ORNL/TM-2004/115

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December 2004

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managed by
UT-Battelle, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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Acknowledgment

The authors would like to thank Sid Diamond of the Department of Energy, who initially identified the tooling issue and has enthusiastically supported this work; David Greene and Sugit Das of the Oak Ridge National Laboratory for many helpful suggestions; and Ed Ungar of Taratec Corporation and Curt Lavender of the Pacific Northwest National Laboratory for carefully reviewing the report.

Abstract

The use of lightweight and highly formable advanced materials in automobile and truck manufacturing has the potential to save fuel. Advances in tooling technology would promote the use of these materials. This report describes an energy savings analysis performed to approximate the potential fuel savings and consequential carbon-emission reductions that would be possible because of advances in tooling in the manufacturing of, in particular, non-power-train components of passenger cars and heavy trucks. Separate energy analyses are performed for cars and heavy trucks. Heavy trucks are considered to be Class 7 and 8 trucks (trucks rated over 26,000 lbs gross vehicle weight).

A critical input to the analysis is a set of estimates of the percentage reductions in weight and drag that could be achieved by the implementation of advanced materials, as a consequence of improved tooling technology, which were obtained by surveying tooling industry experts who attended a DOE Workshop, Tooling Technology for Low-Volume Vehicle Production, held in Seattle and Detroit in October and November 2003.

The analysis is also based on 2001 fuel consumption totals and on energy-audit component proportions of fuel use due to drag, rolling resistance, and braking. The consumption proportions are assumed constant over time, but an allowance is made for fleet growth. The savings for a particular component is then the product of total fuel consumption, the percentage reduction of the component, and the energy audit component proportion. Fuel savings estimates for trucks also account for weight-limited versus volume-limited operations. Energy savings are assumed to be of two types: (1) direct energy savings incurred through reduced forces that must be overcome to move the vehicle or to slow it down in braking. and (2) indirect energy savings through reductions in the required engine power, the production and transmission of which incur thermodynamic losses, internal friction, and other inefficiencies. Total savings for an energy use component are estimated by scaling up the direct savings with an approximate total-to-direct savings ratio.

Market penetration for new technology vehicles is estimated from projections about scrappage. Retrofit savings are assumed negligible, but savings are also assumed to accrue with increases in the fleet size, based on economic growth forecasts. It is assumed that as vehicles in the current fleet are scrapped, they are replaced with advanced-technology vehicles. Saving estimates are based on proportions of new vehicles, rather than new-vehicle mileages. In practice, of course, scrapped vehicles are often replaced with used vehicles, and used vehicles are replaced with new vehicles. Because new vehicles are typically driven more than old, savings estimates based on count rather than mileage proportions tend to be biased down (i.e., conservative).

Savings are expressed in terms of gallons of fuel saved, metric tons of CO2 emissions reductions, and percentages relative to 2001 levels of fuel and CO2. The sensitivity of the savings projections to inputs such as energy-audit proportions of fuel consumed for rolling resistance, drag, braking, etc. is assessed by considering different scenarios.

Though based on many approximations, the estimates approximate the potential energy savings possible because of improvements in tooling. For heavy trucks, annual diesel savings of 2.4-6.8 percent, and cumulative savings on the order of 54-154 percent, of 2001 consumption could accrue by 2050. By 2050, annual gasoline savings of 2.8-12 percent, and cumulative savings on the order of 83-350 percent of 2001 consumption could accrue for cars.

1. Introduction

The use of lightweight and highly formable advanced materials in automobile and truck manufacturing has the potential to save fuel. Advances in tooling technology would promote the use of these materials. This report describes an energy savings analysis performed to approximate the potential fuel savings and consequential carbon-emission reductions that would be possible because of advances in tooling in the manufacturing of, in particular, non-power-train components of passenger cars and heavy trucks. Light trucks are not considered in this analysis, though comparable savings could be expected for them as well.

A critical input to this analysis is a set of estimates of the percentage reductions in weight and drag that could be achieved by the implementation of advanced materials—as a consequence of improved tooling technology. These estimates were obtained by surveying tooling industry experts who attended the DOE Workshop, Tooling Technology for Low-Volume Vehicle Production, which was held in Seattle and Detroit in October and November 2003.

Saricks, Vyas, Stodolsky, and Maples (2003) have recently dealt with the topic of technologies for improving the energy efficiency of heavy trucks. These authors consider potential savings projections for both powertrain and non-powertrain technologies, though they do not consider savings due strictly to improvements in tooling. They consider non-powertrain technologies for reducing aerodynamic drag, rolling resistance, accessory loads, and mass, and, on the basis of data sources such as the *Technology Roadmap* (DOE 2000), they make savings projections, expressed as percentages, for various technologies. Their conclusions are based mostly on judgment, however, rather than new data or analysis. For example, they state that "since future year fuel prices were not available during this analysis, an approach based on technical judgment was employed, although it is acknowledged that pressures imposed by fuel price and perhaps future petroleum supply security concerns will be important accelerants to promulgation of these technologies." The authors also state at the outset that although such analyses ordinarily involve market-share penetration models, no such models are available for heavy trucks.

The main reason the conclusions of Saricks et al are based so heavily on judgment is limitations in available data. Speed, for example, is the main determinant, in the savings due to reducing aerodynamic drag, and yet there seems to be little statistical data on heavy truck speeds. (There is some data on driving patterns based on driver and flee-manager interviews.) However, despite the data limitations, an attempt is made here to derive projections of potential savings due specifically to tooling more formally than Saricks et al have in the general case. Market penetration is estimated from projections about scrappage based on a scrappage model of Greenspan and Cohen (1996), which is the model used to compute scrappage estimates for the *Transporation Energy Data Book* (DOE 2003). Sensitivity of savings projections to inputs such as energy-audit proportions of fuel consumed for rolling resistance, drag, and braking is assessed by considering different scenarios. We express projections in terms of gallons of fuel saved, in addition to savings percentages. And, the analysis here is based on the new expert input from the attendees of the tooling workshop.

The energy analyses assume that as vehicles in the current fleet are scrapped, they are replaced with advanced technology vehicles. Fuel savings begin to accumulate as each scrapped vehicle is replaced, because of the reductions in weight and aerodynamic drag of the new vehicle. Retrofit savings are assumed negligible, but savings are also assumed to accrue with increases in the fleet size. Separate energy analyses are performed for cars and heavy trucks. Heavy trucks are considered to be Class 7 and 8 trucks (trucks rated over 26,000 lbs gross vehicle weight).

The assumptions are approximations made to simplify the analysis. Because vehicle counts are more straightforward to model than vehicle mileages, savings estimates are based on percentages of new vehicles, rather than new-vehicle mileages. However, new vehicles are typically driven more than old: if X% of vehicles are scrapped and replaced with new vehicles, then more than X% of total fleet mileage should be by new vehicles. (Mileage is correspondingly reduced in the remainder of the fleet as it ages.) Therefore, the effect of basing savings estimates on vehicle rather than mileage percentages is to make the savings estimates smaller (more conservative).[1]

Fuel savings in a truck depend on whether the truck's operation is weight-limited or volume-limited. Weight limits are due to legal limits on weight; volume limits are due to finite vehicle volumes. If the tare weight of a truck is reduced, then, if the truck's operation is weight limited, energy savings are incurred through larger payloads and fewer trips. If the truck's operation is volume limited, the payload is the same, but there are savings because of tare weight reductions though reduced rolling resistance and reduced dissipated kinetic energy in braking. Fuel savings depend on mileage, brake applications, and gross vehicle weights (GVWs). In this sense, passenger car operation is also volume limited.

Fuel savings due to aerodynamic drag reduction depend on mileage and speed. Ideally an analysis of energy savings could be based on joint statistical data about mileage, brake applications, GVW, weight/volume limited operation, and speed. For each combination of these factors, the vehicle miles of operation would determine the savings. Unfortunately, such a data base would be a considerable undertaking, and future values would still have to be projected.

Alternatively, the analysis here is based on fuel consumption totals and energy-audit component proportions of fuel use due to drag, rolling resistance, and braking. The consumption proportions are assumed constant over time, but an allowance is made for fleet growth. The savings for a particular component is then the product of total fuel consumption, the percentage reduction of the component, and the energy audit component proportion.

The energy audit component proportions themselves have proportions due to

1. direct energy savings incurred through reduced forces that must be overcome to move the vehicle or to slow it down in braking
2. indirect energy savings through reductions in the required engine power, the production and transmission of which incur thermodynamic losses, internal friction, and other inefficiencies

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[1] This was pointed out to us by Ed Unger of Taratec Corporation.

In this report, the total savings for an energy-use component is estimated simply by scaling up the direct savings with an approximate total-to-direct savings ratio. Though maximum engine efficiency actually depends on a complex tuning of transmission and engine characteristics, this relationship is beyond the scope of the approximate analysis considered here.

Fuel consumption totals are obtained from FHWA's *Highway Statistics Series* (http://www.fhwa.dot.gov/policy/ohpi/hss/index.htm) and R. L. Polk's Trucking Industry Profile data (http://www.polk.com/products/plist.asp). Energy audit proportions are from the *Technology Roadmap* (DOE 2000) and other sources. Savings percentage estimates are obtained from the tooling workshop survey results. For trucks, estimates of the percentages of weight-limited and volume-limited operation based on various sources. The savings calculations are developed in Section 2.

This analysis is an approximation. Growth in the fleet sizes is estimated from economic forecasts. The results of the tooling survey are based on judgment, not experimentation. Sophisticated simulation of fuel consumption over various driving cycles was considered beyond the scope of the analysis. Several of the parameter inputs are expressed as ranges, however, and multiple estimates are computed to assess sensitivity over the ranges.

Results of the survey of tooling industry experts are summarized in Section 3. Section 4 contains an analysis of scrappage. Economic growth forecasts and growth in fleet size and fuel consumption are considered in Section 5. Tables of estimates of energy savings and CO_2 emission reductions are presented in Section 6. Conclusions and limitations are in Section 7

2. Weight and Drag

2.1. Weight and Drag in Heavy Trucks

Let $\mathbf{P_d}$ denote the proportion of energy consumed *directly* in overcoming aerodynamic drag. This refers to the energy transferred to air molecules because of drag as the vehicle passes through the air, but it does not refer, for example, to the energy lost *indirectly* as heat by the engine in powering the vehicle through the air. Let $\mathbf{P_w}$ denote the fleet-wide proportion of weight-limited operations. The proportion of volume-limited operations is then $1\text{-}\mathbf{P_w}$. For volume-limited operations, let $\mathbf{P_r}$ denote the fleet-wide proportion of energy consumed directly for overcoming rolling resistance, and let $\mathbf{P_b}$ denote the proportion consumed directly in braking. Again, this includes kinetic energy converted to waste heat because of rolling and braking resistance, but it does not included energy lost indirectly by the engine in providing the power to do so. We will assume these fleet-wide quantities are static, that is, constant in time.

Similarly, in this report, direct energy *savings* will refer to force-over-distance energy savings that result from reduced drag or mass. The energy to overcome these forces is delivered from the engine by the drivetrain, but the engine and drivetrain incur concomitant losses in producing and delivering this energy, and those losses are reduced if less energy must be delivered. Indirect savings will refer to the reduction in these concomitant losses. Indirect savings and therefore total (direct plus indirect) savings will be assumed to be proportional to the direct savings. Let $\mathbf{F_d}$ and $\mathbf{F_w}$ denote the total-to-direct proportionality constants for energy savings resulting, respectively, from reduced drag and weight.

Let $\mathbf{C_d}$ denote the coefficient of drag. If the drag coefficient is reduced from say $\mathbf{C_d}$ to $\mathbf{C_d'}$, then, for either weight or volume-limited traffic, elementary physics tells us that at any fixed speed, the energy expended to overcome drag is reduced in proportion to $(\mathbf{C_d} - \mathbf{C_d'})/\ \mathbf{C_d}$. Hence, this is also true for any statistical distribution of speeds, where, again, we assume the fleet-wide distribution is static in time. Here $(\mathbf{C_d} - \mathbf{C_d'})/\ \mathbf{C_d}$ represents savings due to improvements in tooling technology, over and above the standard technology. This allows for improvements in the standard technology as well as improvements in tooling technology.

Then

$$\textbf{Aerodynamic drag reduction fuel savings in year Y} \approx$$

$$\textbf{(Annual fuel consumption)} \times \textbf{(Proportion growth + Proportion vehicles scrapped in Y)} \times \mathbf{F_d} \times \mathbf{P_d} \times (\mathbf{C_d} - \mathbf{C_d'})/\ \mathbf{C_d}$$

$$+ \textbf{ Annual drag savings for vehicles new in years before Y}$$

We have assumed here that $\mathbf{P_d}$ is the same for both the advanced and standard technologies, though of course a weight or drag reduction would cause $\mathbf{P_d}$ to change very slightly. The quantity $(\mathbf{C_d} - \mathbf{C_d'})/\ \mathbf{C_d}$ is one of the quantities estimated by the tooling workshop attendees.

"Annual fuel consumption" in the above expression refers to the baseline value. (Growth is modeled through the "Proportion growth" term.") The baseline is taken as the estimate of the 2001 total for combination trucks, found in the *Transportation Energy Data Book* (Davis and Diegel, 2003, Table 5.2). This value may be slightly small, because it excludes single unit trucks (ibid, Table 5.1). However, most of the savings estimates discussed here are reported as percentages of the 2001 total, which, by cancellation, do not depend on the 2001 total itself.

Weight reduction fuel savings are due to reduced rolling resistance (through reduced inertia) and reduced dissipated braking heat. For a given GVW, elementary physics shows that rolling resistance and braking savings are proportional to Δ/GVW, where Δ is the tare reduction. Thus

Volume-limited weight reduction fuel savings for year Y ≈

(Annual fuel consumption) × (Proportion growth + Proportion vehicles scrapped in Y)
× F_w × (1- P_w) × (P_r + P_b)

× (Tare/GVW) × (Proportion reduction in tare)

+ Annual volume-limited weight savings for vehicles new in years before Y

The proportion reduction in tare is one of the quantities reckoned by the workshop survey respondents.

Weight limited mileage is mileage for which a lower tare would increase the payload. Note that weight-limited mileage can therefore be mileage with GVW < GVWR (GVW Rated). Consider, for example, a delivery truck on a route with multiple deliveries. The truck is likely to start out at the legal weight limit, but after the first delivery, its weight is below the legal limit. Nevertheless, its weight is still limited, now by the legal GVWR minus the weight of the first delivery. Thus a tare reduction also allows in practice for bigger less-than-full loads. Under this definition, return-empty mileage is not weight limited, because the savings for a tare reduction for any return-empty mileage are the same whether the trip was weight or volume limited at the start. Return-empty mileage will be accounted for as described below.

The savings for weight-limited mileage with larger payloads are through reductions in numbers of trips. In this analysis it is assumed that increasing the payload increases the ton-mileage per trip in the same proportion and decreases the number of trips by the corresponding reciprocal proportion. This approximation is inexact because the number of trips is integer-valued (not continuous) and because changing the payload could affect optimal itineraries. Thus the ton-mileage per trip might not increase in exactly the same proportion as the payload. Nevertheless, laws of large numbers suggest that that the approximation is reasonable for large populations of trucks. Note that return-empty mileages are thus incorporated into savings for weight-limited trips, because return empty trips are correspondingly reduced (approximately).

By the above assumptions,

Weight-limited weight reduction fuel savings in year Y ≈

(Annual fuel consumption) × (Proportion growth + Proportion vehicles scrapped in Y) × $\mathbf{P_w}$ × (Tare/Payload) × (Proportion reduction in tare)

+ Annual weight-limited weight savings for vehicles new in years before Y.

Payload refers here to the total initial payload, which is GVWR - Tare. This varies from truck to truck, though to a lesser extent than volume-limited GVW's vary.

The approximate net fuel savings for trucks is then the sum of the above three approximate savings for aerodynamic drag, weight-limited weight savings, and volume-limited weight savings. To use these approximations, we need estimates for $\mathbf{P_d}$, $\mathbf{P_w}$, $\mathbf{P_r}$, $\mathbf{P_b}$, $\mathbf{F_d}$, $\mathbf{F_w}$ and ($\mathbf{C_d}$ - $\mathbf{C_d}$')/ $\mathbf{C_d}$, for the tare-to-GVW ratio for volume-limited operation, and for the tare-to-payload ratio for weight-limited operations. We also need estimates for the percent of vehicles scrapped. To estimate carbon emissions savings, we need a fuel-to-carbon conversion factor. The estimates used for this analysis are listed in Table 1.

The ideal values to use for the tare-to-GVW and tare-to-payload ratios would be fleet-wide averages. In the absence of statistical data, the values used here for these quantities are judgment estimates based on sources such as Eberhardt (www.osti.gov/fcvt/deer2002/eberhardt.pdf, page 10) and others. Thus, roughly, a representative tare weight for a heavy truck is about 30,000 lbs. A representative GVW, in volume-limited operations, is about 60,000 lbs. So, a representative value for the volume-limited **Tare/GVW** is 30,000/60,000 = 0.5. Similarly a typical weight-limited payload is 45,000 lbs, implying a GVW of about 75,000 pounds. This is less than 80,000 pounds, because full loads of discrete materials (e.g., large electric motors) do not necessarily weigh to the legal limit, and because, even for bulk haul, weight limited loads are not necessarily full (as with delivery trucks). So in the weight-limited case, a representative value for **Tare/Payload** is 30,000/45,000 = 2/3.

The error in these estimates is almost surely much smaller than, for example, the standard deviation of the statistical distribution for individual trucks, and is likely to be small compared to the error ranges for the other quantities. For example, if the representative weight-limited payload is taken to be 50,000 lbs. (80,000 – Tare) instead of 45,000, the **Tare/Payload** ratio is .6 rather that 2/3. This difference is small in comparison with, for example, the estimation range for proportion reduction in tare weight. Therefore the **Tare/Payload** and **Tare/GVW** estimates are used *per se* in the equations, without also guessing a range for them.

Values in this report for $\mathbf{F_d}$ and $\mathbf{F_w}$, the total-to-direct energy savings proportionality constants, are also approximate. According to the *Technology Roadmap* (DOE 2000), "At highway speeds, the fraction of fuel expended to overcome aerodynamic drag is approximately half of the fuel not expended in engine losses. Reducing aerodynamic drag by 25% results in savings in fuel consumption for steady highway travel in the range of 10 to 15%." On the other hand, according to the *Technology Roadmap*, aerodynamic losses are 21.25% (100 × 85/400) of the total losses for a Class 8 truck going 65 miles per hour. Thus a 25% drag reduction reduces the energy lost *directly* to drag by 100 ×.25 × .2125 = 5.3%, and the total savings of 10 to 15% is 1.88 to 2.82

Table 1. Parameter Values for Heavy Truck (Class 7, 8)
Energy Savings Through Improved Tooling

Parameter	Value	Range	Source
Annual fuel consumption	25,555 million gallons	–	Trans. Energy Data Book (2003; Tables 5.1, 5.2; value for 2001)
$\mathbf{P_d}$	.20	.091-.2125	*Technology Roadmap**
$\mathbf{P_w}$	.15	.10-.50	*Technology Roadmap* and Taratec (2002)
$\mathbf{P_r}$	.10	.0497-.1275	*Technology Roadmap**
$\mathbf{P_b}$	.04	0-.0567	*Technology Roadmap**
$\mathbf{F_d}$	2.35	1.88-2.82	*Technology Roadmap**
$\mathbf{F_w}$	2.6	–	*Technology Roadmap**
Approximate Tare/GVW (volume limited)	.5 = 30,000/60,000	–	Eberhardt†
Approximate Tare/Payload (weight limited)	2/3 = 30,000/45,000	–	Eberhardt†
Pct. vehicles scrapped in year Y	(see Section 4)	–	Scrappage Analysis for Trans. Energy Data Book (2003)
Fleet growth	1.5% of current stock per year	–	EIA** (see Section 5)
$\mathbf{(C_d - C_d')/ C_d}$	.03	.02-.05	DOE Tooling Workshop
Proportion Reduction in Tare Weight	.05	.03-.10	DOE Tooling Workshop
Diesel Gallons to $\mathbf{CO_2}$ Metric tons	.01016042	–	EIA††

*DOE (2000)
†www.osti.gov/fcvt/deer2002/eberhardt.pdf (page 10)
**http://www.eia.doe.gov/oiaf/aeo/supplement/pdf/supplement_tables(2004).pdf
††ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/pdf/1605EZ02.pdf (page 22)

(10/5.3 to 15/5.3) times the direct savings. The average of these two figures, 2.35, will be used in this report for the value of $\mathbf{F_d}$ for heavy trucks.

According to the *Technology Roadmap*, “Industry experience indicates that for a typical Class 8 tractor-trailer combination running on an interstate circuit, a 30% decrease in total vehicle tire-rolling resistance would improve fuel consumption by approximately 10%.” However, the *Technology Roadmap* also cites 12.75% (100 × 51/400) as the percentage of energy lost *directly* to rolling resistance by a tractor trailer going 65 miles per hour. Therefore a 30% decrease in total vehicle tire-rolling resistance would result in a 3.83% (.30 × 12.75%) savings in *direct* energy loss to rolling resistance. The total savings is thus 2.6 (10/3.83) times the direct savings. Therefore, 2.6 is used as the value for $\mathbf{F_w}$ for heavy trucks.

Unburned diesel fuel translates proportionately to reduced CO_2 emissions. Multipliers to convert gallons of diesel to pounds of CO_2 can be obtained from the Energy Information Agency (EIA) (ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/pdf/1605EZ02.pdf). According to EIA, 22.4 pounds of CO_2 are released for each consumed gallon of diesel fuel. In Table 1, pounds are converted to metric tons using the conversion 2204.63 pounds per metric ton.

The values for $\mathbf{P_d}$, $\mathbf{P_r}$, $\mathbf{P_b}$ in Table 1 were computed from energy audit data for Class 7 and 8 vehicles in the *Technology Roadmap* (DOE 2000). The range of $\mathbf{P_w}$ was from the *Technology Roadmap* and from an analysis performed by Taratec Corporation (Taratec 2002) of data from FHWA's Vehicle Traffic Information System.

The values in Table 1 were used to calculate the energy savings estimates for heavy trucks. To assess sensitivity and to obtain a range of estimates, various scenarios were also considered. This is discussed in Section 6.

2.2. Weight and Drag in Cars

Savings for cars are calculated essentially as above for trucks, except that for cars there is no weight-limited component of mileage or savings ($\mathbf{P_w} = 0$), and of course the equation parameters have different values. Table 2 shows the parameter estimates used for cars. The values for $\mathbf{P_d}$, $\mathbf{P_r}$, $\mathbf{P_b}$ in Table 2 were computed from urban and highway-driving energy audit data for mid-size automobiles from the Partnership for a New Generation of Vehicles (PNGV), as given, for example, by Plotkin et al (2001). Values of $\mathbf{F_d}$ and $\mathbf{F_w}$ for cars were obtained as follows.

Greene, Gibson, and Dunleep (2003) quote 6.6% and 2.2% as the percentage reduction in fuel use for each percent reduction in weight or drag respectively. (These authors refer for these figures to a 1993 report by Energy and Environmental Analysis, Inc.). According to the PNGV energy audit data, rolling resistance and braking account for 4.2% (7.1%) + 5.8% (2.2%) of fuel use for the urban (highway) driving cycle. Adding the above figures for rolling resistance and braking gives totals of 10.0% (9.3%) of fuel used in the urban (highway) cycles. From these results, a 1% weight reduction would result in a .1% (or .093%) reduction in energy consumed directly for braking and rolling resistance, and this appears to be relatively invariant to the driving cycle. Therefore, the value for $\mathbf{F_w}$ is taken as 6.6 (.66/.1).

Similarly, according to the PNGV energy audit, the direct energy savings for a 1% reduction in Cd should be in the range .026-.109%. The ratio of the total to the direct value should therefore be in the range 2.02 to 8.46 (i.e., .22/.109 to .22/.026). That is a wide range. However, the lower (2.02) figure corresponds to the highway cycle, during which engine losses are slightly higher (69.2% vs 62.4%) and during which idling losses are much lower (3.6% vs 17.2%). Therefore the most conservative 2.02 figure is probably also the best figure to use in the range 2.02 to 8.46. Thus the value 2.02 was taken as the value for $\mathbf{F_d}$.

The values used for $\mathbf{F_d}$ and $\mathbf{F_w}$ are not for any particular fuel cycle (e.g., urban or highway). As with the heavy trucks, various scenarios were considered to assess the sensitivity of the calculations and to provide a range of estimates (see Section 6).

Table 2. Parameter Values for Passenger Cars
Energy Savings Through Improved Tooling

Parameter	Value	Range	Source
Annual fuel consumption	73,261 million gallons	–	Trans. Energy Data Book (2003; Table 4.1; value for 2001)
$\mathbf{P_d}$	.080	.026-.109	PNGV*
$\mathbf{P_r}$	.050	.042-.071	PNGV*
$\mathbf{P_b}$	.040	.022-.058	PNGV*
$\mathbf{F_d}$	2.02	–	Greene et al, 2003
$\mathbf{F_w}$	6.6	–	Greene et al, 2003
Tare/GVW	3100/3400 = .91	–	Eberhardt†
Pct. vehicles scrapped in year Y	(see Section 4)	–	Scrappage Analysis for Trans. Energy Data Book (2003)
Fleet growth	.098% of current stock per year	–	EIA** (see Section 5)
$\mathbf{(C_d - C_d')/ C_d}$	.015	0-.030	Tooling Workshop
Proportion Reduction in Tare Weight	.10	.05-.20	Tooling Workshop
Gasoline Gallons to $\mathbf{CO_2}$ Metric tons	.00889036	–	EIA††

*See Plotkin et al (2001).

†www.osti.gov/fcvt/deer2002/eberhardt.pdf (page 10)

**http://www.eia.doe.gov/oiaf/aeo/supplement/pdf/supplement_tables(2004).pdf

††ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/pdf/1605EZ02.pdf (page 22)

3. Survey of Tooling Industry Experts

The attendees of the Tooling Technology Workshop were asked to fill out a survey questionnaire containing questions about (1) the extent to which barriers in tooling are impeding the implementation of lightweight and aerodynamic parts in automobile and truck manufacturing, and (2) the potential weight and drag reduction improvements that could be achieved because of the elimination of those barriers. Survey respondents were also asked to rate their ability to answer the various questions. As described below, the self-assessments were used in computing estimates from the responses to the other questions. The survey questionnaire is in Appendix A.

Twenty six Seattle workshop attendees and thirty two Detroit attendees turned in the questionnaires. However, not every respondent answered every question. The survey results for questions other than the self-assessments are summarized in Figures 1-4.

3.1. Self-assessments

In the self-assessment scores, Seattle attendees tended to rate themselves a little lower than Detroit attendees rated themselves, particularly for survey questions 2 and 4 (see Appendix A). For questions 2 and 4, average scores were lower by .39 and .36 percentage points. For survey questions 1 and 3, Seattle scores were higher by .12 and lower by +.06 percentage points. Seattle and Detroit self-assessment scores were not significantly different, however (by chi-square frequency test). However, a number of the ratings themselves (i.e., answers to question 1-4) were significantly different, with Detroit attendees tending to be a little more optimistic. This was particularly the case for questions 3a and 3b about tare weight reductions possible because of improvements in tooling (see Figures 1-4, particularly 3a and 3b).

Optimism bias in the Detroit relative to the Seattle responses was not unexpected, because of the slightly different focuses of the two workshops. (The focus in Seattle was on identifying the industrial needs to reduce cost and development times for tooling in the first workshop. The focus in Detroit was on emerging tooling technologies, prospective solutions, and the merits of government investment in the second workshop.) Because of the focus differences, the Seattle responses were expected to be more realistic, on average. However, there are only 26 Seattle responses. Considerable statistical improvement in estimates computed from the results may be possible by including some or all of the additional 32 Detroit responses.

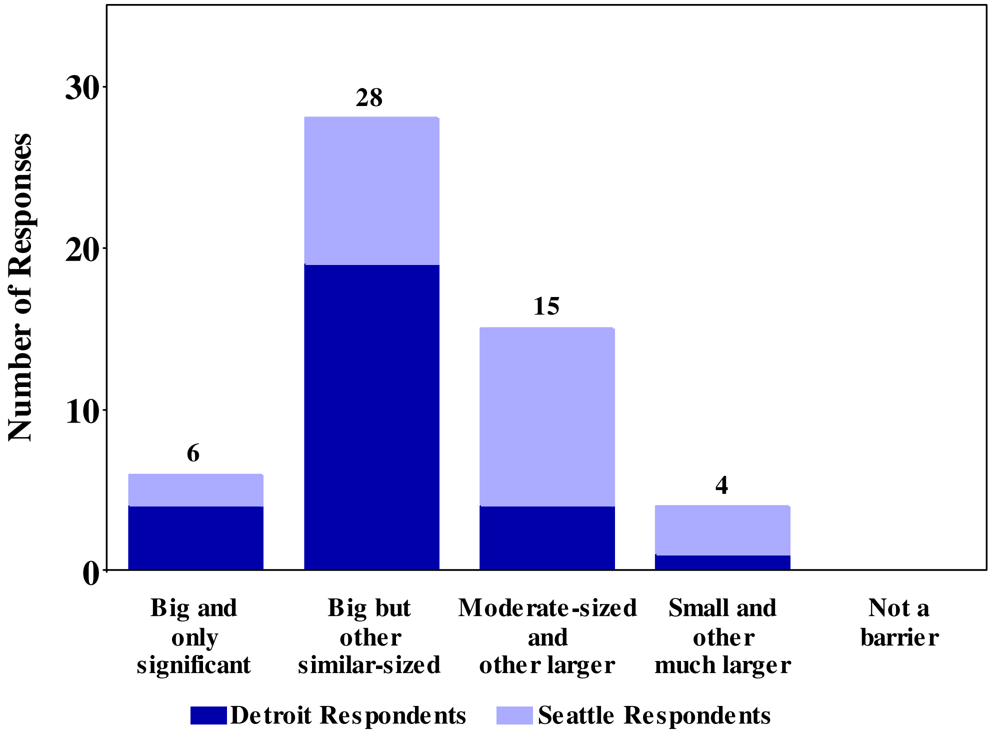

Figure 1. How much of a barrier is tooling to implementation of lightweight/aerodynamic parts?

For both the Seattle and Detroit workshop attendees, individual question responses with corresponding self-assessments of "poor" were excluded. Because the Detroit respondents tended to be slightly more optimistic in their ratings (see Figures 1-4), the questionnaire responses were analyzed both with and without Detroit responses with corresponding "fair" self-assessment ratings. For some of the questions, for example Question 3a about the tare reduction for Class 8 trucks, the Detroit responses were significantly higher (more optimistic, p=.006 for Question 3a). By excluding the Detroit responses rated as "fair", the apparent optimism bias in the Detroit relative to the Seattle results was reduced. Therefore individual question responses with corresponding self-assessments of "poor" were not used for either Seattle or Detroit workshop attendees, and questions with corresponding self-assessments of "fair" from the Detroit (only) workshop were not used in the analysis.

Figure 1 shows that most of the workshop attendees believe that tooling is a significant barrier to implementing lightweight and aerodynamic parts, but that there are other comparable barriers as well. Figures 2a and 2b show that they think that appreciable improvements in tooling costs (mean = 39%) and lead times (mean = 38%) are needed to significantly reduce the tooling barrier. These results verify what might be expected for attendees of a tooling workshop—that they see tooling barriers as substantial yet of a degree that is feasible to address.

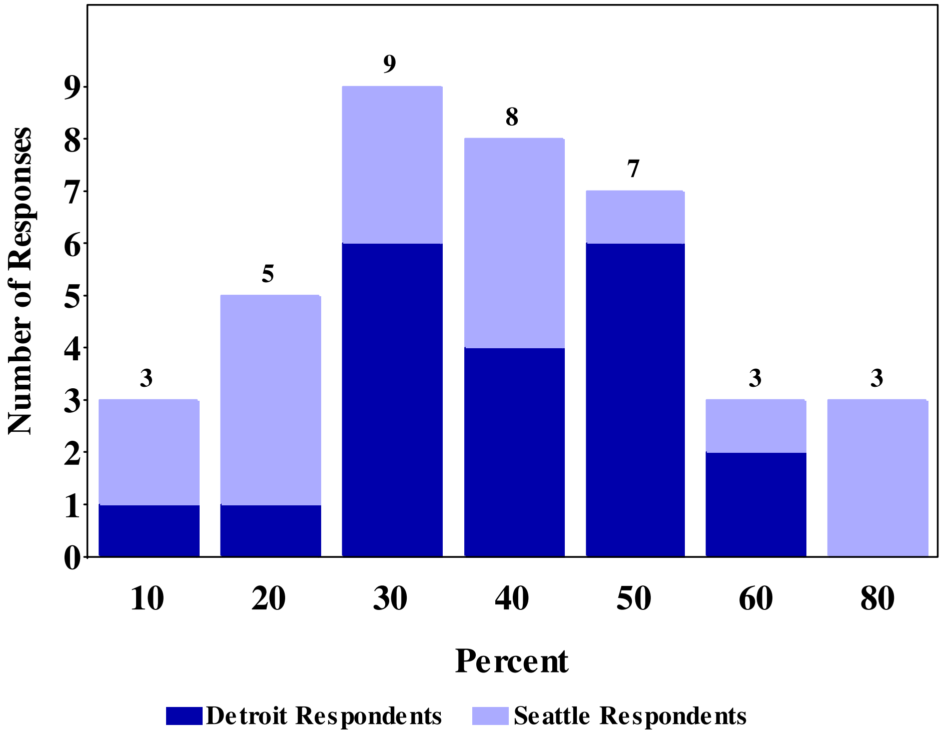

Figure 2a. How much improvement in tooling technology cost is needed to significantly reduce the barrier referred to in Question 1.

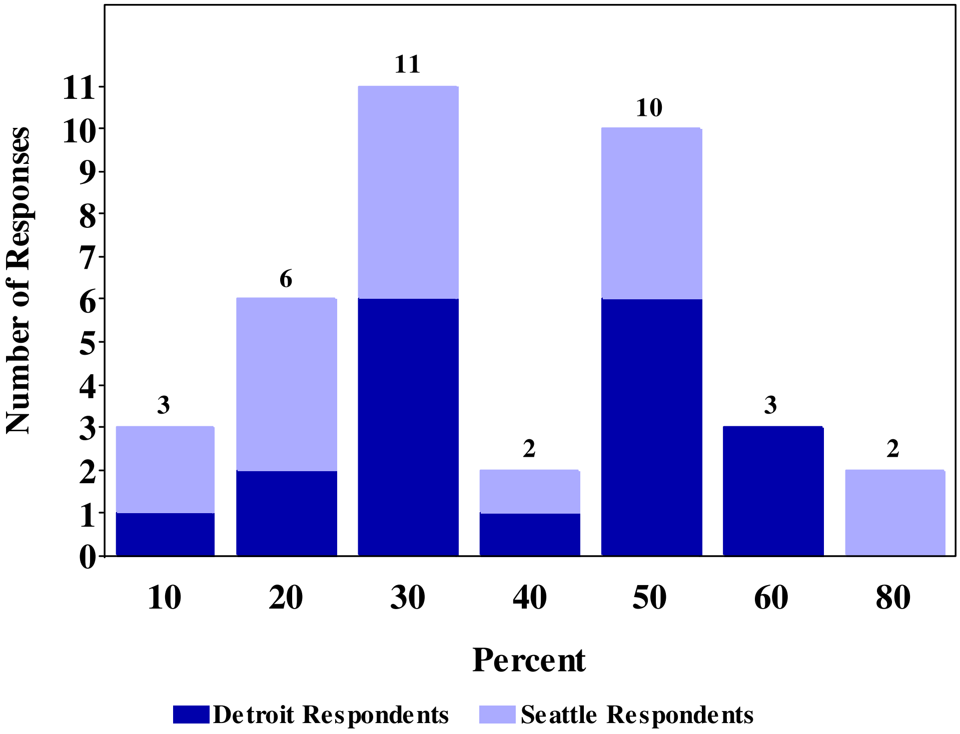

Figure 2b. How much improvement in tooling technology lead time is needed to significantly reduce the barrier referred to in Question 1.

3.2. Estimates of Weight Reduction

Figure 3a shows that 5-10% was the modal response (the "plurality vote") of the workshop attendees for the percentage of tare weight reduction in Class 8[2] trucks possible because of improvements in tooling technology. The next highest response category was 3-5%. Figure 3b shows that 10-20% was the modal response for tare weight reduction possible for family sedans because of improvements in tooling technology. The next highest response category was 5-10%.

These results suggest that 5% would be a good candidate for the approximate percentage tare weight reduction in Class 8 trucks possible because of improvements in tooling, and 10% would be a good candidate for the approximate percentage for family sedans. Low and high values of 3% and 10% for Class 8 trucks and 5% and 20% for family sedans would be reasonable candidates for assessing the sensitivity of the approximations.

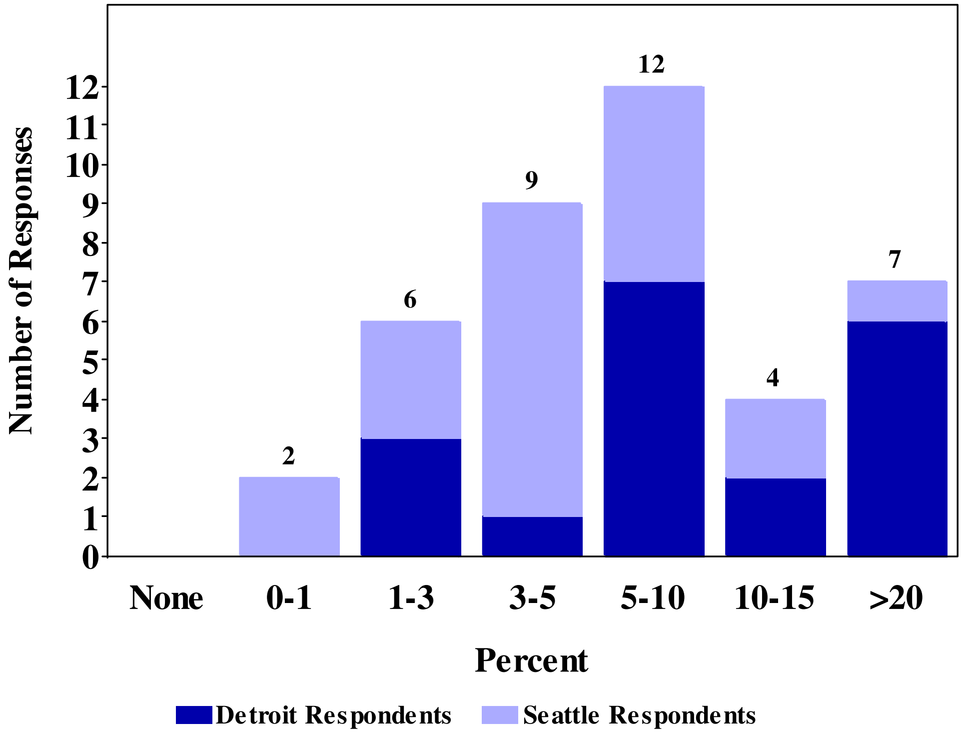

Figure 3a. Best estimates of the Class 8 truck tare weight reduction achievable through improved tooling technology.

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[2] Although "Class 8" rather than "Class 7 and 8" or "heavy" was used to phrase the survey questions, Class 7 trucks actually make up only 8.6% of the combined fleet of Class 7 and 8 trucks, and use only 5.9% of the Class 7 and 8 combined fuel (DOE 2003, Table 5.4).

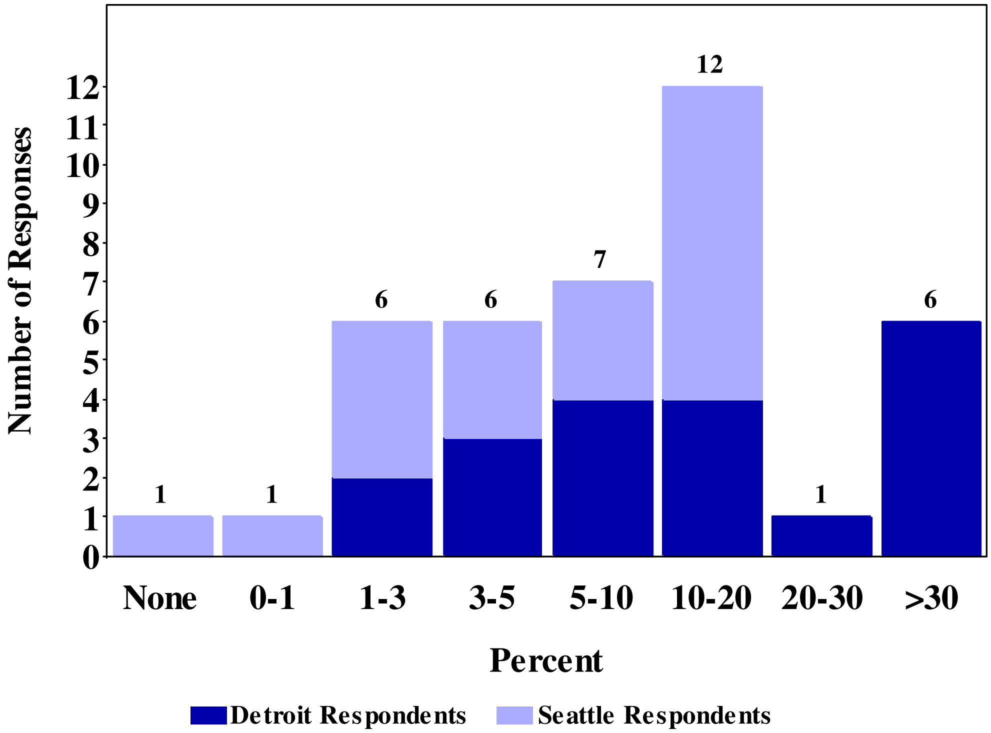

Figure 3b. Best estimate of the family sedan tare weight reduction achievable through improved tooling technology.

3.3. Estimates of Drag Reduction

Figure 4a shows that 2-3% was the modal response for the percentage of drag coefficient reduction in Class 8 trucks possible because of improvements in tooling technology. The next highest response category was 3-5%. Figure 4b shows that there were two modal responses, 0-1% and 2-3% for the percentage of drag coefficient reduction in family sedans possible because of improvements in tooling technology. For some reason there is a division in these responses, with only two respondents selecting the 1-2% category.

These results suggest that 3% would be a good candidate for the approximate percentage drag coefficient reduction in Class 8 trucks possible because of improvements in tooling, and 1.5% would be a good candidate for the percentage for family sedans. Low and high values of 2 and 5% for Class 8 trucks and 0 and 3% for family sedans would be reasonable candidates for assessing the sensitivity of the approximations.

Many workshop attendees indicated that percentage improvements considerably greater than the modal responses would be possible for both weight and drag reductions. However, those responses tended to be primarily from Detroit attendees. Figures 3a and 3b, and 4a and 4b, show that Seattle workshop attendees were on average slightly less optimistic about the percentages than Detroit attendees. The above approximations and low-high sensitivity ranges are reasonable, especially given that Seattle responses are likely to be more realistic.

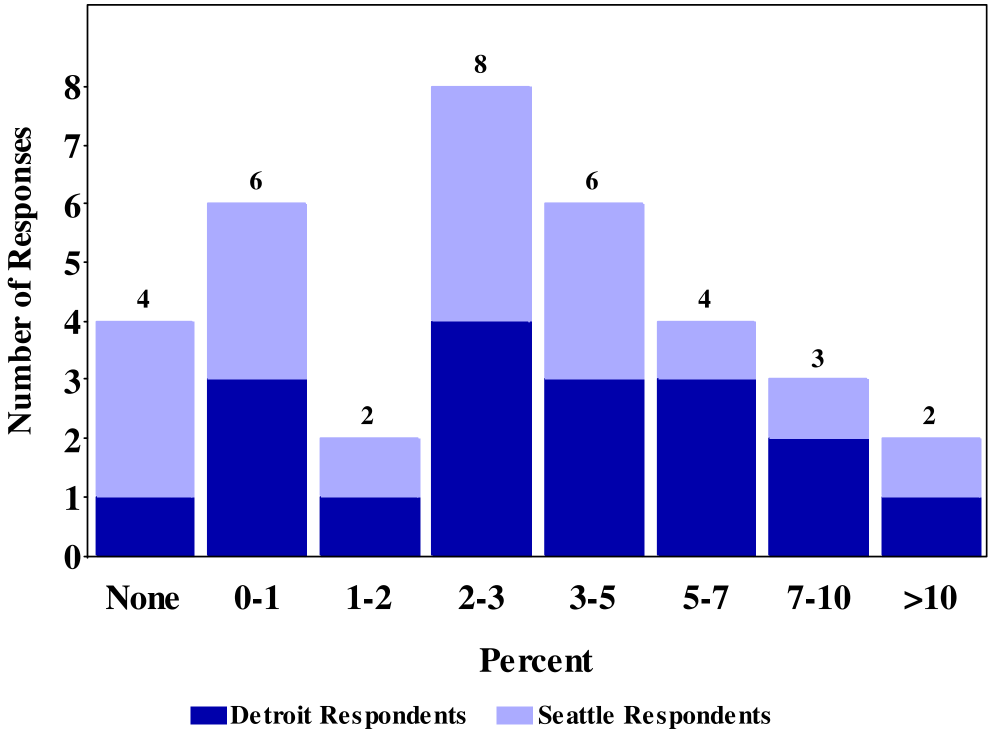

Figure 4a. Best estimate of the Class 8 truck drag coefficient reduction achievable through improved tooling technology.

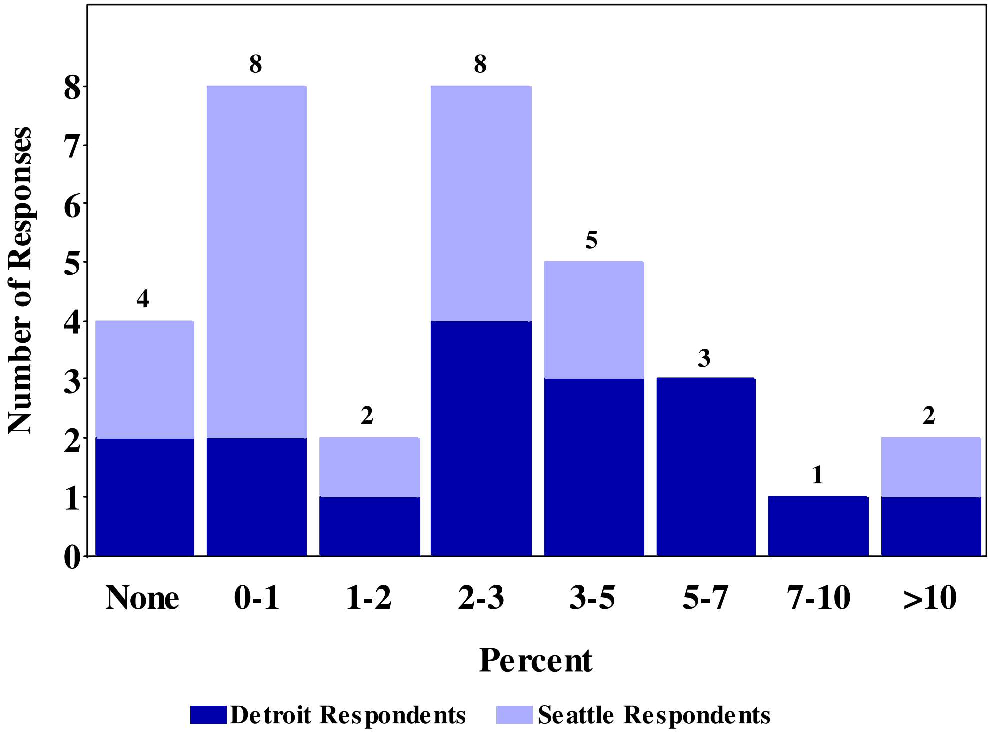

Figure 4b. Best estimates of the family sedan drag coefficient reduction achievable through improved tooling technology.

4. Scrappage Forecasts

To estimate the potential energy savings due to improvements in tooling technology, we need to estimate the scope of potential applications. In this case, an application will be assumed to occur when a new vehicle with the new technology is put to use. To estimate the potential number of technology applications, we will use estimates (projections) of the scrappage of old vehicles together with projections of fleet growth, which is considered in the next section.

Scrappage statistics are presented in the *Transportation Energy Data Book* (Davis and Diegel, 2003). Scrappage (survival) curves are presented for passenger cars, light trucks, and heavy trucks. Heavy trucks are defined in the Data Book as Class 7 and 8 trucks. Although the Data Book's scrappage data has not been updated since 2001, and the scrappage analysis is based on data for years 2000 and earlier, the Data Book scrappage data is still the most recent available. Therefore, we will base our estimates of the benefits of improved tooling on this Data Book scrappage data and analysis.

Because of data limitations, and because the scrappage models are derived empirically, the Data Book scrappage estimates are based on different models for passenger cars and heavy trucks. The model for Class 7 and 8 trucks is

$$\begin{gathered}\mathbf{log(Vehicle\ count) = a_m + b_m \times Age^2} \\ \mathbf{+\ d \times (Lag\ unemployment\ rate)} \\ \mathbf{+\ e \times (Ratio\ of\ repair\ to\ new\text{-}vehicle\ cost\ indexes)}\end{gathered}$$

where **Vehicle count** denotes the number of vehicles surviving at the given age, **m** denotes model year, and the $\mathbf{a_m}$, $\mathbf{b_m}$, **d**, and **e** are fitted parameters. Separate a's and b's are fit for each model year. Other explanatory variables, for example diesel fuel costs, were considered for this model, but were not ultimately included.

For passenger cars, the model is

$$\begin{gathered}\mathbf{log(Survival) = b_m \times Age^2 + c \times Age^3} \\ \mathbf{+\ d \times (Unemployment\ rate)} \\ \mathbf{+\ e \times (Lag\ unemployment\ rate)} \\ \mathbf{+\ f \times (Ratio\ of\ repair\ to\ new\text{-}vehicle\ cost\ indexes)} \\ \mathbf{+\ g \times (Gasoline\ price\ index)}\end{gathered}$$

where **survival** is the proportion of vehicles surviving at the given age, **m** denotes model year, and $\mathbf{b_m}$ and **c-g** are fitted parameters.

These models are fit (for the Data Book) using vehicle registration counts from the R. L. Polk Co., Detroit, Michigan, and from unemployment rates and price indexes (independent variables) from the Bureau of Labor Statistics (http://www.bls.gov/bls/proghome.htm). For both cars and trucks, different Data Book scrappage curves are estimated for each model year for which ample data is available (up to 1990).

However, examination of the Data Book scrappage curves shows that (1) vehicle survival has improved over time, though changes in survival curves have been slow, and (2) for any given model year, quite a few years of data are necessary to reliably estimate the survival curve. Point (2) holds especially for heavy trucks, which have relatively long lifetimes and little scrappage in the first five or ten years. Because of (2), we cannot reliably estimate survival curves for any recent model year (e.g., 1998) on the basis solely of the survival record for vehicles from that year. Rather, survival records for vehicles of earlier model years have to be combined to improve the statistical fit. In addition, differences in accounting over the years have introduced problems in combining scrappage estimates from different years.

In view of these difficulties, for the tooling policy analysis, one scrappage curve was picked from one model year for cars and from one model year for heavy trucks. From the scrappage curves in the Data Book, 1985 appears to be a good choice of model year for heavy trucks, and 1990 appears a good choice for passenger cars, because enough time has elapsed to allow these curves to be estimated well. Historical averages (for 1984 through 2000 for trucks and 1981 through 2000 for cars) were used as values in the equation for the various unemployment rates and cost indexes. These curves are shown in Figure 5. Using the curves, survival rates were computed for vehicles of any age and used to estimate scrappage counts, for vehicles of all ages, for each year subsequent to 2000. By approximation, these scrappage counts can be slid forward to start at the year that tooling technology changes are assumed to take place. This approach is used in Section 6.

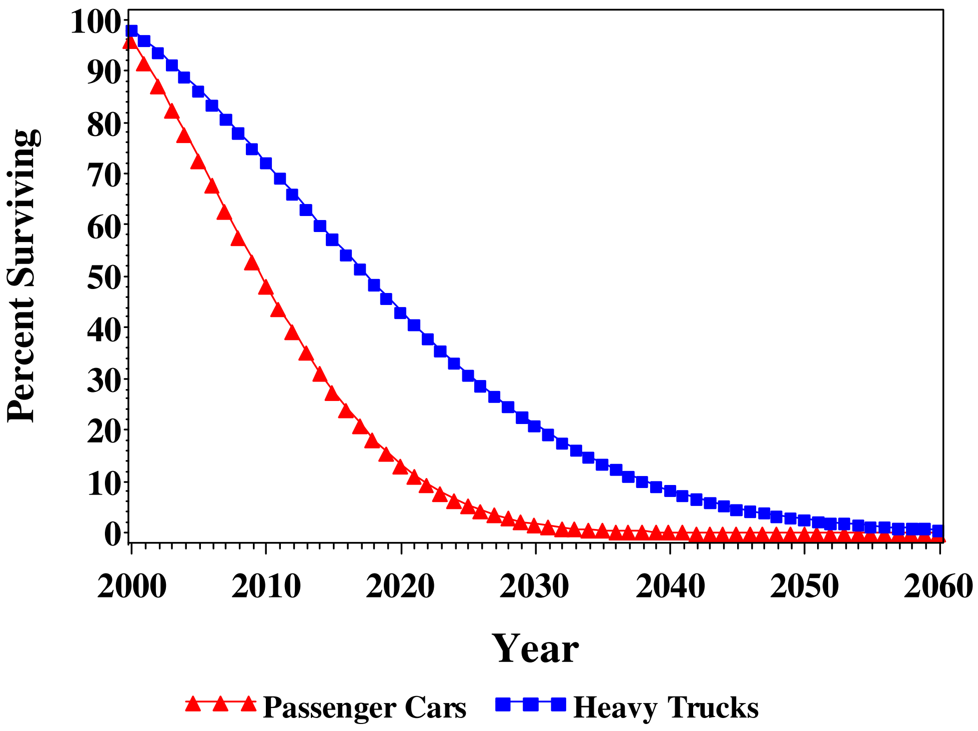

Figure 5. Survival curves used to estimate scrappage of existing heavy truck and car fleets. Curves here begin in 2000. These curves are slid forward in time to estimate potential fuel savings (Section 6).

5. Fleet Growth

Figure 6 shows that over the past twenty or thirty years, the nation's heavy truck fleet has grown approximately in proportion to the U.S. gross domestic product. That growth has been substantial. The fleet size and GDP have doubled, roughly, in the last twenty years.

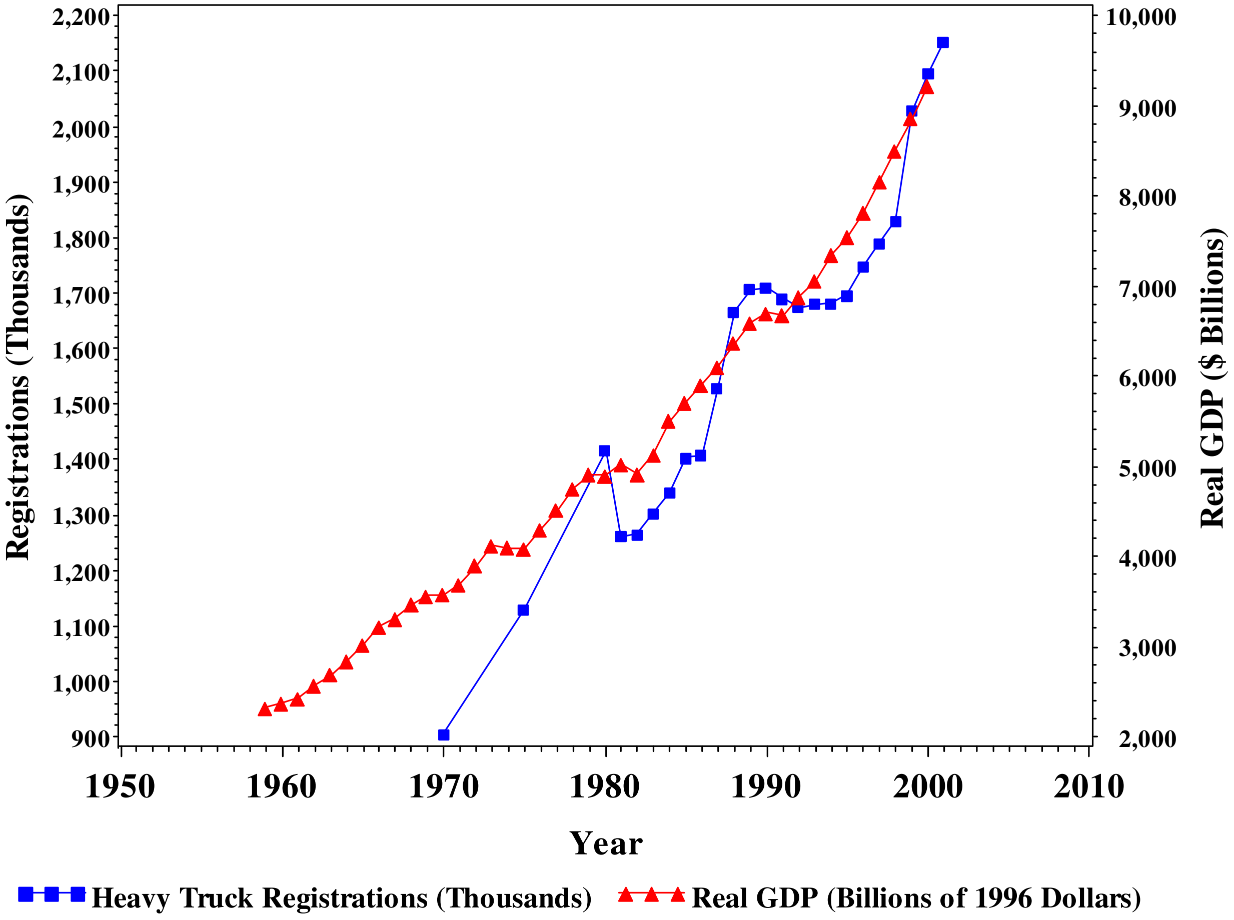

Figure 6. Concurrent growth of heavy truck fleet size and real gross domestic product in 1996 dollars. Sources: *Transportation Energy Data Book* (Davis and Diegel, 2003, Table 5.2), and the Economic Report of the President (http://w3.access.gpo.gov/usbudget/fy2003/erp.html).

However, past performance does not guarantee of future results. It would be inappropriate simply to extrapolate fleet growth rates forward in time. The EIA (2004) publishes forecasts of energy consumption to 2025. Part of the EIA analysis involves projecting fleet sizes for heavy trucks and cars. These projections are published in *Supplemental Tables to the Annual Energy Outlook 2004* (http://www.eia.doe.gov/oiaf/aeo/supplement/index.html; pages 102 and 105 for heavy trucks; pages 64 and 66 for cars). The fleet size for heavy trucks fuel is projected to increase from 4.53 million in 2001 to 5.46 million in 2013 and to 6.17 million in 2025. The fleet size for cars is projected to grow more modestly: from 128.89 million in 2001 to 130.55 million in 2013 and to 131.93 million in 2025. (As in recent years, the fleet size is projected to grow much more for light trucks than for cars.) For heavy trucks, this an increase of 36.2% or 1.5% per year. For automobiles, the increase is 2.35% or .098% per year. These growth rates were used along with the other inputs to compute the fuel savings and emissions reductions estimates

6. Fuel Savings and Emission Reductions

The values in Tables 1 and 2 can now be combined with the scrappage forecasts in Sections 4 and 5, and substituted into the equations in Section 2 to estimate potential savings due to improvements in tooling. Starting with a fleet of heavy trucks assumed to consume 35,287 million gallons of diesel annually (Table 1) and a fleet of cars assumed to consume 73,261 million gallons of gasoline annually (Table 2), new-technology vehicles enter the fleet to replace scrapped vehicles and as the fleet grows, at which point savings begin to accrue. The annual distribution of speeds and mileages per vehicle in the fleets are assumed to remain constant. It follows that the proportions of total fuel consumed to overcome drag, to overcome rolling resistance, and in braking, are constant over time.

6.1. Input Value Ranges

The proportions of fuel consumed to overcome drag and rolling resistance, and for braking are not known exactly. They depend on fleet-wide speed and mileage distributions, for which little statistical data is available. Similarly, truck fuel savings depend on the fleet-wide percentage of weight-limited operations, for which little reliable data is available. Therefore these quantities are estimated on the basis of energy audit analyses and industry experience. To assess the sensitivity of the estimates, several driving scenarios are used to represent different proportions of energy consumed because of drag, rolling resistance, and braking. A "Faster" scenario assumes more high-speed driving and less braking, but more savings due to drag reduction. A "Slower" scenario assumes less high-speed driving and more braking, but less savings due to drag reduction. A "Middle" scenario is computed using the point estimates in Tables 1 and 2 (second columns) for $\mathbf{P_d}$, $\mathbf{P_r}$, and $\mathbf{P_b}$. Table 3 shows these scenarios and the values used for cars and trucks.

Table 3. Proportion of Energy Consumption Values for Drag, Rolling Resistance, and Braking—Values Used to Estimate Potential Savings

Vehicle Type	Driving Scenario	P_d	P_r	P_b
Heavy Trucks	Slower	.0910	.0497	.0567
	Middle	.2000	.1000	.0400
	Faster	.2125	.1275	.0000
Passenger Cars	Slower	.026	.042	.058
	Middle	.080	.050	.040
	Faster	.109	.071	.022

Similarly, for the heavy trucks, potential savings are calculated for the proportion of weight-limited operations $\mathbf{P_w}$ = .1, .15, and .5.

Low, Middle, and High "optimism" values were also used for the drag and weight reduction savings estimates. These are based on the lower and upper endpoints and the modal values derived in Section 4 from the tooling workshop survey data.

Because not all parameters in the savings calculation would be expected to occur simultaneously at their extremes, not every parameter is given a value range in the sensitivity assessment. Single values rather than ranges were used for economic (fleet) growth and for the total-to-direct savings ratios $\mathbf{F_d}$ and $\mathbf{F_w}$, because these values enter the savings equations as multipliers of $\mathbf{P_d}$ or $\mathbf{P_b} + \mathbf{P_r}$, which *are* represented as ranges and which depend on the driving scenarios. Different economic growth and different total-to-direct savings multipliers would affect the savings calculation, however.

Table 4. Savings Proportion Estimates from Tooling Workshop Survey Respondents—Values Used to Estimate Potential Savings

Vehicle Type	Survey Respondent Optimism	Drag Savings	Weight Savings
Heavy Trucks	Low	.02	.03
	Middle	.03	.05
	High	.05	.10
Passenger Cars	Low	.000	.05
	Middle	.015	.10
	High	.030	.20

Savings due to tooling are assumed to begin in 2010. Potential savings estimates were calculated for fifty years. Results are presented here for cumulative savings estimates in 2015, 2025, and 2050.

6.2. Estimates of Potential Savings and Reductions

Fuel savings and emissions reductions are presented here three ways, as savings for individual years (Tables 5 and 6), as cumulative savings summed over years (Tables 7 and 8), and as saving for individual years broken into components for drag and weight reductions (Tables 9 and 10). These tables are restricted to the middle driving scenario, and the truck estimates are restricted to the case $\mathbf{P_w} = .15$ (15% weight-limited operations). More complete tables are in Appendices B and C. However, as discussed under "Sensitivity" below, other than the differences across time, most of the differences in the savings and emissions estimates are accounted for by differences in the inputs for the survey respondents savings proportion estimates. Thus most of the variation in the estimates is in fact reflected in the ranges of results in Tables 5-10.

Table 5. Potential Savings Due to Improvements in Tooling for Heavy Trucks (Middle Driving Scenario and $P_w = .15$ only)

Year	Optimism	Potential Savings (Millions of Gallons)	Potential CO_2 Reduction (Millions of Metric Tons)	Potential Savings/Reduction Percent of 2001 Total
2015	Low	91	1	.36
	Middle	140	2	.56
	High	260	3	1.0
2025	Low	270	3	1.0
	Middle	420	4	1.6
	High	760	8	3.0
2050	Low	610	6	2.4
	Middle	960	10	3.8
	High	1,700	18	6.8

Table 6. Potential Savings Due to Improvements in Tooling for Cars (Middle Driving Scenario Only)

Year	Optimism	Potential Savings (Millions of Gallons)	Potential CO2 Reduction (Millions of Metric Tons)	Potential Savings/Reduction Percent of 2001 Total
2015	Low	550	5	.75
	Middle	1,200	10	1.6
	High	2,300	21	3.2
2025	Low	1,500	13	2.0
	Middle	3,100	27	4.2
	High	6,100	55	8.4
2050	Low	2,100	18	2.8
	Middle	4,300	38	5.9
	High	8,600	77	12

Table 7. Potential Cumulative Energy Savings Due to Improvements in Tooling for Heavy Trucks (Middle Driving Scenario and P_w = .15 only)

Year	Optimism	Cumulative Potential Savings (Millions of Gallons)	Cumulative Potential CO_2 Reduction (Millions of Metric Tons)	Cumulative Potential Savings/Reduction Percent of 2001 Total
2015	Low	430	4	1.2
	Middle	680	7	1.9
	High	1,200	12	3.5
2025	Low	3,000	31	8.6
	Middle	4,800	48	14
	High	8,600	88	24
2050	Low	19,000	200	55
	Middle	30,000	310	86
	High	55,000	560	160

Table 8. Potential Cumulative Energy Savings Due to Improvements in Tooling for Cars (Middle Driving Scenario Only)

Year	Optimism	Cumulative Potential Savings (Millions of Gallons)	Cumulative Potential CO2 Reduction (Millions of Metric Tons)	Cumulative Potential Savings/Reduction Percent of 2001 Total
2015	Low	310	3	1.2
	Middle	490	5	1.9
	High	880	9	3.4
2025	Low	2,200	22	8.5
	Middle	3,400	35	13
	High	6,200	63	24
2050	Low	14,000	140	54
	Middle	22,000	220	85
	High	39,000	400	150

Table 9. Energy Savings Due to Tooling Improvements for Trucks by Savings Component (Middle Driving Scenario Only)

Year	Optimism	Potential Drag Savings (Millions of Gallons Diesel)	Potential Drag Savings (Percent of 2001 Total)	Weight Limited Weight Savings (Millions of Gallons Diesel)	Volume Limited Weight Savings (Millions of Gallons Diesel)	Total Weight Savings (Millions of Gallons Diesel)	Potential Weight Savings (Percent of 2001 Total)
2015	Low	55	.21	10	27	37	.14
	Middle	82	.32	16	45	61	.24
	High	140	.54	32	90	120	.48
2025	Low	160	.63	28	79	110	.42
	Middle	240	.94	47	130	180	.70
	High	400	1.6	93	260	360	1.4
2050	Low	370	1.4	64	180	250	.96
	Middle	550	2.2	110	300	410	1.6
	High	920	3.6	210	610	820	3.2

Tables 5 show potential individual-year savings estimates for heavy trucks; Table 6 shows individual-year estimates for cars. These tables indicate little initial savings, but greater savings as time progresses, as the fleet is replaced and as it grows. Tables 7 and 8, which are cumulative-savings analogs of Tables 6 and 7, show even greater increases as savings accrue over time. By 2025, the total cumulative savings for the middle-optimism estimate for cars is 36% of the year 2001 annual total. The corresponding cumulative savings percentage for trucks is 13%. By 2050, the total savings for the middle-optimism estimate for cars is 170% of the 2001 total. The same savings percentage for trucks is 85%. The savings for trucks reflect slower scrappage rate than for cars but also reflect more rapid growth projections for the total fleet. These estimates all vary substantially, depending on the degree of optimism, from roughly 50% to 200% of the corresponding middle-level estimate.

Table 9 shows potential individual-year savings estimates for heavy trucks, with separate entries for drag reductions, and for weight-limited weight reductions and volume-limited weight reductions. Most of the savings are for drag reduction, though weight-reduction savings are about 60-90% of the drag savings, depending on the measure of overall optimism. For cars, weight savings estimates are much greater than drag savings estimates, regardless of the level of optimism.

Table 10. Energy Savings Due to Tooling Improvements for Cars by Savings Component (Middle Driving Scenario Only)

Year	Optimism	Potential Drag Savings (Millions of Gallons Gasoline)	Potential Drag Savings (Percent of 2001 Total)	Potential Weight Savings (Millions of Gallons Gasoline)	Potential Weight Savings or Reduction Percent of 2001 Total
2015	Low	0	.00	550	.75
	Middle	49	.07	1,100	1.5
	High	99	.14	2,200	3.0
2025	Low	0	.00	1,500	2.0
	Middle	130	.18	2,900	4.0
	High	260	.36	5,900	8.0
2050	Low	0	.00	2,100	2.8
	Middle	180	.25	4,100	5.6
	High	370	.50	8,200	11

6.3. Sensitivity

Although Tables 5-10 contain entries only for years 2015, 2025, and 2050, corresponding savings estimates were actually computed for all years from 2010 to 2060. An analysis of variance performed with this data shows that degree-of-optimism has a much greater effect on the savings estimates than either differences in driving scenarios (through $\mathbf{P_d}$, $\mathbf{P_r}$, and $\mathbf{P_b}$) or the proportion of weight-limited operations. This can also be seen by examining the results in Appendices B and C, which for simplicity are again only for years 2015, 2025, and 2050. A 50%-200% range about the middle point estimates roughly accounts for not just optimism differences (as discussed above), but for differences in the driving scenario estimates and the weight-limited operations proportion as well. Sensitivity to values for the parameters $\mathbf{F_d}$ or $\mathbf{F_w}$ is assumed to be reflected here through the various values of the other parameters. This analysis does not include sensitivity to values used for the rate of economic growth.

7. Conclusion

The estimates of potential savings generated for this report are based on many approximations. They are based on judgments of industry experts, in many cases where statistical data, were it available, could be usefully applied. For example, heavy truck speed and braking data, obtained through GPS and other computer-tracking systems, perhaps in cooperation with the trucking industry, would lead to better estimates of actual speeds and braking. Those estimates could be used as input to refine values for the drag, rolling resistance, and braking energy audit proportions ($\mathbf{P_d}$, $\mathbf{P_r}$, $\mathbf{P_b}$). Better values for $\mathbf{P_w}$ could likely be obtained, also with industry assistance. Even the *joint* statistical distributions of these quantities might be estimated. An allowance is made here for growth in fleet sizes, but the savings analysis is otherwise based on the simplifying approximation that the (joint) statistical distributions of the inputs (e.g., speed and braking) are constant in time. Of course these distributions could change.

Only one fleet growth scenario is considered here. No consideration is given to the possibility of disrupted oil supplies or conversion to a hydrogen fuel economy. Total energy savings are assumed proportional to direct energy savings. A more sophisticated approach with computer simulations under many driving cycle scenarios was considered beyond the scope of the report. The values assumed for $\mathbf{F_d}$ and $\mathbf{F_w}$ for the total-to-direct savings ratios are only approximate. Drag and volume-limited weight savings increase in proportion to these quantities, but sensitivity to the values used for them is not formally assessed.

Other limitations in the analysis include the assumption that energy for tooling itself is negligible in the life cycle of manufactured parts. That energy would in fact slightly offset energy savings. The analysis also assumes 100% penetration as vehicles are replaced; no old-technology parts are used. The first savings due to replacement with new-technology vehicles are assumed to be in 2010 (exactly). Light trucks are not considered in the analysis.

Despite these limitations, the values in Tables 5-10 do approximately estimate the potential energy savings possible because of improvements in tooling. For heavy trucks, cumulative diesel savings on the order of 54-154 percent of 2001 consumption could accrue by 2050. By 2050, gasoline cumulative savings on the order of 83-350 percent of 2001 consumption could accrue for cars.

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Appendix A. Tooling Technology Survey

1. How much of a barrier is tooling to implementation of lightweight/aerodynamic parts?
    - It is big and the only significant barrier.
    - It is big and there are other similar sized barriers
    - It is a moderate sized barrier, and there are other larger barriers
    - It is a relatively small barrier, and there are other much larger barriers
    - It is not a barrier at all

2. How much improvement in tooling technology is needed to significantly reduce this barrier (i.e., X % cost reduction AND lead time reduction of Y% are needed)?

	Cost	Lead time
10% improvement would greatly impact the decision to implement		
20%		
30%		
40%		
50%		
60%		
80%		

3. What is your best estimate of the vehicle tare weight reduction that could be achieved, by the implementation of lightweight materials, as a consequence of improved tooling technology?

Class 8 Trucks	Family Sedans
None	None
0 – 1%	0 – 1%
1 – 3%	1 – 3%
3 – 5%	3 – 5%
5 - 10%	5 - 10%
10 – 15%	10 – 20%
15 – 20%	20 – 30%
> 20%	> 30%

4. What is your best estimate of the vehicle drag coefficient reduction that could be achieved by the implementation of lightweight materials, as a consequence of improved tooling technology?

Class 8 Trucks pulling Van Trailers	Family Sedans
None	None
0 – 1%	0 – 1%
1 – 2%	1 – 2%
2 – 3%	2 – 3%
3 – 5%	3 – 5%
5 – 7%	5 – 7%
7 - 10%	7 - 10%
> 10%	> 10%

5. Please rate your ability to accurately answer each of the previous questions.

	Q1	Q2	Q3	Q4
Excellent				
Very good				
Good				
Fair				
Poor				

Appendix B. Estimates of Potential Savings for Heavy Trucks

Table B. Estimates of Potential Savings for Heavy Trucks

Year	Optimism	Driving Scenario	Proportion Weight Limited	Cumulative Potential Savings (Millions of Gallons)	Cumulative Potential CO_2 Reduction (Millions of Metric Tons)	Cumulative Potential Savings/Reduction Percent of 2001 Total
2015	Low	Slower	0.10	175	2	.685
	Low	Slower	0.15	179	2	.701
	Low	Slower	0.50	208	2	.813
	Low	Middle	0.10	305	3	1.19
	Low	Middle	0.15	310	3	1.21
	Low	Middle	0.50	348	4	1.36
	Low	Faster	0.10	306	3	1.20
	Low	Faster	0.15	311	3	1.22
	Low	Faster	0.50	345	4	1.35
	Middle	Slower	0.10	278	3	1.09
	Middle	Slower	0.15	284	3	1.11
	Middle	Slower	0.50	332	3	1.30
	Middle	Middle	0.10	477	5	1.87
	Middle	Middle	0.15	486	5	1.90
	Middle	Middle	0.50	549	6	2.15
	Middle	Faster	0.10	477	5	1.87
	Middle	Faster	0.15	485	5	1.90
	Middle	Faster	0.50	543	6	2.12
	High	Slower	0.10	513	5	2.01
	High	Slower	0.15	527	5	2.06
	High	Slower	0.50	622	6	2.44
	High	Middle	0.10	862	9	3.37

Table B. Estimates of Potential Savings for Heavy Trucks						
Year	**Optimism**	**Driving Scenario**	**Proportion Weight Limited**	**Cumulative Potential Savings (Millions of Gallons)**	**Cumulative Potential CO_2 Reduction (Millions of Metric Tons)**	**Cumulative Potential Savings/Reduction Percent of 2001 Total**
	High	Middle	0.15	880	9	3.44
	High	Middle	0.50	1,006	10	3.94
	High	Faster	0.10	855	9	3.35
	High	Faster	0.15	872	9	3.41
	High	Faster	0.50	986	10	3.86
2025	Low	Slower	0.10	1,232	13	4.82
	Low	Slower	0.15	1,261	13	4.93
	Low	Slower	0.50	1,463	15	5.73
	Low	Middle	0.10	2,146	22	8.40
	Low	Middle	0.15	2,184	22	8.55
	Low	Middle	0.50	2,451	25	9.59
	Low	Faster	0.10	2,154	22	8.43
	Low	Faster	0.15	2,188	22	8.56
	Low	Faster	0.50	2,431	25	9.51
	Middle	Slower	0.10	1,954	20	7.65
	Middle	Slower	0.15	2,002	20	7.83
	Middle	Slower	0.50	2,339	24	9.15
	Middle	Middle	0.10	3,359	34	13.1
	Middle	Middle	0.15	3,423	35	13.4
	Middle	Middle	0.50	3,866	39	15.1
	Middle	Faster	0.10	3,357	34	13.1
	Middle	Faster	0.15	3,415	35	13.4
	Middle	Faster	0.50	3,819	39	14.9
	High	Slower	0.10	3,610	37	14.1

Table B. Estimates of Potential Savings for Heavy Trucks						
Year	**Optimism**	**Driving Scenario**	**Proportion Weight Limited**	**Cumulative Potential Savings (Millions of Gallons)**	**Cumulative Potential CO_2 Reduction (Millions of Metric Tons)**	**Cumulative Potential Savings/Reduction Percent of 2001 Total**
	High	Slower	0.15	3,706	38	14.5
	High	Slower	0.50	4,380	45	17.1
	High	Middle	0.10	6,063	62	23.7
	High	Middle	0.15	6,190	63	24.2
	High	Middle	0.50	7,078	72	27.7
	High	Faster	0.10	6,019	61	23.6
	High	Faster	0.15	6,134	62	24.0
	High	Faster	0.50	6,943	71	27.2
2050	Low	Slower	0.10	7,809	79	30.6
	Low	Slower	0.15	7,992	81	31.3
	Low	Slower	0.50	9,275	94	36.3
	Low	Middle	0.10	13,607	138	53.2
	Low	Middle	0.15	13,848	141	54.2
	Low	Middle	0.50	15,536	158	60.8
	Low	Faster	0.10	13,652	139	53.4
	Low	Faster	0.15	13,872	141	54.3
	Low	Faster	0.50	15,409	157	60.3
	Middle	Slower	0.10	12,386	126	48.5
	Middle	Slower	0.15	12,691	129	49.7
	Middle	Slower	0.50	14,829	151	58.0
	Middle	Middle	0.10	21,295	216	83.3
	Middle	Middle	0.15	21,696	220	84.9
	Middle	Middle	0.50	24,509	249	95.9
	Middle	Faster	0.10	21,284	216	83.3

Table B. Estimates of Potential Savings for Heavy Trucks						
Year	**Optimism**	**Driving Scenario**	**Proportion Weight Limited**	**Cumulative Potential Savings (Millions of Gallons)**	**Cumulative Potential CO_2 Reduction (Millions of Metric Tons)**	**Cumulative Potential Savings/Reduction Percent of 2001 Total**
	Middle	Faster	0.15	21,649	220	84.7
	Middle	Faster	0.50	24,211	246	94.7
	High	Slower	0.10	22,882	232	89.5
	High	Slower	0.15	23,493	239	91.9
	High	Slower	0.50	27,769	282	109
	High	Middle	0.10	38,438	391	150
	High	Middle	0.15	39,242	399	154
	High	Middle	0.50	44,868	456	176
	High	Faster	0.10	38,156	388	149
	High	Faster	0.15	38,888	395	152
	High	Faster	0.50	44,012	447	172

Appendix C. Estimates of Potential Savings for Cars

Table C. Estimates of Potential Savings for Cars

Year	Optimism	Driving Scenario	Cumulative Potential Savings (Millions of Gallons)	Cumulative Potential CO_2 Reduction (Millions of Metric Tons)	Cumulative Potential Savings/Reduction Percent of 2001 Total
2015	Low	Slower	2,078	18	2.84
	Low	Middle	1,870	17	2.55
	Low	Faster	1,932	17	2.64
	Middle	Slower	4,209	37	5.75
	Middle	Middle	3,907	35	5.33
	Middle	Faster	4,092	36	5.59
	High	Slower	8,419	75	11.5
	High	Middle	7,814	69	10.7
	High	Faster	8,185	73	11.2
2025	Low	Slower	14,092	125	19.2
	Low	Middle	12,683	113	17.3
	Low	Faster	13,105	117	17.9
	Middle	Slower	28,552	254	39.0
	Middle	Middle	26,500	236	36.2
	Middle	Faster	27,757	247	37.9
	High	Slower	57,105	508	77.9
	High	Middle	53,001	471	72.3
	High	Faster	55,515	494	75.8
2050	Low	Slower	67,410	599	92.0
	Low	Middle	60,669	539	82.8
	Low	Faster	62,692	557	85.6
	Middle	Slower	136,586	1,214	186

Table C. Estimates of Potential Savings for Cars					
Year	**Optimism**	**Driving Scenario**	**Cumulative Potential Savings (Millions of Gallons)**	**Cumulative Potential CO_2 Reduction (Millions of Metric Tons)**	**Cumulative Potential Savings/Reduction Percent of 2001 Total**
	Middle	Middle	126,769	1,127	173
	Middle	Faster	132,783	1,180	181
	High	Slower	273,171	2,429	373
	High	Middle	253,539	2,254	346
	High	Faster	265,565	2,361	362

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