DOE SuperTruck Program Benefits Analysis

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Foreword

The gross domestic product (GDP), and hence the economic activity, of the U.S. is strongly linked to freight transport (ton-miles). Heavy-duty Class 8 tractor-trailer trucks haul about 69 percent of all freight tonnage and as much as 80 percent of the total quantity of goods transported. They account for over 20 percent of the fuel consumed in the U.S.[1]

Fuel cost is the number one expense for truck fleets which are operating on razor-thin profit margins. About 87 percent of fleets operate less than 6 trucks. Many of the over 3 million truck drivers are not part of fleets but are independent owner-operators[2]. Increased freight efficiency (ton-miles per gallon of fuel) not only represents one of the most promising pathways for rapidly reducing the Nation's oil consumption, but also increases the likelihood of the industry's survival in a tough business climate.

SuperTruck is a DOE-funded, industry cost-shared initiative focused on developing and demonstrating technologies to improve the overall freight efficiency of heavy-duty Class 8 tractor-trailer trucks. Historically, DOE-sponsored heavy-duty truck engine technologies have been quickly adopted within the heavy truck fleet because of rapid market turnover and dramatic cost savings to the owner/operators. Technologies developed under the *SuperTruck* initiative are expected to be quickly adopted as well.

The goal of *SuperTruck* is to develop and demonstrate by 2015, a 50 percent improvement in freight efficiency (ton-miles per gallon) for Class 8 long-haul trucks compared to current models. At least 20 percent is expected to be achieved through heavy-duty engine improvements, and the rest from reduction in aerodynamic losses, reduction in vehicle weight and auxiliary loads, and other approaches such as hybridization. *SuperTruck* is a cross-cutting, collaborative industry cost-shared research and development effort sponsored by the U.S. DOE Vehicle Technologies Program (VTP) and supported by the Advanced Combustion Engine R&D, Vehicle and Systems Simulation and Testing, and Materials Technology subprograms. The four competitively selected industry *SuperTruck* project teams are headed by Cummins Inc., Daimler Trucks North America LLC, Navistar, Inc., and Volvo Technology of America, Inc. These industry teams make up over 90 percent of the heavy truck market and as such, DOE expects to achieve a broad market reach with energy savings and emission reduction technologies coming from this effort.

This report presents an analysis conducted for the Vehicle Technologies Program (VTP) to ascertain the fuel saving benefits of achieving the goals of the *SuperTruck* initiative and to determine if the benefits are commensurate with the Federal investment in this effort. Benefits

[1] 21st Century Truck Partnership – Roadmap and Technical White Papers, December 2006, p. 5. [http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/21ctp_roadmap_2007.pdf]
[2] "R&D Opportunities for Heavy Trucks," DOE, June 2009. [http://www1.eere.energy.gov/vehiclesandfuels/pdfs/truck_efficiency_paper_v2.pdf]

are calculated by characterizing the SuperTrucks, estimating a per-truck fuel efficiency benefit and associated incremental cost, and estimating market uptake for estimating at the national scale. Because the mix of technologies used to attain the *SuperTruck* goals is unique to each team, specific information describing the performance attributes of the engines and vehicle platforms were provided by each of the industry teams. The attributes used in the analysis were based either on the representative configuration of the platforms that are being developed or best assumptions available. A market penetration model estimates market uptake as a function of SuperTruck characterization. The entire process draws both on the expertise of industry partners and leverages the tools built during past DOE efforts to quantify the benefits of Federal government investment.

The results are based on analysis of two technology platforms that roughly represent an advanced conventional (non-hybrid) Class 8 tractor-trailer and a hybrid Class 8 tractor-trailer. Market penetration of each platform was analyzed separately under two sets of economic assumptions:

- Low market potential assumptions: low fuel price and high technology costs, and
- High market potential assumptions: high fuel price and low technology costs.

Under favorable technology cost and fuel price assumptions, market penetration estimates are significant and range from 19% to 59% in 2020 and 36% to 73% in 2050. This would result in an average cumulative fuel savings equivalent to 185 million bbl of oil by 2020 and 4450 million bbl by 2050. It should be noted that the fuel prices under this favorable case are an extrapolation of current levels and trends. Even under the assumption of relatively high technology costs low fuel prices, the analysis shows promising market potential ranging from 2% to 22% of new class 8 combination unit vehicle miles in 2020 and 8% to 36% by 2050. This results in a cumulative fuel savings, on average, of 48 million bbl of oil by 2020 and 1590 million bbl by 2050. It's worth noting that even in the least favorable scenario, the *SuperTruck* initiative is expected to yield fuel savings benefits of between over $80 billion and over $400 billion. Given that these benefits are accrued as the result of government investment of $138 million, the return on investment is at least 500:1, at the low end. A return on investment of this magnitude in considered very favorable and would seem to justify the Federal investment in this project.

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List of Abbreviations

APU - auxiliary power unit
bbl - barrels
BTE - brake thermal efficiency
DPF - diesel particulate filter
EGR - exhaust gas recirculation
GPRA - Government Performance and Results Act
HTEB - Heavy Truck Energy Balance model
HTEMS - Heavy Truck Energy Modeling System
mbpd - million barrels per day
NAS - National Academy of Sciences
ORC - organic Rankine cycle
SCR - selective catalytic reduction
TAE - TA Engineering, Inc.
VIUS - Vehicle Inventory and Use Survey
VTP - Vehicle Technologies Program
VVA - variable valve actuation
WHR - waste heat recovery

1.0 Introduction

1.1 Background

This report presents the methodology, inputs, and results of the analysis of the estimated benefits associated with the SuperTruck Initiative. SuperTruck is a cross-cutting, collaborative research and development project sponsored by the U.S. DOE Vehicle Technologies Program (VTP) and supported by multiple subprograms. The initiative is co-funded by VTP and industry partners, and all technologies remain proprietary to the four industry teams:

- Cummins / Peterbilt,
- Detroit Diesel / Daimler,
- Navistar, and
- Volvo.

Each industry team is working independently to attain the following program goals:

1. Demonstrate a 50% improvement in overall freight efficiency of a Class 8 tractor-trailer, measured by ton-miles per gallon, relative to a baseline truck defined by the industry team. At least 20% of this improvement must be due to goal 2 below.
2. Develop an engine capable of achieving 50% brake thermal efficiency (BTE) engine as measured on a dynamometer under a load representative of a level road at 65 mph.
3. Identify key pathways to achieving 55% BTE in a heavy-duty diesel engine.

There are many different technologies and approaches under development that could be implemented to meet the SuperTruck goals. Over a 3 to 5 year performance period, the participants must develop, test, and ultimately demonstrate a full-scale vehicle. Bringing these technologies to a sufficient state of maturity and integrating them into a complete vehicle system within the timeframe of the project presents significant challenges and uncertainties. For a research team pursuing a single solution under a hard deadline, this results in a high level of risk should a problem arise along a critical development path.

Part of the program strategy by the DOE Vehicle Technologies Program is to fund multiple teams simultaneously and separately to pursue the same goals to mitigate this risk. Each industry team has selected a research and development strategy consistent with their experience, customer base, and business model. This approach is believed to significantly enhance the probability of success and the anticipated public benefits that result from the government investment.

The mix of technologies used to attain the SuperTruck goals is unique to each partner. As a result, the cost of the vehicle platforms and performance in various duty cycles will differ. These features are important factors in determining market potential and thus fuel savings. In order to simplify the analysis, two technology platforms were analyzed that roughly represent an advanced conventional approach (non-hybrid) and a hybrid vehicle approach. Each platform was analyzed separately under two sets of economic assumptions:

- Low market potential assumptions: low fuel price and high technology costs, and
- High market potential assumptions: high fuel price and low technology costs.

In order to assess fuel consumption benefits and technology costs, specific information describing the performance attributes of the engines and vehicles being developed was requested from the industry participants. Much of this information is proprietary in nature and protected under the SuperTruck contract agreements. As a result, this information is not reproduced in this document. In addition, results are not reported for individual teams, but are reported either as ranges or for the representative platforms that were developed.

1.2 Analysis Overview

The SuperTruck benefits analysis applies a market-based approach adapted from the methodology used annually to estimate heavy truck VTP program benefits in support of the federal government budget request process. This analysis approach has been used by VTP for more than 10 years. During this time, the associated modeling tools also have been used to analyze the impact of various policy and technology scenarios.

The SuperTruck benefits analysis generally follows the annual program benefit analysis methodology. First, information was gathered from program participants regarding each team's baseline truck, the advanced technologies to be included in the SuperTruck configuration, the expected fuel efficiency benefit of these technologies, and the drive cycle for which these benefits were estimated. The contribution of component technologies to the total vehicle efficiency improvement was then disaggregated by technology area. Market penetrations were estimated based on two generic baseline truck configurations incorporating SuperTruck technologies and comparing to the baseline.

To estimate SuperTruck vehicle costs, the baseline and advanced technology descriptions and fuel efficiency estimates were compared to analysis performed by TIAX for the National Academy of Sciences (NAS) (TIAX, 2009) and prior analyses conducted by TA Engineering, Inc. (TAE). The TIAX analysis discusses factors that impact the costs of component technologies and provides a range of likely costs. Using this information, TAE developed a low and high cost estimate for each SuperTruck configuration. These costs and fuel economies were used in estimating market penetrations relative to the baseline truck configurations. The resulting estimated new fleet fuel economies were then used to project future fuel consumption and savings. This methodology is described in more detail in Section 2.0.

1.3 Document Contents

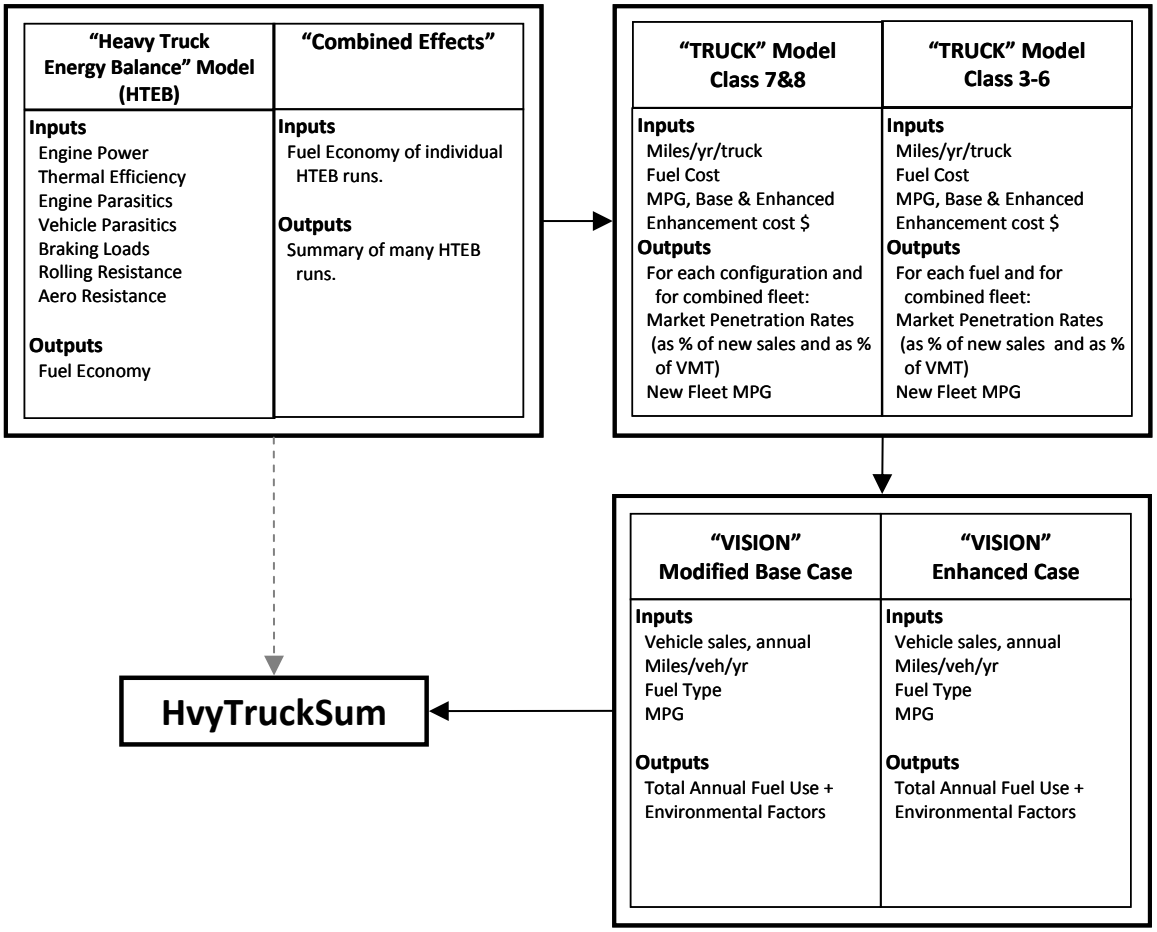
This document is organized as follows. Section 2.0 describes the analysis methodology in more detail. Baseline and SuperTruck configuration descriptions are provided in Section 3.0. The results of the technology costs analysis are summarized in Section 4.0. The inputs and results of the fuel consumption benefits analysis are provided in Section 5.0. Section 6.0 provides a summary of the analysis and makes some observations. Due to confidentiality issues, the discussions in this document are representative of the general research and development approaches of the participants rather than being specific to a single developer, approach, engine, or vehicle configuration.

2.0 Methodology

2.1 Approach

The SuperTruck benefits analysis applies a market based approach adapted from the methodology used annually in support of VTP reporting requirements under the Government Performance and Results Act (GPRA). This methodology employs results from a survey conducted by the American Trucking Associations to assess driver payback tolerance for investment in energy cost reducing technologies. The GPRA analysis for VTP estimates energy and environmental benefits of heavy vehicle program elements using the Heavy Truck Energy Modeling System (HTEMS) illustrated in Figure 2-1. HTEMS consists of a set of linked Excel workbooks that are used to calculate the annual energy consumption of heavy trucks in weight classes 3 through 8 with projections from the current year up through the year 2050. Truck annual operating profiles are based on the U.S. Census Bureau's 2002 Vehicle Inventory and Use Survey (VIUS) (USDOC, 2004) data for vehicles less than two years old. As indicated in Section 1.2, the methodology has been in use for an extended period. During this time, the HTEMS components have undergone frequent upgrade and have been used to analyze the impact of various policy and technology scenarios (see ANL, 2007).

Figure 2-1: Heavy Truck Energy Modeling System Used for GPRA Analysis



In general, the HTEMS consists of four analytic steps as described below:

1. Estimate fuel efficiency benefit of individual advanced technologies and of the complete vehicle systems using the Heavy Truck Energy Balance model (HTEB);
2. Estimate market penetration of advanced vehicle platforms relative to baseline platforms and resulting new fleet fuel economy using the TRUCK model;
3. Estimate energy, oil, and carbon emission savings using Argonne National Laboratory's VISION model; and
4. Generate results tables and graphics by truck class and VTP program element using the HvyTruckSum worksheet.

The methodology used for the SuperTruck benefits analysis follows this general approach with some modifications as described below.

First, for the GPRA analysis, the baseline truck configuration and fuel economy is based on the EIA's Annual Energy Outlook reference case. Advanced vehicle platforms are developed to be

representative of all VTP research goals relating to heavy trucks. The HTEB is then used to estimate the fuel economy of the advanced platforms. For the SuperTruck analysis, information was gathered from program participants regarding each team's baseline Class 8 truck, the advanced technologies to be included in the team's SuperTruck configuration, the expected fuel efficiency benefit of these technologies, and the drive cycle for which these benefits were estimated. These baseline and SuperTruck configurations were modeled with the HTEB to provide fuel economy results that approximated the simulations and analyses performed by the industry teams. As in the GPRA analysis, the HTEB then was used to assess the contribution of component technologies, grouped by technology area, to the total vehicle efficiency improvement.

The SuperTruck program analysis results in four baseline trucks and four advanced configurations. These baseline trucks were characterized using trucks and duty cycles specific to each industry team. Due mainly to differences in assumed duty cycles and loading conditions, the resulting fuel economies did not align with the historic sales fleet captured in VISION. Since it was desirable to have a baseline consistent with the VISION model, TAE developed a Baseline Case projected fuel economy using the most recent GPRA analysis baseline. For each industry team, a fuel economy "multiplier" was calculated as the ratio of the SuperTruck fuel economy to that team's baseline truck. These ratios were then applied to the Baseline Case to create the SuperTruck Case fuel economies.

The SuperTruck cost analysis followed the same approach and used the same sources as prior GPRA analyses. To estimate SuperTruck vehicle costs, the baseline and advanced technology descriptions and fuel efficiency estimates were compared to analyses previously conducted by TAE. This work was based on heavy truck technology implementation and analysis performed by TIAX for the National Academy of Sciences (NAS) (TIAX, 2009).

The remainder of the SuperTruck benefits analysis approach is identical to the methodology used for the latest GPRA analysis. The estimated costs and fuel economies were used as inputs to the TRUCK model to estimate market penetrations relative to the Baseline Case truck. TRUCK estimates of new fleet fuel economies then were used as inputs to a stock tracking worksheet that applies the VISION model vehicle sales and scrappage rates and projects future fuel consumption and savings relative to the Baseline Case VISION model run. This methodology is described in more detail in the following subsections.

2.2 Data Collection

The analysis team gathered information directly from the industry participants in order to define each participant's baseline truck configuration, their SuperTruck configuration, the fuel and freight efficiency improvements attributable to the SuperTruck component technologies, and the drive cycle(s) used to assess these benefits. The analysis team first reviewed industry partner status reports to obtain general information regarding the technologies and approaches being pursued. The team then gathered more detailed information through

teleconferences, reviews of technical reports, and data exchanges. Table 2-1 illustrates the specific data requested in order to model both the baseline and SuperTruck configurations using the HTEB.

The TAE analysis team documented their understanding of the vehicle and technology development characteristics and submitted this information to the corresponding development team for review and comment. Follow-up discussions and revisions were conducted. However, the detailed information and data required to perform the analysis documented in this report is proprietary in nature (subject to non-disclosure agreements) and therefore is not provided here. This task involved significant effort and cooperation on behalf of the industry participants for which the analysis team is grateful.

Table 2-1: HTEB Model Inputs Data Request

	Units	Baseline	SuperTruck
Drive Cycle Data			
Velocity vs Time	NA	Provide Data	
Engine Power vs Time	NA	Provide Data	
Braking Drag vs Time	NA	Provide Data	
Grade vs Time	NA	Provide Data	
Truck Characteristics			
Max rated engine power	kW		
Weight	lbs		
Drag Coefficient (Cd)	NA		
Frontal Area	sq. ft.		
Rolling Friction Coefficient (Cf)	NA		
Speed Dependant Rolling Resistance (Crr)	NA		
Idle Hours	hrs/yr		
Idle Fuel Consumption Rate	gal/hr		
Avg Fuel Consumption Rate	gal/hr		
Average operating speed	mph		
Engine Peak Frictionless Efficiency	%		
Internal Engine Parasitics (1)			
Pistons & Rings	kW		
Connecting rod and crankshaft bearings	kW		
Valvetrain/camshaft	kW		
Engine Accessory Loads (1)			
Fuel injector pump	kW		
Power Steering	kW		
Oil pump	kW		
Coolant pump	kW		
Fan	kW		
Vehicle Auxiliary Loads (2)			
Alternator	amp		
Air Conditioner	ton		
Air Brake Compressor	HP		
Drivetrain Parasitics (Avg for Drive Cycle) (3)			
Transmission	kW		
Driveshaft	kW		
Axle/Transaxle	kW		
Differential	kW		
Axle & Wheel Bearings	kW		
Brake Drag	kW		
Driving Loads (Avg for Drive Cycle)			
Avg Engine Power	kW		
Aerodynamic Load	kW		
Tire Rolling Resistance	kW		
Tire RR, Velocity Dependant	kW		
Braking Drag	kW		
Energy Recovery (Avg for Drive Cycle)			
Regenerative Braking	kW		
WHR	kW		

(1) Model input is actually % of engine rated power. Assumed constant over cycle.
(2) Could provide kW.
(3) Model input is actually % of average power. Assumed to vary over cycle.

Note: Some inputs are redundant to allow an iterative mathematical balance in the model or to calculate any information that is unavailable.

2.3 Analysis of Efficiency Benefit

For each industry participant, the baseline and SuperTruck configurations were modeled with the HTEB using inputs provided by the participants. This spreadsheet uses a static analysis to represent the average power flows during a drive cycle. Therefore, both the truck and the duty cycle must be characterized. Figure 2-2 illustrates the HTEB worksheet, populated with data representative of current truck technology and calculating power flows over the HHDDT65 drive cycle.[3] The data shown is for illustration only and does reflect SuperTruck participant information nor represent SuperTruck baselines or drive cycles. Additional worksheets are used to input aerodynamic and rolling resistance properties and to calculate these and other losses.

HTEB results were compared to power flows provided by the participants and model inputs were adjusted until reasonable agreement was achieved. The data provided by the industry partners were derived from a variety of sources including hardware tests, dynamic simulations, engineering estimation, and program targets. Therefore, exact agreement was not expected and performance characteristics are subject to change as the program develops.

While many HTEB inputs were provided by the participants, some values were not available or were proprietary to team members that had not supplied permission to share the data. To achieve reasonable agreement between the HTEB and the industry-supplied results, adjustments were made to inputs where such uncertainties remained. For example, the HTEB requires estimates of theoretical frictionless engine efficiency, internal engine friction, and various engine parasitics. In general, the teams measured BTE on a dynamometer and only some participants provided measurements of specific parasitics. None of the teams estimated theoretical frictionless efficiency. Where information was lacking, TAE made assumptions based on prior experience.

The resulting tuned HTEB then was used to estimate the fuel economy benefit of the advanced technology vehicle, calculated as the ratio of the SuperTruck fuel economy relative to the baseline truck. The tuned HTEB was also used to assess the contribution of component technologies, grouped by technology area, to the total vehicle efficiency improvement. The following categories were used:

- Engine efficiency, accessories, auxiliaries, and drivetrain,
- Waste heat recovery,

[3] The Heavy Heavy-Duty Diesel Truck (HHDDT) schedule is a chassis dynamomter test developed by the California Air Resources Board with the cooperation of West Virginia University. The full cycle consists of four modes, including idle, creep, transient and cruise. The HHDDT65 cycle combines elements of each of these modes and achieves a maximum speed of 65 mph.

- Aerodynamics and rolling friction, and
- Hybridization.

Although mass reduction was achieved through both material substitution and design, these benefits were assumed to result in an equivalent increase in freight weight and no net change in truck operating weight. Therefore, mass reduction increases freight efficiency (ton-miles/gal) but does not decrease fuel consumption.[4] The contribution of each technology area to individual truck fuel consumption improvement then was applied to total in-use fuel savings.

[4] With this assumption, the fuel economy of a truck over a 24-hour duty cycle will not change as a result of reductions in mass. However, fewer truck-miles would be required to move an equivalent amount of freight (ton-miles). This effect was beyond the scope of this analysis.

Figure 2-2: HTEB Model Illustration

Truck Energy Balance Model Version 2.0

(User inputs are highlighted in yellow)

1. To develop new configuration, set 'Average Power' estimate (I91) = 'Peak Power' (H8)
2. Click on "Solve Energy Balance" to determine average power (H9 and I91) and fuel economy (cells H27 and E92).
3. Adjust efficiency (H14) and other parameters as needed to achieve performance goal. Repeat energy balance operation (step 2).

Solve Energy Balance

Truck Type:	Cycle:					
2010 Tractor Trailer	HHDDT65 unfiltered			<< Note: Specify truck types on "Type Info" worksheet.		
TRUCK POWER TRAIN ENERGY ITEM	Units			Value		Notes
Engine Peak Power Rating	kW			350	469	hp
Estimated Engine Average Power Rating	kW			153	206	
Assumed Average Truck Speed	MPH			50.10		Average speed over assumed driving cycle. Linked to 'Type Info'
Effective Truck Speed for Aerodynamics	MPH			57.60		Linked to 'Type Info' page
Fuel Type				Diesel		Fuel for heating value and part-load efficiency curve
Engine Peak Thermal Efficiency				44.00%		
Cycle Avg Percent Full Load				43.8%		
Cycle Efficiency Factor				96.8%		
Average Frictionless Cycle Efficiency:				42.6%		
Fuel Consumption Rate	gal/hr			9.6		
Non-Idle Fuel Economy	MPG			5.24		Calculated
Cycle Time per Year	hr			2000		From 'Type Info' page
Non-cycle Idle Time per Year	hr			1429		From 'Type Info' page
Idle Fuel Consumption Rate:	gal/hr			0.70		
Idle Fuel Consumption:	gal/yr			1000.00		
Non-Idle Fuel Consumption	gal/yr			19112.00		
Total Fuel Consumption	gal/yr			20112.00		
Overall Average Fuel Economy	MPG			4.98		
Power Consumption	Units	Load	Effy/COP	kW	Balance	
Internal Engine Parasitics						
Demand as % of Engine Full Load Capacity						
Pistons & Rings	%	0.25%		0.9		
Connecting rod and crankshaft bearings	%	0.50%		1.8		
Valvetrain/camshaft	%	0.50%		1.8		
Less Total Internal Engine Parasitics				4.4		
= Gross Engine-Out Power					149.0	
Gross Power-Out Engine Efficiency					41.4%	
Engine Accessory Loads						
Demand as % of Engine Full Load Capacity						
Fuel injector pump	%	0.30%		1.05	43.05%	BTE at peak power, incl fuel inj., oil & collant pumps and WHR.
Power Steering	%	0.25%		0.88	40.48%	BTE at average cycle power
Oil pump	%	0.30%		1.05		
Coolant pump	%	0.30%		1.05		
Fan	%	0.25%		0.88		
Less Total Engine Aux Loads				4.9		
= Net Engine-Out Power					144.1	
Net Engine-Out Power Efficiency					40.0%	
Vehicle Auxiliary Loads						
Average Loads						
Alternator	amp	130	0.8	1.95		Assumes 12 V
Air Conditioner	ton	1.25	2	2.20		
Air Brake Compressor	HP	1.5	0.48	2.33		
Less Total Veh. Aux. Loads				6.5		
= Net Available Engine Power					137.7	
Net Engine-Out Power Efficiency					38.2%	
Drivetrain Parasitics						
Demand as % of						
Transmission	avg power	2.00%		3.1		
Driveshaft	avg power	1.00%		1.5		
Axle/Transaxle	avg power	1.00%		1.5		
Differential	avg power	1.00%		1.5		
Axle & Wheel Bearings	avg power	1.00%		1.5		
Brake Drag	avg power	0.00%		0.0		
Less Total Drivetrain Parasitics				9.2		
= Net Available Power to Tires	93%	Drivetrain Efficiency			128.4	
Net Engine-Out Power Efficiency					35.6%	
Waste Heat Recovery						
Rankine Cycle	0%	0.0		0.0		% of Total Waste Heat Recovered as Usable Energy (Waste heat includes radiated losses and exhaust)
Turbo Compounding	0%	0.0		0.0		
= Total Power Available from WHR				0.0	128.4	
Net Engine-Out Power Efficiency					35.6%	
Driving Loads (See 'Aero & Tires' Sheet)						See 'Aero & Tires' & 'Braking Power' Sheets to make changes.
Aerodynamic Load	1.00	64.7		64.7		
Tire Rolling Resistance	1.00	38.9		38.9		
Tire RR, velocity dependent	1.00	0.0		0.00		
Acceleration/Braking Energy	1.00	24.9		24.9		Cycle acceleration/deceleration energy divided by driving cycle time.
= Total Non-Hybrid Driving Loads				128.4		
Hybrid Power System	Hybrid?					
Percent braking energy recovery	FALSE	0.0%	0.0			includes motor/generator and battery charge/discharge efficiency
Net Braking energy lost				24.9		
Adjusted (Hybrid) Total Driving Load				128.4		
Balancing Value for Average Power				kW	153.4	Average Power Result
mpg =	4.98			Remainder	0.0	Remainder must = 0 for energy balance to occur. Click "Solve Energy Balance" button to find average power.

2.4 Cost Analysis

The methodology used for this analysis applies a market based approach that compares the purchase cost of advanced technology trucks relative to a baseline truck to the value of the advanced trucks' future fuel savings. Therefore, it is necessary to estimate the cost of each SuperTruck configuration relative to the respective baseline. The industry teams were not asked to estimate these costs. Based on prior TA Engineering experience, requests for input on cost for developing technologies can be problematic as it may raise concerns about price objectivity. At least during the early phases of a research and development activity, cost (or price) issues typically are not addressed until some level of proof of concept is established. Therefore, the costs used for this analysis were developed by the analysis team using published reports and were not provided by the industry participants. This approach uses the same database for each participant and the results represent "best estimates" available from publicly available and peer-reviewed sources.

To estimate SuperTruck vehicle costs, the baseline and advanced technology descriptions and fuel efficiency estimates were compared to analysis performed for the National Academy of Sciences (NAS) (TIAX, 2009). This report was developed and reviewed by a team of respected engineers, economists, and analysts drawn from government, industry, and academia. It represents the most comprehensive and relevant database of cost information for near- and medium-term heavy truck technologies for reducing fuel consumption. Additional insights were drawn from prior TAE project experience and from a study performed for the Northeast States Center for a Clean Air Future (NESCCAF, 2009). As described above, while each participant's SuperTruck configuration reflected the program goals of 50% BTE and a 50% improvement over the participant's baseline, the SuperTruck component technologies differed among the participants. This variation was reflected in the cost estimates. In addition, the TIAX (2009) analysis provides a range of costs for various technologies and components as well as a discussion of the factors that drive these costs. TAE used this information to develop two cost scenarios representing a low and high cost estimate for each configuration.

2.5 Fuel Prices

Two fuel price cases were constructed based on EIA's AEO2011 and AEO2012 early release. The AEO2012 reference case, with extrapolation to 2050, was used as "low" oil price case. Since the early release does not include a high oil price case, one was constructed by calculating the ratio of the AEO2011 high price case relative to the reference case and applying this ratio to the AEO 2012 reference case. The resulting prices are shown in Table 2-2.

Table 2-2: Fuel Price Projection

Year	Diesel Price 2010 $/million BTU Reference	Diesel Price 2010 $/million BTU High (est.)	Diesel Price 2010 $/gallon Reference	Diesel Price 2010 $/gallon High (est.)
2010	21.87	21.86	2.73	2.73
2011	27.72	27.71	3.47	3.46
2012	27.34	30.90	3.42	3.86
2013	25.06	32.99	3.13	4.12
2014	26.41	35.93	3.30	4.49
2015	27.46	37.84	3.43	4.73
2016	27.86	38.97	3.48	4.87
2017	28.39	39.22	3.55	4.90
2018	28.45	39.28	3.56	4.91
2019	28.80	39.66	3.60	4.96
2020	29.06	39.88	3.63	4.98
2021	29.28	40.93	3.66	5.12
2022	29.42	41.64	3.68	5.20
2023	29.90	42.07	3.74	5.26
2024	30.16	42.89	3.77	5.36
2025	30.50	42.79	3.81	5.35
2026	30.85	43.78	3.86	5.47
2027	31.12	43.84	3.89	5.48
2028	31.32	43.76	3.91	5.47
2029	31.65	44.56	3.96	5.57
2030	32.06	45.06	4.01	5.63
2031	31.64	45.27	3.95	5.66
2032	31.73	45.61	3.97	5.70
2033	32.00	45.97	4.00	5.75
2034	32.42	46.78	4.05	5.85
2035	32.77	47.16	4.10	5.89
2036	32.91	47.59	4.11	5.95
2037	33.06	48.03	4.13	6.00
2038	33.20	48.47	4.15	6.06
2039	33.35	48.91	4.17	6.11
2040	33.50	49.36	4.19	6.17
2041	33.64	49.81	4.21	6.23
2042	33.79	50.26	4.22	6.28
2043	33.94	50.72	4.24	6.34
2044	34.09	51.19	4.26	6.40
2045	34.24	51.66	4.28	6.46
2046	34.39	52.13	4.30	6.52
2047	34.54	52.61	4.32	6.58
2048	34.69	53.09	4.34	6.64
2049	34.85	53.58	4.36	6.70
2050	35.00	54.07	4.37	6.76

2.6 Baseline Case

The fuel economy benefit of each SuperTruck configuration estimated by TA Engineering was evaluated against the corresponding baseline truck and duty cycle for that team. However, to project future fuel savings, it was necessary to construct a baseline future sales fleet fuel economy consistent with the historical in-use fleet fuel economies in the VISION model in terms of fleet mix and duty cycle. Therefore, the baseline future fuel economy from the most recent GPRA analysis was used.

This baseline was constructed by removing the impact of DOE sponsored technologies from the AEO2011 reference case as documented in TAE (2012b). The projected new fleet fuel economy in the Baseline Case improves 2.75% from 6.20 mpg in 2011 to 6.38 mpg in 2035. The sales fleet incorporates some aerodynamic improvements that are mostly offset by increases in fuel consumption due to emission control and after-treatment technologies. Projected sales fleet fuel economies for the SuperTruck cases were held constant throughout the analysis period and were calculated by applying the improvement from the HTEB analysis to the baseline 2015 fuel economy.

2.7 Market Penetration Analysis

The TRUCK 5.0 model was used to estimate the market shares of the SuperTruck platforms. The TRUCK model estimates market penetration rates of proposed energy-saving technologies based on their relative economic benefit. The scope of the economic benefits covers the expected fuel cost savings derived from improvements in fuel economy or from switching to an alternative fuel. At the user's discretion, differences in expected maintenance and/or engine rebuild and replacement costs may be considered. For the SuperTruck analysis, only fuel cost savings were considered. The TRUCK model calculates annual cost savings relative to a baseline vehicle and uses a payback algorithm to project market penetrations within 10,000-mile mileage cohorts. The results are used to develop mileage-weighted new fleet fuel economies (TAE, 2012a).

For the SuperTruck analysis, the HTEB was used to estimate the fuel economy benefit of each platform relative to the corresponding team's baseline. The ratio of the SuperTruck configuration fuel economy to the team's baseline was then applied to the 2015 Baseline Case fuel economy to calculate the SuperTruck fuel economy in 2015. This value was held constant throughout the analysis (from 2015-2050). For each platform, the incremental cost of the advanced technology was assumed to apply in 2015 and to decrease 25% over 25 years. These results were used as inputs to the TRUCK model to estimate market penetrations relative to the Baseline Case.

Although the TRUCK 5.0 model can simultaneously compete three alternative technology platforms against one baseline vehicle, the SuperTruck analysis did not compete any of the four

participant team configurations against each other. Instead, two platforms were chosen to be representative of the anticipated program outcome. These two platforms were analyzed individually against the Baseline Case fuel economies and the results are presented in Section 5.2.

2.8 Fuel Savings Estimation

The Baseline Case new fleet fuel economy projection was applied to the VISION model to project future fuel consumption. The fuel savings for the SuperTruck cases were calculated using a separate spreadsheet tool linked to the VISION run. This spreadsheet projects miles of travel and fuel use by heavy vehicles sold after 2010 and estimates fuel and carbon savings relative to the Baseline Case. This tool uses VISION methodology and parameters, including sales projections, scrappage rates, and age-dependent mileage. Therefore, this approach provides results consistent with VISION runs but is simpler to utilize.

3.0 Technology Descriptions

In order to mitigate the risk posed by the challenging SuperTruck goals, four industry teams were co-funded to independently pursue these goals as discussed in Section 1.1. Each team selected a development path consistent with their experience, customer base, and business model. Therefore, each team uniquely defined their baseline truck and determined the approaches to be considered for the SuperTruck vehicle. This section provides an overview of the baseline characteristics and discusses the range of technologies investigated by the teams.

3.1 Baseline Configurations

Each industry team defined a baseline truck as their "best-in-class" commercially available 2009 model. The four baseline truck configurations varied in terms of engine specifications, tractor profile, and empty weight. In addition, each team used a unique 24-hour duty cycle, representative of their market, to estimate fuel economy and freight efficiency. Table 3-1 provides an overview of the baseline configurations along with HTEB estimates of their fuel efficiencies over the team-specified duty cycles. It should be noted that not all teams provided values for aerodynamic and rolling resistance characteristics. Where necessary, TAE estimated these parameters using defaults from prior analyses or using supplemental information provided by the participants.

Table 3-1: Baseline Truck Configurations

Characteristic	units	avg	std. dev
Engine			
Displacement	l	13.8	1.3
Peak power	hp	470	14
BTE, peak[1]	%	43.1%	2.0%
Tractor-Trailer System			
Total weight	lbs	65,000	0
tractor + trailer	lbs	32,493	892
freight	lbs	32,508	892
Aerodynamics[2]			
Cd	NA	0.58	0.03
Frontal area	sf	113.4	1.7
Rolling resistance[2]			
Crr	NA	0.00570	0.00112
Fuel Efficiency (24-hour duty cycle)[3]			
Fuel Economy	mpg	5.54	0.50
Freight Efficiency	ton-mpg	90.0	7.4

[1]BTE includes some parasitics which differ by participant.
[2]Not all participants provided values. Some values estimated by TAE.
[3]Efficiencies are estimated by TAE over 24-hour duty cycle which differs among participants.

3.2 SuperTruck Configurations

The SuperTruck goals are demonstrations of a class 8 truck with an engine BTE of 50% and a freight efficiency improvement of 50% relative to the baseline truck. To meet these goals, the development teams are in the process of defining SuperTruck configurations that implement a variety of technologies and strategies. Table 3-2 provides an overview of the engine and truck characteristics representing the current status of the SuperTruck configurations. Because program participants started work at different times, parameter values represent varying levels of confidence and many are program targets. The values provided by the participants represent best estimates based on their work to date. Efficiency values were estimated by TA Engineering using the HTEB.

Table 3-2: SuperTruck Configurations

Characteristic	units	avg	std. dev
Engine			
Displacement	l	12.7	2.2
Peak power	hp	428	49
BTE, peak[1]	%	48.6%	0.9%
Tractor-Trailer System			
Total weight	lbs	65,000	0
tractor + trailer	lbs	30,733	2,672
freight	lbs	34,267	2,672
Aerodynamics[2]			
Cd	NA	0.36	0.05
Frontal area	sf	112.2	2.0
Rolling resistance[2]			
Crr	NA	0.00438	0.00034
Fuel Efficiency (24-hour duty cycle)[3]			
Fuel Economy	mpg	9.3125	0.98
Freight Efficiency	ton-mpg	160.2	27.7
Freight Efficiency Improvement Relative to Baseline	%	77%	16%

[1]BTE includes some parasitics which differ by participant.
[2]Not all participants provided values. Some values estimated by TAE.
[3]Efficiencies are estimated by TAE over 24-hour duty cycle which differs among participants.

To achieve the characteristics summarized in Table 3-2, the development teams are investigating a wide range of technologies and strategies as discussed below. This discussion is organized according to the following energy loss or functional areas:

1. Engine design and combustion processes;
2. Engine friction and parasitics;
3. Driveline losses;

4. Waste heat recovery;
5. System controls;
6. Emission controls, after-treatment, and energy impacts;
7. Aerodynamics and rolling friction;
8. Weight reduction;
9. Hybridization;
10. Idle reduction; and
11. Freight efficiency.

3.2.1 Engine Design and Combustion Processes

Base engine improvements are being explored using a variety of approaches, including:

- Advanced combustion modes such as low temperature combustion;
- Increased peak cylinder pressure and compression ratio;
- Variable valve actuation (VVA);
- Improved turbocharger efficiency;
- Advanced controls; and
- Engine down-speeding, engine downsizing, etc.

Combustion chamber design is a major focus for all teams. In some instances redesign of piston bowl geometries and high performance pistons are targeted. Engine control algorithms typically are optimized for fuel efficiency at the cost of higher NOx, which is compensated for through improvements in the exhaust after-treatment system. In addition to the approaches above, alternate combustion regimes are being explored as pathways toward achieving 55% BTE. These modes include premixed charge compression ignition (PCCI), partially premixed combustion (PPC), and reactivity controlled compression ignition (RCCI).

3.2.2 Engine Friction and Parasitics

In most cases, reductions in friction losses external to the engine are being investigated for the cooling fan, alternator, air compressor, air conditioner, oil pumps, and water pumps. Efficiency gains are realized through design changes and advances in system controls. To reduce accessory loads, variable displacement oil pumps and variable speed water pump are being incorporated in some SuperTruck configurations. Reductions in accessory and auxiliary loads are achieved through advances in system controls, electrification, and hybridization in some instances. Internal engine losses are reduced through various approaches such as the design and use of low friction pistons, rings, coatings, cylinder materials and configurations, power transfer and crankcase hardware, as well as thermal insulation in various engine parts.

3.2.3 Driveline Losses

The SuperTruck configurations are addressing driveline losses on several fronts. Automated manual transmission is a key enabler of efficiency improvements achieved through down-speeding of the engine and enhanced control of engine speed. Development efforts are addressing optimization of the controls and improving drivability. Several SuperTruck configurations incorporate smart axle technologies with and without improved lubricant and temperature management. In hybrid approaches, driveline losses are reduced through development of advanced gearboxes and controls.

3.2.4 Waste Heat Recovery

All the SuperTruck configurations incorporate an organic Rankine cycle (ORC) waste heat recovery (WHR) system that recovers heat from the exhaust gas recirculation (EGR) loop and the exhaust stream. The recovered energy is fed back to the shaft for mechanical power or used for electrical loads. In addition to the ORC, all teams have considered implementing mechanical or electrical turbo-compounding that recovers exhaust heat. Electrical coupling of WHR is particularly attractive when implementing a hybrid drivetrain. Not all teams are implementing turbo-compounding to achieve the 50% BTE engine. However, it may be included in meeting the secondary SuperTruck goal of demonstrating path toward a 55% BTE engine.

In some cases, the additional mechanical power is used to enable engine downsizing without loss of performance. In other cases, the engine is not downsized but average loads are lower. WHR also contributes to improvements in fuel consumption by altering the engine fuel consumption map. The WHR system can enable additional fuel consumption and cost benefits by replacing the EGR cooler and improving the efficiency of the turbo-charger.

3.2.5 System Controls

The SuperTruck configurations apply improvements in vehicle controls**.** Predictive algorithms to optimize fuel economy for truck routes and torque management are being explored to limit excessive accelerations based on vehicle mass and road grades. The engine control algorithms are optimized for fuel efficiency at the cost of higher NOx, which is enabled through improvements in the efficiency of the exhaust after-treatment system. Approaches for reducing auxiliary and accessory loads include optimizing operation and centralizing energy management. With and without hybridization, control algorithms balance conservation and performance of regenerative braking systems, auxiliary power units, and transmission overdrive operation.

3.2.6 Emission Control, Exhaust After-treatment, and Energy Impact

The SuperTruck configurations incorporate various enhancements to the baseline exhaust after-treatment systems. In selective catalytic reduction (SCR) systems, the efficiency of the

after-treatment system is enhanced through the application of lower pressure-differential EGR, optimized sizing of the diesel particulate filter (DPF) and SCR systems, changes in materials and catalysts, and improved after-treatment controls. In addition to SCR systems, high rate EGR and lean NOx catalysts are being explored. Emission after-treatment improvements have two key enablers: transmission controls that allow engine down-speeding and waste heat recovery which alters the engine emissions map. The emissions impacts of advanced and alternative combustion regimes are also being explored. For example, PCCI may enable simultaneous reduction of fuel consumption and engine-out emissions.

3.2.7 Aerodynamics and Rolling Friction

The SuperTruck configurations represent complete tractor redesign that is estimated to significantly reduce the coefficient of drag (C_d). Various degrees of trailer redesign are being explored, such as the latest advancements in fairings and skirts with component geometries optimized for the complete vehicle and altering the shape and size of the trailer. All SuperTruck approaches include wide-based, low coefficient of rolling friction (C_{rr}) tires.

3.2.8 Weight Reduction

Weight reductions in SuperTruck configurations are being achieved through redesign of components and structures as well as material substitution in the chassis, brake drums, cab, trailer, suspension, wheels, and axles. Some light-weighting will offset increased weight due to powertrain hybridization and other components (e.g., WHR) but the goal is to achieve overall weight reduction that can contribute to increased freight weight.

3.2.9 Hybridization

Both parallel and series-parallel hybrid configurations are being pursued. Regenerative braking and energy storage for hotel loads is also being explored without implementation of a full hybrid powertrain.

3.2.10 Idle Reduction

Hoteling loads will be met by auxiliary power units (APUs), energy management, hybrid powertrains, and combinations of these approaches. Reductions in climate control loads during hoteling will be achieved through incorporation of advanced materials in the cab, such as insulating materials and reflective coatings. Energy recovered from the drive cycle through centralized energy management and regenerative braking will be used to offset overnight/hotel loads. Various APU types are being investigated, including battery, combustion, fuel cell, and combinations of these approaches.

3.2.11 Freight Efficiency

A fifty percent (50%) improvement in "Freight efficiency" is one of the stated performance goals of the SuperTruck program. It is calculated in ton-miles per gallon over a 24-hour duty cycle defined individually by each project team. All duty cycles incorporate 14 hours of driving and 10 hours of engine-off and hoteling loads. At least 20% of the freight efficiency improvement must be due to an engine capable of achieving 50% BTE at loads representing 65 mph on a level road. In addition, the SuperTruck program requires that the test cycle be representative of typical long-haul operations and that at least 75% of the distance traveled represent highway conditions. Each of the research teams developed representative drive cycles based on analysis of data from actual U.S. truck routes. The resulting 14-hour drive cycles consist of mostly highway cruise with average speeds between 55-65 mph and grades up to +/-7%. For a given development team, duty cycles are identical for the baseline and SuperTruck calculations. However, hoteling loads may be met by idling the truck engine under the baseline and by other alternatives in the SuperTruck. For both configurations, the gross vehicle weight is 65,000 lb. Therefore, any weight reductions in the cab and trailer are assumed to result in an equivalent increase in freight capacity. Freight efficiency improvements arise from three sources:

- Reduced drive cycle power losses which increase driving fuel economy (mpg),
- Reduced fuel requirements to meet hoteling loads which increases 24-hour duty cycle fuel economy (mpg), and
- Vehicle weight reductions which increase freight weight and thus freight efficiency in ton-mpg.

4.0 Vehicle Incremental Cost

The cost of the baseline truck configurations is in the range of $150,000-$200,000, excluding the trailer. This estimate is based on research on current product offerings and represents an engine that complies with EPA's 2010 emission standards.[5] Sleeper cab truck costs vary considerably depending on options and the addition of cab comforts (e.g., refrigerators, satellite radios, etc.) often adds more to the cost than differences in engine offerings. The baseline estimate is provided as a reference point and reality check for considering the incremental costs of the SuperTruck platforms relative to the baseline.

The market penetration analysis considers only the cost differential between the SuperTruck vehicles and trucks that are expected to be commercially available during the timeframe of the analysis (2015-2050). In this way, the economic benefits of the fuel saving technologies are compared to the costs associated with achieving these benefits. It should be noted that the baseline trucks were defined from 2009 commercially available models and therefore were compliant with EPA emission standards in effect in that year. However, all trucks sold in 2015 will need to comply with the more stringent NOx standards that became fully effective in 2010. Therefore, for cost purposes, the baseline trucks were assumed to comply with 2010 standards using an approach consistent with the industry team's commercially available models. Any costs associated with the emission control technologies implemented between MY2009 and MY2010 were not included in the incremental cost of the SuperTruck vehicles. Although these technologies do impact fuel consumption, no changes were made to the baseline vehicle performance characteristics provided by the industry teams.

Table 4-1 lists all technologies and approaches identified as being considered by the SuperTruck teams along with incremental cost estimates for each. Costs were not available for some approaches as indicated by blank rows in Table 4-1. Most of these approaches are assumed to add little to no cost, such as changes in system controls, or are assumed to be incorporated in the costs for other technologies or approaches. The costs shown are assumed to apply in 2015 and were used to develop high and low cost estimates for the four SuperTruck configurations that are expected to meet the 50% BTE engine goal. Not all technologies and approaches shown are currently incorporated in these configurations. Platform costs were rounded to the nearest $100. For confidentiality protection, platform incremental costs are not reported for each participant.

In general, hybrid configurations resulted in higher incremental costs than non-hybrids. However, configurations with large net mass reductions resulted in costs that approached the hybrids. Incremental costs ranged from $36,700 for a non-hybrid configuration with low-cost assumptions to $102,500 for a hybrid configuration and high-cost assumptions. All incremental costs were assumed to decline 25% over 25 years following introduction in 2015.

[5] Personal communication with Conrad Martin, Truck Enterprises Hagerstown, Inc., April 19, 2012. Additional data was gathered from multiple dealer websites.

Table 4-1: Advanced Technology Cost Estimates for 2015

Technology	Cost Range Low	Cost Range High	Notes
Base Engine			
Combustion chamber design	500	1500	TIAX Table 4-7
Combustion process advances			Not implemented in 50% BTE engines
Cylinder deactivation			Included in engine design and adv'd engine controls
VVA	300	300	TIAX Table 4-8
Fuel injection advances	500	500	TIAX Table 4-7
Friction reduction (materials, lubes, etc.)	500	500	TIAX Table 4-9 - various coating materials
Turbo-charger improvements	0	0	Assumes minor design changes
Enhanced EGR	750	750	TIAX
Engine downsize	-860	-1720	Engineering estimate
Advanced engine controls	60	150	TIAX Table 4-7
Downspeeding			Assumed low to no cost
Auxiliaries and Parasitics			
Variable displ / speed pumps (oil / water)	200	500	
Steering pump improvements (VD and other)	200	500	
Advanced controls			Assumed low to no cost
Electrification	1000	2000	
Waste Heat Recovery			
Turbo-compounding, electrical w/ hybridization	3000	4000	TIAX Table 3-2
Turbo-compounding, electrical w/ hybridization	6000	7000	TIAX Table 3-2
Turbo-compounding, mechanical	2000	3000	TIAX Table 3-2
Organic Rankine cycle	7200	15000	TIAX Table 4-11
Exhaust Aftertreatment/Emission Control			
SCR + DPF efficiency improvements	0	1000	relative to 2010 compliant engine
DOC + DPF + SCR efficiency improvements	0	1000	relative to 2010 compliant engine
High rate EGR + PCCI + LNT + DPF	1500	3000	relative to 2010 compliant engine
Accessories			
Electrification	1000	2000	Low value w/ hybrid or WHR
Advanced controls			Assumed low to no cost
Drivetrain			
Driveline friction reduction	0	500	TIAX Section 4.5.1
Automatic manual transmission (AMT)	4500	5700	TIAX Table 4-46
Other transmission advances	4500	5700	TIAX Table 4-46
Improved axle efficiency	200	300	TIAX Section 4.5.1
Advanced materials (weight and friction redux)			Included in mass reduction
Aerodynamics			
Smartway Tractor and Smartway Trailer	0	3000	TIAX Table 3-5
Improved Smartway Tractor and Smartway Trail	0	5750	TIAX Table 3-5
Tractor-trailer redesign	8000	16000	TIAX Table 3-5: Cd imp (30% to 47%)
Rolling Friction			
Wide-base tires	1800	1800	TIAX Table 4-33 tractor/trailer
Next-gen wide-base tires	1800	1800	available 2015
Hybridization			
Mild (regenerative braking & idle engine-off)			Not currently implemented by any team
Parallel	35000	45000	TIAX Table 4-56 low production mode
Series-parallel	45000	55000	TIAX Table 4-56 low production mode
Idle (Non-Hybrid Approaches)			
APU	6000	8000	TIAX Table 4-65
Other	3000	8000	Reduce load demand through cab insulation.
Mass Reduction			
Lt-wt wheels for wide-base singles			Included in advanced materials
Advanced materials	2000	42000	TIAX Table 4-39, calculated from $/lb scale
Tractor-trailer redesign			Included in redesign for aerodynamics

5.0 Benefits Estimation

5.1 Inputs

Analysis of the vehicle characteristics provided by the project teams resulted in fuel economy ratios (SuperTruck relative to the baseline for each team) that were very similar across the teams, ranging from 1.65 to around 1.7. The hybrid platforms provided somewhat higher fuel consumption benefits. However, the estimated costs for the hybrid configurations were significantly higher unless a large net mass reduction was included in the non-hybrid platform.

Two technology platforms, based on a generalization of developer inputs, were selected for analysis as shown in Table 5-1. Platform A represents an advanced conventional vehicle and platform B represents a full hybrid configuration. Costs shown are incremental to the baseline vehicle, which typically costs in the range of $150,000 to $200,000 for the tractor only. Incremental costs include a redesigned trailer that provides both improvements in aerodynamics and reductions in mass.

Table 5-1: Market Penetration Analysis Inputs

		A	B
Configuration		Conventional	Hybrid
Fuel Economy			
2015 Baseline mpg		6.15	6.15
2015 SuperTruck mpg		10.17	10.43
Multiplier		1.653	1.696
Incremental Cost			
Low	**2015**	$36,700	$75,500
	2040	$27,400	$56,300
High	**2015**	$56,400	$102,500
	2040	$42,000	$76,400
Contribution to Fuel Savings			
Engine Efficiency, Accessories, Auxiliaries & Drive Train		26.3%	15.4%
Aerodynamics & Rolling Friction		69.3%	39.9%
Waste Heat Recovery		4.4%	27.4%
Hybrid		0.0%	17.3%
Total		100.0%	100.0%

Note: Platforms A and B are generalized groups of technologies representing two approaches to meeting the SuperTruck goals and do not represent specific team configurations.

These two platforms are assumed to be optimized in terms of the benefits and costs of the two approaches and differ by more than the addition of a hybrid powertrain. The hybrid is assumed to take advantage of synergies among electrification of accessories, waste heat recovery, regenerative braking, and systems for meeting hotel loads. Since the two platforms share the

same goals for engine peak BTE and freight efficiency improvement, tradeoffs were made among the functional areas. The hybrid powertrain provides more opportunity to use recovered energy, so this approach is assumed to use more aggressive WHR compared to the conventional approach. This is offset by less aggressive improvements in base engine efficiency and aerodynamic drag reduction. In addition, the hybrid provides fewer opportunities for weight reduction. Reductions in tractor and trailer weight are assumed to allow for an equivalent increase in cargo weight and do not contribute to fuel savings. They do, however, influence the costs shown in Table 5-1.

For the non-hybrid platform, 69% of the fuel savings can be attributed to reduced aerodynamic drag and rolling friction. Engine and drivetrain efficiency improvements, not including WHR, contribute an additional 26%, while WHR provides about 4%. For the hybrid platform, reduced aerodynamic drag and rolling friction still provide the largest share of the benefits at 40%. WHR provides 27%, hybridization provides 17%, and engine and drivetrain improvements provide the remaining 15%. Note that synergies available due to hybridization are attributed to the functional areas where applied and not to hybridization itself.

The large difference in the contribution of WHR to fuel savings between the two platforms is due to assumptions about the platform designs. It is possible that these inputs understate the potential for WHR in the advanced conventional truck, though no more is necessary to meet the SuperTruck goals. Similarly, these inputs may overestimate the potential for WHR in the hybrid, though they are based on input from the development teams and other published sources. The intent is that each platform as a system represents the best potential from each approach in terms of benefit/cost based on the information received during this study.

The combination of two technology platforms, two vehicle incremental cost cases (high and low), and two oil price cases (high and low) results in a total of eight cases. To simplify the analysis and stay within the scope of the task, only four cases representing low and high market potential were analyzed. The low market case combines high technology costs with reference fuel prices. The high market case combines low technology costs with high fuel prices. The remaining cost/price cases would provide market penetration results within the range of those analyzed.

5.2 Market Penetration Results

The analysis results are highly sensitive to assumptions about incremental costs and fuel prices. Table 5-2 shows the market penetration estimates for both platforms and each of the cost/price assumptions. This analysis did not compete the two SuperTruck configurations against each other. Therefore, each of the four columns in Table 5-2 present the total market share for SuperTruck vehicles under four separate scenarios defined by technology cost, fuel price, and platform approach assumptions. Under the low technology cost / high oil price assumptions, the non-hybrid platform quickly attains a large market share of nearly 60% of new class 8 combination unit vehicle miles by 2020 and reaches 73% by 2050. The hybrid platform

achieves lower market share due to higher incremental cost. However, these shares are still significant at 19% by 2020 and 36% by 2050. Note that the market shares for each platform would be lower if both A and B were competing in the market simultaneously.

Under less optimistic assumptions about vehicle incremental costs along with lower fuel prices, the non-hybrid platform attains 22% market share in 2020 and approaches 36% by 2050. Although these market penetrations are considerably lower than the alternative cost/price case, they are still significant. Under these cost/price assumptions, the hybrid platform attains far less market share at 2.3% by 2020 and 7.5% by 2050

Table 5-2: Market Penetration Results as a Percentage of Vehicle Miles for New Combination Unit Trucks

	Low Tech Cost and High Oil Price		High Tech Cost and Reference Oil Price	
	Adv'd Conv.	Hybrid	Adv'd Conv.	Hybrid
2020	59.1%	18.9%	21.7%	2.3%
2025	65.2%	25.5%	27.2%	4.0%
2030	67.9%	29.9%	32.1%	5.5%
2035	71.2%	32.7%	33.6%	6.5%
2040	71.8%	33.7%	34.5%	6.9%
2045	72.5%	35.8%	35.6%	7.1%
2050	73.3%	36.2%	35.7%	7.5%

Note: Market penetrations are reported as a percentage of vehicle miles for new trucks rather than as a percentage of sales. This approach more accurately represents fuel savings attributable to the increased fuel economy of these vehicles.

Table 5-3 summarizes the impact of these market penetrations on the new and in-use fleet fuel economies for combination unit trucks. In the favorable cost/price case, market penetration of advanced conventional diesel trucks increases the fuel economy of the sales fleet by 30% in 2020 (8.16 versus 6.27 mpg) and 38% by 2050. As the stock of trucks gradually turns over, this results in an increase in the in-use fleet fuel economy of about 15% in 2020 and 38% by 2050. For the same cost/price assumptions, market penetration of the hybrid platform increases new truck fleet fuel economy by 8% in 2020 and 16% by 2050. In-use fleet fuel economy increases by 4% in 2020 and ramps up to 16% by 2050.

Under the less favorable cost/price assumptions, introduction of the advanced conventional diesel truck increases new fleet fuel economy by 9% to 15% and in-use fleet fuel economy by 4% to 15% between 2020 and 2050. For these same cost/price assumptions, market penetration of the hybrid platform increases new fleet fuel economy by 1% to 3% and in-use fleet fuel economy by 0.3% to 3% between 2020 and 2050.

Table 5-3: Fleet Fuel Economies

New Fleet Fuel Economy, mpg diesel

		Low Tech Cost and High Oil Price		High Tech Cost and Reference Oil Price	
	Baseline	Adv'd Conv.	Hybrid	Adv'd Conv.	Hybrid
2020	6.27	8.16	6.80	6.86	6.33
2025	6.31	8.45	7.03	7.06	6.41
2030	6.35	8.59	7.21	7.24	6.49
2035	6.38	8.75	7.33	7.31	6.55
2040	6.41	8.80	7.39	7.37	6.58
2045	6.44	8.85	7.49	7.43	6.62
2050	6.47	8.90	7.52	7.46	6.66

In-Use Fleet Fuel Economy, mpg diesel

		Low Tech Cost and High Oil Price		High Tech Cost and Reference Oil Price	
	Baseline	Adv'd Conv.	Hybrid	Adv'd Conv.	Hybrid
2020	6.23	7.14	6.47	6.49	6.25
2025	6.29	7.82	6.76	6.78	6.35
2030	6.32	8.24	6.97	7.00	6.41
2035	6.35	8.52	7.15	7.17	6.48
2040	6.39	8.69	7.29	7.28	6.54
2045	6.42	8.80	7.40	7.36	6.59
2050	6.45	8.87	7.48	7.43	6.63

5.3 Fuel Consumption Results

Table 5-4 summarizes the fuel consumption results for the Baseline and SuperTruck Cases. Table 5-5 shows the annual energy savings in million barrels per day (mbpd) and as a percentage of the Baseline Case consumption. Under favorable cost/price assumptions, sales of the advanced conventional diesel truck save about 13% of annual consumption in 2020 and 27% by 2050. Sales of the hybrid truck save 4% of annual consumption in 2020 and 14% by 2050. Under less favorable cost/price assumptions, savings from sales of the advanced conventional truck look much like the hybrid case under the favorable cost/price assumptions at 4% of annual use in 2020 and 13% in 2050. For the less favorable economic conditions, the hybrid platform saves less than 1% of consumption in 2020 and about 3% in 2050. Note that since the market shares were not estimated for both platforms competing in the market simultaneously, the fuel savings results for the conventional and hybrid platforms cannot be added.

Table 5-4: Fuel Consumption, mbpd

		Low Tech Cost and High Oil Price		High Tech Cost and Reference Oil Price	
	Baseline	Conv.	Hybrid	Conv.	Hybrid
2020	1.75	1.53	1.69	1.68	1.75
2025	1.89	1.52	1.76	1.75	1.87
2030	2.03	1.55	1.84	1.83	2.00
2035	2.16	1.61	1.92	1.92	2.12
2040	2.35	1.73	2.06	2.06	2.30
2045	2.52	1.84	2.19	2.20	2.46
2050	2.683	1.95	2.31	2.33	2.61

Table 5-5: Annual Energy Savings

	Low Tech Cost and High Oil Price		High Tech Cost and Reference Oil Price	
	Adv'd Conv.	Hybrid	Adv'd Conv.	Hybrid
2020	0.223	0.066	0.072	0.007
2025	0.370	0.131	0.138	0.017
2030	0.473	0.190	0.197	0.030
2035	0.550	0.242	0.245	0.043
2040	0.624	0.291	0.290	0.056
2045	0.682	0.334	0.324	0.065
2050	0.732	0.369	0.354	0.074

	Low Tech Cost and High Oil Price		High Tech Cost and Reference Oil Price	
	Adv'd Conv.	Hybrid	Adv'd Conv.	Hybrid
2020	12.7%	3.7%	4.1%	0.4%
2025	19.6%	6.9%	7.3%	0.9%
2030	23.3%	9.4%	9.7%	1.5%
2035	25.4%	11.2%	11.3%	2.0%
2040	26.5%	12.4%	12.3%	2.4%
2045	27.0%	13.3%	12.8%	2.6%
2050	27.3%	13.8%	13.2%	2.8%

Table 5-6 shows cumulative energy savings in million barrels (bbl) and as a percentage of cumulative Baseline Case fuel consumption by class 8 combination unit trucks since 2015. Under favorable economic assumptions, market penetration of the advanced conventional diesel truck cumulatively saves about 8% of consumption by 2020 and 22% by 2050. Sales of the hybrid truck are estimated to save 2% by 2020 and about 10% by 2050. Under less favorable economic assumptions, the advanced conventional is estimated to save 10% of cumulative consumption by 2050, while the hybrid is estimated to save about 2% by 2050.

Table 5-6: Cumulative Energy Savings

Cumulative Energy Savings, million bbl

	Low Tech Cost and High Oil Price		High Tech Cost and Reference Oil Price	
	Adv'd Conv.	Hybrid	Adv'd Conv.	Hybrid
2020	289	79	88	7.1
2025	863	270	291	30
2030	1,657	574	608	74
2035	2,606	977	1,021	143
2040	3,700	1,477	1,522	237
2045	4,903	2,056	2,089	350
2050	6,203	2,706	2,713	478

Cumulative Energy Savings, % of Baseline 2015+

	Low Tech Cost and High Oil Price		High Tech Cost and Reference Oil Price	
	Adv'd Conv.	Hybrid	Adv'd Conv.	Hybrid
2020	7.9%	2.2%	2.4%	0.2%
2025	12.3%	3.8%	4.1%	0.4%
2030	15.6%	5.4%	5.7%	0.7%
2035	18.0%	6.8%	7.1%	1.0%
2040	19.8%	7.9%	8.2%	1.3%
2045	21.2%	8.9%	9.0%	1.5%
2050	22.2%	9.7%	9.7%	1.7%

6.0 Summary and Observations

The benefits analysis reported in this document shows a wide range of market potentials for vehicles meeting the SuperTruck goals as met by the development teams. These benefits are based on a payback model which is driven by technology and fuel cost assumptions. Therefore, the reported market potential depends on future fuel prices and vehicle incremental costs, both of which carry significant uncertainty.

Under favorable technology cost and fuel price assumptions, market penetration estimates are significant and range from 19% to 59% in 2020 and 36% to 73% in 2050. This would result in cumulative fuel savings equivalent to 80 to 290 million bbl of oil by 2020 and 2,700 to 6,200 million bbl by 2050. It should be noted that the fuel prices under this favorable case are an extrapolation of current levels and trends. Even under the assumption of fairly high technology costs and fuel prices lower than current levels and trends, the analysis shows promising market potential ranging from 2% to 22% of new class 8 combination unit vehicle miles in 2020 and 8% to 36% by 2050. This results in cumulative fuel savings equivalent to 7 to 88 million bbl of oil by 2020 and 480 to 2,700 million bbl by 2050.

The SuperTruck development teams are approaching the project goals with a full vehicle systems approach. All teams have made significant progress toward meeting these goals and provided configuration details and anticipated benefits. The information represented a combination of test data, simulation results, engineering estimates, and program goals. Since some research areas are further along than others and some teams have been under contract longer than others, the relative confidence in the estimates varies by technology area and development team. Final configurations may change and freight efficiency improvements may be either higher or lower than the estimates calculated in this analysis.

At this stage of the program, much of the available data comes from component tests and simulations. Full vehicle systems will likely demonstrate interactive effects that are not currently fully evaluated. For example, trailer technology effects and interactions with the tractor may not be adequately represented in the information provided to date. As the program matures and these uncertainties are reduced, the benefits analysis can be updated with improved data.

While all teams are working toward the same program goals, there are differences in the development approaches. These variations reflect differences in markets and areas of company focus, as well as regional differences. Such variety is generally desirable from both a market and a technology risk standpoint.

The analysis results reported here show that there is significant market potential for fuel saving technologies that can achieve the SuperTruck goals. The development teams expressed their interest in commercialization of the component technologies being investigated under this project. They are well aware of the truck buyers' requirements for fairly rapid economic return

on their investment and are using these considerations to set priorities for near-term commercial development.

The market penetration calculation used for this analysis applied a fairly conservative adoption rate based on payback period. However, it did not incorporate any measure of consumer resistance or risk aversion. This could be a factor for the following issues:

- **Increased complexity of engine and exhaust after-treatment systems**: Historically, implementation of EGR, DPFs, and SCR to meet tightening EPA emissions standards has met market resistance due to perceptions about changes in frequency of repairs and difficulties encountered with these repairs.
- **Use of vehicle controls such as automated manual transmissions and torque control**: While these approaches improve fuel economy, the level of impact on other vehicle performance attributes remains to be determined. Accordingly, the development teams are focusing on both performance and fuel efficiency.

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