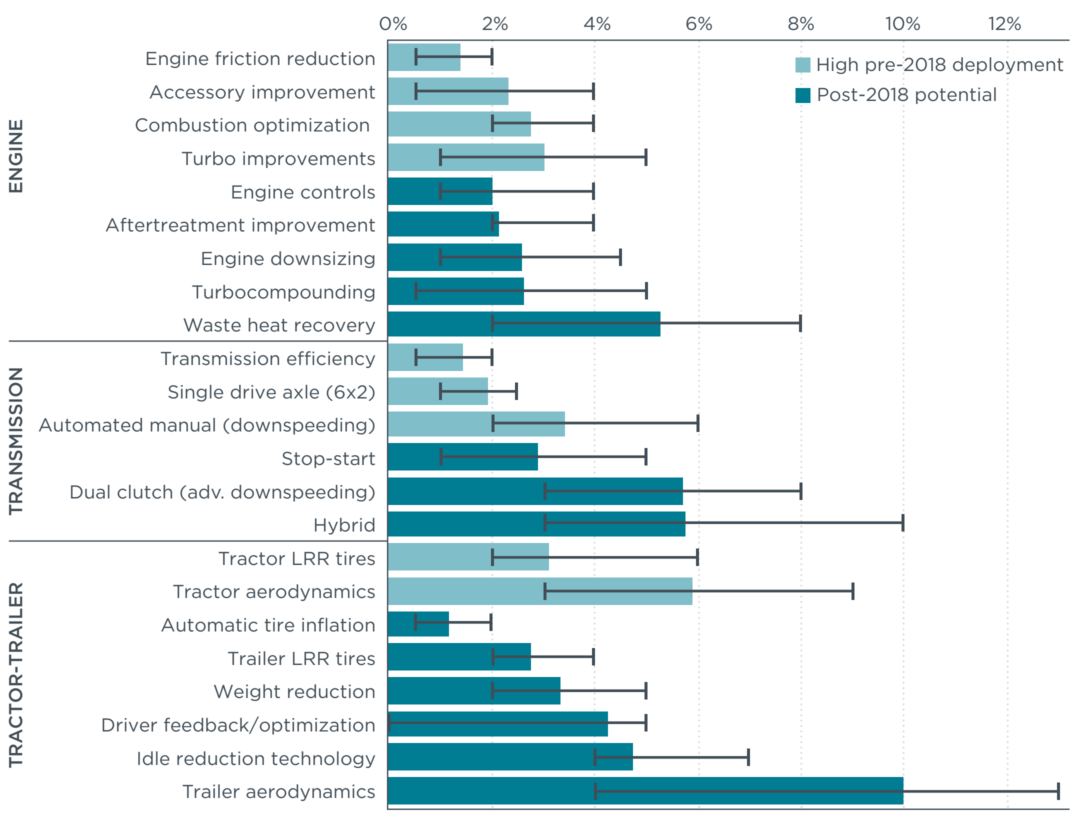

Figure ES-1. Stakeholder workshop findings regarding technologies' percent fuel consumption benefits in representative line-haul Class 8 tractor-trailers

As shown in the figure, the workshop stakeholder feedback indicated that there are a number of technologies entering the market now that will be relatively mainstream before 2018. These technologies include engine-related improvements (e.g., further engine friction reduction, accessory improvements, and combustion improvements), driveline improvements (transmission efficiency, 6x2 single axle drive, and automated manual transmissions), and tractor tire and aerodynamic improvements. In many cases these technologies have already entered the tractor-trailer market to some extent as the industry responds to prevailing efficiency regulations and works to reduce its fueling costs. In addition to discussing the adoption curve of existing technologies, the workshop dialogue also discussed many more advanced engine, transmission, and tractor-trailer load technologies that could be deployed in the 2020-2030 timeframe.

The findings from this analysis, in turn, point to several research and policy implications for the in-development heavy-duty vehicle US greenhouse gas emission and efficiency standards for 2020 and beyond.

1. **High technology potential for tractor-trailers beyond Phase I** — Going beyond the Phase I U.S. regulatory requirements, fuel consumption reduction by as much as 15% from advanced engine technology, 8% from integrated engine-transmission approaches with downspeeding, and 10-15% from trailer technologies were found to be feasible.
2. **Uneven market uptake of tractor-trailer efficiency technology** — The workshop identified how fleets use different processes, parameters, and criteria to vet efficiency technologies. Varying technology investment criteria and factors (e.g., access to capital, return on investment, payback period, driver feedback, technology validation, uncertain fuel saving benefits) are among the barriers mentioned that impede the adoption of advanced efficiency technologies.
3. **Regulatory modifications necessary to capture efficiency technologies' real-world benefits** — To capture real-world impacts, vehicle certification protocols would need to capture the fuel efficiency of the vehicle as an integrated whole. New testing procedures for powertrains would be needed to encourage emerging advanced transmission technologies like dual-clutch transmissions with engine downspeeding. Expanding the regulatory purview to incorporate trailers will be critical to fully promote technologies that greatly reduce tractor-trailer road load. In addition, modifications to regulatory test procedures to better represent real-world operation (e.g., greater weight on low engine speeds, addition of grade) would better promote emerging powertrain technical efficiency approaches with substantial real-world benefits that are not credited in the existing standard test procedures.

I. INTRODUCTION

Diesel-fueled combination tractor-trailers are the prime movers to transport most manufactured goods throughout world economies. These vehicles have made many technical advances over the years, including in safety and air quality-related emissions. However, they have done relatively little to increase their fuel economy. In the United States tractor-trailers' average fuel economy has remained at approximately six miles per gallon diesel for nearly two decades (Davis et al, 2013). Combination tractor-trailers represent a relatively small percentage of vehicles — less than 2% of overall US on-road vehicle sales and stock — but about 20% of all on-road transportation oil use and climate emissions (US EIA, 2013). These tractor-trailers' overall fuel consumption was about 2 million barrels per day (mbd) in 2013 and is projected to grow to over 2.4 mbd by 2030 (US EIA, 2013).

Tractor-trailers' substantial contribution to oil use, their associated carbon emissions, and their potential to increase efficiency with advanced technologies all make them a prime area of interest for increased efficiency. The 2011 adoption of heavy-duty vehicle efficiency standards by the U.S. Environmental Protection Agency (US EPA) and the National Highway Traffic Safety Administration (NHTSA) placed significant new requirements on engine and truck manufacturers to increase the efficiency of their products through 2018 using 'off-the-shelf' technologies that were immediately ready to deploy (US EPA and NHTSA, 2011a). Building on this first phase of standards, the federal government has initiated proceedings for a proposed second phase of heavy-duty vehicle efficiency standards for 2019 and beyond, with a timetable that includes proposed standards in early 2015 and final regulations in early 2016 (White House, 2014).

The next phase of standards will build upon the existing, foundational 2014-2018 standards to develop standards that could provide a more significant push for drawing new advanced technology into the new heavy-duty vehicle fleet through 2025, or perhaps the 2030 timeframe. Among the more critical questions for the next phase of regulations is what emerging efficiency technologies are available for Class 8 tractor-trailers. Efficiency improvements from the engine, transmission, and trailers all could play important roles. The workshop "Emerging Technologies for Heavy-Duty Vehicle Fuel Efficiency" sought to bring together expert stakeholders to help inform on technology availability, effectiveness, and applicability of new heavy-duty tractor-trailer efficiency technologies. The workshop, held in Washington DC on July 22, 2014, was convened by the American Council for an Energy-Efficient Economy (ACEEE) and the International Council on Clean Transportation (ICCT). The meeting included representatives from leading technology suppliers, original equipment manufacturers, tractor-trailer fleet users, research groups, non-profit organizations, and government agencies to discuss fuel-saving technologies for tractor trucks. The focus of the workshop was to discuss emerging tractor-trailer fuel efficiency technologies, their timing, and their potential to increase tractor-trailer efficiency in the 2015-2030 timeframe.

II. COMPILATION OF WORKSHOP TECHNOLOGY INFORMATION

The workshop included a number of steps to encourage participants to share information about tractor-trailer technology developments. In advance of the workshop, the speakers were encouraged to speak about their companies' particular development, deployment, and effective benefits of efficiency technologies for tractor-trailers. Also in advance of the workshop, a handout was distributed that included a list of applicable efficiency technologies, their estimated fuel consumption impact, and commercial availability timing projections based on the literature. During the workshop, the sessions were designed for ample amounts of time to discuss the specific technology areas and to help vet and refine the understanding of efficiency technologies. This section highlights the background technology data that was distributed to, and summarized and discussed by, workshop participants, as well as insights about the various efficiency technology areas gained from the various sessions.

TECHNOLOGY BACKGROUND

Leading up to the original 2014-2018 US heavy-duty vehicle efficiency rulemaking, a number of technical analyses informed on applicable technologies and their potential to reduce fuel consumption in engines and vehicles. Most prominently, there were three studies — NESCCAF (Cooper et al, 2009); TIAX (Kromer et al, 2009); and National Research Council (NRC, 2010) — that provided technology descriptions, technology-specific fuel consumption reduction estimates, and expert assessments on the viability of heavy-duty vehicle technologies that could increase efficiency. These studies highlighted engine, transmission, and road load technologies that were available and emerging, primarily in the 2015-2020 timeframe. Generally, these studies showed how the Class 8 line-haul segment had the largest potential — up to 30-40% — fuel consumption reduction among the heavy-duty vehicle classes.

The regulatory assessment by US EPA and NHTSA toward the 2014-2018 standards built upon the technical work of the NESCCAF, TIAX, and NRC with extensive communication with engine and vehicle manufacturers and technology suppliers. Ultimately the new standards would require a 6% reduction in heavy-duty diesel engine fuel use and an approximate overall 18-23% fuel consumption reduction from Class 8 line-haul tractor-trailers with sleeper cabs (ICCT, 2012). The US EPA and NHTSA regulatory assessment indicated that probable technology paths for compliance included the deployment of engine friction reduction, combustion optimization, turbocharging system improvements, tractor aerodynamic drag improvements, tractor tire rolling resistance improvements, a relatively small amount of tractor weight reduction, and idle reduction technology (US EPA and NHTSA, 2011b). Although efficiency technologies were identified in areas of trailer aerodynamics, trailer tires, transmissions, and hybridization, the agencies did not target specific reductions in these areas within the regulation.

Based primarily on the NRC, TIAX, and NESCCAF work, as well as a number of other sources from the research literature, Table 1 lists efficiency technologies and summarizes key factors about their effectiveness and timing. This summary table was utilized in the pre-workshop handout on the "conventional wisdom" regarding tractor-trailer efficiency technologies from previous work, the literature, and more recent reports and presentations. As shown in the table, each technology has its associated low and high fuel consumption impact, based on the technology's impact on representative real-world line-haul highway driving. The percent fuel consumption reduction values are based from a 2010 baseline, due to this being a commonly used benchmark in most studies for tractor-trailers with modern emission control systems. The table also indicates the approximate timing for which technologies are expected to substantially penetrate the new tractor-trailer fleet. The more near-term technologies, as shown, are expected to achieve at least a 50% share by 2018 (i.e., at the end of the adopted Phase I regulations). The longer-term technologies identified by the sources are generally expected to each be feasibly deployable in significant shares of new tractors for line-haul applications in the 2025 timeframe. Workshop participants were asked to provide input to the technology list, the benefits, and the timing through the presentations, the question-and-answer sessions, and the survey.

Table 1. Potential technologies for 2015-2030 Class 8 line-haul applications

	Technology	Percent fuel consumption reduction from 2010 baseline *		Deployment at >50% of new Class 8 sales by 2018	Significant deployment (10%+ sales) feasible before 2025?	Data source#
		Low	High			
Engine	Engine friction reduction	0.5%	2%	X	X	1,2,3
Engine	Electrical pumps, engine accessories	0.5%	4%	X	X	1,2,3,5
Engine	Combustion optimization (injection, high press.)	2%	4%	X	X	1,2
Engine	Model-based advanced engine control	1%	4%		X	2,9
Engine	Aftertreatment improvement	2%	4%		X	1,2,7
Engine	Turbocharging system improvements	1%	5%	X	X	1,2,3,4,7
Engine	Mechanical turbocompounding	0.5%	4%	X	X	1,2,4,5
Engine	Electrical turbocompounding	0.5%	5%		X	1,2,4
Engine	Waste heat recovery	2%	8%		X	2,3,4,7
Engine	Engine downsizing	1%	4.5%		X	8,9
Transmission	Efficiency (friction reduction, direct drive)	0.5%	2.0%	X	X	2
Transmission	Single drive axle (6x2)	1%	2.5%	X	X	1,2,11
Transmission	Automated manual (with downspeeding)	2%	3%	X	X	2,3,6,7
Transmission	Dual-clutch transmission (with downspeeding)	3%	8%		X	6,7
Transmission	Stop-start (idle off, coasting)	0%	2%		X	8
Transmission	Hybrid (regen. braking, coasting, torque assist)	3%	5%		X	6,8
Tractor-trailer	Aerodynamics (tractor)	3%	9%	X	X	1,2
Tractor-trailer	Aerodynamics (trailer)	8%	13%		X	8
Tractor-trailer	Aerodynamics (tractor-trailer)	10%	20%		X	2,3,8,13
Tractor-trailer	Low rolling resistance tires (tractor)	2%	6%	X	X	1,8
Tractor-trailer	Low rolling resistance tires (trailer)	2%	4%		X	2,3,8
Tractor-trailer	Low rolling resistance tires (tractor-trailer)	4%	10%		X	1,2,3,8
Tractor-trailer	Automatic tire inflation system	0.5%	2%		X	8,12
Tractor-trailer	Weight reduction (chassis, trailer optimization)	2%	5%		X	1,2,9,10
Tractor-trailer	Idle reduction technology	4%	7%		X	1,2
Tractor-trailer	Road load optimization (GPS, predictive cruise, driver feedback)	0%	5%		X	6

* *Percents are in fuel consumption reduction per ton-mile, from representative 2010 engine and tractor-trailer baseline in representative real-world long-haul operation; fuel consumption reduction percents are not simply additive.*

\# *Sources: (1) US EPA and NHTSA, 2011b; (2) NRC, 2010; (3) Kromer et al, 2009; (4) Cooper et al, 2009; (5) Manufacturer input, from US EPA and NHTSA, 2011b; (6) Industry communication; (7) Stanton, 2013; (8) Sharpe et al, 2014; (9) Rotz, 2014; (10) Reinhart, 2014; (11) NACFE, 2013; (12) Benedict, 2014; (13) Golsch, 2013*

EFFICIENCY TECHNOLOGY

Overview of presentations

The workshop was designed to address each of the broad technology areas of tractor-trailers, including sessions on engine and powertrain, full vehicle, and road load technologies. The workshop agenda is shown in the Appendix. The agenda included an engine technology integration session, with presentations from Cummins and Daimler on emerging engine technologies and strategies that included detailed discussions on engine downsizing, downspeeding, and waste heat recovery. The following session on full-vehicle efficiency entailed presentations from Eaton and Volvo on their integrated powertrain technology and vehicle design developments. A section on road load technology included Wabash and SmartTruck presentations on reducing tractor-trailer loads with aerodynamics, weight reduction, and low rolling resistance tires. As multiple presenters and participants pointed out, the technology areas are interlinked in terms of joint technology developments, interaction and synergistic effects of the various technologies, and component sizing contingencies. The workshop also included a presentation by US EPA and NHTSA to provide an overview of their activity toward the development of the next phase of greenhouse gas emission and fuel efficiency standards (Spears and Tamm, 2014).

Table 2 summarizes quantitative statements on technical efficiency improvements from tractor-trailer technologies from each of the workshop presentation speakers. The presenters were invited to speak as candidly as possible about their ongoing technology developments, and the potential for those technologies to deliver efficiency benefits in the 2020-2030 timeframe. The table compiles statements about the potential of various technologies. The presenters each made important clarifications about the precise context (e.g., the applicable duty cycle) for each number that was presented.

Table 2. Summary of key technology statements from workshop speakers

Session	Speaker	Affiliation	Technology statements *
Overview	Ron Graves (for Ken Howden)	U.S. DOE (ORNL)	• Identify technologies that achieve 21st Century Truck Partnership goals of 39% fuel consumption reduction (5.8 to 9.4 mpg) and 4400 lb mass reduction • SuperTruck teams exceeding 50% brake thermal efficiency targets • SuperTruck teams exceeding 50% increase in freight efficiency
Engine	Gary Salemme	Cummins	• 9-15% overall engine improvement from 2017 baseline, including 4-5% from engine waste heat recovery • 3-5% from engine powertrain integration
	Donald Keski-Hynnila	Daimler	• Achieve SuperTruck goal of 50% increase in freight efficiency through engine improvements (20%) and vehicle improvements (30%)
Full vehicle	Tom Stoltz	Eaton	• 2-3% from transmission efficiency and lightweighting (300-500 lb reduction) • 1.5-3% from optimized gear ratios and automated mechanical transmission to reduce driver variability and misuse • 1.5-5% from engine-transmission integration, downsizing, reduced engine transients, excursions, lower cruise speed • 3-4% from look-ahead predictive shifting • 10% from hybridization (with downsized engines, low coefficient of drag) • 33% from aerodynamics, hybridization
	Tony Greszler	Volvo	• Volvo is first to offer dual-clutch transmission (Europe, early 2014) • Achieving over 50% brake thermal engine efficiency in SuperTruck • 14% tractor-trailer efficiency increase from 2017 to 2020 • 20% tractor-trailer efficiency increase from 2017 to 2025
Road load	Jamie Scarcelli	Wabash	• 1-2% trailer mounted gap reducers • 1-6% trailer boat tail • 4-8% trailer side skirt • 1-5% trailer under tray system • 2-4% low rolling resistance tires • Over 2500 lbs in trailer lightweighting options
	Mitch Greenberg	SmartTruck	• 5% from SmartWay technologies (skirts, boat tails, undertrailer systems) • 8% from SmartWay Elite (skirts, boat tails, undertrailer systems, nose) • 40% aero drag reduction from tractor upgrade • 60% aero drag reduction from tractor upgrade and SuperTruck trailer

** Percents are in fuel consumption reduction unless specified otherwise*

The U.S. DOE presentation provided an overview of the 21st Century Truck Partnership and SuperTruck programs technical accomplishments and goals. The 21st Century Truck Partnership goals included reducing fuel consumption by 39%, increasing fuel economy by over 62%, and reducing curb mass by over 4000 lbs for tractor-trailers in representative line-haul conditions (Graves and Howden, 2014). In addition, the presentation indicated that SuperTruck industry teams were exceeding the DOE targets to demonstrate an increase in brake thermal engine efficiency to achieve 50%, and also to increase tractor-trailer freight efficiency by 50%. The following section describes in further detail some of the efficiency technology statements by subsequent speakers as well as some of the comments, question-and-answer dialogue from each session, and feedback from the participant survey responses (See survey in the Appendix) within each technology area.

Engine and transmission technology

The Cummins presentation (Salemme, 2014) focused on engine-specific opportunities. The Cummins presentation highlighted how advanced combustion, turbocharger and air handling, friction and parasitic load reduction, increased peak cylinder pressure, aftertreatment, heat transfer management, downspeeding, and waste heat recovery (WHR) could deliver 9-15% fuel consumption reduction from the 2017 requirement on the certification cycle. “Our vehicle work and the engine work have given us a good foundation as we look to future efficiency improvements,” Salemme stated, “When we think of future technologies, SuperTruck is our baseline.” Cummins also indicated how increasing advanced and precise engine controls — although not a listed technology with a particular fuel consumption benefit — is an underlying technology enabler for all the rest. Also, Cummins indicated that powertrain integration technology, including shift optimization, cycle efficiency management, and hybridization, could deliver another 3-5% improvement. Salemme also noted that the findings of a recent analysis by several non-governmental organizations (NRDC et al. 2014) regarding the potential for tractor-trailer engine efficiency improvement were consistent with Cummins’ presentation on expected engine efficiency potential.

Keski-Hynilla (2014) provided a number of considerations from Daimler’s perspective on engine downspeeding and downsizing. Although Daimler has achieved about 4% fuel efficiency gain from downsizing in their SuperTruck program, they pointed out that there is ‘no one size fits all’ solution for engines. “A range of displacements is necessary to meet power and torque requirements across a broad range of applications,” Keski-Hynilla observed. Downspeeding is getting a lot of attention both from manufacturers and users, but it can introduce drivability challenges as a result of increased low-speed torque demands and the need for rapid transmission shifting.

Stoltz and Dorobantu (2014) from Eaton itemized a number transmission-related fuel-consumption improvements for line haul vehicles, including 4.5-8% from advanced transmission, 1.5-5% from engine-transmission-integration, 2-4% from associated driver improvement, and 2-10% from hybridization. As reported, automated manual transmissions (AMTs) are already seeing 10-30% market share within several major tractor-trailer product lines in 2014, and these transmission technologies could penetrate above half of new sales by 2018. However, Stoltz remarked that current AMTs were developed from existing manual transmissions with automation, whereas future AMTs will use improved controls, smarter gearing (e.g., smaller gear ratios for higher cruise gears), and improved optimization for greater efficiency. As a result, many participants felt that AMTs could become dominant in new tractors within the 2020 timeframe. Eaton highlighted that progressing from automated manual to dual-clutch transmission technology is key enabler for more advanced engine downspeeding and engine and turbocharging optimization for far greater efficiency gains.

It was also suggested by Eaton that the key to understanding powertrain benefits is a holistic systems-based approach that includes engine, transmission, and tractor-trailer road load characteristics. For example, the justification to install even $30-50 efficiency improvements on transmissions used to be difficult, but, now, considering the holistic benefits for the overall tractor-trailer, these propositions become clearly beneficial. Eaton also pointed out how reduced vehicle loads from aerodynamics are critical for powertrain sizing, and efficiency synergies with hybridization technology. The Eaton presentation reported that a 10% fuel consumption reduction was feasible from hybridization in line-haul applications in 2025-2030. This would follow from lowering tractor-trailer drag coefficient from 0.65 in 2014 to 0.35, which, in addition to reducing fuel consumption directly, would also increase energy recapture through regenerative braking on negative grade road segments. One participant indicated that advanced hybrid line-haul technology, assuming a battery breakthrough, could even deliver a 20% fuel consumption reduction over the longer term.

Several other powertrain-related insights and issues arose through the workshop dialogue. In reference to the engine and transmission technologies generally, a number of participants noted how cycle-dependent the technologies' efficiency gains can be. For example, the fuel consumption impacts are dependent on drive routes, duty cycles, highway speeds, and payload. It was pointed out that engine downsizing, though a key CO_2-reduction strategy, is not beneficial for all duty cycles and could present a concern for tractor resale in some cases, depending on the second and third uses of the tractors. Several participants noted that smaller engines may be challenged by steep road grades, lower durability, more heat rejection, and greater back pressure sensitivity. Less variability in natural gas prices than diesel or gasoline may attract truckers to opt for this technology, but some fuel-efficient technologies like WHR may not be economical for natural gas applications.

Vehicle technology

Greszler (2014) provided details on the technologies and potential fuel consumption reduction from tractor-trailers from Volvo's perspective in the 2020-2025 timeframe. The Volvo presentation included discussion of many of the powertrain technologies from above, and also included insights on comprehensive full-vehicle accounting of efficiency. The presentation listed technology packages for the 2020 and 2025-and-beyond timeframes. Greszler noted that there is the potential to improve tractor-trailer fuel efficiency by 14% in 2020 and by 20% in 2025 from a 2017 baseline. Greszler noted there are key duty cycle questions to any such efficiency projections. As part of those projections, he noted that trailers can lower overall vehicle power demand by 10-12%, and 6x2 single axle driveline configurations reduce weight by 400-500 lbs, lower friction, and lower rolling resistance. Reflecting on recent market trends, Greszler mentioned that matching engines to transmissions could be a strategy for companies; for example, Volvo trucks now are 85% powered by Volvo engines because these are the engines offered with Volvo's popular automated manual transmission. Relatedly, another participant similarly indicated that the majority of Daimler Truck North America trucks have Detroit Diesel engines. While the technologies listed by Volvo for 2020 are generally very similar to those in Table 1, the 2025-and-beyond technologies include some additional fuel-saving strategies. For example, Greszler mentioned platooning, higher power density (via lightweighting), advanced combustion (e.g., partially pre-mixed combustion, homogeneous charge compression ignition), alternative (i.e., non-diesel) fuels, elimination of EGR, new architecture (e.g., non-four-stroke), roadway electrification, non-conventional hybrids (e.g., compressed air, flywheel), longer and heavier combinations, and autonomous vehicles.

Scarcelli (2014) indicated that Wabash has already begun deploying many of the load reduction technologies for the goal of increasing freight efficiency. For example, he indicated that about 60% of van trailers built by Wabash in 2014 have skirts, 30% have tire inflation systems, and low rolling resistance tires are now standard equipment for Wabash, unless trailers are specified otherwise. Wabash reported on how lightweighting technology is really a customer decision based on cost considerations related to their payload and the value of the products. A total of over 2500 lbs in lightweighting options are offered to fleets, including options for the use of new materials and lightweight designs floors, sidewalls, crossmembers, landing gear, rims, hubs and drums. He stated that the company goals are to deploy 1500 lbs of lightweighting per trailer. An example of a European prototype trailer by Don Bur was reported upon that provides 15% efficiency improvement over US trailers, but US bridge height restrictions preclude such tapered geometry technology.

Several other tractor and trailer insights and issues arose through the workshop dialogue. It was highlighted at many points that trailer aerodynamics are largely being driven by California's requirements for SmartWay devices, but that the use of all the various aerodynamic devices and tire technologies is mixed overall. Greenberg (2014) indicated that moving beyond the original SmartWay to a SmartWay Elite-type technology package would deliver almost twice the benefits (i.e., 9% vs 5% fuel economy increase) with boat tails, under trailer, and nose devices. He noted that, while the drag coefficient of a typical tractor-trailer today is about 0.6, drag coefficients in the vicinity of modern sport utility vehicles (0.45) or even the best production car (0.23) could be achievable and would increase miles per gallon by over 50%. Greenberg also underscored the importance of equipment robustness and positive driver interaction. One participant suggested that the trailer aerodynamic improvements could indeed achieve up to 13% fuel consumption reduction, but that for some applications and trailer types, gains could be as low as 4%.

Other technologies

There were a number of technologies that participants pointed out that were not included in the above Table 1 efficiency technology list. Among the omitted technologies were ones that result in operational efficiency improvements and ones that involve alternative fuels. Operational efficiency technologies include speed limiters, increasing truck sizes and weights, predictive cruise control, and truck platooning with vehicle connectivity. Alternative fuels that were discussed include various natural gas-derived fuels (compressed natural gas, liquefied natural gas, di-methyl ether) and biofuels (e.g., renewable natural gas, drop-in biofuels, biodiesel, renewable diesel, and biomass-derived di-methyl ether). Although many of these technologies do not offer tractor-trailer technical efficiency advantages in regulatory tests, they can of course potentially reduce petroleum use and greenhouse gas emissions. In addition, the question of reducing the efficiency gap between natural gas and diesel was raised; many diesel efficiency technologies (e.g., engine friction reduction, parasitic load reduction) were transferrable, but more advanced technologies including WHR would be challenged by their respective payback period. Finally, a participant remarked that, in the 2030 timeframe, roadway electrification for freight trucks (e.g., on the Interstate 710 corridor in California) could also be a possibility.

CAPTURING REAL-WORLD BENEFITS IN REGULATORY PROTOCOLS

At several points, participants indicated that regulatory certification protocols would need to evolve beyond their Phase 1 forms to adequately reflect technologies that integrate engine and transmission or powertrain and vehicle. Technologies that were identified as not being adequately promoted include engine downsizing, engine down-speeding, transmission efficiency, single drive 6x2 axle, predictive cruise, AMT, DCT, start-stop, hybridization, and all trailer technologies. These technologies are not measured in standard engine emission test cycles nor are they adequately captured in the US EPA Greenhouse gas Emissions Model (GEM) simulation. It was acknowledged that it is possible to gain innovative technology credits for some of these technologies, but this has proven to be "extremely difficult." Developing improved specifications for idle reduction technologies that customers would accept was mentioned. Several participants also indicated the need for better promotion of low-carbon fuels like natural gas (compressed, liquefied, di-methyl ether, biomass-based), and drop-in biofuels.

Several ideas were discussed that could help the regulatory protocols to more fully promote tractor-trailer efficiency technologies. Altering the engine test cycle itself from the 13-mode Supplemental Emissions Test or Ramped Mode Cycle was mentioned. A re-weighting of the engine test points to focus more on lower engine speed operating points (i.e., the lower rpm "A," rather than the "C" points) that are more representative of real-world engine operation was also suggested (see DieselNet, 2010, 2000). Several companies indicated that a test procedure shift toward lower speed points is supported by real-world data and is also increasingly important for emerging advanced powertrain technologies that are moving toward further optimization and downspeeding. No participants objected or suggested otherwise. The use of engine-specific data, rather than default engine maps, along with some adjustment for transient effects, would also increase the ability of the regulatory certification model (GEM) to reflect real world technology effects.

The regulatory agency representatives, at multiple points, encouraged participants to share ideas and data related to these questions about testing protocols, real-world driving factors, and any associated technology interactions. Among the ideas mentioned, incorporating varying payload, perhaps linked to engine size, was discussed as a way to accommodate the diversity of payloads and uses in the fleet. Modifying the tractor test procedure to include grade was discussed to reflect greater load variation and better promote optimized powertrain sizing, predictive cruise control, and hybrid technology. In addition, new regulatory requirements would be needed for trailers to promote available and emerging aerodynamic, low rolling-resistance, and lightweighting technologies across the fleet. Protocols could also be developed to promote increased engine efficiency and reduced fuel carbon intensity for alternative fuels like natural gas and biofuels.

FLEET PERSPECTIVE

A fleet session was organized with representatives from J.B. Hunt, United Parcel Service (UPS), and North American Council for Freight Efficiency (NACFE) to get their perspective on various fuel efficient technologies and better understand how they make purchasing decisions for these products and what factors are most important in their decision-making.

Fleets discussed how they are already using many efficiency technologies to reduce their fuel consumption. The use of 6x2 axle configurations and trailer skirts is common, as they are low cost technologies that are a good fit for many fleets. Alternative fueled vehicles are also being purchased for particular applications. On the other hand, fleets had tried some of the new technologies in the past but noted several technical or operational limitations. For example, fleets are not widely deploying trailer back-end aerodynamic devices because of operational freight loading issues, and they also have had difficulties finding auxiliary power units that met all their needs to allow greatly reduced idling. Alternative fuels — although far less common in usage than many engine efficiency, transmission, and trailer technologies — were discussed at many points. It was noted that natural gas fuels and some biofuels are cost-competitive with diesel prices, depending on local conditions, prices, and fleet patterns. The workshop included lengthy discussion about what factors are most important in deploying emerging technologies. A number of monetary and non-monetary criteria that influence the uptake of technologies were described.

A number of cost-related factors were identified as being part of fleets' technology decisions. Varying technology investment criteria and factors include capital expenditures, return on investment, net present value, payback period, driver feedback, technology validation, and resale value. These various cost factors reflect how different fleet players provide different criteria in their cost accounting. One participant indicated that some fleets are constrained by access to capital for additional technology options, and that fleets would have to move more from capital-constrained "CapX" accounting to "net present value" to better take into account fuel savings in the upfront purchasing decision. It was noted that unresolved uncertainties about key factors (e.g., future fuel cost, efficiency benefits) made incorporation of future fuel savings in the decision-making process quite difficult. Several participants noted the lack of trust in any particular data source on the fuel-saving potential of any particular technology. As a result, fleets typically had various types of experimental testing, utilized limited fleet deployment initially, and monitored feedback and driver reactions to better understand the real-world fuel-saving for their own fleet operations. Lack of validated information on real-world benefits for the various efficiency technologies was identified as a clear barrier to the increased adoption of advanced efficiency technologies, as it precluded any rigorous fleet cost assessment. It was suggested that SmartWay verification thus can serve as a "ticket to entry" for new technologies.

While some fleets sought to estimate the payback period and other cost factors when purchasing new technologies, many fleets considered other non-monetary factors as well. Panelist Mike Roeth made this point, commenting, "fuel savings and upfront cost are the biggest factors. But other benefits and consequences always occur in the real world. For instance, maintenance, driver costs, infrastructure." Product maturity, driver receptiveness, and expected durability were noted as parameters that were considered in the fleet purchasing by a number of stakeholders. Technology complexity was cited as a potential barrier, with examples of exhaust gas recirculation and waste heat recovery cited as the types of technologies about which some fleets could have reservations. Technologies tend to initially be resisted due to driver and fleet questions about their cost, complexity, and perceived questions about their maturity; however these problems have been overcome in important instances. For instance, automated manual transmissions were initially resisted, but now fleets are generally finding substantial efficiency gains for most drivers, and fleets “need AMTs in order to get new drivers” due to the popularity of the technology. These considerations led to a participant’s conclusion that the timing of any requirements is critical, and sufficient lead-time is needed to accommodate fleet uptake of emerging technologies. Some fleets also consider their corporate sustainability and carbon-intensity goals before making their choices about technology. Overall, through the panel discussion, it became clear that different fleets use different processes, parameters, and criteria to vet new technologies.

III. FINDINGS AND CONCLUSIONS

The focus of the workshop was to discuss emerging tractor-trailer efficiency technologies, their timing, and potential to increase tractor-trailer efficiency in the 2020-2030 timeframe. Through the industry expert presentations, the solicitation of stakeholder input via the surveys, and the participation in the technical exchanges in each session, the workshop generated diverse stakeholder feedback. This report summarizes the key take-away conclusions and insights from the proceedings. In particular, the final conclusions summarized here are regarding efficiency technology potential, uneven fleet incorporation of efficiency technology, and regulatory changes to promote various technologies for their real-world benefits. The findings from this report in turn, point to several research and policy implications for the in-development US greenhouse gas emission and efficiency standards for tractor-trailers for 2020 and beyond.

High technology potential for tractor-trailers beyond Phase I — Figure 1 summarizes the findings from the workshop regarding the timing of tractor-trailer efficiency technologies entering the fleet and their estimated fuel consumption as a percent from a 2010 baseline. The figure is based on technical research literature (see above Table 2), materials from industry presenters, and feedback solicited from the workshop participants. As shown in the figure, the workshop stakeholder feedback indicated that there are a number of technologies that already are substantially entering the fleet now and will be relatively mainstream before 2018 (i.e., within the first phase of efficiency standards). For example, these technologies include engine-related improvements (e.g., engine friction reduction, accessory improvements, and combustion improvements), driveline improvements (transmission efficiency, 6x2 single axle drive, and automated manuals), and tractor tire and aerodynamic improvements. These technologies are largely already entering the tractor-trailer market as the industry responds to prevailing efficiency regulations and works to reduce fueling costs. The low and high error bars indicate the variation in technology from the data sources and the survey respondents. These ranges represent the potential for improvement and optimization in future technology developments among the technologies that are already in the market.

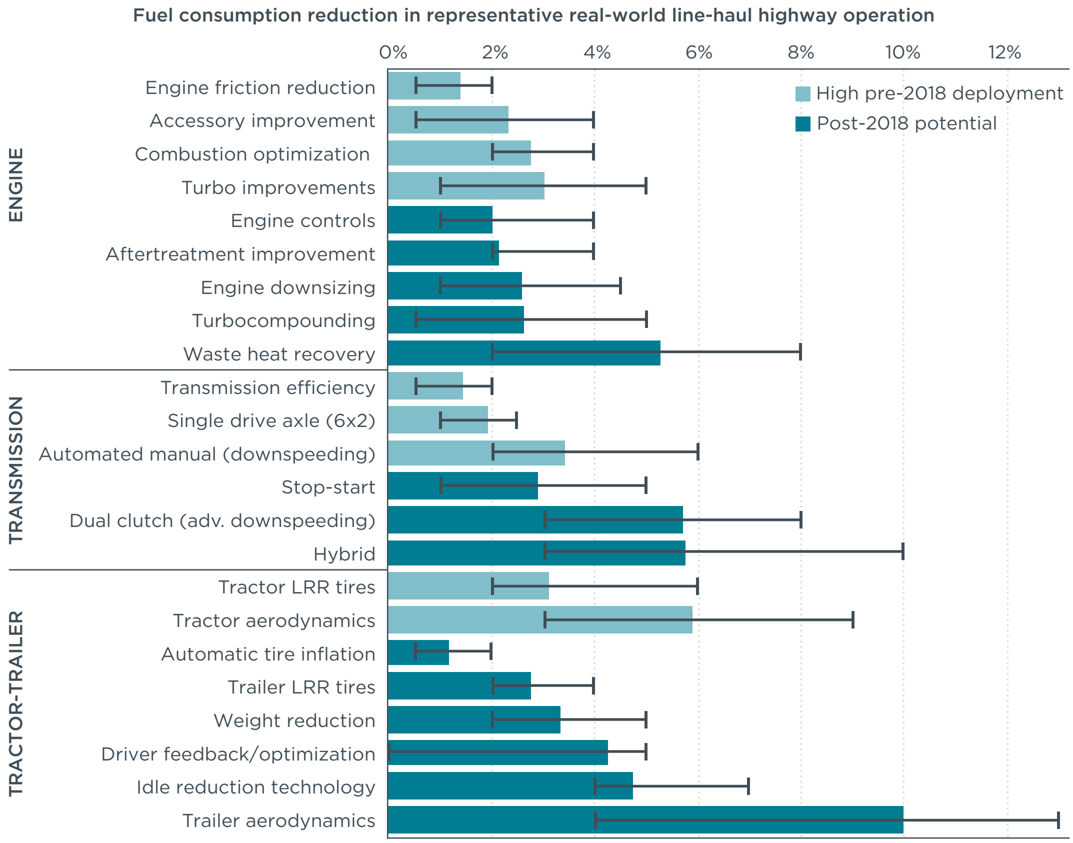

Figure 1. Stakeholder workshop findings regarding technologies' percent fuel consumption benefits in representative conditions for line-haul Class 8 tractor-trailers from a 2010 baseline

The workshop dialogue also discussed many more advanced engine, transmission, and tractor-trailer load technologies that could be deployed in the 2018-2030 timeframe. Going beyond the first phase of US regulatory requirements, fuel consumption reduction by as much as 15% from advanced engine technology, 8% from integrated engine-transmission approaches with downspeeding, and 10-15% from trailer technologies are expected to be available in the 2020-2030 timeframe. These stakeholder workshop results across the technology areas are broadly consistent with a recent analysis of tractor-trailer efficiency opportunities (NRDC et al, 2014). Among the prominent approaches identified are dual-clutch transmissions that enable greater downspeeding for greater efficiency, load reduction technologies that allow greater engine downsizing, waste heat recovery, hybridization, and integrated energy management approaches. Although these individual technologies and their benefits were identified, determining the total tractor-trailer technology potential requires investigation of the interactions involved in the integrated use of packages of the various technologies through vehicle simulation modeling.

Uneven market uptake of tractor-trailer efficiency technology. Although the workshop identified many available and emerging technologies that offer substantial efficiency improvements for tractor-trailers, these technologies' deployment in the fleet has been uneven. There were examples of technologies that are being driven into the marketplace via regulatory requirements. For example, engine and tractor aerodynamics technologies are driven by federal efficiency regulations, and trailer technologies are being driven by

California's regulatory requirements. There were other examples, like automated manual transmissions and single drive axle 6x2 configurations, that are not significantly required or fully promoted by regulations but that are, nonetheless being increasingly adopted by some fleets.

The discussion about factors that drive efficiency technologies in fleets helped clarify why market adoption of emerging technologies has been mixed. A number of monetary and non-monetary criteria were discussed as factors that dictate, and generally impede, the uptake of technologies that appear to be very cost-effective and have very attractive payback periods. Varying technology investment criteria and factors (e.g., return on investment, net present value, payback period, driver feedback, resale value, technology validation) reflect how different players utilize different criteria in their decision making. Lack of information about validated real-world benefits for the various efficiency technologies was identified as a clear barrier to the increased adoption of advanced efficiency technologies. Other potential impediments for some fleets include driver resistance, technology maturity, technology complexity, and durability of the various technologies. It was clear that different fleets use different processes, parameters, and criteria to vet new technologies, and establishing sufficient lead-time for fleet technology uptake would be important for any future potential efficiency requirements.

Regulatory modifications necessary to capture efficiency technologies' real-world benefits — The stakeholders identified a number of modifications in regulatory scope and test protocols that would be needed to better promote the full deployment of the efficiency technologies into the fleet. Vehicle certification protocols would have to capture full-vehicle performance to best reflect real-world technology benefits. Inclusion of a clear-cut regulatory path and test procedure for advanced, integrated powertrain technology is important. Regulatory testing procedures for powertrains would need to be developed to better encourage emerging advanced transmission technologies like dual-clutch transmissions with downspeeding that are being developed by a number of companies. Regulatory inclusion of trailers will be key to the development and uptake of cost-effective technology that goes beyond the actions of the SmartWay program and the California requirements. Expanding the regulatory purview to incorporate trailers is critical to fully promote the potential to reduce their tractor-trailer road load (including aerodynamics, low rolling resistance tires, and lightweighting) and incorporate these changes into powertrain and auxiliary system design to achieve secondary efficiency benefits.

Modifications to regulatory test procedures to better represent real-world operation could better account for and promote emerging powertrain technical efficiency approaches with substantial real-world benefits that are not credited in the existing standard protocols. For example, acknowledging how real-world operation is increasingly at lower engine speeds will help promote integrated engine-transmission approaches, including automated manual and dual-clutch transmissions optimized for engines with downspeeding and downsizing. In addition, the inclusion of grade would help to better promote optimal powertrain sizing, as well as help promote integrated energy management and hybridization technologies. Finally the inclusion of test procedures or segmentation that incorporates the variation in payload and tractor-trailer curb weight could better promote technologies' real-world impact for given engine sizes.

To conclude, the July 2014 workshop created a stage for stakeholder deliberations related to U.S. heavy-duty vehicle efficiency technology. The various workshop stakeholders represented technology suppliers, original equipment tractor and trailer manufacturers, tractor-trailer fleet users, research groups, non-profit organizations, and government agencies. These stakeholders discussed key emerging technologies for engines, transmissions, tractors, and trailers that could be deployed in the 2020-2030 timeframe. This report captures the latest industry thinking and updates the conventional wisdom on the various emerging technologies in order to help inform the regulatory deliberations to come through 2014 and 2015. As introduced in the beginning of this report, although they represent a small fraction of the U.S. vehicle fleet, tractor-trailers represent substantial and disproportionate contributions to fuel consumption and greenhouse gas emissions. Line-haul tractor-trailers have seen relatively little fuel efficiency improvement in the last two decades. This trend is changing, though, as tractor-trailers are set to see a significant fuel efficiency increase from the first phase of regulations through 2018. With a next phase of the regulations that promotes the full range of fuel efficiency opportunities, tractor-trailers could see much greater efficiency gains from 2020 on.

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APPENDIX

WORKSHOP AGENDA

ACEEE — American Council for an Energy-Efficient Economy
icct — THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

July 22, 2014
University of California Washington Center
1608 Rhode Island Ave, NW
Washington, D.C.

Workshop on Emerging Technologies for Heavy-Duty Vehicle Fuel Efficiency

PROGRAM

7:30 am – 8:30 am	**BREAKFAST**	
8:30 am – 9:15 am	**Welcome and Opening Presentation**	
Speakers:	**Steve Nadel**, *ACEEE* and **Drew Kodjak**, *ICCT*	
Presenter:	**Ken Howden**, *21st Century Truck Partnership, Department of Energy*	
9:15 am – 10:25 am	**Engine Technology Integration**	
Moderator:	**Nigel Clark**, *West Virginia University*	
Presenters:	**Gary Salemme**, *Cummins Inc.*, “Emerging Engine Technologies”	
	Donald Keski-Hynnila, *Daimler Trucks NA*, “Engine Downsizing and Downspeeding”	
Q&A		
10:25 am - 10:50 am	**BREAK**	
10:50 am - 12:00 pm	**Full-Vehicle Efficiency**	
Moderator:	**Therese Langer**, *ACEEE*	
Presenters:	**Tom Stoltz**, *Eaton Corporation*, “Powertrain Integration and Hybrids”	
	Tony Greszler, *Volvo*, “Vehicle Energy Management”	
Q&A		
12:00 pm - 1:00 pm	**LUNCH**	
Presenters:	**Matt Spears**, *EPA* and **Jim Tamm**, *NHTSA*	
	“Agencies’ Approach to Evaluating Potential for Savings beyond Phase 1”	
1:00 pm - 2:10pm	**Reducing Road Load**	
Moderator:	**Ben Sharpe**, *ICCT*	
Presenters:	**Jamie Scarcelli**, *Wabash Composites*, “Fuel Efficiency for Trailers”	
	Mitch Greenberg, *SmartTruck Systems*, “Aerodynamics: What’s Next?”	
Q&A		
2:10 pm - 2:30 pm	**BREAK**	
2:30 pm - 3:30 pm	**User Perspective: Adding It All Up**	
Moderator:	**Jason Mathers**, *EDF*	
Panelists:	**Jim Bruce,** *UPS,* **Megan Peters,** *J.B. Hunt*, and **Mike Roeth,** *NACFE*	
	Panel Discussion: “Technology Adoption”	
Q&A		
3:30 pm - 4:00 pm	**Closing Session**	
Moderator:	**Nic Lutsey**, *ICCT*	
4:00 pm	**End of Workshop**	

WORKSHOP SURVEY

Workshop survey: Please fill out the table below

As part of the "Emerging Technologies for Heavy-Duty Vehicle Fuel Efficiency" workshop, ACEEE and ICCT are attempting to collect information related to feasible efficiency technologies in the 2015-2030 timeframe. Please use your expert judgment to fill out the sheet below (*or just selected areas*), regarding the (A) percent fuel consumption reduction; (B) whether the technology is likely to be widely deployed in 2018; (C) whether the technology could see significant deployment in the 2025 timeframe; and (D) any comments regarding constraints, cycle dependency, caveats, new data sources. In addition, please feel free to respond to the more open-ended questions on the following page.

	Technology	**(A)** Percent fuel consumption reduction in representative real-world line-haul operation in 2018-2025 from 2010 baseline	Check X, if applicable **(B)** Deployment at >50% of new Class 8 sales by 2018?	Check X, if applicable **(C)** Is significant deployment (10%+ sales) feasible before 2025?	**(D)** Comments
Engine	Engine friction reduction				
	Electrical pumps, engine accessories				
	Combustion system optimization				
	Model-based engine controls				
	Aftertreatment improvement				
	Turbocharging system improvement				
	Mechanical turbocompounding				
	Electrical turbocompounding				
	Waste heat recovery				
	Engine downsizing				
	Other_____				
	Other_____				
Transmission	Transmission efficiency				
	Single drive axle (6x2)				
	Automated manual (with downspeeding)				
	Dual-clutch transm. (with downspeeding)				
	Stop-start (idle off, coasting)				
	Hybrid (regen., coasting, torque assist)				
	Other_____				
	Other_____				
Tractor-trailer	Aerodynamics (tractor)				
	Aerodynamics (trailer)				
	Aerodynamics (tractor-trailer)				
	Low rolling resistance tires (tractor)				
	Low rolling resistance tires (trailer)				
	Low rolling resistance tires (tractor-trailer)				
	Automatic tire inflation systems				
	Weight reduction				
	Idle reduction technology				
	Road load optimization (GPS, predictive cruise, driver feedback)				
	Other_____				
	Other_____				

Supplemental questions

Other technologies: Are there other technologies, beyond those above, that have substantial potential to increase 2015-2030 Class 8 line-haul tractor-trailer efficiency in the US? If so, please list and describe, and estimate their potential fuel consumption in real-world conditions.

Capturing real-word benefits: Are the real-world benefits of any of the technologies listed inadequately reflected under current certification protocols? If so, please state which ones, and why their benefits are not captured at present.

Cost considerations: Are the above technologies of comparable cost-effectiveness in terms of delivering reasonable fuel saving benefit for the upfront technology costs? If not, please give examples of technology areas that you are confident will be dramatically more or less cost-effective.

Further thoughts? Beyond this survey, please feel free to provide any additional information, data, references, etc that you feel have been missing in these stakeholder discussions about technology feasibility, the associated percent fuel consumption reduction, technology cost, or associated areas. Please send further info to Nic Lutsey (*nic@theicct.org*) and Siddiq Khan (*skhan@aceee.org*).

Survey respondent category (please check applicable box):

☐Manufacturer/supplier ☐Fleet ☐Government ☐NGO/Researcher ☐Other___________

Survey respondent info (optional): ____
(Name) (Organization)

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WORKSHOP ATTENDEE LIST

Last Name	First Name	Organization
Atkinson	Chris	Atkinson LLC
Bachman	Joe	US EPA SmartWay
Bernards	Stacey	Honeywell
Berry	Steve	Volvo
Blubaugh	Timothy	TMA/EMA
Bruce	Jim	United Parcel Service
Calviti	Caetano	Navistar
Clark	Nigel	West Virginia University
Cooke	Dave	Union of Concerned Scientists
Delgado	Oscar	International Council on Clean Transportation
Deschatelets	Julie	Environment Canada
Etebari	Mehrun	SAFE
Fenton	Dawn	Volvo
Finkin	Ezra	Diesel Technology Forum
Gordon	Deborah	Allison Transmission Inc.
Graves	Ronald	Oak Ridge National Laboratory
Greenberg	Mitch	SmartTruck Aerodynamics
Greszler	Tony	Volvo
Hess	Christopher	Eaton
Howenstein	Michael	Allison Transmission Inc.
Istenes	Ray	Volvo
Johnson	Dennis	US EPA SmartWay
Keski-Hynnila	Donald	Daimler
Khan	Siddiq	American Council for an Energy-Efficient Economy
Kiker	Patrick	American Council for an Energy-Efficient Economy
Kodjak	Drew	International Council on Clean Transportation
Koplin	Amy	Daimler
Kubsh	Joseph	MECA
Langer	Therese	American Council for an Energy-Efficient Economy
Lipman	Zoe	Blue-Green Alliance
Lutsey	Nic	International Council on Clean Transportation
Mathers	Jason	Environmental Defense Fund
May	Derek	Pollution Probe
Miller	Chris	Advanced Engine System Institute
Mormino	Brian	Cummins Inc.
Nadel	Steve	American Council for an Energy-Efficient Economy
Nassar	Josh	UAW
Pelli	Alida	American Council for an Energy-Efficient Economy
Peters	Megan	J.B. Hunt

Last Name	First Name	Organization
Quinn	Pat	Heavy Duty Leadership Group
Roeth	Mike	North American Council for Freight Efficiency
Sachs	Harvey	American Council for an Energy-Efficient Economy
Salemme	Gary	Cummins Inc.
Scarcelli	James	Wabash Composites
Sharpe	Ben	International Council on Clean Transportation
Skelton	Eric	NESCAUM
Spears	Matt	US EPA
Stoltz	Tom	Eaton
Tamm	James	NHTSA
Tonachel	Luke	NRDC
Van Amburg	Bill	CALSTART
Waltzer	Sam	EPA SmartWay
Werthamer	Mallory	American Council for an Energy-Efficient Economy
Yeager	Jackie	Cummins Inc.