Reinventing Fire
Transportation Sector
Methodology

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INTENT

The Reinventing Fire (RF) transportation analysis estimates the techno-economic potential for efficiency gains in the U.S. transportation sector between 2010 and 2050. This analysis has been conducted to understand the transportation sector's potential to reduce nationwide fossil fuel consumption and to integrate its findings with the other sectors analyzed in *Reinventing Fire*.

SECTOR APPROACH

Our analysis splits the U.S. transportation sector into four distinct subsectors focused on the major vehicle classes: autos, heavy trucks, airplanes, and "remaining sectors"[1]. Within each subsector we estimate the capital investment and the fuel- and cost-saving potential of two major pathways to enhanced transportation efficiency in the U.S.:

1) **Improved Design**: Estimates potential efficiency gains through 2050 for lightweight, "vehicle fit," electrified light-duty trucks and autos; streamlined superefficient trucks with enhanced operational productivity; and biofuel-powered advanced-technology airplanes.
2) **Improved Use**: Estimates the potential for reduced automobile, plane, and heavy truck vehicle-miles traveled (VMT) via user-side changes including congestion pricing mechanisms, increased use of rail and sea intermodal platforms, and investments in telepresence technologies.

The results of the analysis within the subsectors are then integrated into an economy-wide model that compares total sector costs and benefits over time and calculates the net present value discounted at the societal 3% real rate described in the Reinventing Fire Synthesis Model Methodology.

Key model inputs include vehicle stock by class, fuel economy measures, incremental technology costs, retooling rates, VMT reduction estimates, and consumer adoption rates. All fuel consumption, baseline efficiency, price, seat-mile demand, and VMT data are taken from the Energy Information Administration (EIA)'s 2010 *Annual Energy Outlook* (AEO 2010). Since the AEO 2010 forecast ends in 2035, we linearly extrapolate EIA projections through 2050 to reach the timespan of Reinventing Fire. Unless otherwise noted, all costs and savings are NPV with an assumed societal 3% discount rate.

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[1] Includes rail, military, pipeline, commercial light trucks (medium-duty vehicles), buses, domestic mail shipments, and recreational boats.

After estimating the effect of these pathways on fuel use, the analysis surveys the potential for biofuels to substitute for remaining 2050 fossil-fuel demand.

AUTOS

APPROACH

In order to compare efficiency, we use three major vehicle classes for both cars and light trucks. All mpg estimates use the EPA standard "on-road" fuel economy test cycle calculation commonly used for vehicles in the U.S.

1) *EIA Vehicle (Baseline)*
   2050 mpg — car: 38/light truck: 30
   i. The baseline automobile is derived from a new sales-weighted average for price and fuel economy across standard and alternate fueled vehicles to create the EIA Car and EIA Light Truck.[2]

2) *Evolutionary*
   2050 mpg — car: 52/light truck: 40
   i. Based on client work within the automotive industry, Evolutionary vehicles have 50% better fuel economy than current EIA vehicles. These autos combine moderate gains in efficiency with ease of production. They require no substantial changes to manufacturing when compared to a typical automotive factory.

3) *Revolutionary*
   2050 mpg-e — car: 239/light truck: 193
   i. With extensive data from RMI's work on the Hypercar[3], we use a cost model for superefficient battery-electric and fuel cell vehicles for both cars and light trucks. These vehicles are designed to compete with the retail price of EIA's average automobile.

Consumer Adoption Model. The RF – Transportation consumer adoption model (adapted and updated from the widely-syndicated consumer adoption model used in RMI's previous major transportation work, *Winning the Oil Endgame*) assumes that consumers will not purchase a more

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[2] EIA Vehicles are derived from *Annual Energy Outlook 2010*. Washington DC: U.S. Energy Information Administration, May 11. http://www.eia.gov/oiaf/archive/aeo10/index.html.

[3] Acher, Zoe, Alok Pradhan, and Alexander Gerson. 2009. "Case Study: Hypercar." Rocky Mountain Institute, 2009.

efficient auto if it takes longer than three years for the incrementally more expensive higher efficiency auto to pay for itself in fuel savings. We model this dynamic by assuming that at the three-year payback or shorter, consumers will choose to purchase the more expensive efficient vehicle. If the simple payback exceeds three years, the consumer will choose the next most efficient vehicle with a three-year or better payback—either the Evolutionary or the EIA vehicle.

Given the initial high price of Revolutionary vehicles, they see no adoption and no cost reductions through economies of scale within our consumer adoption model. This is unrealistic. Firstly, luxury markets allow automakers to introduce nascent technologies before rolling them into mass-market vehicles. Second, consumer choice is driven by much more than fuel efficiency and price. Third, as noted in *Reinventing Fire*, p. 269, n. 82, a great many U.S. car-buyers say they'd accept a 5-year payback on efficiency. However, in order to keep our modeling approach transparent and consistent, our model does not consider the intricacies of consumer choice, especially among early adopters and niche markets. We instead focus only on a limited number of variables within the mass market.

Policy Implementation. Given the simplicity of our model as described above, a policy driver is necessary to drive the adoption of Revolutionary vehicles well beyond initial high-end luxury market penetration. The policy accelerator (in this case a size- and revenue-neutral feebate that's phased out 10–15 years after introduction as costs come down) is calculated based on the retail price difference between Revolutionary and EIA vehicles and their relative efficiencies. The initial feebate helps to drive initial adoption and bring Revolutionary vehicles down three synergistic learning curves: batteries/fuel cells, carbon fiber cost, and carbon fiber manufacturing.[4] Once Revolutionary+ vehicles become cheap enough to pay back their incremental cost with three years of fuel savings, we assume that consumers will adopt them instead of EIA vehicles or Evolutionary autos. Once Revolutionary+ autos become cost-competitive within the three-year payback horizon, the feebate also fades away.

VMT, Stocks, and Sales. To match overall VMT as predicted by EIA, we adopt learning curves from Oak Ridge National Laboratory for miles driven by vintage year of vehicle. Using the full vehicle stock, we calculate our predicted VMT along these curves and scale them to match EIA's predicted VMT growth.

New sales and vehicle stocks are based on EIA forecasts. This led us to develop our own retirement rates for vehicles based on logistic curves (Formula 1) since EIA-provided curves led to a large negative number of vehicles in 2050 for certain vehicle classes.

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[4] While the analysis uses feebates as the enabling policy, a number of other options exist that could also help drive scale and cost reductions. These include federal fleet procurement programs, cash for clunkers-like rebate mechanisms, and affordable government financing programs.

Retooling Rates. In the context of RF – Transportation, retooling rates determine how quickly factories can invest and re-equip their facilities to integrate new materials and architectures into their assembly lines. For AEO 2010, EIA's retooling rate assumes that it takes 14 years for factories to retool from 10% of new production capacity to 90% of new production capacity. To match EIA's retooling rate, we fit a logistic curve (Formula 1) and assume that in the first year 1% of factories would be retooled.

Formula 1: Logistic retooling (retirement) curve, R(t) is the percentage of new production capacity retooled

$$R(t) = \frac{1}{1 + \exp^{\alpha(t-\beta)}}$$

We then perturb EIA's standard retooling rate to generate scenarios based on different levels of demand for Revolutionary+ autos.

VMT REDUCTIONS

Our RF Transportation analysis considers a series of use-based strategies and their potential to reduce estimated VMT growth. VMT reductions affect payback, savings, and consumer adoption rates discussed above by reducing the number of autos on the road and lowering annual VMT. Without reliable estimates on the timeframes associated with VMT reduction approaches, percentage VMT reductions have been applied to an instantaneous adoption scenario in 2050.

Table 1 shows the VMT reduction estimates and their associated ranges. Estimates are drawn from several studies and organized according to the RF Transportation analysis. As a conservatism, our modeling results adopt the lower end of the range for each estimate. Cost data for each measure are also included and integrated into our society-wide cost analysis.

Table 1: Summary of VMT reduction strategies, percentage ranges, and costs

Overall VMT Lever	**Sub-levers**	**% Savings relative to EIA estimate (minimum)**	**% Savings relative to EIA estimate (maximum)**	**Cost (billion 2009 $)**
Innovative Pricing	VMT Tax	12%	15%	$167.73
	Pay-as-you-drive insurance	2%	8%	$167.73
	Parking Pricing	1%	3%	$0.05
Alternative Commuting	Carsharing	2%	7%	$0.20
	Telecommuting	1%	3%	(incl. in SG)
	Carpooling	2%	4%	$107.10
Smart Growth	Smart Growth	20%	40%	$332.22

Transportation System Efficiency	System Efficiency	6%	14%	$53.96
	Total	**46%**	**84%**	**$829**

HEAVY TRUCKS

APPROACH

As with light-duty vehicles, efficiency gains are separated into design- and use-oriented analyses. The design analysis focuses on projected costs and incremental fuel economy improvements from a range of efficiency technologies.

To determine the potential for operational efficiency improvements, we quantitatively focus on four strategies: operational refinements, intermodal shipping, logistical improvements, and expanded use of long combination vehicles (LCVs). With the exception of operational improvements, these approaches serve to reduce heavy truck VMT and allow trucks to carry heavier loads. The details of the analysis are described below.

Heavy Truck Design. Cost and fuel savings estimates from several different studies form the basis of a supply curve to analyze the cost effectiveness of technological efficiency improvements compared to the baseline vehicle (Table 2).

Table 2: Baseline class-8 truck characteristics

Characteristic	Value
Diesel Price/U.S. gallon (2009 $)	$3.00
Duty Cycle	120,000 miles/year
Baseline fuel economy	6 mpg
Tare Weight	37,500 lb.
Length	53 ft.
Tire Configuration	Standard steel-rim dual tires
Idle reduction technology	none
Drag coefficient	0.59
Rolling resistance	0.0068
Transmission	10-speed manual

The analysis considers the following technological improvements (Table 3). Savings are multiplied, not added, to account for cumulative effects. Along these same lines, aerodynamic improvements rely on cumulative contributions to heavy truck efficiency given their synergistic effects with one another. Accordingly, the aerodynamic package applied to our RF heavy truck integrates a full tractor skirt, trailer skirt, fairings, and a trailer tail.

To evaluate each measure, we calculated the cost of conserved energy for the specific efficiency technologies. This divides the marginal cost of buying, installing, and maintaining the more efficient device by its discounted stream of lifetime energy savings. Herein, C is installed capital cost, *i* is annual real discount rate (assumed to be .15), S is the rate at which the device saves energy (bbl/y), and n its operating life. We assume that the technology will be adopted if the cost of saved energy is below retail diesel prices.

Formula 2: The dollar cost of saving one barrel of oil equals:

$$\frac{Ci}{S[1-(1+i)^{-n}]}$$

This analysis identified a 45% aggregate design improvement in efficiency. However, AEO 2010 includes a baseline improvement in efficiency from 2010–2035. Accordingly, we include their baseline improvements in our analysis. After extrapolating AEO 2010's projected improvements past 2035 and into 2050, the RF transportation analysis concludes that an additional 30% technology-based efficiency gain is possible and economical in addition to AEO 2010 baseline improvements extrapolated into 2050.

Table 3: Summary of heavy truck technological improvements and efficiency gains

Technology Suite	% **Fuel Economy gain over Baseline (actual)**	**Specific Improvement**
Mass Reduction	5%	2,850 lb tare weight reduction
Full Aerodynamic Design (Tractor + Trailer)	11%	23% reduction in drag (Cd reduced to 0.45)
Tires/Wheels	5%	33% reduction in rolling resistance (Crr reduced to 0.0046)
Engine	16%	N/A
Auxiliary Powered Unit	6%	N/A
Automated Manual Transmission	2%	N/A
Totals	**45%**	

Heavy Truck VMT and Integration. In order to accurately combine the design and use- oriented efficiency gains, the percentage improvements are sequenced and combined as described in Table 4 below.

Logistics

The RF Transportation analysis surveyed best practices and estimates that eliminating backhauls and consolidating loads could eliminate 15% of truck ton-miles. The sequencing of this efficiency gain is displayed in Table 4 and is treated as a VMT reduction.

Operational Improvements

Improvements to driver training are separated from design-based improvements and implemented in addition to the technology package described in Table 3. Enhanced operations are treated as an improvement to fuel economy, attributable to maximum speed reductions and efficiency-based driver training.

Double Trailers/LCVs[5]

Data taken from industry reports are used to estimate the potential for system-wide efficiency gains from using LCVs in the appropriate heavy truck fleet segments. Cost data for additional trailers is also included in our society-wide transportation savings model.

Intermodal

Two major industry reports[6] provide estimates for shifting heavy truck shipments onto integrated sea and rail intermodal systems. These estimates are combined with an industry wide 5% packaging improvement as demonstrated by Walmart[7] and other companies.

All efficiency gains are applied to a fleetwide instantaneous adoption scenario in 2050 with the results phased in linearly between 2010 and 2050.

Table 4: Summary of heavy truck design and use improvements by 2050

Sequenced RF 2050 Changes:	VMT (billions)	Equivalent diesel mpg	Consumption (Mbbl/d)	Reduction (Mbbl/d)	% Reduction
EIA 2050	452	7.8	3.8	-	-
EIA 2050—No mpg improvement	452	6.1	4.9	-	-
RF Design Changes	452	11.0	2.7	1.1	29%
RF Operational Improvements	452	11.7	2.5	0.2	4%
RF Logistical Improvements	384	11.7	2.1	0.4	10%
RF Double Trailers	384	13.5	1.9	0.3	7%
RF Intermodal Shifts	257	13.5	1.2	0.6	16%

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[5] Northeast States Center for a Clean Air Future, International Council on Clean Transportation, Southwest Research Institute, and TIAX. 2009. *Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO_2 Emissions.* Boston, MA: Northeast States Center for a Clean Air Future. http://www.nescaum.org/documents/heavy-duty-truck-ghg_report_final-200910.pdf; Ogburn, Michael, Laurie Ramroth, and Amory Lovins. 2008. *Transformational Trucks: Determining the Energy Efficiency Limits of a Class-8 Tractor-Trailer.* Snowmass, CO: Rocky Mountain Institute, July. http://www.rmi.org/rmi/Library/T08-08_TransformationalTrucksEnergyEfficiency.

[6] Lanigan, Jack, John Zumerchik, Jean-Paul Rodrigue, Randall Guensler, and Michael Rodgers. 2006. "Shared Intermodal Terminals and the Potential for Improving the Efficiency of Rail-Rail Interchange." Presented to the Transportation Research Board Committee on Intermodal Freight Terminal Design and Operations at the 86th Annual Meeting of the Transportation Research Board. Washington DC, January 21–25. http://people.hofstra.edu/Jean-paul_Rodrigue/downloads/TRB_JPR_2007.ppt.; Global Insight. 2006. *Four Corridor Case Studies of Short-Sea Shipping Services: Short-Sea Shipping Business Case Analysis*. Transportation Research Board. http://www.marad.dot.gov/documents/USDOT_-_Four_Corridors_Case_Study_(15-Aug-06).pdf.

[7] Walmart. 2010. *Walmart Global Sustainability Report 2010 Progress Update*. Walmart. http://cdn.walmartstores.com/sites/sustainabilityreport/2010/WMT2010GlobalSustainabilityReport.pdf.

Cumulative Reduction	**67%**

AIRPLANES

APPROACH

As with heavy trucks and light-duty vehicles, efficiency gains are quantified with respect to both design and use. Design-related efficiency is quantified based on future airplanes in their entirety rather than individual design changes. Use-related efficiency includes both pilot- and airline-related operational improvements and technologies.

Airplane Design. The overall efficiency gain associated with particular models is derived from studies of new airplane designs within each size class: narrowbody, widebody, and regional. The widebody class is further subdivided into three categories: very large, large, and medium. Each size class is assumed to evolve from a design based on today's technology (i.e., a *737* replacement that incorporates *787* technology) to more advanced designs that depart from the standard tube-and-wing configuration and apply such technologies as active flow control (AFC), boundary layer inlet (BLI), and propulsion-airframe integration (PAI). Two radically new designs are considered for implementation in the longer term: blended wing body (BWB) and strut-braced wing (SBW).

Percent reduction in fuel use (fuel burn per seat) for each future airplane design is relative to existing 2010 airplane designs. A stock turnover model (discussed below) is then used to determine the 2050 fleet makeup by model and to calculate an aggregate fuel savings in 2050. The fleet of future airplanes considered in the analysis along with the efficiency improvement associated with each design is outlined in Table 5.

Table 5 – Airplane baseline efficiency, RF improvements, and fleet composition[8]

Widebody	

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[8] Efficiency improvements are quantified according to: The Boeing Company. 2010. Boeing Begins Assembly of First 747-8 Intercontinental. The Boeing Company. http://boeing.mediaroom.com/index.php?s=43&item=1200; Frank Gern et al. 2005. "Transport Weight Reduction through MDO: The Strut-Braced Wing Transonic Transport." Toronto, Ontario, CA: AIAA Fluid Dynamics Conference and Exhibit; Kawai, Ronald T, Douglas M Friedman, and Leonel Serrano. 2006. *Blended Wing Body (BWB) Boundary Layer Ingestion (BLI) Inlet Configuration and System Studies.* National Aeronautics and Space Administration; National Aeronautics and Space Administration and Massachusetts Institute for Technology. 2010. *NASA N+3 MIT Team Final Review*. National Aeronautics and Space Administration Langley Research Center; Royal Aeronautical Society. 2010. *Air Travel—Greener by Design Annual Report 2009–2010*. Royal Aeronautical Society; Bushnell, Dennis M. February 2010. Email Communication; Daggett, David L. 2002. *Ultra Efficient Engine Technology Systems Integration and Environmental Assessment.* National Aeronautics and Space Administration. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20020064732_2002107516.pdf.

(1) Very Large	
Baseline (tube-and wing)	0%
(747-8)	16%
BWB (see below)	
(2) Large	
Baseline (tube-and wing)	0%
777 Replacement (strut-braced wing)	41%
Blended-Wing-Body (BLI, AFC, PAI)	59%
(3) Medium	
Baseline (tube-and wing)	
787	20%
787 Replacement (strut-braced-wing)	70%
Narrowbody	
Baseline (tube-and wing)	0%
Re-Engined 737	15%
787-based 737 Replacement	19%
Advanced 737 Replacement	70%
Regional Jets	
Baseline (tube-and wing)	0%
Re-Engined	15%
Re-Engined Advanced	30%
Advanced Reg Replacement (Scaled from 737 strut-braced-wing)	70%

Aggregate 2050 fuel savings are calculated for the freight fleet according to the assumption that, due the emergence of new, high-efficiency freight-specialized airplanes such as the *747-8F* and patterns observed among large industry carriers, freight stock will no longer consist of 25-year-old airplanes from retired commercial stock but rather will shift toward new airplanes. However, stock turnover is a challenge for freight carriers as much as passenger carriers, so 50% of the freight airplane stock is assumed to consist of new airplanes; the remainder is of average stock efficiency.

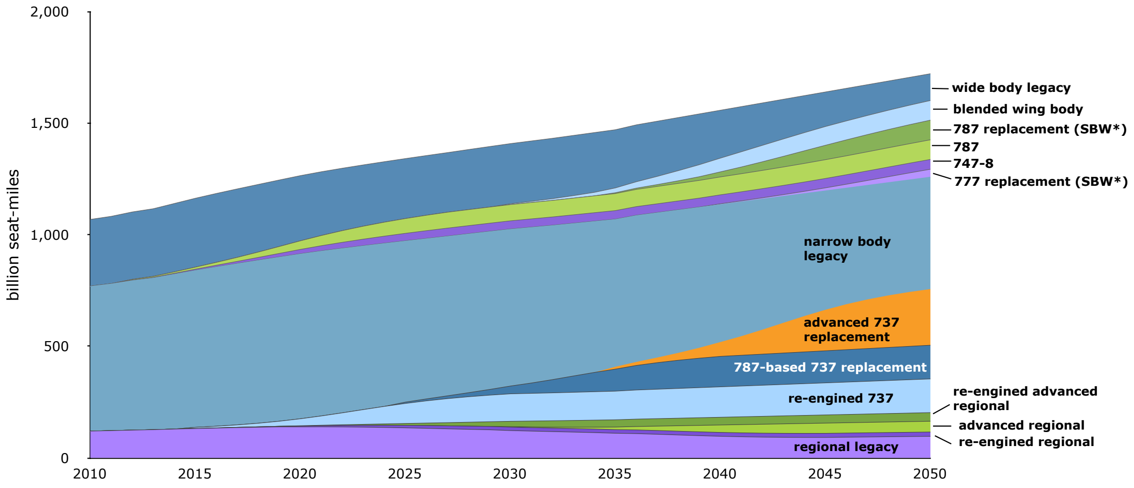
Airplane Use. Use-related 2050 fuel usage reduction is calculated as a percent reduction to fleetwide commercial usage phased in linearly between 2010 and 2050. The percentage savings are applied in sequence so that the percentage reduction for each change applies only to the fuel usage remaining after any previous changes. In particular, all design-related efficiency improvements are implemented prior to any reductions associated with use. The sequence of use-related improvements is tabulated below.

Table 6: Airplane use-related efficiency gains

Operational Improvements	8.8%
Trip Passenger Reductions	2.5%
Load Factor Improvement	3.5%

Stock Turnover Model. The airplane stock turnover model calculates the quantity of seat-miles that will be serviced by each airplane model in 2050. For each class (narrowbody, widebody, and regional) individual airplane models capture a segment of seat-miles demanded. The adoption rate of new airplanes is quantified as a function of seat miles demanded based on the historically-based analog of jets replacing propeller aircraft.[9] As a conservatism, no airplane design is assumed to exceed one-fourth of seat- mile demand within a given class despite several airplane models' and their derivatives' having done so in the past. Adoption rates for advanced aircraft such as the SBW and BWB are generally assumed to capture more of the market than their more incrementally designed predecessors since they offer particularly compelling fuel savings. This assumption is uncertain, however, since adoption rate would be largely driven by the cost of producing these more advanced aircraft, and such cost estimates are themselves either nonexistent or highly uncertain.

Figure 1: Seat miles demand outlook with Reinventing Fire technology portfolio



*strut braced wing

REMAINING SECTORS

Other vehicle classes use fuel besides planes, heavy trucks, and autos. We term these vehicle classes—from commercial light-duty trucks to recreational boats and buses to motorcycles—

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[9] Rahul Kar, Philippe A Bonnefoy, and John R. Hansman. 2009. "Dynamics of Implementation of Mitigating Measures to Reduce Commercial Aviation's Environmental Impacts." Presented at the Aviation Technology, Integration, and Operations Conference. American Institute of Aeronautics and Astronautics.

"Remaining Sectors." Since this sector is we apply a weighted-average percentage fuel savings to the entire subsector[10] based on the efficiency potential analyzed for trucks, planes, and autos.

BIOFUELS

APPROACH

The biofuels model calculates U.S. biofuel supply and cost by considering five categories of inedible feedstock (in order of increasing cost): agricultural residue, mill residue, dedicated energy crops, municipal solid waste, and forestry residue, with supply growth projected to 2050. Three conversion processes are modeled: bio-enzyme conversion (cellulosic ethanol) and two types of thermochemical processes (pyrolysis oil refining and Fischer-Tropsch gasification). Algal biofuel supply is assumed to undergo an autotrophic conversion process.[11]

FEEDSTOCK SUPPLY & COST

Edible feedstocks do not contribute to the U.S. supply of biofuel in our analysis due to adverse effects historically observed in world food markets when fuel feedstocks compete with human nutrition. Nonedible agricultural residue from 18 major crops is the largest and cheapest source of U.S. biofeedstock supply. Agricultural residue supply projections assume growth in U.S. food output commensurate with U.S. gross domestic product (GDP) growth. Forestry and mill residue, on the other hand, do not sustain growth in line with GDP, maintaining a historically observed[12] 1% growth rate. Dedicated energy crop supply is based on data points for 2010, 2020, and 2030, and extrapolated to 2050 assuming an annual growth rate equal to that of U.S. food crops.[13] Municipal solid waste is assumed to grow at an annual rate commensurate with that of U.S. population. [14]

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[10] Lubricants are the only transportation end-use not included in this analysis of AEO 2010's data.

[11] U.S. Department of Energy. 2010. "National Algal Biofuels Roadmap" U.S. Department of Energy.

[12] Forestry Inventory Analysis National Program. 2002. "Major trends in the U.S., 1953-2002." Forestry Inventory Analysis National Program. http://www.fia.fs.fed.us/slides/major-trends.ppt.

[13] National Academy of Sciences. 2009. *Liquid Transportation Fuels from Coal and Biomass: Technological Status, Costs, and Environmental Impacts*. National Academy of Sciences; Walsh, M. 2008. *U.S. Cellulosic Biomass Feedstock Supplies and Distribution.* M&E Biomass. http://ageconsearch.umn.edu/bitstream/7625/2/U.S.%20Biomass%20Supplies.pdf.

[14] U.S. Department of Agriculture and Economic Research Service. 2010. *Real Historical Gross Domestic Product (GDP) and Growth Rates of GDP*. U.S. Department of Agriculture and Economic Research Service. http://www.ers.usda.gov/data/macroeconomics/data/historicalrealgdpvalues.xls; Perlack, Robert, Lynn Wright, and Anthony Turhollow. 2005. *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: Technical Feasibility of a Billion-Ton Annual Supply*. U.S. Department of Agriculture. http://www.scag.ca.gov/rcp/pdf/summit/billion_ton_vision.pdf;
U.S. Forest Service. 2010. *1996, 2001, 2006 Primary Mill Residues Data (from USFS TPO database)*. U.S. Forest Service; U.S. Forest Service. *Timber Product Output (TPO) Reports.* U.S. Forest Service. http://srsfia2.fs.fed.us/php/tpo_2009/tpo_rpa_int1.php.

The cost per ton of biofeedstock contributes a variable cost to the total cost for each conversion process. Potentially substantial cost and risk reductions from innovations in portable, decentralized conversion technology opportunistically scavenging locally and temporarily available feedstocks are not included.[15]

CONVERSION COST

Industry studies[16] are used to calculate all remaining conversion costs, including fixed/variable operation and maintenance costs and overnight capital costs. A utility cost reduction results from coproduct electricity generation, and an adjustment is made to account for the refiner's margin. A continuous learning-curve function is developed according to methodology laid out by EIA in order to account for the reduction in capital cost as a function of quantity of plants built. The learning curve incorporates EIA's adjustment factors for technology optimism and contingency.

The key variables[17] in cost calculations for each conversion process are derived from two industry studies. A real levelized capital charge rate of 14.38%/y is applied to account for the cost of and recovery of capital.[18] The model calculates total conversion cost for each process by feedstock. The supply curve is built from the resulting cost values in combination with a total fuel supply calculation.

SOCIETAL COSTS AND SAVINGS

APPROACH

To estimate economy-wide costs and savings, the RF – Transportation analysis integrates the results from our automobile consumer adoption model, heavy trucking model, and aviation model. Infrastructure costs are also included for a mix of electric vehicles and fuel cell vehicles (described below).

The cost assumptions for heavy trucks and planes are as follows:

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[15] Lovins, Amory B., and James Newcomb. 2010. "Bioconversion: What's the right size?," video brief to National Research Council Panel on Alternative Liquid Transportation Fuels. February 20. Rocky Mountain Institute and Bio Economic Research Associates.

[16] *Annual Energy Outlook 2010*. Washington DC: U.S. Energy Information Administration, May 11. http://www.eia.gov/oiaf/archive/aeo10/index.html.;Thomas G Kreutz, et al. 2008. *Fischer-Tropsch Fuels from Coal and Biomass.* Princeton Environmental Institute; R.L. Bain. 2007. *World Biofuels Assessment: Worldwide Biomass Potential Technology Characterizations.* National Renewable Energy Laboratory.

[17] Key variables include plant capacity, overnight capital cost, unit plant cost, plant life, non-feedstock variable and fixed operations and maintenance costs, refiner's margin, and coproduct credits.

[18] (Kreutz, Larson, et al. 2008)

Heavy Trucks. The cost analysis is based on three major technology packages:

1) The RF technology package outlined in table 3 (applies to most class-8 trucks)
2) RF technology package plus a hybrid drive for regional/mixed duty routes.
3) RF technology package with double trailer costs included.

These three packages are applied to the relevant class-8 fleet segments in order to produce a more robust cost estimate.

Planes. No reliable cost data exist for next-generation efficient plane designs that go beyond the 20% efficiency gain of Boeing's 787 *Dreamliner*. Accordingly, we linearly scale the 787's 20% efficiency gain and its incremental cost to our assumed 2050 54% fleetwide efficiency gain. After arranging the three major airplane classes (narrowbody, widebody, and regional) by carrying capacity, the model applies the appropriate incremental costs and efficiency gain to each segment and compares end-fuel use with AEO 2010 projections.

EV and Hydrogen Infrastructure Costs. The RF – Transportation analysis assumes a 50/50 split between fuel cell vehicles (FCV) and battery-electric vehicles (BEV) by 2050. Hydrogen infrastructure costs are derived from a National Academies report[19] and scaled to the applicable FCV stock from the RF – Transportation analysis. FCV infrastructure costs are treated very conservatively, both to illustrate high-end FCV costs and to provide an estimate consistent with a full BEV deployment scenario. BEVs are assumed to require 1.1 charging stations per vehicle. We apply 91% of the required charging stations to average level 2 (220-volt) home installations and 9% to costlier level 3 (direct current (DC) fast charging) public stations.

Avoided Investment. An oil-free future also generates savings from avoided domestic oil-supply investment. The analysis scales the International Energy Agency's estimate for global investment in oil supply from 2010-2030 and applies it to U.S. oil production under the Reinventing Fire scenario.[20]

COMBINED SAVINGS

Table 7: Aggregate capital costs and savings for RF – transportation (Billions 2009$ NPV)

Vehicle Class	Savings	Investment	Net Savings
Trucks	$1,076	$225	$851

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[19] Ramage, Michael. 2008. *Transitions to Alternative Transportation Technologies; a Focus on Hydrogen*, Presentation to The National Academies. http://www.hydrogen.energy.gov/pdfs/htac_july08_ramage.pdf.

[20] International Energy Agency. 2010. *IEA World Energy Outlook 2010*. International Energy Agency. http://www.iea.org/Textbase/npsum/weo2010sum.pdf . Even with the efficient transportation system modeled in *Reinventing Fire*, the analysis estimates that oil-based fuels will still power some trucks, autos, and planes into 2050. Accordingly, the avoided investment savings take into account remaining domestic oil consumption and supply under the Reinventing Fire scenario.

Planes	$285	$213	$72
Autos	$4,164	$1,604[21]	$2,560
Avoided Investment	$274	---	$275
	Use Investment	$473	
	EV/Hydrogen Infrastructure Investment	$698	
	Total Investment	$2,043	
	Total Net Savings:	**$3,757**	

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[21] Includes use and EV/Hydrogen infrastructure investment.