European Union Greenhouse Gas Reduction Potential for Heavy-Duty Vehicles

Report

Prepared for:
The International Council on Clean Transportation
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Date: December 23, 2011

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Legal Disclaimer

Acknowledgments

The authors gratefully acknowledge the guidance and support of Fanta Kamakaté, Ben Sharpe, and Peter Mock of the International Council on Clean Transportation and Christophe Rochefordiere, Peter Brunner, and Ian Hodgson of the European Commission.

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Executive Summary

To support development of a European Union (EU) strategy for reducing greenhouse gas (GHG) emissions from the heavy-duty vehicle (HDV) sector, the report entitled "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy" was prepared for the European Commission by AEA and Ricardo.[1] The report itemized the potential fuel efficiency improvement technologies that may be applied to various HDV segments and assessed their fuel consumption and CO_2 benefits and their costs. Technologies were applied, as appropriate, to eight vehicle segments: Service, Urban Delivery, Municipal Utility, Regional Delivery, Long Haul, Construction, Bus, and Coach. The GHG reductions in each segment were calculated based on the benefits offered by applying the technologies to today's vehicles. Through scenario projections, a major conclusion of the report was that total GHG emissions from the HDV fleet are unlikely to be reduced significantly below 2010 levels by 2030.[2]

The goal of this TIAX study is to examine the data and assumptions used by AEA-Ricardo to derive conclusions regarding the GHG reduction potential of HDVs in the EU. This analysis is based on a comparison between HDV technologies offered in the United States (US) and those offered in the EU. Many of the vehicle and engine manufacturers that sell products in the US are EU-based, and thus technologies are expected to be similar. Previous studies conducted by the National Research Council (NRC)[3] and TIAX on behalf of the National Academy of Sciences (NAS)[4] suggested that the GHG reduction potential for the US HDV sector may be significant. These studies were informed by interviews with and data from the major US HDV and engine manufacturers, many of whom serve the EU markets as well, and this analysis builds from the data collected in the NRC and TIAX/NAS studies. By methodically comparing the data and assumptions between the EU and the US, the objective is to determine whether conclusions for the US HDV sector may apply to the EU and to quantify the potential GHG reductions that may be achievable.

This assessment draws from the data gathered for the AEA-Ricardo study and supplements the analysis with additional input gathered from original equipment manufacturers (OEMs) by NRC and TIAX. The eight vehicle segments selected by AEA-Ricardo to represent the HDV market in the EU have been closely matched to vehicle segments in the US according to vehicle and engine characteristics and applications. For each segment, fuel efficiency improvement technologies are considered where appropriate for that segment. The technologies fall into seven broad categories:

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1. Hill, N., S. Finnegan, J. Norris, C. Brannigan, D. Wynn, H. Baker, I. Skinner. "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy." Prepared by AEA and Ricardo for European Commission – DG Climate Action, DG ENV. 070307/2009/548572/SER/C3. February 22, 2011.

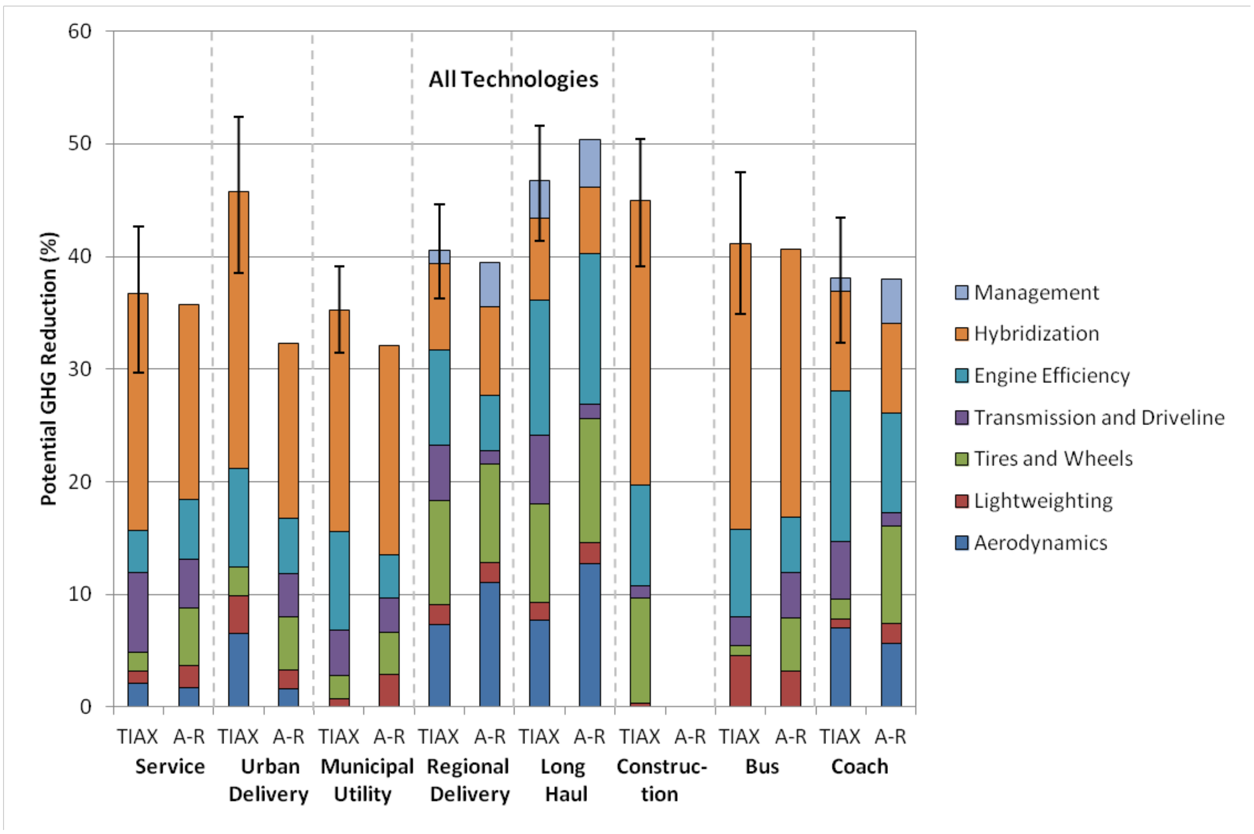
2. AEA-Ricardo projected that the baseline HDV population in the EU would grow from 7.8 million vehicles in 2010 to 10.1 million vehicles in 2030, corresponding to GHG levels of 275 million tonnes in 2010 and 349 million tonnes in 2030.

3. National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." http://www.nap.edu/catalog/12845.html. 2010.

4. Kromer, M., W. Bockholt, M. Jackson. "Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles." Prepared by TIAX LLC for National Academy of Sciences. November 19, 2009.

- Aerodynamics
- Lightweighting
- Tires and wheels
- Transmission and driveline
- Engine efficiency
- Hybridization
- Management

This analysis finds that across the eight vehicle segments, potential vehicle-level GHG benefits from all technologies available in the 2015 to 2020 timeframe (Figure ES-1) range from 30 to 52 percent and are slightly higher than the EU benefits reported by AEA-Ricardo and lower than the US benefits reported by NRC. In general, the higher EU benefits of this study are a result of the greater benefits from hybridization, engine efficiency, and transmission and driveline improvements that were estimated in this study.



(A-R: AEA-Ricardo)

Figure ES-1. Potential New EU Vehicle GHG Reductions from All Technologies

The relative shares of fuel consumption by each vehicle segment suggest that it may be more effective to target fuel efficiency improvement technologies in some segments than others. Technologies for the Long Haul segment, many of which are applicable to similar vehicles in the Regional Delivery segment, may offer the greatest impact. In addition, the Service, Bus, and Coach segments are also attractive because they offer mass-market or relatively uniform vehicles across the segment that can benefit from the same technologies. Conversely, technologies for the

Urban Delivery, Municipal Utility, and Construction segments may offer the least impact because these segments are highly fragmented, with a variety of vehicle types and configurations. Accordingly, EU strategies aimed at reducing overall GHG emissions from the heavy-duty sector may benefit from specifically targeting the high fuel consumption, uniform vehicles of the Long Haul, Regional Delivery, Service, Bus, and Coach segments and regarding the remaining segments as a single group. A similar approach has already been taken in the US heavy-duty GHG regulation.

The specific technologies considered for each vehicle segment in this analysis are grouped by category in Table ES-1. Across the vehicle segments, among the most cost effective[5] technologies are low rolling resistance tires, low rolling resistance wide-base tires, transmission friction reduction, and predictive cruise control. Among the least cost effective technologies are automatic tire inflation and material substitution for lightweighting.

Translating vehicle-level benefits to the segment level, Table ES-2 shows the absolute GHG benefits of applying the technologies across each population of vehicles. AEA-Ricardo estimated that 7.8 million heavy-duty vehicles were on the road in the EU in 2010 and projected that this number would grow to 10.1 million by 2030. After accounting for the growth in vehicle population, applying all applicable fuel-saving technologies to all new HDVs starting in 2020 has the potential to reduce 2030 GHG emissions to 28 percent below 2030 BAU levels.

This assessment provides total potential GHG benefits from a full spectrum of options for the heavy-duty sector, and the determination of which technologies and packages will be applied to achieve what magnitude of benefits is left to policymakers and the marketplace. Adoption of these technologies will be a function of regulatory requirements (e.g., vehicle emissions standards, fuel economy standards, and incentives) and vehicle owner economics, and will also be driven by additional factors such as end user acceptance and driver retention. In the US, mandatory heavy-duty fuel consumption reductions of up to 23 percent by 2017 are moving OEMs to adopt many of the technologies described above, including aerodynamic improvements, engine friction reduction, advanced fuel injection, advanced turbocharging, parasitic loss reduction, waste heat recovery, lightweighting, low rolling resistance tires, and idle reduction.[6,7] These technologies will be options for improving HDV efficiency in the EU as well.

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5 Cost effectiveness as defined by total lifetime GHG reduction divided by initial technology cost in 2010€

6 Reiskin, J.S. “OEMs Detail Design Innovations to Meet New Greenhouse Rules.” *Transport Topics*, pg. 5 and 28. August 22, 2011.

7 Galligan, J. “The Push for Mileage.” *Light & Medium Truck*, pg. 16-18. September 2011.

Table ES-1. Technologies by Vehicle Segment

Technology		Vehicle Segment: Service	Urban Delivery	Municipal Utility	Regional Delivery	Long Haul	Construction	Bus	Coach
Aerodynamics	Aft box taper		✓						
	Boat tail				✓	✓			
	Box skirts		✓						
	Cab side extension or cab/box gap fairings		✓						
	Full gap fairing				✓	✓			
	Full skirts				✓	✓			
	Roof deflector		✓						
	Streamlining	✓							✓
Lightweighting	Material substitution	✓	✓	✓	✓	✓	✓	✓	✓
Tires and Wheels	Automatic tire inflation on vehicle/tractor				✓	✓	✓		✓
	Automatic tire inflation on trailer				✓	✓			
	Low rolling resistance tires	✓		✓				✓	✓
	Low rolling resistance wide-base single tires		✓		✓	✓	✓		
Transmission and Driveline	Aggressive shift logic and early lockup	✓		✓					
	Increased transmission gears	✓		✓					
	Transmission friction reduction	✓		✓	✓	✓	✓	✓	✓
Engine Efficiency	Improved diesel engine	✓	✓	✓	✓	✓	✓	✓	✓
Hybridization	Dual-mode hybrid	✓			✓	✓			
	Parallel hybrid		✓				✓		✓
	Parallel hydraulic hybrid			✓					
	Series hybrid							✓	
Management	Predictive cruise control				✓	✓			✓
	Route management					✓			
	Training and feedback					✓			

Table ES-2. Potential GHG Reductions by Segment

Vehicle Segment	2010*		2030, Projected*		2030 Emissions Reduction, Assuming All Applicable Technologies (million tonnes)	2030 Emissions Relative to 2030 BAU Levels, Assuming All Applicable Technologies (%)
	Population (million vehicles)	CO_2e Emissions (million tonnes)	Population (million vehicles)	BAU CO_2e Emissions (million tonnes)		
Service	1.90	35	2.60	48	11	76%
Urban Delivery	0.45	12	0.55	15	4	71%
Municipal Utility	0.40	15	0.60	23	5	79%
Regional Delivery	1.20	40	1.75	58	15	74%
Long Haul	2.00	100	2.60	130	39	70%
Construction	1.00	30	1.25	38	12	67%
Bus	0.45	25	0.44	24	6	75%
Coach	0.40	18	0.30	14	3	75%
All Segments	**7.80**	**275**	**10.09**	**349**	**96**	**72%** (28% reduction)

BAU: business as usual, using baseline vehicle technologies and assuming no underlying changes in fuel economy over time
* Population numbers and projections for each EU vehicle segment are derived from AEA-Ricardo's report. All CO_2e levels are given as well-to-wheel emissions and are derived from AEA-Ricardo's emissions allocations as described in Section 3: Methodology.

As in the US, the market adoption of the various fuel efficiency improvement technologies in the EU will be influenced by policies and economics. Policies—including fuel economy regulations, low carbon fuel standards, financial incentives, and public procurement mandates—will determine the fuel efficiency and carbon intensity of heavy-duty transportation in the EU. Economics for vehicle owners in the form of payback through fuel savings will be one of the significant factors that dictate the viability and market demand for these technologies. As the EU considers a path of GHG reductions from the HDV sector, the technologies highlighted in this assessment may enable significant benefits to be achieved.

1. Background

To support development of a European Union (EU) strategy for reducing greenhouse gas (GHG) emissions from the heavy-duty vehicle (HDV) sector, the report entitled "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy" was prepared for the European Commission by AEA and Ricardo.[8] The report itemized the potential fuel efficiency improvement technologies that may be applied to various HDV segments and assessed their fuel consumption and CO_2 benefits and their costs. Based on these benefits and costs, the report created two scenarios: a "Cost Effective" scenario, where technologies with a payback of three years or fewer are adopted by the HDV market over time, and a "Challenging" scenario, where technologies likely to be commercialized between 2010 and 2030 are adopted over time regardless of payback periods. Technologies were applied, as appropriate, to eight vehicle segments: Service, Urban Delivery, Municipal Utility, Regional Delivery, Long Haul, Construction, Bus, and Coach. The GHG reductions in each segment were calculated based on the benefits offered by applying the technologies to today's vehicles. Through scenario projections of future vehicle populations, a major conclusion of the report was that GHG emissions from HDVs were unlikely to be reduced significantly below 2010 levels by 2030. This conclusion, however, was based on two factors. First, the methodology for estimating GHG emissions relied on specific assumptions regarding market uptake for each technology, which in effect dictated the GHG emissions achieved by 2030, without allowing for potential legislation that would require technologies to achieve certain GHG standards. Second, the technologies included in the "Cost Effective" scenario projection did not appear to be consistent with the stated methodology of including only technologies offering payback periods of three years or fewer, thereby giving GHG emissions results that do not clearly correspond to the available technologies. (See Section 3: Assumptions for more details).

The goal of this TIAX study is to examine the data and assumptions used by AEA-Ricardo to derive conclusions regarding the GHG reduction potential of HDVs in the EU. This analysis is based on a comparison between HDV technologies offered in the United States (US) and those offered in the EU. Many of the vehicle and engine manufacturers that sell products in the US are EU-based, and thus technologies are expected to be similar. Previous studies conducted by the National Research Council (NRC)[9] and TIAX on behalf of the National Academy of Sciences (NAS)[10] suggested that the GHG reduction potential for the US HDV sector may be significant. These studies were informed by interviews with and data from the major US HDV and engine manufacturers, many of whom serve the EU markets as well, and this analysis builds from the data collected in the NRC and TIAX/NAS studies. By methodically comparing the data and assumptions between the EU and the US, the objective is to determine whether conclusions for

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8 Hill, N., S. Finnegan, J. Norris, C. Brannigan, D. Wynn, H. Baker, I. Skinner. "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy." Prepared by AEA and Ricardo for European Commission – DG Climate Action, DG ENV. 070307/2009/548572/SER/C3. February 22, 2011.

9 National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." http://www.nap.edu/catalog/12845.html. 2010.

10 Kromer, M., W. Bockholt, M. Jackson. "Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles." Prepared by TIAX LLC for National Academy of Sciences. November 19, 2009.

the US HDV sector may apply to the EU and to quantify the potential GHG reductions that may be achievable.

Between the EU and the US, there are several key differences in the HDV market that are considered in this analysis and reflected in the vehicle baselines and applicable technologies. In Europe, vehicle length restrictions generally pertain to the entire length of the vehicle, rather than only the trailer as in the US As a result, the cab-over-engine design is the dominant configuration for tractors in the EU, while the long-nosed configuration is employed in the US The geometry of the tractor affects which aerodynamic devices are applicable to the vehicles, and many of the devices considered for US vehicles by the NRC study do not apply to EU vehicles, especially since many of them (e.g., cab skirts) have already been integrated into EU vehicle designs. Furthermore, with the exception of vehicles in the Coach segment, EU vehicles are governed with lower speed limits than in the US Because vehicle drag is related to the cube of the vehicle's speed and rolling resistance is directly related to the vehicle's speed, the lower speed limit for EU vehicles may lead to lower baseline fuel consumption and higher fuel economy than for US vehicles. However, fuel efficiency is also determined by other factors, such as vehicle weight and duty cycles, and thus conclusions about how vehicles in the two regions compare in terms of fuel efficiency cannot be made unless the vehicles are comparable in such respects.

This report begins with a discussion of the methodology used by TIAX to evaluate potential GHG reductions in the heavy-duty sector, followed by the key assumptions on which this evaluation is based. Next, the vehicle baselines for the eight segments are described in terms of their weights, engine sizes, transmissions, emissions standards, and fuel consumption. Fuel efficiency improvement technologies are then applied to these baseline vehicles, and their fuel consumption benefits and costs are quantified. Following a discussion of heavy-duty market dynamics and technology implications, this report concludes with summary of the outlook for GHG reductions from HDVs in the EU.

2. Methodology

At a high level, the methodology for this analysis follows the four major steps shown in Figure 2-1. Drawing from AEA-Ricardo's expertise and familiarity with the EU heavy-duty market, this analysis examines in detail the assumptions, costs, and benefits of various fuel efficiency improvement technologies. These technologies are applied to representative vehicles within distinct vehicle segments within the market to determine the total potential GHG benefits achievable for HDVs.

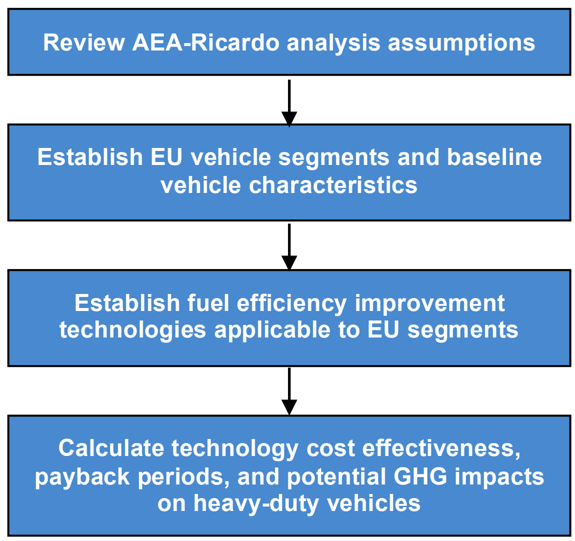

Figure 2-1. Overall Analysis Methodology

This assessment draws from the data gathered for the AEA-Ricardo study and supplements the analysis with additional input gathered from original equipment manufacturers (OEMs) by NRC and TIAX/NAS in the aforementioned studies.[11,12] Representative EU vehicles in the eight HDV segments selected by AEA-Ricardo have been closely matched to comparable vehicles in the US according to vehicle and engine characteristics and applications. For each representative vehicle, fuel efficiency improvement technologies are considered where appropriate vehicle. The technologies fall into seven broad categories:

- Aerodynamics
- Lightweighting
- Tires and wheels
- Transmission and driveline

[11] National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." http://www.nap.edu/catalog/12845.html. 2010.

[12] Kromer, M., W. Bockholt, M. Jackson. "Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles." Prepared by TIAX LLC for National Academy of Sciences. November 19, 2009.

- Engine efficiency
- Hybridization
- Management

This analysis relies on GHG reduction benefits and technology costs[13] determined by NRC and TIAX/NAS on the basis of OEM input. The technologies evaluated in this analysis are those that improve the fuel economy of the vehicles and thus implicitly consider only tailpipe emissions of GHGs. As such, vehicles that replace diesel fuel with alternative fuels (e.g., natural gas, electricity) are omitted from the combined technologies packages, as the benefits offered by these fuels contain an upstream component (i.e., in the production and distribution of the fuels) that cannot be directly compared the tailpipe emissions benefits of the other technologies. The potential GHG benefits of alternative fuels are discussed in Section 6: Heavy-Duty Market Discussion.

This assessment of the potential GHG reductions for HDVs in the EU begins by describing the baseline vehicles chosen to represent the heavy-duty sector and confirming the similarity of US vehicles to EU vehicles. The baseline vehicles are characterized by gross vehicle weight rating (GVWR), engine size and specifications,[14] transmission type, emissions control, aerodynamics, fuel economy, annual activity, and average GHG emissions.[15] The fuel consumption benefits of individual technologies for each representative vehicle are combined to estimate the maximum technically achievable GHG benefits for that segment. A goal of this analysis is to present these benefits without imposing economic or policy thresholds or speculating on market acceptance or penetration, allowing policymakers to make these determinations. The GHG benefits, first expressed as tailpipe emissions reduction percentages, are applied to baseline vehicles to derive per-vehicle benefits in terms of actual reductions in CO_2 equivalents.

Because the ultimate objective is to evaluate future GHG reduction opportunities, this assessment assumes model year 2014 vehicles meeting Euro VI emissions standards as the baseline, including any fuel efficiency improvement technologies that are likely to have already been applied by that time. Section 4: Vehicle Baselines describes in detail the technologies that are assumed to be incorporated as standard features in the 2014 vehicles. This study differs from the AEA-Ricardo study in the basic assumption regarding the effect on fuel consumption of moving to Euro VI standards. The AEA-Ricardo study reported that a 3 percent penalty would result from the integration of diesel particulate filter (DPF) technology into emissions control systems in order to meet Euro VI emissions standards.[16] (Euro V standards are currently being met primarily with selective catalytic reduction (SCR) systems.) AEA-Ricardo assumed that active regeneration of the DPF would be needed in Euro VI configurations; however, the US

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[13] Costs presented in this report are given in 2010 euros. Costs originally given in US dollars are converted to 2010 euros using a conversion rate of 2010€0.75 per 2010$1.00.

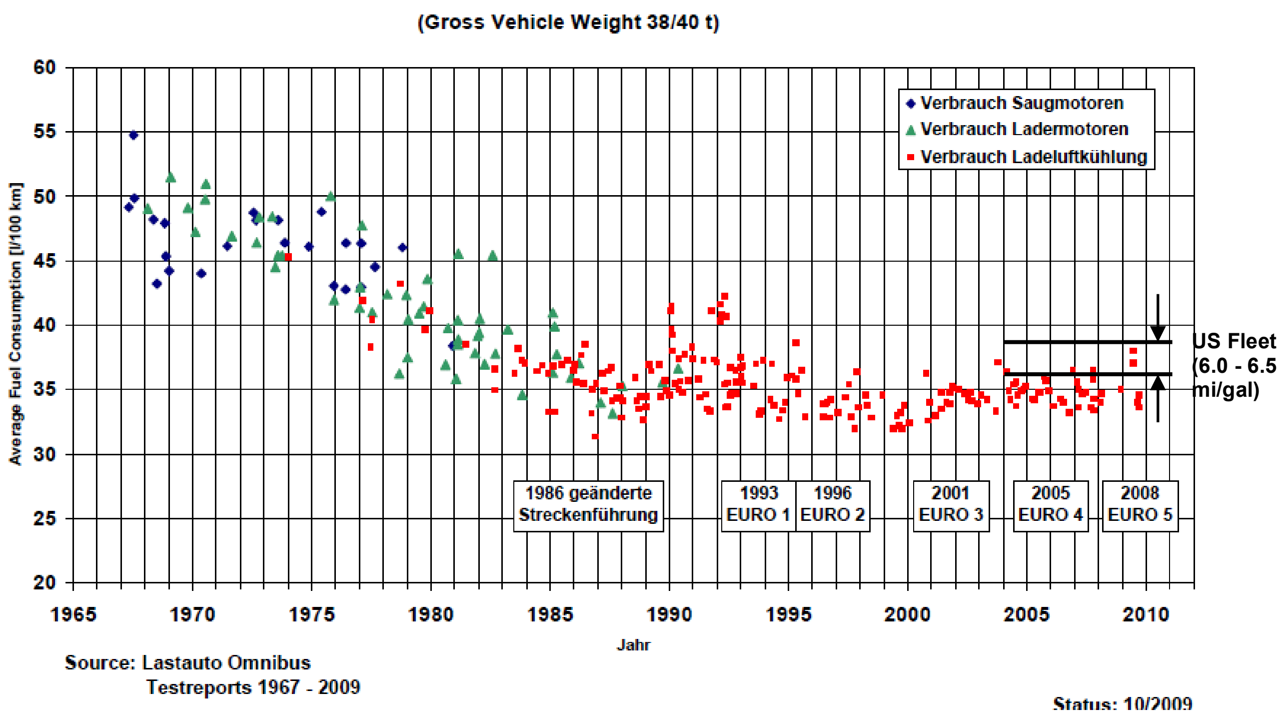
[14] Including details regarding cylinder pressure, fuel injection, turbochargers, controls, and peak thermal efficiencies

[15] GHG emissions from today's vehicles have been estimated by AEA-Ricardo using a top-down approach that allocates total CO_2 emissions from road transport to individual vehicle segments. See Figure 4-7 of Hill, N., S. Finnegan, J. Norris, C. Brannigan, D. Wynn, H. Baker, I. Skinner, "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy," prepared by AEA and Ricardo for European Commission – DG Climate Action, DG ENV, 070307/2009/548572/SER/C3, February 22, 2011.

[16] See page 117 of Hill, N., S. Finnegan, J. Norris, C. Brannigan, D. Wynn, H. Baker, I. Skinner, "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy," prepared by AEA and Ricardo for European Commission – DG Climate Action, DG ENV, 070307/2009/548572/SER/C3, February 22, 2011.

experience with 2010 standards using the same combination of aftertreatment technologies has improved fuel consumption from the 2007 configurations because active regeneration has been substantially reduced, if not eliminated. For US 2010 systems, engine-out NOx was increased, and engine-out particulate was reduced. This reduces the particulate buildup on the DPF and, under most operating conditions, the need for active regeneration. Although the DPF will add some additional back pressure, this analysis assumes the manufacturers will offset this possible increase in fuel consumption with better system calibration, due in part to the learning from the experience with US 2010 systems. Historical trends in average fuel consumption for EU vehicles (Figure 2-2) suggest that this assumption may be reasonable. This analysis therefore assumes that a regeneration penalty would not result. Some manufacturers concur with this assessment of fuel consumption penalties, stating that Euro VI models may offer the same fuel consumption as Euro V models.[17] As a conservative assumption, the following analysis assumes 0 percent change in fuel consumption for Euro VI vehicles compared to today's vehicles. The fuel economy values for each vehicle segment, derived from the AEA-Ricardo analysis, are summarized in Table 2-1. Note that these fuel economies are segment averages and thus are not necessarily the fuel economies of specific vehicles in the segments.

At present, no official GHG accounting tool or model for the EU is widely used, and thus this analysis relies on the AEA-Ricardo inventory of CO_2 emissions from each vehicle segment. The emissions were derived from an allocation of total road transport emissions based on fuel consumption and vehicle characteristics, and the allocations are presented in Table 2-2.



Reference: Schuckert, M. "CO_2 Footprint for Heavy Duty Vehicles." Daimler Trucks. ISPRA. April 19, 2010.

Figure 2-2.EU Average Long Haul Fuel Consumption

17 Scania. "Pressroom: Scania Euro 6." http://www.scania.com/media/calendar/2011/scania-euro-6/pressroom-scania-euro-6.aspx. March 31, 2011.

Table 2-1. Baseline 2014 EU Fuel Economies

Vehicle Segment		EU Fuel Economy
Service	mi/gal	14.7
	L/100 km	16.0
Urban Delivery	mi/gal	11.2
	L/100 km	21.0
Municipal Utility	mi/gal	4.3
	L/100 km	55.2
Regional Delivery	mi/gal	9.3
	L/100 km	25.3
Long Haul	mi/gal	7.7
	L/100 km	30.6
Construction	mi/gal	8.8
	L/100 km	26.8
Bus	mi/gal	6.5
	L/100 km	36.0
Coach	mi/gal	8.5
	L/100 km	27.7

Reference: Hill, N., S. Finnegan, J. Norris, C. Brannigan, D. Wynn, H. Baker, I. Skinner. "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy." Prepared by AEA and Ricardo for European Commission – DG Climate Action, DG ENV. 070307/2009/548572/SER/C3. February 22, 2011.

Table 2-2. EU Heavy-Duty GHG Allocation by Vehicle Segment

Vehicle Segment	GHG Emissions by Segment (%)
Service	13
Urban Delivery	4
Municipal Utility	5
Regional Delivery	15
Long Haul	36
Construction	11
Bus	9
Coach	7

Reference: Hill, N., S. Finnegan, J. Norris, C. Brannigan, D. Wynn, H. Baker, I. Skinner. "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy." Prepared by AEA and Ricardo for European Commission – DG Climate Action, DG ENV. 070307/2009/548572/SER/C3. February 22, 2011.

In addition to the achievable GHG reductions per vehicle, this analysis further explores the potential benefits of the fuel efficiency improvement technologies in terms of cost effectiveness, which is defined as the GHG benefit (expressed as lifetime kilograms of CO_2 reduced) divided by the capital cost in 2010€. This metric can be used from a policy perspective to compare technology options across vehicles according to the ultimate goal of reducing carbon emissions. Another useful metric is the payback period, defined as the period of time until fuel savings are equal to the initial cost of the fuel efficiency improvement technology.

For purposes of putting the per-vehicle benefits into the fleet-wide context, this analysis applies the per-vehicle GHG reductions to the vehicle populations projected by AEA-Ricardo[18] to offer a point of reference for the magnitude of impacts achievable. The per-vehicle reductions by segment are multiplied by the projected number of vehicles in each segment to derive the total HDV fleet reductions. As with the AEA-Ricardo study, the fleet-wide GHG reductions are assessed for the year 2030. The adoption of vehicle technologies will be a gradual process, and this approach assumes that the advanced technologies are adopted as packages on all new vehicles beginning in the year 2020 (corresponding to the time frame in which the technologies considered here become available). The phase-in of these technologies packages will occur as the HDV fleet turns over, such that as each vehicle reaches the end of its lifetime, it is replaced with a new vehicle that incorporates all technologies applicable to its segment.[19] As the HDV fleet turns over, the relative fraction of vehicles with these advanced technology packages increases. While heavy-duty vehicles often have lifetimes of 20 or more years, the majority of VKT typically occurs in the early years of the vehicle's life. To reflect this decline in activity over vehicle lifetime, assumptions were made about the fraction of total vehicle activity in 2030 that would come from vehicles having the advanced technology packages (i.e. those vehicles sold in 2020 or later). See Table 6-2 for more details.

The baseline vehicles in this study differ most from those of the AEA-Ricardo study in that 2014 vehicles meeting Euro VI emissions standards are assumed (in contrast to 2010 vehicles meeting Euro V emissions standards). The technologies differ in that some automation of transmissions is assumed in this study, whereas none was assumed in the AEA-Ricardo study. Where the AEA-Ricardo study did not specifically list the segment-specific technologies incorporated into baseline vehicles, the table above infers the baseline technologies by examining which technologies are considered as options by AEA-Ricardo. The effects of these differences between the two studies are discussed in greater detail in the following sections.

Unlike the AEA-Ricardo analysis, this analysis assumes no inherent fuel consumption changes over time, i.e., all fuel consumption changes are the direct results of specific technologies applied in the analysis. Because the baseline vehicles are assumed to be 2014 vehicles meeting Euro VI standards, fuel economy improvements between 2010 (the year of AEA-Ricardo's current GHG levels) and 2014 (the year of baseline vehicles in this analysis) are accounted for by assuming the adoption of certain aerodynamics and transmission technologies (itemized by segment in Section 5: Fuel Efficiency Improvement Technologies). For comparison, Table 2-3 summarizes the key differences in analysis methodology between this study and the AEA-Ricardo study, including estimates of benefits gained from technologies assumed to be already in place by 2014.

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[18] Populations for each of the eight vehicle segments have been projected to 2030. See Figure 4-7 of Hill, N., S. Finnegan, J. Norris, C. Brannigan, D. Wynn, H. Baker, I. Skinner, "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy," prepared by AEA and Ricardo for European Commission – DG Climate Action, DG ENV, 070307/2009/548572/SER/C3, February 22, 2011.

[19] Recognizing that this approach assumes that technologies can be applied to all vehicles within the segment, which may or may not be true, given that each segment is composed of multiple vehicle types

Table 2-3. Comparison of Key Analysis Methodologies

	TIAX	AEA-Ricardo
Baseline vehicles	• 2014 vehicles meeting Euro VI standards (EGR+DPF+SCR) • No aerodynamic trailers or fairings • Regular rolling resistance tires, no wide-base single tires • No engine turbocompound or waste heat recovery, engine specifications corresponding to those of US 2010 engines* • No hybridization • No predictive cruise control	• 2010 vehicles meeting Euro V standards (SCR) • No aerodynamic trailers or fairings • Regular rolling resistance tires, no wide-base single tires • No engine turbocompound or waste heat recovery, other engine specifications unknown • No hybridization • No predictive cruise control
Additional segment-specific technologies incorporated:		
Service	• Automatic transmission (0 to 5% fuel consumption benefit over manual transmission)	• Manual transmission
Urban Delivery	• Manual transmission • Integrated air dam, cab side edge turning vanes	• Manual transmission • Integrated air dam, cab side edge turning vanes
Municipal Utility	• Automatic transmission (0 to 5% fuel consumption benefit over manual transmission)	• Manual transmission
Regional Delivery	• Automated manual transmission (4 to 8% fuel consumption benefit over manual transmission) • Aerodynamic tractor with integrated air dam, cab side edge turning vanes, roof and side air deflector	• Manual transmission • Aerodynamic tractor with integrated air dam, cab side edge turning vanes, roof and side air deflector
Long Haul	• Automated manual transmission (4 to 8% fuel consumption benefit over manual transmission) • Aerodynamic tractor with integrated air dam, cab side edge turning vanes, roof and side air deflector (3 to 4% improvement over AEA-Ricardo aerodynamic tractor)	• Manual transmission • Aerodynamic tractor with integrated air dam, cab side edge turning vanes, roof and side air deflector • Engine specifications unknown
Construction	• Manual transmission	• Manual transmission
Bus	• Automatic transmission (0 to 5% fuel consumption benefit over manual transmission)	• Manual transmission
Coach	• Automated manual transmission (4 to 8% fuel consumption benefit over manual transmission)	• Manual transmission
Fuel economy projections	• No underlying fuel economy changes over time (i.e., all fuel economy increases result directly from application of specific technologies)	• Natural powertrain improvements ranging from 0 to 0.5% from previous year • Fuel consumption improvements ranging from 0 to 0.5% from previous year • Fuel consumption penalties ranging from 0 to 3% from previous year
Market uptake model	• Application of technology packages to all new vehicles starting in 2020 • No uptake percentages specified, uptake in 2030 depends on vehicle turnover within each segment, as defined by average vehicle lifetime	• Application of individual technologies to vehicles at specified uptake rates • Uptake percentages by year for new vehicles and HDV fleet, ranging from 0 to 80% in 2010 and 0 to 100% in 2030 across segments

*Engine specifications in this study correspond to those of US 2010 engines, as follows: 6 to 9 L engines with 190 to 200 bar cylinder pressure, 2,000 bar common rail fuel injection, multiple injections per cycle electrically actuated variable geometry turbocharger, open-loop emission controls, and peak thermal efficiency 42 to 43%; 11 to 13 L engines with 210 to 220 bar cylinder pressure, 2,200 to 2,400 bar common rail fuel injection, rate shaping, multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop controls, and peak thermal efficiency 43 to 44%.

3. Assumptions

The following is a list of the general assumptions made in this analysis. Some assumptions are made to reconcile information presented in the AEA-Ricardo report with the data inputs in this analysis, and others are made to provide a reference point for potential GHG benefits. Additional detailed assumptions regarding vehicle baselines and fuel efficiency improvement technologies are presented in Section 4: Vehicle Baselines and Section 5: Fuel Efficiency Improvement Technologies.

Assumptions:

- The fuel efficiency improvement technologies and their associated costs offered by manufacturers in US are similar to those offered by manufacturers in the EU.[20]

- Vehicles baselines reflect 2014 technologies meeting Euro VI emissions standards.

- The fuel efficiency improvement technologies considered are expected to be available in the 2015 to 2020 timeframe. While they may not yet be available today, interviews conducted with OEMs in the NRC and TIAX/NAS studies indicate that these technologies are likely to be available with the stated fuel efficiency benefits and at the stated costs in the near term.

- The total combined benefit of individual vehicle fuel efficiency improvement technologies is calculated as follows:[21]

  $$\textit{Combined fuel consumption benefit (\%)} = 100\times(1-(1-\frac{FCB_1}{100})\times(1-\frac{FCB_2}{100})\times\ldots\times(1-\frac{FCB_i}{100}))$$

  where FCB_i is the percent fuel consumption benefit of the ith technology. The combined benefit is then applied to the representative vehicle, which is defined by unique characteristics and duty cycle.

- Costs presented in this report are given in 2010 euros. Costs originally given in 2009 US dollars are converted to 2010 euros using a conversion rate of 2010$1.02 per 2009$1.00 and 2010€0.75 per 2010$1.00.

- The GHG emissions presented in Figure 4-7 of the AEA-Ricardo report are assumed to be in units of kilotonnes of CO_2 equivalents rather than tonnes.

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[20] Note that many EU manufacturers also offer similar products in the US These manufacturers include Daimler Trucks, DAF (Kenworth and Peterbilt as part of PACCAR in the US), and Volvo.

[21] See note under Table S-1 of National Research Council, “Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles,” http://www.nap.edu/catalog/12845.html, 2010.

- As mentioned in Section 1: Background, the technologies included in the "Cost Effective" scenario projection of the AEA-Ricardo study did not appear to be consistent with the stated methodology of including only technologies offering payback periods of three years or fewer. For example, the technologies that define the Coach segment in the "Cost Effective" scenario in Figure 4-9 of the AEA-Ricardo report are presented as: automated manual transmission, full hybrid, flywheel hybrid, stop/start system, low rolling resistance tires, automatic tire pressure adjustment, and predictive cruise control. However, the payback periods for these seven technologies are listed in Table 4.23 as: 16.2, 16.7, 3.2, 1.5, 0.8, 40.9, and 1.9 years, respectively. As defined, the "Cost Effective" scenario should only incorporate technologies that offer payback within three years, and hence, the automated manual transmission, full hybrid, and automatic tire pressure adjustment technologies should not have been included in the Coach segment for this scenario, whereas single wide tires, spray reduction mud flaps, lightweighting, and controllable air compressor should have been included.

  For comparison with the results of this analysis, the AEA-Ricardo "Cost Effective" scenario, nominally using technologies with payback periods of three years or fewer, is assumed to be defined by the technologies listed in Table 4.23 rather than those listed in Figure 4-9.

- The representative vehicle for the Construction segment is assumed to be a dump truck. The details of the potential benefits for the Construction segment are not explicitly described in the AEA-Ricardo report.

4. Vehicle Baselines

The tables in this section compare vehicle characteristics between the EU and the US in eight heavy-duty segments and serve two purposes: to establish the similarity between vehicles in the two regions and to describe the baseline vehicle configurations to which technologies are added in Section 5: Fuel Efficiency Improvement Technologies. In some cases, multiple configurations may be offered by manufacturers, and the assumed predominant configuration is listed. The baseline tables list the GVWRs, engine displacements, engines, transmissions, emissions controls, and vehicle configurations assumed to be representative of each vehicle segment. Annual activity, fuel economy, and fuel consumption for the EU are derived from AEA-Ricardo's study as average characteristics across the EU-27 member states, and those for the US are derived from NRC's study as ranges across vehicles within each segment.

The EU vehicles are based on the characteristics presented in the AEA-Ricardo study, and the US vehicles are matched to those characteristics and cross-checked with the vehicles considered in the NRC study. Examples of representative vehicles within each segment are provided as well. Because this analysis is aimed at future fuel efficiency improvements and GHG reductions, the baseline vehicles for the EU are assumed to be 2014 vehicles that meet Euro VI emissions standards using the same emissions control devices as EPA 2010 vehicles.

Vehicles in the EU and the US are similar in many ways, yet differ in some key areas, including vehicle length, number of axles, number of tires, and driveline configuration. For example, Tables 4-1 through 4-3 offer details on differences in tractors and trailers between the EU and the US Tables 4-4 through 4-11 show that one major difference with EU vehicles is the use of the cab-over-engine design.

It is important to note, however, that the EU segment characteristics listed in the following tables were described by AEA-Ricardo to reflect the average of multiple types of vehicles within the segments. While each segment in this analysis is assumed to be nominally represented by the example vehicles in the tables, the segments as categorized by AEA-Ricardo actually comprise a range of vehicles, spanning a range of associated characteristics. For example, while the Service segment is represented in this analysis by the US equivalent of a Class 2b vehicle (11,030 pounds or 5 tonnes), the segment as defined by AEA-Ricardo encompasses a broader set of vehicle weights and configurations, including all heavy-duty vehicles 7,716 to 16,535 pounds (3.5 to 7.5 tonnes) GVWR. As another example, the fuel economies provided by AEA-Ricardo for the Bus and Coach segments are significantly higher than those of the US because these average values include not only 40-foot buses and standard coaches but also minibuses and smaller vehicles used in Bus and Coach operations.[22] Because the eight vehicle segments for the EU are each composed of a variety of vehicle sizes and makes, the average characteristics given do not characterize every individual vehicle in that segment nor do they necessarily match the comparative U.S vehicles, which describe one category of vehicle in that segment. As a result,

[22] As described by AEA-Ricardo, the Bus and Coach segments are composed 40.3% of buses and coaches weighing less than 35,274 pounds (16 tonnes) and 59.7% of buses and coaches weighing more than 35,274 pounds (16 tonnes). For comparison, a 40-foot bus and a standard coach weigh approximately 40,000 pounds (18 tonnes) and 50,000 pounds (22 tonnes), respectively.

the comparison of EU and US baseline vehicles yields some differences in characteristics, including fuel economy and fuel consumption. Furthermore, while recognizing that each segment in reality consists of multiple vehicle types, the fuel efficiency improvement technologies considered for each segment are assumed to be applied to the representative example vehicle shown in the baseline tables. Accordingly, technologies included or not included for each representative vehicle should not be considered to define the entirety of potential improvements for all vehicles in that segment.

Table 4-1. Example of EU-US Tractor Differences

Trailer/Vehicle Characteristics	EU	US
Width (m)	2.55	2.6
Height (m)	4 (maximum)	4.09
Length (m)	5.7-6.5	7.9
Frontal area (m^2)	<10	10
Number of axles	2	3
Number of tires	6 (dual)	10 (dual)
Driveline configuration	4x2	6x4
Weight (tonne)	7	8.6

Table 4-2. Example of EU-US Trailer Differences

Trailer/Vehicle Characteristics	EU	US
Width (m)	2.55	2.6
Height (m)	4 (maximum)	4.09
Length (m)	13.62	15.15
Tractor-trailer gap (m)	0.53-0.87	1.02-1.14
Typical king pin distance (m)	1.668	0.914
Number of axles	3	2
Number of tires	6 (single)	8 (dual)
Tare weight (kg)	5,650	6,124
Payload (kg)	17,240	17,240
Total vehicle GVW (tonne)	40	36.3
Total vehicle length (m)	16.5	21.3-22.9

(In addition, US 53-foot dry van trailers have solid side walls, whereas EU trailers tend to have curtain side walls.)

Table 4-3. Tractor-Trailer Differences in the EU vs. the US

Parameter	EU	US
C_d	~US*	0.62-0.64
C_{rr}	—	0.0068
Trailer	13.6 m	53-foot standard box
Engine	11-15L	11-15L
Transmission	Automated manual**	10-speed manual
Governed speed	55 mi/hr (90 km/hr)**	75 mi/hr (120 km/hr)
GVW	88,000-97,000 lb (40-44 tonnes)	80,000 lb (36 tonnes)
Fuel economy/consumption	6.7-7.8 mi/gal (30-35 L/100km)	6.5 mi/gal (36 L/100km)
Fuel price	€1.3/L	€0.75/L

*Cab-over-design Cd probably greater than US aero-tractor, but this is offset by smaller tractor trailer gap.

**Lower EU speed offers 4.5% fuel consumption benefit; automated manual transmission offers 6% benefit.

Table 4-4. Baseline Vehicles in the Service Segment

Service	EU	US
Example	Mitsubishi Fuso FG 	Isuzu NPR 
Engine displacement (L)	3.907	3
Engine*	Diesel: turbocharged, high pressure common rail (1,800 bar)	Diesel: turbocharged, high pressure common rail (1,800 bar)
Transmission	6-speed automatic	6-speed automatic
Emissions control	Euro VI: EGR+DPF+SCR	EPA 2010: EGR+DPF+SCR
Vehicle configuration	Front bumper with air dam	Front bumper with air dam
Segment Characteristics:		
GVWR (lb)	7,716 to 16,535	8,500 to 16,000†
GVWR (kg)	3,500 to 7,500	3,856 to 7,257†
Annual activity (mi)	21,748 (average)	15,000 to 60,000†
Annual activity (km)	35,000 (average)	24,141 to 96,560†
Fuel economy (mi/gal)	14.7 (average)	8 to 13†
Fuel consumption (L/100km)	16.0 (average)	18 to 29†

Engine displacement, transmission, and vehicle configuration information are derived from manufacturer websites. Engine and emissions control information are assumptions made in this analysis. GVWR, annual activity, fuel economy, and fuel consumption information are provided for the EU by AEA-Ricardo as average values across the EU-27 member states and for the US by NRC.

* Assuming technology to meet Euro VI standards is the same as technology to meet US EPA 2010 standards
† Corresponding to US Class 2b, Class 3, and Class 4 vehicles[23]

(Images courtesy of Mitsubishi Fuso, Isuzu)

[23] National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." http://www.nap.edu/catalog/12845.html. 2010.

Table 4-5. Baseline Vehicles in the Urban Delivery Segment

Urban Delivery	EU	US
Example	DAF LF45 	Kenworth T270 
Engine displacement (L)	6.7	6.7
Transmission	6-speed manual	6-speed manual
Engine*	Diesel: 190 to 200 bar cylinder pressure, common rail fuel injection (2,000 bar), multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop emission controls, peak thermal efficiency 42 to 43%	Diesel: 190 to 200 bar cylinder pressure, common rail fuel injection (2,000 bar), multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop emission controls, peak thermal efficiency 42 to 43%
Emissions control	Euro VI: EGR+DPF+SCR	EPA 2010: EGR+DPF+SCR
Vehicle configuration	Integrated air dam, cab side edge turning vanes	Aerodynamic styled cab including rounded bumper and air dam
Segment Characteristics:		
GVWR (lb)	16,535 to 30,865	16,001 to 26,000
GVWR (kg)	7,500 to 14,000	7,257 to 11,793
Annual activity (mi)	24,855 (average)†	20,000 to 75,000‡
Annual activity (km)	40,000 (average)†	32,187 to 120,701‡
Fuel economy (mi/gal)	11.2 (average)†	5 to 12‡
Fuel consumption (L/100km)	21.0 (average)†	20 to 47‡

Engine displacement, transmission, and vehicle configuration information are derived from manufacturer websites. Engine and emissions control information are assumptions made in this analysis. GVWR, annual activity, fuel economy, and fuel consumption information are provided for the EU by AEA-Ricardo as average values across the EU-27 member states and for the US by NRC.

* Assuming technology to meet Euro VI standards is the same as technology to meet US EPA 2010 standards

† Average of EU heavy-duty vehicles used for distribution in cities or suburban sites of consumer goods from a central store to selling points; rigid trucks only

‡ Corresponding to US Class 5 and Class 6 vehicles[24]

(Images courtesy of DAF, Kenworth)

[24] National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." http://www.nap.edu/catalog/12845.html. 2010.

Table 4-6. Baseline Vehicles in the Municipal Utility Segment

Municipal Utility	EU	US
Example	DAF CF 75 	Peterbilt 320 
Engine displacement (L)	9.2	8.9
Engine*	Diesel: 190 to 200 bar cylinder pressure, common rail fuel injection (2,000 bar), multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop emission controls, peak thermal efficiency 42 to 43%	Diesel: 190 to 200 bar cylinder pressure, common rail fuel injection (2,000 bar), multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop emission controls, peak thermal efficiency 42 to 43%
Transmission	6-speed automatic	6-speed automatic
Emissions control	Euro VI: EGR+DPF+SCR	EPA 2010: EGR+DPF+SCR
Segment Characteristics:		
GVWR (lb)	16,535 to 61,729	66,000‡
GVWR (kg)	7,500 to 28,000	30,000‡
Annual activity (mi)	15,534 (average)†	15,000‡
Annual activity (km)	25,000 (average)†	24,140‡
Fuel economy (mi/gal)	4.3 (average)†	3.3‡
Fuel consumption (L/100km)	55.2 (average)†	71‡

Engine displacement, and transmission, information are derived from manufacturer websites. Engine and emissions control information are assumptions made in this analysis. GVWR, annual activity, fuel economy, and fuel consumption information are provided for the EU by AEA-Ricardo as average values across the EU-27 member states and for the US by TIAX/NAS.

* Assuming technology to meet Euro VI standards is the same as technology to meet US EPA 2010 standards

† Average of EU heavy-duty vehicles used for municipal utility purposes, e.g., refuse collection, road sweeping

‡ Corresponding to average US refuse hauler[25]

(Images courtesy of DAF, Peterbilt)

[25] Kromer, M., W. Bockholt, M. Jackson. “Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles.” Prepared by TIAX LLC for National Academy of Sciences. November 19, 2009.

Table 4-7. Baseline Vehicles in the Regional Delivery Segment

Regional Delivery	EU	US
Example	Volvo FE 	Peterbilt 337 
Engine displacement (L)	7.2	6.7
Engine*	Diesel: 190 to 200 bar cylinder pressure, common rail fuel injection (2,000 bar), multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop emission controls, peak thermal efficiency 42 to 43%	Diesel: 190 to 200 bar cylinder pressure, common rail fuel injection (2,000 bar), multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop emission controls, peak thermal efficiency 42 to 43%
Transmission	6- to 12-speed automated manual	10-speed automated manual
Emissions control	Euro VI: EGR+DPF+SCR	EPA 2010: EGR+DPF+SCR
Vehicle configuration	Integrated air dam, cab side edge turning vanes, roof and side air deflector	Aerodynamic styled cab including rounded bumper and air dam
Segment Characteristics:		
GVWR (lb)	16,535 to over 35,274	26,001 to over 33,000‡
GVWR (kg)	7,500 to over 16,000	11,794 to over 14,969‡
Annual activity (mi)	37,282 (average)†	25,000 to 75,000‡
Annual activity (km)	60,000 (average)†	40,234 to 120,701‡
Fuel economy (mi/gal)	9.3 (average)†	4 to 8‡
Fuel consumption (L/100km)	25.3 (average)†	29 to 59‡

Engine displacement, transmission, and vehicle configuration information are derived from manufacturer websites. Engine and emissions control information are assumptions made in this analysis. GVWR, annual activity, fuel economy, and fuel consumption information are provided for the EU by AEA-Ricardo as average values across the EU-27 member states and for the US by NRC.

* Assuming technology to meet Euro VI standards is the same as technology to meet US EPA 2010 standards

† Average of EU heavy-duty vehicles used for regional delivery of consumer goods from a central warehouse to local stores (inner-city or suburban, also mountain road goods collections); rigid and articulated trucks

‡ Corresponding to US Class 7 and 8a vehicles[26]

(Images courtesy of Volvo, Peterbilt)

[26] National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." http://www.nap.edu/catalog/12845.html. 2010.

Table 4-8. Baseline Vehicles in the Long Haul Segment

Long Haul	EU	US
Example	MAN TGX 	Peterbilt 386 
Engine displacement (L)	12.4	12.9
Engine*	Diesel: 210 to 220 bar cylinder pressure, common rail fuel injection (2,200 to 2,400 bar), rate shaping, multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop controls, peak thermal efficiency 43 to 44%	Diesel: 210 to 220 bar cylinder pressure, common rail fuel injection (2,200 to 2,400 bar), rate shaping, multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop controls, peak thermal efficiency 43 to 44%
Transmission	10- to 18-speed automated manual	10- to 18-speed automated manual
Emissions control	Euro VI: EGR+DPF+SCR	EPA 2010: EGR+DPF+SCR
Vehicle configuration	Integrated air dam, cab side edge turning vanes, roof and side air deflector	Aerodynamic styled cab including rounded bumper and air dam
Segment Characteristics:		
GVWR (lb)	35,274 to over 88,200	33,001 to over 80,000‡
GVWR (kg)	16,000 to over 40,000	14,969 to over 36,364‡
Annual activity (mi)	80,778 (average)†	75,000 to 200,000‡
Annual activity (km)	130,000 (average)†	120,701 to 321,869‡
Fuel economy (mi/gal)	7.7 (average)†	4 to 7.5‡
Fuel consumption (L/100km)	30.6 (average)†	31 to 59‡

Engine displacement, transmission, and vehicle configuration information are derived from manufacturer websites. Engine and emissions control information are assumptions made in this analysis. GVWR, annual activity, fuel economy, and fuel consumption information are provided for the EU by AEA-Ricardo as average values across the EU-27 member states and for the US by NRC.

* Assuming technology to meet Euro VI standards is the same as technology to meet US EPA 2010 standards

† Average of heavy-duty vehicles used for delivery to international sites; rigid and articulated trucks

‡ Corresponding to US Class 8b vehicles[27]

(Images courtesy of MAN, Peterbilt)

[27] National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." http://www.nap.edu/catalog/12845.html. 2010.

Table 4-9. Baseline Vehicles in the Construction Segment

Construction	EU	US
Example	Volvo FE 	Peterbilt 348 
Engine displacement (L)	7.2	8.3
Engine*	Diesel: 190 to 200 bar cylinder pressure, common rail fuel injection (2,000 bar), multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop emission controls, peak thermal efficiency 42 to 43%	Diesel: 190 to 200 bar cylinder pressure, common rail fuel injection (2,000 bar), multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop emission controls, peak thermal efficiency 42 to 43%
Transmission	9-speed manual	9-speed manual
Emissions control	Euro VI: EGR+DPF+SCR	EPA 2010: EGR+DPF+SCR
Segment Characteristics:		
GVWR (lb)	16,535 and 88,185	26,001 to over 33,000‡
GVWR (kg)	7,500 to 40,000	11,794 to over 14,969‡
Annual activity (mi)	24,855 to 37,282 (average)†	25,000 to 75,000‡
Annual activity (km)	40,000 to 60,000 (average)†	40,234 to 120,701‡
Fuel economy (mi/gal)	8.8 (average)†	4 to 8‡
Fuel consumption (L/100km)	26.8 (average)†	29 to 59‡

Engine displacement and transmission information are derived from manufacturer websites. Engine and emissions control information are assumptions made in this analysis. GVWR, annual activity, fuel economy, and fuel consumption information are provided for the EU by AEA-Ricardo as average ranges and values across the EU-27 member states and for the US by NRC.

* Assuming technology to meet Euro VI standards is the same as technology to meet US EPA 2010 standards

† Average of heavy-duty vehicles used for on- and off-road construction (e.g., concrete mixers, dump trucks); rigid and articulated trucks

‡ Corresponding to US Class 7 or 8a dump truck[28]

(Images courtesy of Volvo, Peterbilt)

[28] National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." http://www.nap.edu/catalog/12845.html. 2010.

Table 4-10. Baseline Vehicles in the Bus Segment

Bus	EU	US
Example	Mercedes-Benz Citaro 	New Flyer Xcelsior 
Engine displacement (L)	6.37	8.9
Engine*	Diesel: 190 to 200 bar cylinder pressure, common rail fuel injection (2,000 bar), multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop emission controls, peak thermal efficiency 42 to 43%	Diesel: 190 to 200 bar cylinder pressure, common rail fuel injection (2,000 bar), multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop emission controls, peak thermal efficiency 42 to 43%
Transmission	6-speed automatic	6-speed automatic
Emissions control	Euro VI: EGR+DPF+SCR	EPA 2010: EGR+DPF+SCR
Segment Characteristics:		
GVWR (lb)	Less than 33,069 to over 39,683	40,350[‡]
GVWR (kg)	Less than 15,000 to over 18,000	18,341[‡]
Annual activity (mi)	31,069 (average)[†]	40,000[‡]
Annual activity (km)	50,000 (average)[†]	64,374[‡]
Fuel economy (mi/gal)	6.5 (average)[†]	3.5[‡]
Fuel consumption (L/100km)	36.0 (average)[†]	67[‡]

Engine displacement, transmission, and vehicle configuration information are derived from manufacturer websites. Engine and emissions control information are assumptions made in this analysis. GVWR, annual activity, fuel economy, and fuel consumption information are provided for the EU by AEA-Ricardo as average values across the EU-27 member states and for the US by TIAX/NAS.

* Assuming technology to meet Euro VI standards is the same as technology to meet US EPA 2010 standards

† Average of all buses in categories of less than 33,069 pounds (less than 15 tonnes), e.g., minibuses; 33,069 to 39,683 pounds (15 to 18 tonnes), e.g., typical 40-foot (12-meter) bus; and over 39,683 pounds (over 18 tonnes), e.g., articulated and double decker buses. These categories span two-axle, three-axle, double decker, and articulated buses, which accounted for 68.4, 5.1, 8.0, and 18.6 percent, respectively, of EU-27 bus registrations between 2007 and 2009.[29]

‡ Corresponding to 40-foot US transit bus[30]

(Images courtesy of Mercedes-Benz, New Flyer)

[29] Hill, N., S. Finnegan, J. Norris, C. Brannigan, D. Wynn, H. Baker, I. Skinner. "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy." Prepared by AEA and Ricardo for European Commission – DG Climate Action, DG ENV. 070307/2009/548572/SER/C3. February 22, 2011.

[30] Kromer, M., W. Bockholt, M. Jackson. "Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles." Prepared by TIAX LLC for National Academy of Sciences. November 19, 2009.

Table 4-11. Baseline Vehicles in the Coach Segment

Coach	EU	US
Example	Volvo 9700 	Volvo 9700 
Engine displacement (L)	12	12
Engine*	Diesel: 210 to 220 bar cylinder pressure, common rail fuel injection (2,200 to 2,400 bar), rate shaping, multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop controls, peak thermal efficiency 43 to 44%	Diesel: 210 to 220 bar cylinder pressure, common rail fuel injection (2,200 to 2,400 bar), rate shaping, multiple injections per cycle, electrically actuated variable geometry turbocharger, open-loop controls, peak thermal efficiency 43 to 44%
Transmission	12-speed automated manual	12-speed automated manual
Emissions control	Euro VI: EGR+DPF+SCR	EPA 2010: EGR+DPF+SCR
Segment Characteristics:		
GVWR (lb)	Less than 39,683 to over 39,683	49,280[‡]
GVWR (kg)	Less than 18,000 to over 18,000	22,400[‡]
Annual activity (mi)	32,311 (average)[†]	56,000[‡]
Annual activity (km)	52,000 (average)[†]	90,123[‡]
Fuel economy (mi/gal)	8.5 (average)[†]	5.7[‡]
Fuel consumption (L/100km)	27.7 (average)[†]	41[‡]

Engine displacement and transmission information are derived from manufacturer websites. Engine and emissions control information are assumptions made in this analysis. GVWR, annual activity, fuel economy, and fuel consumption information are provided for the EU by AEA-Ricardo as average values across the EU-27 member states and for the US by TIAX/NAS.

* Assuming technology to meet Euro VI standards is the same as technology to meet US EPA 2010 standards

† Average of all coaches in categories of less than 39,683 pounds (less than 18 tonnes), e.g., vans and minivans; and over 39,683 pounds (over 18 tonnes), e.g., over-the-road coaches. These categories span two-axle, three-axle, double decker, and articulated coaches, which accounted for 65.0, 32.1, 2.8, and 0.2 percent, respectively, of EU-27 coach registrations between 2007 and 2009.[31]

‡ Corresponding to US motor coach[32]

(Images courtesy of Volvo)

31 Hill, N., S. Finnegan, J. Norris, C. Brannigan, D. Wynn, H. Baker, I. Skinner. "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy." Prepared by AEA and Ricardo for European Commission – DG Climate Action, DG ENV. 070307/2009/548572/SER/C3. February 22, 2011.

32 Kromer, M., W. Bockholt, M. Jackson. "Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles." Prepared by TIAX LLC for National Academy of Sciences. November 19, 2009.

5. Fuel Efficiency Improvement Technologies

Across all eight vehicle segments, the technology packages selected for potential GHG reductions in this analysis are very comparable to those of the AEA-Ricardo analysis. Both analyses make use of technologies for lightweighting, engine efficiency, and hybridization (Table 5-1). The AEA-Ricardo analysis provides benefits and costs for lightweighting in each of the segments, but these values are not necessarily associated with any particular weight reductions that would be achievable for those segments. Because the level of possible material substitution varies by segment, this analysis uses values derived from the TIAX/NAS analysis, which gives benefits and costs that correspond to specific weight reductions.

In engine efficiency, the approach taken by the AEA-Ricardo study was to apply natural powertrain over time to the vehicles, independent of the technology options, and the only individual engine improvements considered were controllable air compression, electrical turbocompounding, and heat recovery. This analysis takes a similar approach but uses the TIAX/NAS analysis to identify specific changes, such as increased cylinder pressure, increase fuel injection pressure, advanced turbocharging, improved engine controls, waste heat recovery, and electric accessories. AEA-Ricardo's underlying fuel consumption improvements over time were generally similar to or lower in magnitude than the engine efficiency benefits from the TIAX/NAS analysis. AEA-Ricardo also included 3 percent fuel efficiency penalties for Euro VI emissions standards and an additional 3 percent in 2018 for further tightening of the criteria emissions standards.

For hybridization, the AEA-Ricardo, TIAX/NAS, and NRC studies are generally similar in estimated benefits of hybridization for most segments. The AEA-Ricardo considered a variety of hybrid configurations that would enter the marketplace over time, but in terms of maximum potential fuel savings, this study compares the TIAX/NAS hybrid electric architectures to the AEA-Ricado's hybrid electric configurations. The one exception is the in the Municipal Utility segment, where this analysis selects a hydraulic hybrid for comparison with AEA-Ricardo's hydraulic option.

Tables 5-2 through 5-9 below compare the CO_2 and fuel consumption benefits and costs[33] on a per-vehicle basis. These benefits are estimated based on a selection of the fuel efficiency improvement technologies that are expected to be available in the 2015 to 2020 timeframe.[34] As mentioned in Section 3: Assumptions, because many of the same manufacturers offer the same vehicles in both the EU and US markets, the potential technology benefits and costs are expected to be similar between the two regions. The technologies below are those identified and quantified

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[33] Converted to 2010 euros (2010€0.75 = 2010$1.00)

[34] Note that the selection of this future timeframe inherently makes assumptions that technologies are relatively mature and manufactured at high volumes. For further details about the specific technologies included in this report, refer to the sources listed in this section: National Research Council, "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles," http://www.nap.edu/catalog/12845.html, 2010; and Kromer, M., W. Bockholt, M. Jackson, "Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles," prepared by TIAX LLC for National Academy of Sciences, November 19, 2009.

through interviews with the major OEMs by the NRC and TIAX/NAS studies. For comparison, the technologies assessed by AEA-Ricardo are shown italicized in blue. Note that because some technologies would be mutually exclusive (e.g., multiple hybridization systems are unlikely to be added to the same vehicle), the tables indicate which technologies are included in the combined AEA-Ricardo packages.

Table 5-1. High-Level Comparison of TIAX and AEA-Ricardo Technologies Considered

Technology Category	TIAX	AEA-Ricardo
Aerodynamics	Streamlining for service segment and only trailer aerodynamics considered for tractor-trailer combinations*	Streamlining, trailer aerodynamics, and spray reduction mud flaps considered
Lightweighting	Material substitution to achieve certain levels of weight reductions	Level of weight reduction not necessarily specified
Tires and wheels	Low rolling resistance tires, wide-base tires, and automatic tire pressure adjustment considered	Low rolling resistance tires, wide-base tires, and automatic tire pressure adjustment considered
Transmission and driveline	Technologies applied to automatic, manual, and automated manual transmission baselines	All baselines assumed to use manual transmissions
Engine efficiency	Engine improvement packages considered, with higher cylinder and fuel injection pressures, advanced turbocharger geometries, improved controls, heat recovery, electrification of accessories, and higher peak thermal efficiencies	Controllable air compressor, electrical turbocompound, and heat recovery considered; all other engine improvements captured as natural powertrain improvements over time (separate from specific technology options)
Hybridization	Electric and hydraulic hybridization considered	Electric, hydraulic, pneumatic booster, and flywheel hybridization considered
Management	Predictive cruise control and driver aids (route management, training and feedback) considered	Predictive cruise control and driver aids considered

*This analysis assumes that the 2014 tractors offered by OEMs would incorporate aerodynamic designs, including adjustable roof fairings, side skirts, and cab extenders. Further tractor aerodynamics are possible but most likely would require modification of existing EU regulations on vehicle length and use of outside mirrors as examples. Improvements in tractor aerodynamics could reduce the drag coefficient by another 10% or more.

Table 5-2. Technology Options in the Service Segment

Service 	Technology	Fuel Consumption Benefit (%)	Cost (2010€)	Added Weight	Included in AEA-Ricardo Combined Package?	Source
Aerodynamics	10% reduction in aerodynamic drag	2 to 3	77	—	—	TIAX/NAS
	Aerodynamic bodies	*1*	*1,500*	*—*	*Yes*	*AEA-Ricardo*
	Aerodynamics – irregular body type	*1*	*400*	*—*	*No*	*AEA-Ricardo*
	Spray reduction mud flaps	*1*	*14*	*—*	*Yes*	*AEA-Ricardo*
Lightweighting	Material substitution – 5% weight reduction	1 to 1.5	480	-313 lb (-142 kg)	—	TIAX/NAS
	Lightweighting	*2.2*	*375*	*—*	*Yes*	*AEA-Ricardo*
Tires and wheels	Low rolling resistance tires	1 to 2	8	—	—	NRC
	Low rolling resistance tires	*1*	*250*	*—*	*Yes*	*AEA-Ricardo*
	Single wide tires	*4*	*825*	*—*	*Yes*	*AEA-Ricardo*
	Automatic tire pressure adjustment	*1*	*11,790*	*—*	*Yes*	*AEA-Ricardo*
Transmission and driveline	Increased transmission gears – 8-speed automatic	2.7 to 4.1	826	—	—	TIAX/NAS
	Transmission friction reduction	0 to 1	192	—	—	TIAX/NAS
	Improved controls, with aggressive shift logic and early lockup	1.5 to 2.5	46	—	—	TIAX/NAS
	Automated manual	*5*	*3,500*	*—*	*Yes*	*AEA-Ricardo*
Engine efficiency	Improved diesel engine (higher fuel injection, increased cylinder pressure, improved controls and turbocharging)*	4 to 5	1,153	—	—	TIAX/NAS
	Electrical turbocompound	*1*	*7,000*	*—*	*No*	*AEA-Ricardo*
	Heat recovery	*1.5*	*11,570*	*—*	*No*	*AEA-Ricardo*
	Powertrain natural improvement	*6.2*	*—*	*—*	*Yes*	*AEA-Ricardo*
Hybridization	Dual-mode hybrid electric	20 to 30	22,290	250 lb (113 kg)	—	TIAX/NAS
	Pneumatic booster, air hybrid	*1.5*	*800*	*—*	*No*	*AEA-Ricardo*
	Stop/start system	*6*	*640*	*—*	*No*	*AEA-Ricardo*
	Full hybrid (electric)	*20*	*24,000*	*—*	*Yes*	*AEA-Ricardo*
	Flywheel hybrid	*15*	*3,500*	*—*	*No*	*AEA-Ricardo*
	Hydraulic hybrid	*10*	*13,200*	*—*	*No*	*AEA-Ricardo*
Fuel efficiency improvements between 2010 and 2014 (baseline)		2.5	—	—	—	TIAX/NAS
Total combined package, TIAX**		**37 (30 to 43)**	**25,313**			
Total combined package, AEA-Ricardo*		***36***	***42,254***			

*No turbocompound or waste heat recovery

**The total combined benefit of individual fuel efficiency improvement technologies is calculated as follows: *Combined fuel consumption benefit (%)* = $100 \times (1 - (1-FCB_1/100) \times (1-FCB_2/100) \times \ldots \times (1-FCB_i/100))$, where FCB_i is the percent fuel consumption benefit of the ith technology.

Table 5-3. Technology Options in the Urban Delivery Segment

Urban Delivery 	Technology	Fuel Consumption Benefit (%)	Cost (2010€)	Added Weight	Included in AEA-Ricardo Combined Package?	Source
Aerodynamics	Aft box taper	1.5 to 3	384	—	—	TIAX/NAS
	Box skirts	2 to 3	576	—	—	TIAX/NAS
	Cab side extension or cab/box gap fairings	0.5 to 1	442	—	—	TIAX/NAS
	Roof deflector	2 to 3	500	—	—	TIAX/NAS
	Aerodynamic bodies	*1*	*1,500*	*—*	*Yes*	*AEA-Ricardo*
	Aerodynamics – irregular body type	*1*	*400*	*—*	*No*	*AEA-Ricardo*
	Spray reduction mud flaps	*1*	*14*	*—*	*Yes*	*AEA-Ricardo*
Lightweighting	Material substitution – 1,000 lb (454 kg)	3 to 5	3,666	-1,000 lb (-454 kg)	—	NRC
	Lightweighting	*2.2*	*375*	*—*	*Yes*	*AEA-Ricardo*
Tires and wheels	Low rolling resistance wide-base single tires with aluminum wheels (2)	2.1 to 4.2	346	-200 lb (-91 kg)	—	TIAX/NAS
	Low rolling resistance tires	*1*	*250*	*—*	*Yes*	*AEA-Ricardo*
	Single wide tires	*4*	*825*	*—*	*Yes*	*AEA-Ricardo*
	Automatic tire pressure adjustment	*1*	*11,790*	*—*	*Yes*	*AEA-Ricardo*
Transmission and driveline	None (manual transmission automation incorporated into hybridization technology)	—	—	—	—	TIAX/NAS
	Automated manual	*5*	*3,500*	*—*	*No*	*AEA-Ricardo*
Engine efficiency	Advanced 6-9L 2020 engine (220 to 230 bar cylinder pressure, 3,000 bar fuel injection, electrically boosted dual-stage variable geometry turbocharger, improved closed-loop engine controls, electric accessories, peak thermal efficiency 46 to 49%)*	9.4 to 12	3,728	—	—	TIAX/NAS
	Electrical turbocompound	*1*	*7,000*	*—*	*No*	*AEA-Ricardo*
	Heat recovery	*1.5*	*11,570*	*—*	*No*	*AEA-Ricardo*
	Powertrain natural improvement	*6.2*	*—*	*—*	*Yes*	*AEA-Ricardo*
Hybridization	Parallel hybrid electric (engine-off at idle, electric accessories, optimized controls, lighter components)†	25 to 35	14,604	350 lb (159 kg)	—	TIAX/NAS
	Pneumatic booster, air hybrid	*1.5*	*800*	*—*	*No*	*AEA-Ricardo*
	Stop/start system	*6*	*640*	*—*	*No*	*AEA-Ricardo*
	Full hybrid (electric)	*20*	*24,000*	*—*	*Yes*	*AEA-Ricardo*
	Flywheel hybrid	*15*	*3,500*	*—*	*No*	*AEA-Ricardo*
	Hydraulic hybrid	*10*	*13,200*	*—*	*No*	*AEA-Ricardo*
Total combined package, TIAX‡		**46 (39 to 52)**	**24,246**			
Total combined package, AEA-Ricardo‡		***32***	***38,754***			

No turbocompound or waste heat recovery

†Other possible hybridization options include parallel hydraulic hybrid (20-25% benefit at €26,902) and series hydraulic hybrid (40-50% benefit at €34,588).

‡The total combined benefit of individual fuel efficiency improvement technologies is calculated as follows: *Combined fuel consumption benefit (%) =* $100 \times (1 - (1\text{-}FCB_1/100) \times (1\text{-}FCB_2/100) \times \ldots \times (1\text{-}FCB_i/100))$, where FCB_i is the percent fuel consumption benefit of the ith technology.

Table 5-4. Technology Options in the Municipal Utility Segment

Municipal Utility 	**Technology**	**Fuel Consumption Benefit (%)**	**Cost (2010€)**	**Added Weight**	**Included in AEA-Ricardo Combined Package?**	**Source**
Lightweighting	Material substitution – 500 lb (228 kg)	0.7 to 1.2	2,306	-500 lb (-228 kg)	—	TIAX/NAS
	Lightweighting	*4.7*	*5,650*	—	*Yes*	*AEA-Ricardo*
Tires and wheels	Low rolling resistance tires	2.4 to 3	231	—	—	TIAX/NAS
	Low rolling resistance tires	*1*	*300*	—	*Yes*	*AEA-Ricardo*
	Single wide tires	*4*	*825*	—	*Yes*	*AEA-Ricardo*
	Automatic tire pressure adjustment	*1*	*11,790*	—	*Yes*	*AEA-Ricardo*
Transmission and driveline	Increased transmission gears – 8-speed automatic	2 to 3	1,806	—	—	TIAX/NAS
	Reduced parasitics and friction	1	192	—	—	TIAX/NAS
	Aggressive shift logic and early lockup	0.5 to 1	77	—	—	TIAX/NAS
	Automated manual	*5*	*3,500*	—	*Yes*	*AEA-Ricardo*
Engine efficiency	Advanced 6-9L 2020 engine (220 to 230 bar cylinder pressure, 3,000 bar fuel injection, electrically boosted dual-stage variable geometry turbocharger, improved closed-loop engine controls, electric accessories, peak thermal efficiency 46 to 49%)*	9.4 to 12	3,728	—	—	TIAX/NAS
	Electrical turbocompound	*1*	*7,000*	—	*No*	*AEA-Ricardo*
	Heat recovery	*1.5*	*11,570*	—	*No*	*AEA-Ricardo*
	Powertrain natural improvement	*6.2*	—	—	*Yes*	*AEA-Ricardo*
Hybridization	Parallel hydraulic hybrid†	20 to 25	23,059	1,000 lb (454 kg)	—	TIAX/NAS
	Pneumatic booster, air hybrid	*1.5*	*800*	—	*No*	*AEA-Ricardo*
	Stop/start system	*6*	*640*	—	*No*	*AEA-Ricardo*
	Full hybrid (electric)	*20*	*24,000*	—	*No*	*AEA-Ricardo*
	Flywheel hybrid	*15*	*3,500*	—	*No*	*AEA-Ricardo*
	Alternative fuel bodies	*15*	*14,000*	—	*No*	*AEA-Ricardo*
	Hydraulic hybrid	*10*	*13,200*	—	*Yes*	*AEA-Ricardo*
Fuel efficiency improvements between 2010 and 2014 (baseline)		2.5	—	—	—	TIAX/NAS
	Total combined package, TIAX‡	**35 (31 to 39)**	**31,399**			
	Total combined package, AEA-Ricardo‡	***32***	***35,265***			

*No turbocompound or waste heat recovery

†Other possible hybridization options include series hydraulic hybrid (40-50% benefit at €34,588), parallel electric hybrid (25-30% benefit at €14,604), and parallel electric hybrid with electric power take-off (30-35% benefit at €21,137).

[‡]The total combined benefit of individual fuel efficiency improvement technologies is calculated as follows: *Combined fuel consumption benefit (%) = 100 x (1 - (1-FCB_1/100) x (1-FCB_2/100) x … x (1-FCB_i/100))*, where FCB_i is the percent fuel consumption benefit of the *i*th technology.

Table 5-5. Technology Options in the Regional Delivery Segment

Regional Delivery 	Technology	Fuel Consumption Benefit (%)	Cost (2010€)	Added Weight	Included in AEA-Ricardo Combined Package?	Source
Aerodynamics	Boat tail	2 to 4	1,345	—	—	TIAX/NAS
	Full gap fairing	1 to 2	961	—	—	TIAX/NAS
	Full skirts	2 to 3	2,306	—	—	TIAX/NAS
	Aerodynamic trailers	*11*	*3,500*	—	*Yes*	*AEA-Ricardo*
	Aerodynamic fairings	*1*	*1,180*	—	*Yes*	*AEA-Ricardo*
	Spray reduction mud flaps	*2*	*14*	—	*Yes*	*AEA-Ricardo*
Lightweighting	Material substitution – 990 lb (450 kg)	2.2	2,283	-990 lb (-450 kg)	—	TIAX/NAS
	Lightweighting	*2.2*	*375*	—	*Yes*	*AEA-Ricardo*
Tires and wheels	Next generation low rolling resistance wide-base single tires with aluminum wheels (2)	9 to 12	346	-200 lb (-91 kg)	—	TIAX/NAS
	Automatic tire inflation on trailer	0.6	269	—	—	TIAX/NAS
	Automatic tire inflation on tractor	0.6	3,459	—	—	TIAX/NAS
	Low rolling resistance tires	*3*	*350*	—	*Yes*	*AEA-Ricardo*
	Single wide tires	*6*	*825*	—	*Yes*	*AEA-Ricardo*
	Automatic tire pressure adjustment	*2*	*11,790*	—	*Yes*	*AEA-Ricardo*
Transmission and driveline	Transmission friction reduction	1 to 1.5	192	—	—	TIAX/NAS
	Automated manual	*1.5*	*3,500*	—	*No*	*AEA-Ricardo*
Engine efficiency	Advanced 6-9L 2020 engine (220 to 230 bar cylinder pressure, 3,000 bar fuel injection, electrically boosted dual-stage variable geometry turbocharger, improved closed-loop engine controls, electric accessories, peak thermal efficiency 46 to 49%)*	9.4 to 12	3,728	—	—	TIAX/NAS
	Controllable air compressor	*1*	*140*	—	*No*	*AEA-Ricardo*
	Electrical turbocompound	*2.5*	*7,000*	—	*No*	*AEA-Ricardo*
	Heat recovery	*2.5*	*11,570*	—	*No*	*AEA-Ricardo*
	Powertrain natural improvement	*6.2*	—	—	*Yes*	*AEA-Ricardo*
Hybridization	Gen II dual hybrid with all electric capability, electrified accessories, overnight hotel loads, engine-off at idle	8 to 12	17,871	550 lb (249 kg)	—	TIAX/NAS
	Pneumatic booster, air hybrid	*1.5*	*800*	—	*No*	*AEA-Ricardo*
	Stop/start system	*3*	*640*	—	*No*	*AEA-Ricardo*
	Full hybrid (electric)	*10*	*24,000*	—	*Yes*	*AEA-Ricardo*
	Flywheel hybrid	*7.5*	*3,500*	—	*No*	*AEA-Ricardo*
	Alternative fuel bodies	*15*	*14,000*	—	*No*	*AEA-Ricardo*
Management	Predictive cruise control	1 to 2	77	—	—	TIAX/NAS
	Predictive cruise control	*5*	*1,400*	—	*Yes*	*AEA-Ricardo*
Fuel efficiency improvements between 2010 and 2014 (baseline)		6.9	—	—	—	TIAX/NAS
	Total combined package, TIAX**	**41 (36 to 45)**	**32,836**			
	Total combined package, AEA-Ricardo*	***40***	***43,434***			

*No turbocompound or waste heat recovery

**The total combined benefit of individual fuel efficiency improvement technologies is calculated as follows: *Combined fuel consumption benefit (%) =* $100 \times (1 - (1-FCB_1/100) \times (1-FCB_2/100) \times \ldots \times (1-FCB_i/100))$, where FCB_i is the percent fuel consumption benefit of the *i*th technology.

Table 5-6. Technology Options in the Long Haul Segment

Long Haul 	Technology	Fuel Consumption Benefit (%)	Cost (2010€)	Added Weight	Included in AEA-Ricardo Combined Package?	Source
Aerodynamics	Boat tail	2 to 4	1,345	—	—	TIAX/NAS
	Full gap fairing	1 to 2	961	—	—	TIAX/NAS
	Full skirts	2 to 3	2,306	—	—	TIAX/NAS
	Aerodynamic trailers	*11*	*3,500*	—	*Yes*	*AEA-Ricardo*
	Aerodynamic fairings	*0.4*	*1,180*	—	*Yes*	*AEA-Ricardo*
	Spray reduction mud flaps	*3.5*	*14*	—	*Yes*	*AEA-Ricardo*
Lightweighting	Material substitution – 990 lb (450 kg)	2.2	2,283	-990 lb (-450 kg)	—	TIAX/NAS
	Lightweighting	*2.2*	*1,600*	—	*Yes*	*AEA-Ricardo*
Tires and wheels	Next generation low rolling resistance wide-base single tires with aluminum wheels (2)	9 to 12	346	-200 lb (-91 kg)	—	TIAX/NAS
	Automatic tire inflation on trailer	0.6	269	—	—	TIAX/NAS
	Automatic tire inflation on tractor	0.6	3,459	—	—	TIAX/NAS
	Low rolling resistance tires	*5*	*350*	—	*Yes*	*AEA-Ricardo*
	Single wide tires	*5*	*1,300*	—	*Yes*	*AEA-Ricardo*
	Automatic tire pressure adjustment	*3*	*11,790*	—	*Yes*	*AEA-Ricardo*
Transmission and driveline	Transmission friction reduction	1 to 1.5	192	—	—	TIAX/NAS
	Automated manual	*1.5*	*4,716*	—	*No*	*AEA-Ricardo*
Engine efficiency	Advanced 11-15L engine (240 bar cylinder pressure, 4,000 bar super-critical atomization fuel injection, electrically boosted variable geometry turbocharger, improved closed-loop engine controls, bottoming cycle, electric accessories, peak thermal efficiency 51 to 53%)*	14.6 to 17.9	10,415	250 lb (113 kg)	—	TIAX/NAS
	Controllable air compressor	*1.5*	*190*	—	*Yes*	*AEA-Ricardo*
	Electrical turbocompound	*3*	*7,000*	—	*Yes*	*AEA-Ricardo*
	Heat recovery	*5*	*11,570*	—	*Yes*	*AEA-Ricardo*
	Powertrain natural improvement	*6.2*	—	—	*Yes*	*AEA-Ricardo*
Hybridization	Gen II dual hybrid with all electric capability, electrified accessories, overnight hotel loads, engine-off at idle	8 to 12	21,137	750 lb (340 kg)	—	TIAX/NAS
	Pneumatic booster, air hybrid	*3.5*	*800*	—	*No*	*AEA-Ricardo*
	Stop/start system	*1*	*940*	—	*No*	*AEA-Ricardo*
	Full hybrid (electric)	*7*	*24,000*	—	*Yes*	*AEA-Ricardo*
	Flywheel hybrid	*5*	*5,900*	—	*No*	*AEA-Ricardo*
	Alternative fuel bodies	*15*	*14,000*	—	*No*	*AEA-Ricardo*
Management	Predictive cruise control	1 to 2	77	—	—	TIAX/NAS
	Route management	0 to 1	461	—	—	TIAX/NAS
	Training and feedback	1 to 4	615	—	—	TIAX/NAS
	Predictive cruise control	*5*	*1,400*	—	*Yes*	*AEA-Ricardo*
	Vehicle improvements using driver aids	*10*	—	—	*Yes*	*AEA-Ricardo*
Fuel efficiency improvements between 2010 and 2014 (baseline)		10	—	—	—	TIAX/NAS

Total combined package, TIAX**	**47 (41 to 52)**	**43,866**			
Total combined package, AEA-Ricardo*	***50***	***63,894***			

*Waste heat recovery from bottoming cycle
**The total combined benefit of individual fuel efficiency improvement technologies is calculated as follows: *Combined fuel consumption benefit (%) =* $100 \times (1 - (1\text{-}FCB_1/100) \times (1\text{-}FCB_2/100) \times \ldots \times (1\text{-}FCB_i/100))$, where FCB_i is the percent fuel consumption benefit of the *i*th technology.

Table 5-7. Technology Options in the Construction Segment

Construction 	Technology	Fuel Consumption Benefit (%)	Cost (2010€)	Added Weight	Source
Lightweighting	Material substitution – 150 lb (68 kg)	0.3	346	-150 lb (-68 kg)	TIAX/NAS
Tires and wheels	Next generation low rolling resistance wide-base single tires (2)	9 to 12	346	-200 lb (-91 kg)	TIAX/NAS
	Automatic tire inflation	0.6	3,459	—	TIAX/NAS
Transmission and driveline	Transmission friction reduction (manual transmission automation incorporated into hybridization technology)	1 to 1.5	192	—	TIAX/NAS
Engine efficiency	Advanced 6-9L 2020 engine (220 to 230 bar cylinder pressure, 3,000 bar fuel injection, electrically boosted dual-stage variable geometry turbocharger, improved closed-loop engine controls, electric accessories, peak thermal efficiency 46 to 49%)*	9.4 to 12	3,728	—	TIAX/NAS
Hybridization	Parallel hybrid electric vehicle, with engine-off at idle, electric accessories, optimized controls, lighter components	25 to 35	14,604	350 lb (159 kg)	TIAX/NAS
	Total combined package, TIAX**	**45 (39 to 50)**	**22,675**		

Note: no specific technologies are detailed for the Construction segment in the AEA-Ricardo analysis

*No turbocompound or waste heat recovery

**The total combined benefit of individual fuel efficiency improvement technologies is calculated as follows: *Combined fuel consumption benefit (%) = 100 x (1 - (1-FCB_1/100) x (1-FCB_2/100) x … x (1-FCB_i/100))*, where FCB_i is the percent fuel consumption benefit of the *i*th technology.

Table 5-8. Technology Options in the Bus Segment

Bus 	Technology	Fuel Consumption Benefit (%)	Cost (2010€)	Added Weight	Included in AEA-Ricardo Combined Package?	Source
Lightweighting	Material substitution – 2,500 lb (1,134 kg)	5 to 7.5	11,760	-2,500 lb (-1,134 kg)	—	TIAX/NAS
	Vehicle improvements using 5% weight reduction	*3.9*	—	—	*Yes*	*AEA-Ricardo*
Tires and wheels	Low rolling resistance tires	1 to 2	231	—	—	TIAX/NAS
	Low rolling resistance tires	*1*	*350*	—	*Yes*	*AEA-Ricardo*
	Single wide tires	*4*	*825*	—	*Yes*	*AEA-Ricardo*
	Automatic tire pressure adjustment	*1*	*11,790*	—	*Yes*	*AEA-Ricardo*
Transmission and driveline	Reduced parasitics and friction	1	192	—	—	TIAX/NAS
	Automated manual	*5*	*3,500*	—	*No*	*AEA-Ricardo*
Engine efficiency	Advanced 6-9L engine (220 to 230 bar cylinder pressure, 3,000 bar fuel injection, electrically boosted dual-stage variable geometry turbocharger, improved closed-loop engine controls, electric accessories, peak thermal efficiency 46 to 49%)*	9.4 to 12	3,728	—	—	TIAX/NAS
	Electrical turbocompound	*1*	*7,000*	—	*No*	*AEA-Ricardo*
	Heat recovery	*1.5*	*11,570*	—	*No*	*AEA-Ricardo*
	Powertrain natural improvement	*6.2*	—	—	*Yes*	*AEA-Ricardo*
Hybridization	Series hybrid electric	30 to 40	16,910[†]	2,600 lb (1,179 kg)	—	TIAX/NAS
	Stop/start system	*4*	*640*	—	*No*	*AEA-Ricardo*
	Full hybrid (electric)	*30*	*24,000*	—	*Yes*	*AEA-Ricardo*
	Flywheel hybrid	*20*	*3,500*	—	*No*	*AEA-Ricardo*
	Hydraulic hybrid	*15*	*13,200*	—	*No*	*AEA-Ricardo*
Fuel efficiency improvements between 2010 and 2014 (baseline)		2.5	—	—	—	TIAX/NAS
	Total combined package, TIAX[‡]	**41 (35 to 47)**	**32,590**			
	Total combined package, AEA-Ricardo[‡]	***41***	***36,965***			

*No turbocompound or waste heat recovery

[†]Cost for the bus hybrid technology is derived from the subsidized cost of the technology in the US The US Federal Transit Administration offers a 90% subsidy for the cost of the hybrid technology, which is likely to skew the unsubsidized cost. To account for this effect, the subsidized cost is used to derive the EU equivalent cost.

[‡]The total combined benefit of individual fuel efficiency improvement technologies is calculated as follows: *Combined fuel consumption benefit (%)* $= 100 \times (1 - (1-FCB_1/100) \times (1-FCB_2/100) \times \ldots \times (1-FCB_i/100))$, where FCB_i is the percent fuel consumption benefit of the ith technology.

Table 5-9. Technology Options in the Coach Segment

Coach 	Technology	Fuel Consumption Benefit (%)	Cost (2010€)	Added Weight	Included in AEA-Ricardo Combined Package?	Source
Aerodynamics	Streamlining	3 to 10	2,114	—	—	TIAX/NAS
	Aerodynamic fairings	*1*	*350*	—	*Yes*	*AEA-Ricardo*
	Spray reduction mud flaps	*2*	*14*	—	*Yes*	*AEA-Ricardo*
	Vehicle improvements using improved aerodynamics	*4.1*	—	—	*Yes*	*AEA-Ricardo*
Lightweighting	Material substitution – 1,500 lb (680 kg)	1.1	4,612	-1,500 lb (-680 kg)	—	TIAX/NAS
	Vehicle improvements using weight reduction	*2.2*	—	—	*Yes*	*AEA-Ricardo*
Tires and wheels	Low rolling resistance tires	1 to 2	184	—	—	TIAX/NAS
	Automatic tire inflation	0.4	269	—	—	TIAX/NAS
	Low rolling resistance tires	*3*	*350*	—	*Yes*	*AEA-Ricardo*
	Single wide tires	*6*	*825*	—	*Yes*	*AEA-Ricardo*
	Automatic tire pressure adjustment	*2*	*11,790*	—	*Yes*	*AEA-Ricardo*
Transmission and driveline	Transmission friction reduction	1 to 1.5	192	—	—	TIAX/NAS
	Automated manual	*1.5*	*3,500*	—	*No*	*AEA-Ricardo*
Engine efficiency	Advanced 11-15L engine with bottoming cycle (240 bar cylinder pressure, 4,000 bar supercritical atomization fuel injection, electrically boosted variable geometry turbocharger, improved closed-loop engine controls, bottoming cycle, electric accessories, peak thermal efficiency 51 to 53%)*	14.6 to 17.9	10,415	250 lb (113 kg)	—	TIAX/NAS
	Controllable air compressor	*1*	*140*	—	*No*	*AEA-Ricardo*
	Electrical turbocompound	*2.5*	*7,000*	—	*Yes*	*AEA-Ricardo*
	Heat recovery	*2.5*	*11,570*	—	*Yes*	*AEA-Ricardo*
	Powertrain natural improvement	*6.2*	—	—	*Yes*	*AEA-Ricardo*
Hybridization	Gen II parallel hybrid electric	9 to 13	26,902	500 lb (228 kg)	—	TIAX/NAS
	Pneumatic booster, air hybrid	*1.5*	*800*	—	*No*	*AEA-Ricardo*
	Stop/start system	*3*	*640*	—	*No*	*AEA-Ricardo*
	Full hybrid (electric)	*10*	*24,000*	—	*Yes*	*AEA-Ricardo*
	Flywheel hybrid	*7.5*	*3,500*	—	*No*	*AEA-Ricardo*
Management	Predictive cruise control	1 to 2	77	—	—	TIAX/NAS
	Predictive cruise control	*5*	*1,400*	—	*Yes*	*AEA-Ricardo*
Fuel efficiency improvements between 2010 and 2014 (baseline)		6.9	—	—	—	TIAX/NAS
	Total combined package, TIAX*	**384 (32 to 43)**	**47,071**			
	Total combined package, AEA-Ricardo*	***38***	***57,299***			

*Waste heat recovery from bottoming cycle

**The total combined benefit of individual fuel efficiency improvement technologies is calculated as follows: *Combined fuel consumption benefit (%) = 100 x (1 - (1-FCB*$_1$*/100) x (1-FCB*$_2$*/100) x … x (1-FCB*$_i$*/100))*, where *FCB*$_i$ is the percent fuel consumption benefit of the *i*th technology.

The NRC and TIAX/NAS studies present aerodynamic benefits for US vehicles, which may travel at 65 to 75 miles per hour (105 to 120 kilometers per hour). In contrast, EU vehicles, with the exception of vehicles in the Coach segment, are assumed to be governed at 55 miles per hour (90 kilometers per hour), and thus the benefits described for the US are scaled according to speed in this analysis. Fuel consumption is proportional to the cube of the speed at which the vehicles travel, and accordingly, the fuel consumption benefits of aerodynamic technologies for the EU are scaled down from the benefits for the US by the cube of the ratio of the speeds between the two regions. This analysis considers streamlining or aerodynamic improvements for straight trucks and coaches but assumes no aerodynamic improvements for tractors as described in Table 5-1. Similarly, for technologies aimed at rolling resistance, which is directly proportional to speed, the fuel consumptions benefits for the EU are scaled down from the benefits for the US by the ratio of speeds between the two regions.

For the Service segment, single wide tires and automatic tire pressure adjustment are included in this analysis, recognizing that these technologies are likely only applicable to the higher weight vehicles in this segment. This analysis includes technologies applicable to vehicles with automatic transmissions, which are assumed to be the 2014 baseline. As a result, the transmission technologies considered here do not match those of the AEA-Ricardo study, which assumed that the baseline vehicles use manual transmissions.

For the Urban Delivery segment, automatic tire pressure adjustment is not included in this analysis because this technology is unlikely to be applied to vehicles in this segment. Manual transmission automation was not separately included in this analysis, as automation is assumed to be a part of the hybridization technology. Relative to the AEA-Ricardo assessment, this analysis estimates higher benefits due to aerodynamics and lightweighting and slightly higher benefits due to engine improvements and hybridization. This is one of the segments where the estimates of this analysis exceed those of the AEA-Ricardo analysis.

For the Municipal Utility segment, this analysis does not include single wide tires (unlike the AEA-Ricardo analysis), since the NRC study indicated that this technology is unlikely to be adopted for this vehicle segment due to the stop-and-go, mostly low-speed duty cycle. As in the Service segment, this analysis includes technologies applicable to vehicles with automatic transmissions, which are assumed to be the 2014 baseline. AEA-Ricardo assumed that the baseline vehicle was equipped with a manual transmission, so the analysis selected an automated manual transmission to improve fuel consumption. As indicated, the overall results of this analysis closely match those of AEA-Ricardo despite having selected different combination of technologies and estimating different levels of benefits for the same technologies.

For the Regional Delivery and Long Haul segments, this analysis elaborates on the “aerodynamic trailers” and “aerodynamic fairings” of the AEA-Ricardo study by considering boat tails, full gap fairings, and full skirts. The automatic tire pressure inflation of the AEA-Ricardo study is broken out in this study into automatic tire inflation on the tractor and automatic tire inflation on the trailer. The NRC and TIAX/NAS studies suggested that predictive cruise control may offer somewhat lower benefits at significantly lower cost than the AEA-Ricardo study, and thus the NRC and TIAX/NAS values are used in this analysis to ensure that this management technology is not ruled out as a potentially viable and cost effective option. For both segments, the baseline vehicles are assumed to use automated manual transmissions already, and thus transmission automation is not included as a technology option.

For the Bus segment, single wide tires were considered in the AEA-Ricardo analysis but are excluded from this analysis because the NRC report suggested that they are unlikely to be adopted in this segment, again due to the stop-and-go duty cycle. As in the Service and Municipal Utility segments, this analysis includes technologies applicable to vehicles with automatic transmissions, which are assumed to be the 2014 baselines. Accordingly, the transmission technologies considered here do not match those of the AEA-Ricardo study, which assumed that the baseline vehicles use manual transmissions.

For the Coach segment, this analysis considers streamlining from the TIAX/NAS study and assumes that the maximum aerodynamic benefit corresponds to reducing the drag coefficient to 0.36.[35] As in the Bus segment, single wide tires were considered in the AEA-Ricardo analysis but were not included here. Coaches typically have only one axle with dual tires, so it was judged that this segment would use low rolling resistance tires but not the single wide configuration to simplify stocking of differently sized tires. No transmission automation is included because the baseline vehicles are assumed to use automated manual transmissions.

The incorporation of fuel efficiency improvement technologies may add to the total weight of the vehicles, which has the effect of decreasing fuel economy. This effect is taken into account in the calculation of net benefits by applying the fuel consumption penalty resulting from additional weight as a negative lightweighting benefit. The total combined package fuel consumption benefits have therefore been adjusted downward by any increases in vehicle weight.

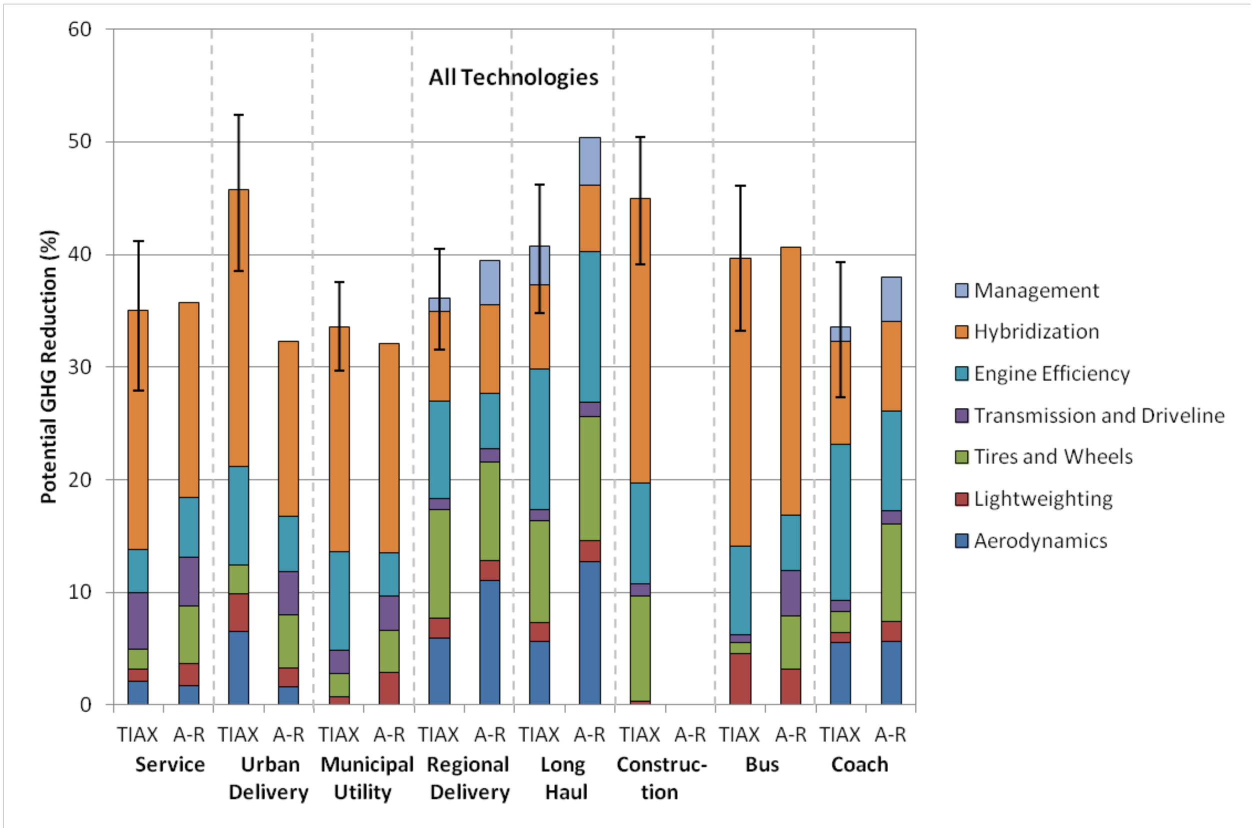
For further details of each of the listed technologies, please refer to:

- National Research Council. “Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles.” http://www.nap.edu/catalog/12845.html. 2010.

- Kromer, M., W. Bockholt, M. Jackson. “Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles.” Prepared by TIAX LLC for National Academy of Sciences, November 19, 2009.

Across the eight vehicle segments, potential vehicle GHG benefits from packages of all technologies for the EU (Figure 5-1) are similar between this analysis and that performed by AEA-Ricardo. In particular, TIAX estimates significantly higher benefits for the Urban Delivery segment, and AEA-Ricardo estimated higher benefits for the Long Haul segment.

[35] MAN. “Streamlining Against Harsh Wind: Aerodynamics in Commercial Vehicles.” http://www.transport-efficiency.com/en/Future_Expertise/Aerodynamics/Aerodynamics.jsp. Accessed October 12, 2011.

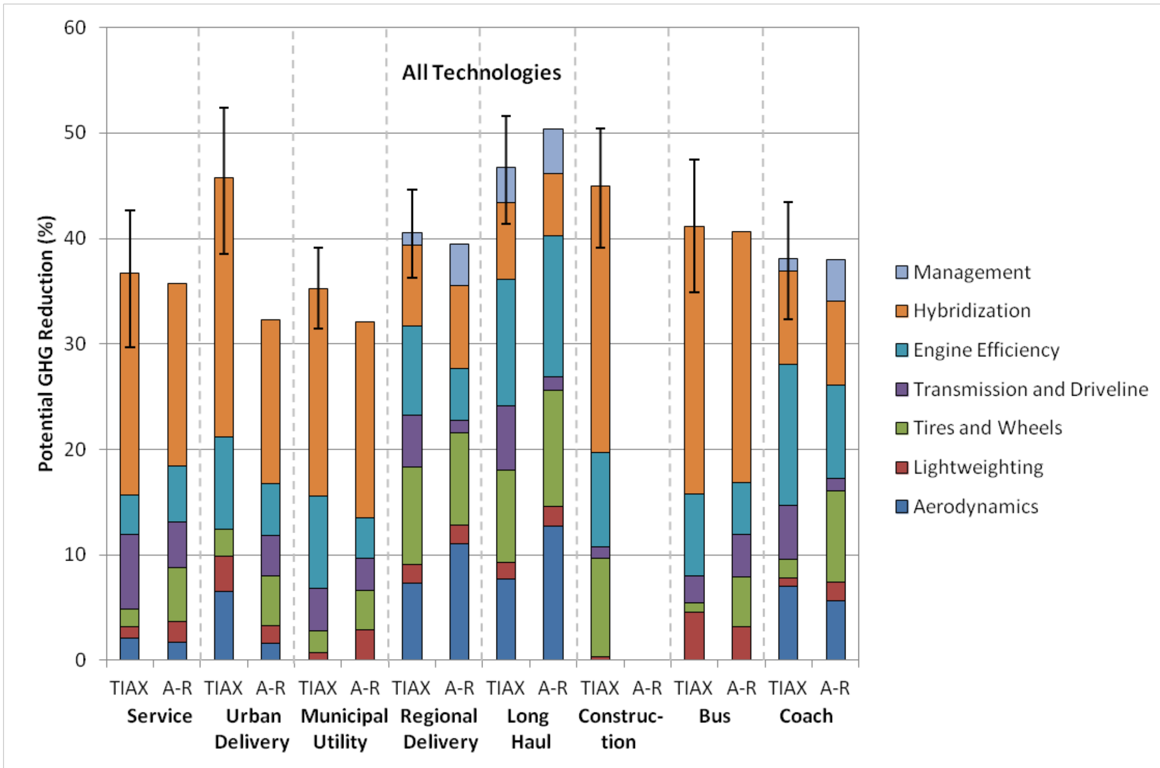


(A-R: AEA-Ricardo)

Figure 5-1.Potential New EU Vehicle GHG Reductions from All Technologies

Figure 5-2 compares the fuel savings estimates for the EU segments to the estimates for the US segments (as documented in the TIAX/NAS and NRC studies). Overall, lower potential savings are estimated for the EU segments than for the comparable US segments. This difference is due mainly to the improved baseline efficiencies for the EU vehicles. For example, in the EU Service segment, diesel engines are the preferred powertrain, whereas in the US, gasoline engines dominate this segment. This alone could explain the 23 percent difference in estimated benefits. Similarly, the difference in the Long Haul segment is mostly likely a result of a combination of factors and technologies, including reduced driving speed, aftertreatment technologies, drivetrain configuration, and wheels and tires. As shown below, these changes could result in 19 percent lower benefits than was estimated for the US 2007 model year vehicle.

- Aerodynamics and lower speeds
  - Fuel savings of 5%
  - Reduced from 105 kph (US) to 90 kph (EU); -0.3% fuel savings per kph
- Engine aftertreatment EGR and DPF (without SCR)
  - Fuel savings of 6%



(US data reproduced from Kromer, M., W. Bockholt, M. Jackson, "Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles," prepared by TIAX LLC for National Academy of Sciences, November 19, 2009.)

Figure 5-2.Potential New EU vs. US Vehicle GHG Reductions from All Technologies

- Transmission and driveline
  - 4x2 tractor configuration and automated manual transmission
  - Fuel savings of 7%
- Tractor and trailer wheels and tires
  - Fuel savings of 3%
- Total estimated EU Long Haul vs. NRC tractor-trailer fuel savings of 19%

A summary of the technology costs and payback periods[36] for each vehicle segment are presented and compared to the values estimated by AEA-Ricardo in Tables 5-10 through 5-13. The technologies in which there are the largest discrepancies in cost and payback period between this analysis and the AEA-Ricardo analysis are: aerodynamics, lightweighting, tires and wheels, engine efficiency, and management. The biggest differences in aerodynamics were in the Service, Urban Delivery, and Coach segments. AEA-Ricardo's estimates were consistently lower

[36] Assuming a fuel price of €1.3/L (based on the average diesel fuel price for September 2011)

Table 5-10. TIAX Technology Costs

Technology		TIAX Technology Cost (2010€)							
		Service	Urban Delivery	Municipal Utility	Regional Delivery	Long Haul	Construction	Bus	Coach
Aerodynamics	Aft box taper		384						
	Boat tail				1,345	1,345			
	Box skirts		576						
	Cab side extension or cab/box gap fairings		442						
	Full gap fairing				961	961			
	Full skirts				2,306	2,306			
	Roof deflector		500						
	Streamlining	77							2,114
Lightweighting	Material substitution	721	3,666	2,306	2,283	2,283	346	11,529	6,918
Tires and Wheels	Automatic tire inflation on vehicle/tractor				3,459	3,459	3,459		269
	Automatic tire inflation on trailer				269	269			
	Low rolling resistance tires	8		231				231	184
	Low rolling resistance wide-base single tires		346		346	346	346		
Transmission and Driveline	Aggressive shift logic and early lockup	46		77					
	Increased transmission gears	826		1,806					
	Transmission friction reduction	192		192	192	192	192	192	192
Engine Efficiency	Improved diesel engine	1,153	3,728	3,728	3,728	10,415	3,728	3,728	10,415
Hybridization	Dual-mode hybrid	22,290			17,871	21,137			
	Parallel hybrid		14,604				14,604		26,902
	Parallel hydraulic hybrid			23,059					
	Series hybrid							16,910*	
Management	Predictive cruise control				77	77			77
	Route management					461			
	Training and feedback					615			

*Cost for the bus hybrid technology is derived from the subsidized cost of the technology in the US The US Federal Transit Administration offers a 90% subsidy for the cost of the hybrid technology, which is likely to skew the unsubsidized cost. To account for this effect, the subsidized cost is used to derive the EU equivalent cost.

Table 5-11. AEA-Ricardo Technology Costs

Technology		AEA-Ricardo Technology Costs (2010€) / Percent AEA-Ricardo Cost Relative to TIAX Cost*							
		Service	Urban Delivery	Municipal Utility	Regional Delivery	Long Haul	Construction	Bus	Coach
Aerodynamics	Aerodynamic trailers/bodies/fairings	1,514 / +1900%	2,680 / +41%		4,680 / +1%	4,680 / +1%			350 / -83%
Lightweighting	Material substitution	375 / -48%	375 / -90%	5,650 / +150%	375 / -84%	1,600 / -30%	Unknown	0 / -100%	0 / -100%
Tires and Wheels	Automatic tire inflation				11,790 / +220%	11,790 / +220%	Unknown		11,790 / +4300%
	Low rolling resistance tires	250 / +3200%		300 / +30%				350 / +52%	350 / +90%
	Low rolling resistance wide-base single tires		1,075 / +210%		1,175 / +240%	1,650 / +377%	Unknown		
Transmission and Driveline	Aggressive shift logic and early lockup	None		None					
	Increased transmission gears	None		None					
	Transmission friction reduction	None		None	None	None	Unknown	None	None
Engine Efficiency	Improved diesel engine	0 / -100%	0 / -100%	0 / -100%	0 / -100%	18,760 / +80%	Unknown	0 / -100%	18,570 / +78%
Hybridization	Full hybrid (electric)	24,000 / +8%	24,000 / +64%		24,000 / +34%	24,000 / +14%	Unknown	24,000 / +42%	24,000 / -11%
	Hydraulic hybrid			13,200 / -43%					
Management	Predictive cruise control				1,400 / +1700%	1,400 / +1700%			1,400 / +1700%
	Driver aid					0 / -100%			

* Relative percent calculated as (AEA-Ricardo value – TIAX value) / TIAX value

Table 5-12. TIAX Technology Payback Periods

Technology		TIAX Payback Period (years)							
		Service	Urban Delivery	Municipal Utility	Regional Delivery	Long Haul	Construction	Bus	Coach
Aerodynamics	Aft box taper		2						
	Boat tail				2	1			
	Box skirts		3						
	Cab side extension or cab/box gap fairings		5						
	Full gap fairing				3	1			
	Full skirts				4	2			
	Roof deflector		2						
	Streamlining	0.4							2
Lightweighting	Material substitution	8	8	14	5	2	6	8	35
Tires and Wheels	Automatic tire inflation on vehicle/tractor				29	11	33		3
	Automatic tire inflation on trailer				2	1			
	Low rolling resistance tires	0.05		1				1	1
	Low rolling resistance wide-base single tires		1		0.2	0.1	0.2		
Transmission and Driveline	Aggressive shift logic and early lockup	0.3		1					
	Increased transmission gears	3		4					
	Transmission friction reduction	1		1	1	0.3	1	1	1
Engine Efficiency	Improved diesel engine	4	3	2	2	1	2	1	3
Hybridization	Dual-mode hybrid	13			4	5			
	Parallel hybrid		5				3		14
	Parallel hydraulic hybrid			6					
	Series hybrid							2	
Management	Predictive cruise control				0.3	0.1			0.3
	Route management					2			
	Training and feedback					0.5			

Diesel fuel price is assumed to be €1.3/L

Table 5-13. AEA-Ricardo Technology Payback Periods

Technology		AEA-Ricardo Payback Period (years) / AEA-Ricardo Period Relative to TIAX Period*							
		Service	Urban Delivery	Municipal Utility	Regional Delivery	Long Haul	Construction	Bus	Coach
Aerodynamics	Aerodynamic trailers/bodies/fairings	Not given	Not given		2.1 to 7.8 / -2 to +6	0.8 to 7.4 / -1 to +7			8.2 / +6
Lightweighting	Material substitution	3 / -5	2 / -6	8.7 / -5	1.1 / -4.2	1.8 / -0.2	Unknown	0 / -8	0 / -35
Tires and Wheels	Automatic tire inflation				38.8 / +10 to +37	9.9 / -1 to +9	Unknown		40.9 / +37
	Low rolling resistance tires	Not given		Not given				Not given	0.8 / +0.2
	Low rolling resistance wide-base single tires		Not given		0.8 to 0.9 / +1	0.2 to 0.7 / +0.1 to +1	Unknown		
Transmission and Driveline	Aggressive shift logic and early lockup	None		None					
	Increased transmission gears	None		None					
	Transmission friction reduction	None		None	None	None	Unknown	None	None
Engine Efficiency	Improved diesel engine	0 / -4	0 / -3	0 / -2	0 / -2	0.3 to 5.87 / -1 to +5	Unknown	0 / -1	19.4 to 32.1 / +16 to +29
Hybridization	Full hybrid (electric)	21.4 / +9	14.3 / +10		15.8 / +11	5.6 / +1	Unknown	4.4 / +2	16.7 / +3
	Hydraulic hybrid			6.4 / +0.3					
Management	Predictive cruise control				1.8 / +2	0.7 / +1			1.9 / +2
	Driver aids					0 / -2			

* Comparison calculated as AEA-Ricardo value minus TIAX value. Some technology payback periods are given as ranges because AEA-Ricardo provided values for subsets of the technologies listed above.

Diesel fuel price was assumed to be €1/L in the AEA-Ricardo study and is assumed to be €1.3/L in this study.

than those estimated here. Costs for automatic tire inflation, low rolling resistance tires, and low rolling resistance wide-base tires were higher than those estimated by TIAX/NAS. The difference in automatic tire inflation technology costs may be explained by noting that the TIAX/NAS study received wildly divergent estimates for the cost of automatic tire inflation systems, ranging from $300 to $13,000 (€230 to €10,000).[37] Thus, the difference between in costs between the two studies is not unexpected. The costs of low rolling resistance tires were higher than those of this study, possibly as a result of different choices in the vehicles selected to represent each segment. For example, this study indicates that low rolling resistance tires may be as inexpensive as €8 for vehicles on the lighter end of the Service segment, whereas AEA-Ricardo reported costs at €250, which may match more closely to vehicles on the heavier end of this segment.

The difference in the costs of improving engine efficiency is mostly due to AEA-Ricardo's estimate that engine improvements such as higher injection pressure or higher cylinder pressures are year-to-year product improvements and were not costed. Although this improvement was also acknowledged in the TIAX/NAS study, estimates of the cost of these year-to-year improvements are repeated and reported in this analysis. AEA-Ricardo's cost for heat recovery technologies was less optimistic than the TIAX/NAS estimates.

Relative to hybrid powertrains, AEA-Ricardo's cost estimates were consistently higher than those estimated by TIAX/NAS. The same was the case for predictive cruise control.

For comparison purposes, using AEA-Ricardo's "Cost Effective" scenario threshold of three years, potential benefits from technologies with payback within three years range from 7 to 50 percent (Figure 5-3), which is similar to the range reported by AEA-Ricardo, although the vehicle segments and technology packages differ significantly. Recognizing that the three-year threshold may be arbitrary from a technology perspective, the US experience has shown that two to three years is approximately the payback required by HDV owners in purchase decisions.[38,39] Assuming that purchase decisions are similar in the EU, using the three-year threshold as one option for categorizing the market viability of technologies may be a fair assumption.

There are several reasons common to multiple vehicle segments that explain the differences among the potential benefits estimated in the three studies. First, the baseline vehicles for the AEA-Ricardo and NRC studies meet Euro V and EPA 2007 emissions standards, respectively, compared to the 2014 vehicles assumed in this analysis, which meet Euro VI standards and already incorporate some of the potential vehicle technologies. As a result, some technologies considered in the AEA-Ricardo and NRC studies are not included as potential technologies in this analysis, because they have already been included in the baseline vehicles. To detail the technology benefit and cost differences between the AEA-Ricardo analysis and this analysis, Tables 5-2 through 5-9 above list the assumed values for each technology.

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37 Kromer, M., W. Bockholt, M. Jackson. "Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles." Prepared by TIAX LLC for National Academy of Sciences. November 19, 2009.

38 Northeast States Center for a Clean Air Future, International Council on Clean Transportation, Southwest Research Institute, TIAX LLC. "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO_2 Emissions." October 2009.

39 National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." http://www.nap.edu/catalog/12845.html. 2010.

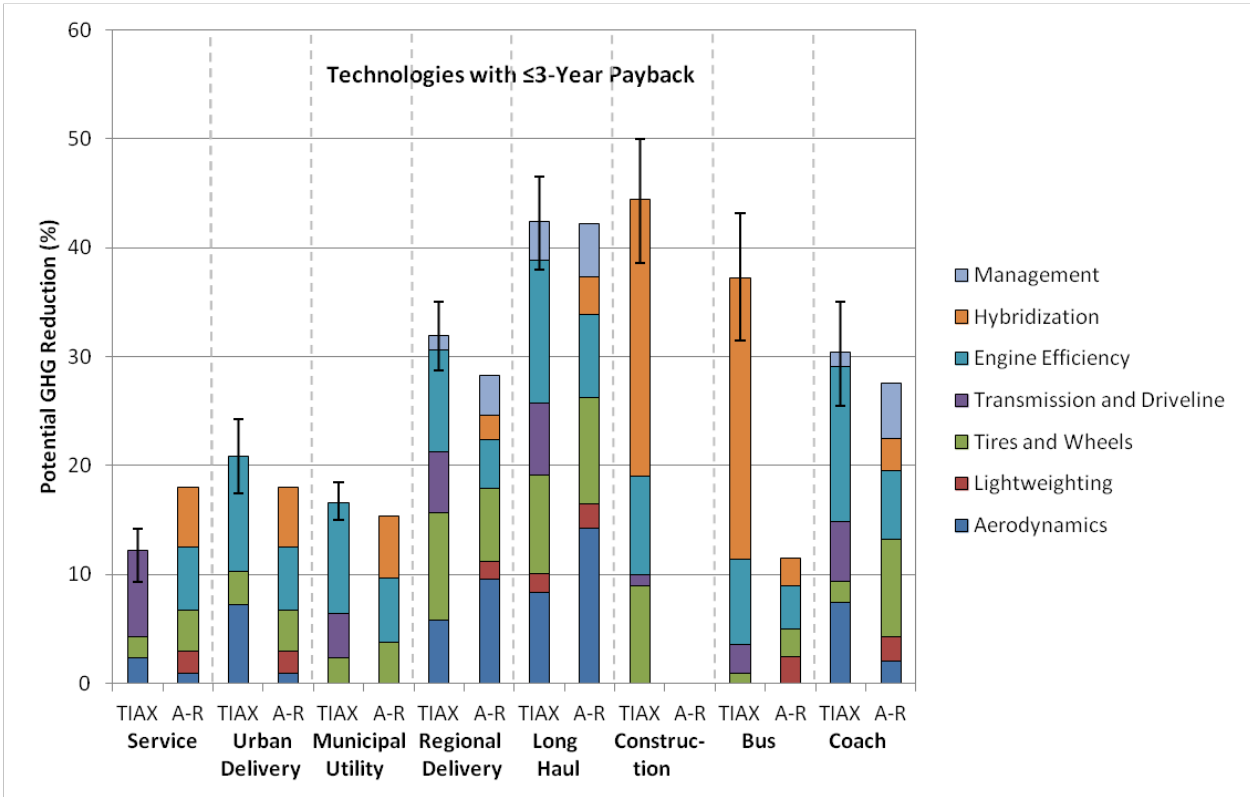


Figure 5-3. Potential New EU Vehicle GHG Reductions from Technologies with Payback within Three Years

As discussed at the beginning of this section, the AEA-Ricardo analysis grouped fuel efficiency advances into natural powertrain improvements and penalties at regular intervals until 2030, and specific engine technologies in that study were limited to controllable air compressors, electrical turbocompounding, and heat recovery. In contrast, this study employs TIAX/NAS and NRC's broader set of available engine improvements and assumes zero emissions legislation penalties.

In the tires and wheels category, this analysis differs from the AEA-Ricardo analysis in that single wide tires are not considered in every category, only in those for which they would be appropriate and likely to be adopted.

In the lightweighting category, the benefits and costs of material substitution are not consistently linked to specific and likely achievable weight reductions in the AEA-Ricardo study. This study uses the values presented in the NRC and TIAX/NAS studies, in which fuel consumption benefits and technology costs are associated with specific levels of achievable weight reductions. For example, in the Long Haul segment, the 990 lb (450 kg) material substitution weight in this analysis corresponds to specific weight savings in front, rear, and side bumpers, chassis, and accessories.

In the transmission and driveline category, this study uses the technologies considered in the NRC and TIAX/NAS studies, which include transmission friction reduction as an option for increasing overall fuel efficiency. Friction reduction was not explicitly included in the AEA-Ricardo analysis, and in general, this analysis shows 1 to 1.5 percent potential benefits in the transmission and driveline category than the AEA-Ricardo analysis. Additionally, while the AEA-Ricardo analysis assumed all baseline vehicles to use manual transmissions, this analysis assumes a mix of automatic, manual, and automated manual transmissions as described in Section 4: Vehicle Baselines, and transmission and driveline technologies are considered as appropriate.

The following sections discuss additional segment-specific reasons for differences between these analysis results and those of the NRC and AEA-Ricardo studies.

Service

The potential combined fuel consumption benefit of all technologies in the Service segment is 30 to 43 percent. These benefits are dominated by hybridization, with significant contributions from engine efficiency and aerodynamics. The comparable US segment from the NRC study is the Class 2b vehicle, and the primary reason for the differences in the technology package and potential benefits seen in this analysis is the NRC study's assumption that the baseline vehicle operates on gasoline, whereas the baseline vehicle for this study is assumed to operate on diesel.

In comparison to the AEA-Ricardo study, the benefits calculated here are very similar and show that hybridization enables the greatest share of potential fuel efficiency gains. For technologies with payback periods of three years or fewer, this analysis shows that 9 to 14 percent benefits may be achieved in the Service segment from transmission and driveline, tires and wheels, and aerodynamics. The AEA-Ricardo analysis showed that a higher magnitude of benefits may be achieved from hybridization, engine efficiency, tires and wheels, lightweighting, and aerodynamics. In addition to the segment-wide differences discussed above, the differences for this segment result from AEA-Ricardo's assumption that the baseline vehicle uses a manual transmission, whereas the 2014 baseline vehicle in this analysis is assumed to use an automatic transmission. Furthermore, the AEA-Ricardo analysis, which phases in technologies over time, considered a stop/start system separately from a full hybrid system, whereas only the full hybrid system is considered in this analysis to estimate per-vehicle fuel savings for both this study and the interpretation of the AEA-Ricardo study.

Urban Delivery

The potential combined fuel consumption benefit of all technologies in the Urban Delivery segment is 39 to 52 percent. These benefits are dominated by hybridization, with significant contributions from engine efficiency and aerodynamics. The comparable US segment from the NRC study is the box truck, which showed similar potential benefits from hybridization, engine efficiency, and aerodynamics. In comparison to the AEA-Ricardo study, the benefits calculated here are similar, though the AEA-Ricardo study reported slightly lower potential hybridization, engine efficiency, and aerodynamic benefits. In addition to the general engine efficiency differences discussed above, the differences in aerodynamics of this segment are explained by noting that that the AEA-Ricardo study looked at unspecified aerodynamic bodies and fairings, while this study specifies aft box tapering, roof deflectors, box skirts, and cab side extensions or cab/box gap fairings.

For technologies with payback periods of three years or fewer, this analysis shows that 17 to 24 percent benefits may be achieved in the Urban Delivery segment from engine efficiency, tires and wheels, and aerodynamics. In contrast, the AEA-Ricardo analysis showed that slightly lower benefits may be achieved from hybridization, engine efficiency, tires and wheels, lightweighting, and aerodynamics.

Municipal Utility

The potential combined fuel consumption benefit of all technologies in the Municipal Utility segment is 31 to 39 percent. These benefits are dominated by hybridization, with significant contributions from engine efficiency. The comparable US segment from the NRC study is the refuse hauler, which showed similar benefits as this analysis. The AEA-Ricardo study reported lower engine efficiency benefits than those estimated in this analysis, for the reasons discussed previously across all vehicle segments.

For technologies with payback periods of three years or fewer, this analysis shows that 15 to 18 percent benefits may be achieved in the Municipal Utility segment from engine efficiency, transmission and driveline, and tires and wheels. In contrast, the AEA-Ricardo analysis showed that slightly lower benefits may be achieved from hybridization, engine efficiency, and tires and wheels.

Regional Delivery

The potential combined fuel consumption benefit of all technologies in the Regional Delivery segment is 36 to 45 percent. These benefits are roughly equally divided among hybridization, engine efficiency, tires and wheels, and aerodynamics, with small contributions from management, transmission and driveline, and lightweighting. The comparable US segment from the NRC study is the tractor-trailer, with benefits similar to those estimated in this study.

The AEA-Ricardo study reported higher aerodynamics benefits and lower hybridization benefits than those estimated in this analysis. The benefits of aerodynamics and hybridization depend on the vehicle's duty cycle. A duty cycle dominated by highway driving will benefit more from aerodynamics than one dominated by stop-and-go city driving. High aerodynamic benefits would have lower hybridization benefits, and high hybridization benefits would have low aerodynamic benefits. Electric hybridization is estimated to offer greater benefits in this analysis than in the AEA-Ricardo analysis due to the assumed stop-and-go duty cycle.

For technologies with payback periods of three years or fewer, this analysis shows that 29 to 35 percent benefits may be achieved in the Regional Delivery segment from management, engine efficiency, transmission and driveline, tires and wheels, and aerodynamics. In contrast, the AEA-Ricardo analysis showed that similar benefits may be achieved from management, hybridization, engine efficiency, tires and wheels, lightweighting, and aerodynamics. The segment-specific differences stem from the assumption in this analysis that trailer aerodynamics in the form of boat tails, full gap fairings, and full skirts are applied to 2014 vehicles with better aerodynamics than today's typical vehicles.

Long Haul

The potential combined fuel consumption benefit of all technologies in the Long Haul segment is 41 to 52 percent. These benefits are roughly equally divided among hybridization, engine efficiency, tires and wheels, and aerodynamics, with small contributions from management, transmission and driveline, and lightweighting. The comparable US segment from the NRC study is the tractor-trailer, with slightly higher potential benefits resulting from the differences in the assumed baseline vehicles, tractor configurations, and speed limits.

As with the Regional Delivery segment, the AEA-Ricardo study reported higher aerodynamics benefits than those calculated in this analysis. The AEA-Ricardo study included aerodynamic trailers/bodies, fairings, and spray reduction mud flaps, while this study includes boat tails, full gap fairings, and full skirts applied to best-in-class 2014 vehicles.

For technologies with payback periods of three years or fewer, this analysis shows that 38 to 47 percent benefits may be achieved in the Long Haul segment from management, engine efficiency, transmission and driveline, tires and wheels, lightweighting, and aerodynamics. In contrast, the AEA-Ricardo analysis showed that higher benefits may be achieved from a combination of management, hybridization, engine efficiency, tires and wheels, lightweighting, and aerodynamic technologies.

Construction

The potential combined fuel consumption benefit of all technologies in the Construction segment is 39 to 50 percent. These benefits are dominated by hybridization, with significant contributions from engine efficiency and tires and wheels. This segment was not considered explicitly for the US in the NRC study, though a bucket truck with power take-off (PTO) was analyzed. In this study, the Construction segment is represented by a dump truck. Note that because the Construction segment contains a variety of vehicles, additional technologies may be applied to these vehicles that are not necessarily included here. For example, for Construction vehicles using PTO, hybridization with electric PTO may be a technology that offers additional benefits.

The AEA-Ricardo study did not describe specific technologies applied to this segment and thus is not compared here.

Bus

The potential combined fuel consumption benefit of all technologies in the Bus segment is 35 to 47 percent. These benefits are dominated by hybridization, with significant contributions from engine efficiency and lightweighting. The US bus segment from the NRC study showed similar potential benefits. The AEA-Ricardo study reports higher tires and wheels benefits than those calculated in this analysis, due the use of single wide tires.

For technologies with payback periods of three years or fewer, this analysis shows that 31 to 43 percent benefits may be achieved in the Bus segment from hybridization, engine efficiency, transmission and driveline, and tires and wheels. In contrast, the AEA-Ricardo analysis showed that significantly lower benefits may be achieved from hybridization, engine efficiency, tires and wheels, and lightweighting. The most significant difference lies in hybridization; this analysis estimates that the large benefit from electric hybridization can be attained cost effectively compared to the AEA-Ricardo analysis.

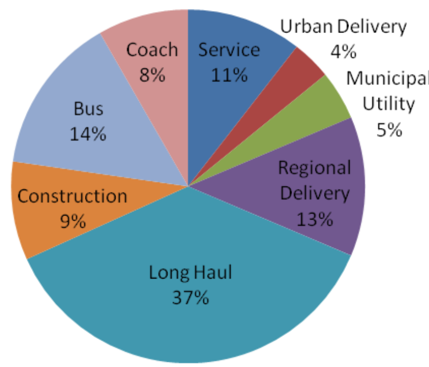
Coach

The potential combined fuel consumption benefit of all technologies in the Coach segment is 32 to 43 percent. These benefits are roughly equally divided among hybridization, engine efficiency, and aerodynamics, with small contributions from tires and wheels and lightweighting. The US coach segment from the NRC study showed slightly lower potential benefits, since hybridization was not included. The AEA-Ricardo study reported higher tires and wheels benefits than those calculated in this analysis, again due to the use of single wide tires.

For technologies with payback periods of three years or fewer, this analysis shows that 26 to 35 percent benefits may be achieved in the Coach segment from engine efficiency, transmission and driveline, tires and wheels, and aerodynamics. The AEA-Ricardo analysis showed that slightly lower benefits are achieved from management, hybridization, engine efficiency, tires and wheels, lightweighting, and aerodynamics. The segment-specific differences stem primarily from AEA-Ricardo's estimate of higher predictive cruise control and aerodynamic benefits.

6. Heavy-Duty Market Discussion

As shown in the previous section, the potential GHG reduction benefits at the vehicle level are significant across all HDV segments, even when technologies with payback periods of three years are considered. The next step is to examine these benefits at the segment level. Figure 6-1 presents the current heavy-duty fuel consumption by segment. As discussed in Section 2: Methodology, these fuel consumption shares are derived from the AEA-Ricardo study.



Reference: Hill, N., S. Finnegan, J. Norris, C. Brannigan, D. Wynn, H. Baker, I. Skinner. "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy." Prepared by AEA and Ricardo for European Commission – DG Climate Action, DG ENV. 070307/2009/548572/SER/C3. February 22, 2011.

Figure 6-1. EU Fuel Consumption by Vehicle Segment

The relative shares of fuel consumption by each vehicle segment suggest that it may be more effective to target fuel efficiency improvement technologies in some segments than others. Technologies for vehicles in the Long Haul segment, many of which are applicable to similar vehicles in the Regional Delivery segment, may offer the greatest impact. In addition, the Service, Bus, and Coach segments are also attractive because they offer mass-market or relatively uniform vehicles across the segment that can benefit from similar fuel savings technologies. Conversely, technologies for the Urban Delivery, Municipal Utility, and Construction segments may offer the least impact because these segments are highly fragmented, with a variety of vehicle types and configurations. Accordingly, EU strategies aimed at reducing overall GHG emissions from the heavy-duty sector may benefit from specifically targeting the high fuel consumption, uniform vehicles of the Long Haul, Regional Delivery, Service, Bus, and Coach segments and regarding the remaining segments as a single group. A similar approach has already been taken in the US heavy-duty GHG regulation.

Using the cost effectiveness metric to compare technologies across vehicle segments, Table 6-1 presents the value of each technology in each segment as the total lifetime GHG reduction divided by the technology cost. The cost effectiveness values are broadly categorized in green for the most cost effective technologies, yellow for somewhat cost effective technologies, and red for the least cost effective technologies. Among the most cost effective technologies are low rolling resistance tires, low rolling resistance wide-base tires, transmission friction reduction, and

Table 6-1. Technology Cost Effectiveness

	Technology	Cost Effectiveness (lifetime kg CO_2e reduced / capital cost in 2010€)							
		Service	Urban Delivery	Municipal Utility	Regional Delivery	Long Haul	Construction	Bus	Coach
Aerodynamics	Aft box taper		25						
	Boat tail				7	8			
	Box skirts		18						
	Cab side extension or cab/box gap fairings		7						
	Full gap fairing				5	6			
	Full skirts				4	4			
	Roof deflector		21						
	Streamlining	51							14
Lightweighting	Material substitution	3	5	2	3	3	5	3	1
Tires and Wheels	Automatic tire inflation on vehicle/tractor				1	1	1		7
	Automatic tire inflation on trailer				7	8			
	Low rolling resistance tires	411		55				34	43
	Low rolling resistance wide-base single tires		48		101	109	175		
Transmission and Driveline	Aggressive shift logic and early lockup	68		50					
	Increased transmission gears	6		7					
	Transmission friction reduction	4		27	21	22	36	32	29
Engine Efficiency	Improved diesel engine	6	12	15	9	5	16	18	7
Hybridization	Dual-mode hybrid	2			2	1			
	Parallel hybrid		8				11		2
	Parallel hydraulic hybrid			5					
	Series hybrid							11	
Management	Predictive cruise control				62	67			88
	Route management					4			
	Training and feedback					14			

Based on similar vehicles in the US, vehicle lifetimes are assumed to be: 10 years for Service, 19 years for Urban Delivery, 17 years for Municipal Utility, 12 years for Regional Delivery, 8 years for Long Haul, 19 years for Construction, 14 years for Bus, and 12 years for Coach. Note that multiple replacements of a technology (e.g., tires) during the vehicle's lifetime are not considered.

predictive cruise control. Among the least cost effective technologies are automatic tire inflation and material substitution for lightweighting.

To put the vehicle-level benefits described above into context, as described in Section 2: Methodology, technology packages are assumed to be incorporated into all new vehicles beginning in 2020. As the HDV fleet turns over, the relative fraction of vehicles with these advanced technology packages increases. The assumed fleet turnover fractions are shown in Table 6-2. A value of 75% implies that 25% of total vehicle kilometers traveled (VKT) in 2030 can be attributed to vehicles that do not have advanced technology packages—that is, vehicles sold prior to 2020. These percentages are meant to reflect the fact that while heavy-duty vehicles often have lifetimes of 20 or more years, the majority of VKT typically occurs in the early years of the vehicle's life.

Table 6-2. HDV Fleet Turnover by 2030

Vehicle Segment	Fraction of Total VKT in 2030 from Vehicles with Advanced Technology Packages (%)*
Service	75%
Urban Delivery	75%
Municipal Utility	75%
Regional Delivery	80%
Long Haul	80%
Construction	75%
Bus	75%
Coach	80%

*Estimates based on annual turnover and VKT patterns of similar vehicles the US; US Environmental Protection Agency, "MOVES2010 Highway Vehicle: Population and Activity Data," EPA-420-R-10-026, November 2010.

Table 6-3 shows the total GHG benefits of applying the technologies to each population of vehicles beginning in 2020. By multiplying the vehicle-level benefits[40] by the number of turned-over vehicles in the fleet, this table presents the total emissions that would result from both a "business-as-usual" case (where current vehicle technologies are used) and an "all applicable technologies" case (where all available fuel efficiency improvement technologies are used in new HDVs). The populations shown below are the 2010 population and the 2030 population, as projected by AEA-Ricardo. For comparison, both the total technologies packages and the three-year payback[41] packages are presented. The same results using AEA-Ricardo's values and TIAX's methodology are also shown in this table.

After accounting for the projected growth in vehicle population in 2030, it is possible to reduce GHG emissions from HDVs in 2030 to 22 percent below 2030 BAU levels using only technologies that offer payback to the end user within three years. Additional technologies can reduce GHG emissions to 28 percent below 2030 BAU levels. The AEA-Ricardo values indicate

[40] These benefits include estimated 2010-2014 benefits (Table 2-3) and the segment-specific benefits in Tables 5-2 through 5-9.

[41] Three years for payback was used by AEA-Ricardo as a threshold for technology adoption. This period is used in this analysis only for comparison purposes and is not intended to suggest any technical rationale nor that this threshold be used universally.

that 18 and 25 percent reductions below 2030 BAU levels are achievable using technologies with three-year payback and all applicable technologies, respectively. Note, however, that these reductions exclude reductions from the Construction segment, for which the AEA-Ricardo report did not specify fuel efficiency improvement technologies.

Table 6-3. Potential GHG Reductions by Segment

Vehicle Segment	2010 Population (million vehicles)	2010 CO_2e Emissions (million tonnes)	Projected 2030 Population (million vehicles)	2030 BAU CO_2e Emissions (million tonnes)	2030 Emissions Reduction, Assuming All Applicable Technologies (million tonnes)		2030 Emissions Relative to 2030 BAU, Assuming All Applicable Technologies (%)		2030 Emissions Reduction, Assuming Only Technologies with ≤3 Year Payback (million tonnes)		2030 Emissions Relative to 2030 BAU, Assuming Only Technologies with ≤3 Year Payback (%)	
					TIAX	A-R	TIAX	A-R	TIAX	A-R	TIAX	A-R
Service	1.90	35	2.60	48	11	11	76%	77%	4	6	92%	88%
Urban Delivery	0.45	12	0.55	15	4	3	71%	80%	2	2	87%	89%
Municipal Utility	0.40	15	0.60	23	5	4	79%	81%	2	2	90%	91%
Regional Delivery	1.20	40	1.75	58	15	15	74%	75%	12	11	80%	82%
Long Haul	2.00	100	2.60	130	39	45	70%	65%	35	38	73%	71%
Construction	1.00	30	1.25	38	12	Unknown	67%	Unknown	12	Unknown	68%	Unknown
Bus	0.45	25	0.44	24	6	6	75%	76%	5	2	78%	93%
Coach	0.40	18	0.30	14	3	3	75%	75%	3	2	80%	82%
All Segments	**7.80**	**275**	**10.09**	**349**	**96**	**88**	**72%**	**75%**	**75**	**62**	**78%**	**82%**

A-R: AEA-Ricardo

BAU: business as usual, using baseline vehicle technologies

Notes:
Population numbers and projections for each EU vehicle segment are derived from AEA-Ricardo's report.
All CO_2e levels are given as well-to-wheel emissions and are derived from AEA-Ricardo's emissions allocations as described in Section 3: Methodology.
"All Segments" totals for AEA-Ricardo technologies do not include reductions from the Construction segment, which were unspecified in the AEA-Ricardo report.

In terms of aerodynamic technologies to increase fuel efficiency and reduce GHG emissions, it is important to match the various improvements being applied to vehicles to provide integrated aerodynamics packages (e.g., cab aerodynamics must be matched to trailer aerodynamics). Furthermore, the consideration of potential aerodynamic technologies (e.g., boat tails or more aerodynamic tractors) should take into account any limitations imposed by vehicle length regulations.

As mentioned previously, this assessment provides the total potential GHG benefits of the full spectrum of options for the heavy-duty sector, and the determination of which technologies and packages will be applied to achieve what magnitude of benefits is left to policymakers and the marketplace. Adoption of these technologies will be a function of policies (e.g., vehicle emissions standards, fuel economy standards, and incentives) and vehicle owner economics, and will also be driven by additional factors such as end user acceptance and driver retention. In the US, mandatory heavy-duty fuel consumption reductions of up to 23 percent by 2017 are moving OEMs to adopt many of the technologies described above, including aerodynamic improvements, engine friction reduction, advanced fuel injection, advanced turbocharging, parasitic loss reduction, waste heat recovery, lightweighting, low rolling resistance tires, and idle reduction.[42,43] These technologies will be options for improving HDV efficiency in the EU as well.

While the focus of this report is on technology options for improving fuel economy and not on policy, it is useful to note that in addition to fuel economy regulations, low carbon fuel standards are another policy tool for achieving GHG reductions. In the US, states that have adopted such standards examine well-to-wheel emissions that look at the full fuel cycle, from fuel production to fuel use. In the EU, Directive 2009/30/EC (Fuel Quality Directive) mandates reductions in lifecycle GHG intensity for fuel supplied for road transport. Well-to-wheel emissions policies are broader than fuel economy policies, which generally focus only on tank-to-wheel emissions. By incorporating upstream emissions, policies can encourage the market adoption of additional technologies not included above, such as alternative fuels. For example, US estimates of full fuel cycle GHG benefits suggest that natural gas and electric vehicles may offer approximately 6 percent[44] and 40 to 90 percent[45] reductions, respectively, compared to diesel vehicles meeting EPA 2010 emissions standards.

A third policy tool that has been implemented in the EU and the US is public procurement requirements. The specific requirements vary, but fundamentally, these policies set criteria and/or processes for purchase and use of vehicles by government agencies and publicly funded organizations. In the US, the Energy Policy Act mandates the purchase of alternative fuel vehicles, the use of alternative fuels in dual fuel vehicles, and the reduction of petroleum fuel consumption by public fleets. In the EU, Directive 2009/33/EC (Clean and Energy-Efficient Road Transport Vehicles Directive) requires that public bus and coach operators take into account the energy consumption and GHG and pollutant emissions of the vehicles over their lifetimes. However, this directive does not set specifications for energy consumption and emissions, allowing contracting authorities, contracting entities, and operators of public transport services to set their own specifications or otherwise incorporate energy and environmental criteria in purchasing decisions. At present, it is unclear what direct effect this directive has had on public procurement due to lack of methodical data collection on the purchase processes and behaviors of the procuring organizations. Available data suggest that buses and coaches are moving toward more stringent emissions standards. In the first survey of public transport statistics conducted by the International Association of Public Transport (UITP), two-thirds of

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[42] Reiskin, J.S. "OEMs Detail Design Innovations to Meet New Greenhouse Rules." *Transport Topics*, pg. 5 and 28. August 22, 2011.

[43] Galligan, J. "The Push for Mileage." *Light & Medium Truck*, pg. 16-18. September 2011.

[44] In the Urban Delivery, Municipal Utility, Regional Delivery, Long Haul, and Bus segments. Note that these natural gas vehicle benefits were calculated for stoichiometric, 3-way catalyst technology, which offers lower fuel economy than diesel. The benefits offered by advanced natural gas engine technologies are expected to be greater than those shown here. Law, K., M. Chan, W. Bockholt, M.D. Jackson, "US and Canadian Natural Gas Vehicle Market Analysis: Comparative Analysis," prepared by TIAX LLC for America's Natural Gas Alliance, December 31, 2010.

[45] In the Service, Urban Delivery, and Bus segments; Law, K., M. Chan, W. Bockholt, M.D. Jackson, "US and Canadian Natural Gas Vehicle Market Analysis: Comparative Analysis," prepared by TIAX LLC for America's Natural Gas Alliance, December 31, 2010.

existing buses in the EU met Euro II and Euro III emissions standards. When questioned about new vehicle acquisition intentions, 68 percent of respondents indicated that they planned to acquire Euro IV vehicles, 33 percent planned to acquire Euro V vehicles, and 27 percent planned to acquire Enhanced Environmentally Friendly Vehicles (EEVs).[46] However, this survey was conducted in 2007, before Directive 2009/33/EC was enacted. Therefore, additional data on the precise motivators of public bus and coach procurement and how operators meet this directive's requirements are needed to understand its true effects. Manufacturers are assisting in the implementation of this directive by offering calculators and tools for the procurement process,[47] and further exploration of how such tools are used in the procurement process will enable a more complete assessment of the directive's impacts.

The other driver of market implementation of fuel efficiency improvement technologies is economics for the vehicle owner. Certain market and vehicle operation characteristics are conducive to favorable end user economics and thus adoption of fuel efficiency technologies. As quantified in the previous section, these characteristics include: high annual activity, high fuel use, low fuel economy, and high fuel price. Aside from technical performance, economics can often be the main market barrier if payback if not attained within two or three years. The reverse is true as well: net lifetime fuel savings can be a significant motivator for purchasers to pay extra for technologies upfront. As such, the vehicle owner economics hinge on fuel prices. Higher fuel prices allow the owner to achieve payback on fuel efficiency improvement technologies more quickly. Compared to US, the EU sees consistently higher fuel prices, and thus from an economic perspective, technologies that may not be commercially viable in the US may be viable in the EU. Stated differently, the more favorable end user economics in the EU may allow certain technologies to see greater market demand than in the US In September 2011, retail diesel fuel prices in the EU ranged from €1.164 to €1.619 per liter.[48] In the same period, US prices averaged €0.546 per liter.[49] Such differences in fuel prices translate to payback periods for the EU that are approximately half as long as those of the US Therefore, economics may be especially powerful a motivator for the EU heavy-duty sector, even more so than for the US heavy-duty sector. With advanced technologies, financial incentives tied to societal benefits and voluntary programs such as SmartWay have been very successful in the US

Finally, payback also depends on the cost of the technologies. The world market, beyond the EU, will help increase demand for fuel savings technologies, allowing costs to decrease as volumes increase. Furthermore, OEMs may be able to introduce advanced technologies into the market sooner than they would otherwise without the broader global market. For example, the cost effectiveness of turbocompounding as an advanced technology in the EU enables the same technology to be offered in the US at larger economies of scale than if the technology were considered for the EU alone. The US market is currently being driven by fuel economy and GHG

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46 Responses are not mutually exclusive; International Association of Public Transport (UITP), "Public Transport Statistics Report," Issue 1, http://www.uitp.org/mos/pics/stats/survey_bus_fleet.pdf, 2007.

47 For example, Scania offers an Environmental Product Declaration Calculator that calculates energy consumption, local emissions (oxides of nitrogen, hydrocarbons, and particulate matter), and global emissions (carbon dioxide) for specific buses and trucks.

48 Europe's Energy Portal. "Fuel Prices." http://www.energy.eu. Accessed September 15, 2011.

49 Using a conversion rate of €0.7216 per US$1.00; Energy Information Administration, "On-Highway Diesel Fuel Prices," http://www.eia.gov/oog/info/twip/twip_distillate.html, accessed September 15, 2011.

standards for 2017 and beyond, which can be expected to help move technologies into the global marketplace with favorable payback periods.

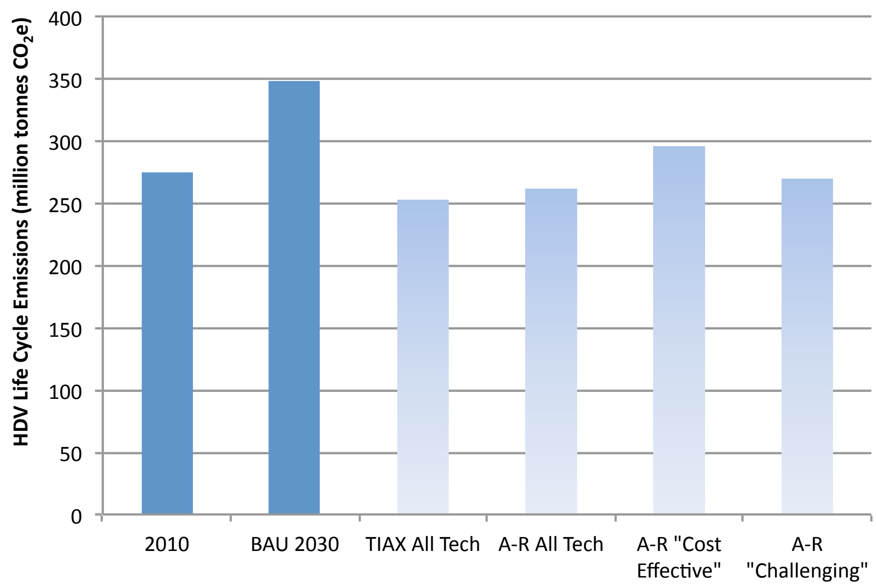
7. Conclusions

This analysis shows that significant GHG reductions are achievable in the EU heavy-duty sector. At the vehicle level, potential benefits of fuel efficiency improvement technologies range from 9 to 50 percent reduction in fuel consumption using only technologies that offer payback within three years. Potential benefits range from 30 to 52 percent using all potential 2015 to 2020 fuel-saving technologies. Aggregated across the vehicle segments, it is possible to reduce GHG emission in 2030 to 22 percent below 2030 business-as-usual GHG levels using only technologies that offer payback within three years. The potential GHG reduction goes up to 28 percent using all applicable technologies on all new HDVs.

These reductions are similar to AEA-Ricardo's findings: using the turnover assumptions of this analysis and applying the AEA-Ricardo per-vehicle estimates, the use of all available technologies can reduce CO_2 emissions in 2030 to 25 percent below 2030 BAU levels.[50] Using the original AEA-Ricardo methodology, in the "Cost Effective" scenario (i.e., with a nominal three-year payback period), CO_2 emissions in 2030 would be 15percent lower than 2030 BAU levels, and in the "Challenging" scenario, CO_2 emissions in 2030 would be 23 percent lower than 2030 BAU levels (Figure 7-1).

The differences between applying the TIAX analysis methodology and the AEA-Ricardo methodology to the AEA-Ricardo values stem primarily from assumptions about market uptake rates. AEA-Ricardo applied specific technology deployment rates for each technology between 2010 and 2030. In the "Challenging" scenario, by 2030, these rates ranged from 0 to 100 percent. For example, market adoption of pneumatic booster hybridization was assumed to be 6 percent in the Long Haul segment and 0 percent in all other segments, whereas market adoption of automatic tire pressure adjustment was assumed to be 100 percent in all segments. In particular, hybridization, which were the AEA-Ricardo technologies offering greatest potential benefits, generally reached market penetration no greater than 30 percent.[51] In contrast to developing uptake rates for each individual technology, the TIAX approach uses technology packages and assumptions about the rate of adoption of these groups of technologies.

[50] Excluding reductions from the Construction segment, for which fuel efficiency improvements were unspecified.



BAU: business as usual
A-R: AEA-Ricardo

Figure 7-1. Comparison of GHG Reduction Analyses

In this analysis, the most cost effective technologies for multiple vehicle segments include low rolling resistance tires, low rolling resistance wide-base tires, transmission friction reduction, and predictive cruise control. Among the least cost effective technologies are automatic tire inflation and material substitution for lightweighting.

Within the eight vehicle segments, the key segments to target based on magnitude of potential GHG reductions, relative share of transportation fuel consumption, and uniformity of vehicle across the segment are the Long Haul, Regional Delivery, Service, Bus, and Coach segments. Combined, these segments account for 83 percent of total fuel consumption by the heavy-duty sector. The remaining segments (Urban Delivery, Municipal Utility, and Construction) are highly fragmented, with vehicles designed for specialized applications, and thus may be more difficult to target for GHG reductions using available technologies.

As in the US, the market adoption of the various fuel efficiency improvement technologies in the EU will be influenced by policies and economics. Policies including fuel economy regulations, low carbon fuel standards, financial incentives, and public procurement mandates will determine the fuel efficiency and carbon intensity of transportation. Economics for vehicle owners in the form of payback through fuel savings will be one of the significant factors that dictate the viability and market demand for these technologies. As the EU considers a path of GHG reductions from the HDV sector, the technologies highlighted in this assessment may enable significant benefits to be achieved.