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From Here to Efficiency: Time Lags between the Introduction of New Technology and the Achievement of Fuel Savings

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From Here to Efficiency: Time Lags between the Introduction of New Technology and the Achievement of Fuel Savings*

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In this paper, the energy savings of new technology offering significant improvements in fuel efficiency are tracked for over 20 years as vehicles incorporating that technology enter the fleet and replace conventional light-duty vehicles. Two separate analyses are discussed: a life-cycle analysis of aluminum-intensive vehicles and a fuel-cycle analysis of the energy and greenhouse gas emissions of double vs. triple fuel-economy vehicles. In both efforts, market-penetration modeling is used to simulate the rate at which new technology enters the new fleet, and stock-adjustment modeling is used to capture the inertia in turnover of new and existing current-technology vehicles. Together, these two effects — slowed market penetration and delayed vehicle replacement — increase the time lag between market introduction and the achievement of substantial energy savings. In both cases, 15–20 years elapse before savings approach these levels.

INTRODUCTION

Time and again, the popular press reports on dramatic efficiency gains of new propulsion technologies or "fuel-efficient" variants of existing technologies. From electric vehicles to hybrids to fuel cells, all have at one time or another been touted as the wave of the future. The public (and, perhaps, their elected representatives) accepts these claims, which may or may not be valid, at least in the short run. It doesn't much matter – regardless of the underlying merit of the technology, expectations are raised to impossible-to-achieve levels in the heat of public enthusiasm.

Can we achieve a further ratcheting of fuel economy standards? Sure. Hybrid vehicles already achieve 50 mpg. Can we reduce air toxics? Sure. Fuel cells have virtually no emissions. Can we reduce greenhouse gas emissions? Sure. Fuel economy at least double that of today's passenger cars can be achieved with either of these propulsion systems. But are these claims achievable anytime soon? As the following analyses show, the answer is much less clear if the effects of market forces, infrastructure constraints, consumer behavior, and turnover within the stock of current-technology vehicles are considered.

The introduction of new technology is not a quick and clear-cut process. Often, it takes years to identify clear "winners" among competing technologies; even in the absence of such competition, the growth of new technologies can seem painfully slow. Market shares, generally expressed as a percentage of new sales, may grow quickly, but the stock of existing vehicles is not readily replaced. Vehicles are long-lived assets. Even after 10 years of service, fewer than a third of those sold in a given year will have been replaced (American Automobile Manufacturers' Association 1997). As new technologies gain market share, conventional vehicles still command a large, albeit declining, share of new sales. Most of these vehicles will still be on the road when new technologies reach market dominance.

This paper discusses the results of two analyses conducted for the Office of Transportation Technologies within the U.S. Department of Energy. The first looks at the potential energy savings of aluminum-intensive vehicles over their life cycle; the second looks at the potential energy savings of interim technologies, in this case, double vs. triple fuel-economy vehicles. Both analyses include a careful consideration of market penetration, calculate fuel-cycle energy savings (and, for aluminum-intensive vehicles, savings from vehicle production as well), and use the same stock survival and usage model. The following discussion describes the two analyses, the penetration assumptions and results, and the stock-modeling approach that was common to both.

Analysis 1: Aluminum-Intensive Vehicles

Maximizing the use of lightweight materials in body and chassis components holds great promise for improving fuel economy. Automakers have long been interested in substituting such materials as aluminum, magnesium, plastics, and glass-fiber composites for non-structural components. However, much less effort has gone into materials substitution in engine and structural applications. Cost has been prohibitive, both for the materials

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themselves and for forming them into high-strength body panels and other structural components. In this analysis, it is assumed that R&D efforts currently under way in this country and abroad will be successful in reducing the cost of producing aluminum for vehicle structures. As a result, an aluminum-intensive vehicle (AIV) will retail for approximately $1200 more than a conventional vehicle (CV), once secondary downsizing and volume production are taken into account (i.e., under mature production conditions). Secondary weight-reduction is assumed to be achieved by reducing engine size and power rating, which will maintain the same power-to-weight ratio as that of a CV. The resulting increase in fuel economy (approximately 17–19% as compared with a comparable CV) is expected to eventually offset the AIV's higher purchase price.

Since AIVs initially cost more than CVs but consume less fuel over their lifetimes, consumer interest will vary; some consumers will not buy because of the high initial cost, while others will buy because of the improved fuel economy. Note that the analysis recognized that the incremental cost of AIVs will be much higher than $1200 during the introductory phase, and this, in turn, will depress initial market success. A market-penetration model that evaluates consumer and vehicle attributes was employed to project market penetration (Vyas et al. 1989, Stodolsky et al. 1995a). Figure 1 shows the market penetration rates produced by modeling the response of different consumer groups to the attributes of aluminum-intensive vs. conventional cars and light trucks, assuming the former are introduced in 2004 (Stodolsky et al. 1995b). Note that these market shares assume that AIVs compete with conventional vehicles only.

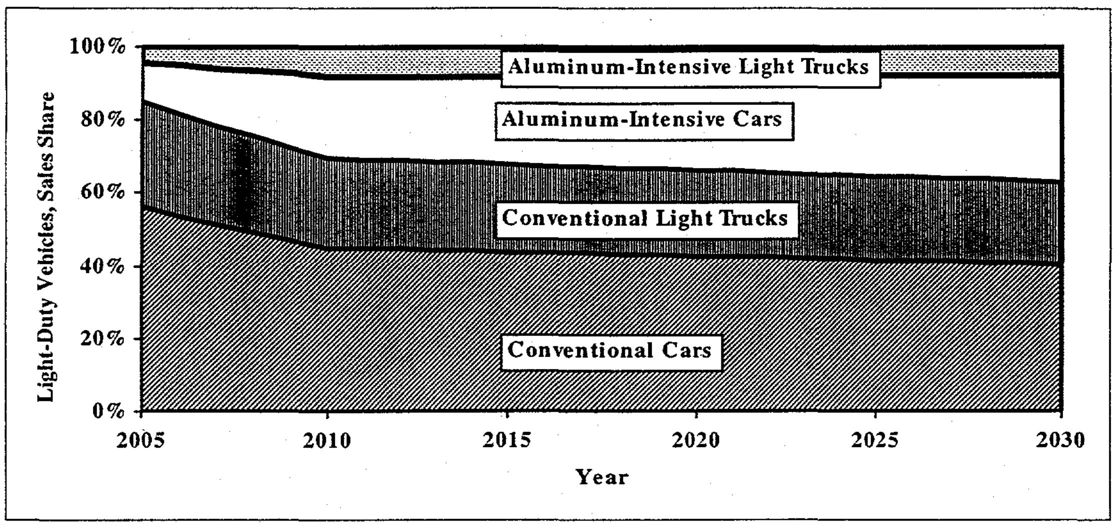

Figure 1 Penetration of New Aluminum-Intensive Vehicles

Life-cycle energy includes all of the energy consumed in the production and use of vehicles (vehicle cycle) and the fuels they consume (fuel cycle). As shown in Figure 2, it includes production of all inputs to fuels and vehicles, production and distribution of fuels and vehicles, vehicle operation, and vehicle disposal/material recovery. Since this is an investigation of materials substitution, analysis of the vehicle cycle (as well as the fuel cycle) is an important component. As shown in Table 1, the baseline, conventional automobile (CV) is assumed to weigh 1441 kg (3170 lb), and the heaviest AIV is assumed to weigh 981 kg (2158 lb) after primary and secondary weight reduction.

In addition to weight reduction, the analysis investigated the effect of recycling on the energy required to manufacture CVs vs. AIVs. Although production of vehicle parts from virgin aluminum requires more than 3.5 times the energy input of producing steel parts, there is essentially no energy benefit in producing parts from *recycled* steel vs. *recycled* aluminum (Table 2). This is a key distinction. Since this analysis tracked vehicles as they were produced (with the materials mix shown in Table 2), entered the fleet, consumed fuel in operation, and eventually were scrapped, the availability of scrap aluminum for AIV production could be explicitly calculated. This is an important improvement over prior analyses in which scrap availability is assumed, often at impossible-to-achieve levels. In this analysis, scrap availability is a function of the materials composition of scrapped vehicles and recycling rates. On the basis of current trends and anticipated developments in materials recovery, recycling is

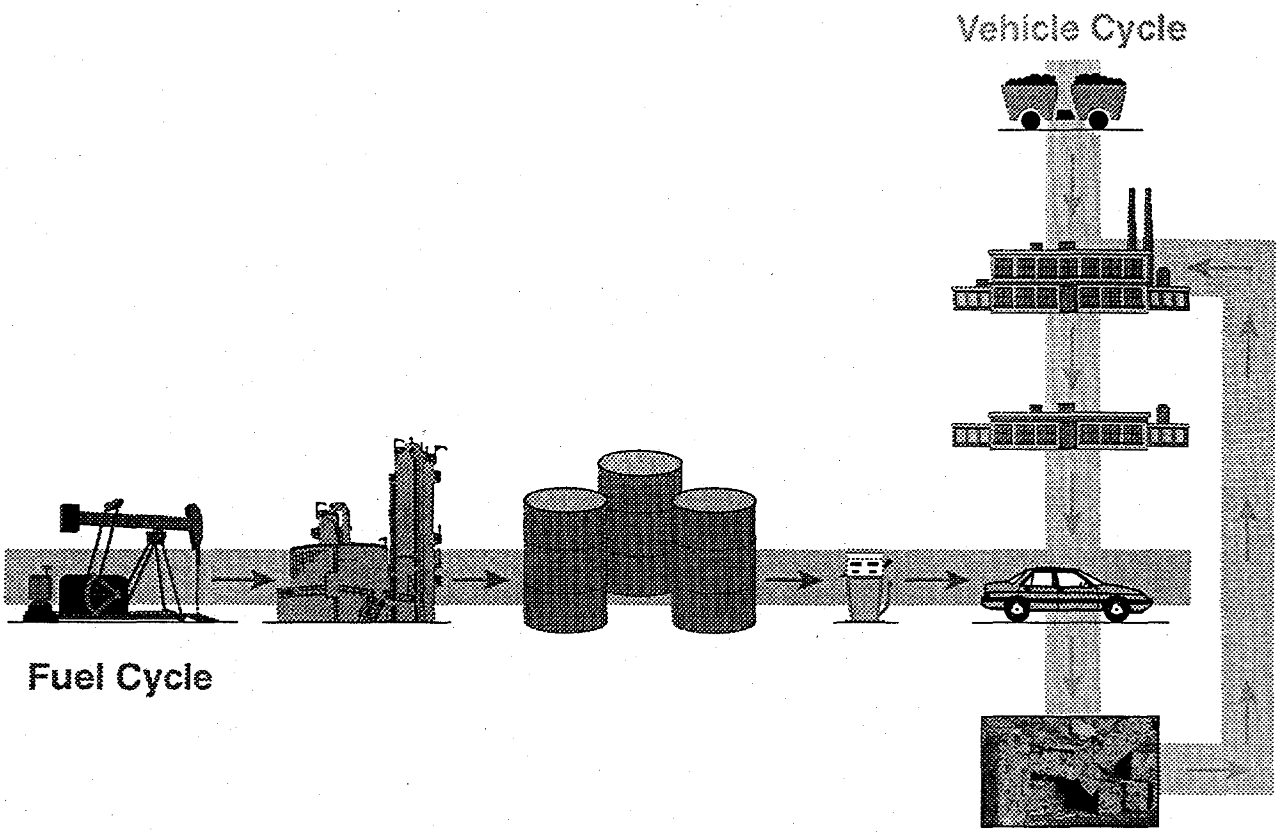

Figure 2 Vehicle And Fuel Cycles: Petroleum-Based Fuels

Table 1 Recycling Rates and Production Energy-Intensity of Aluminum-Intensive-Vehicle Parts from New vs. Recycled Materials[a]

	Percent Recycled		Production Energy (MJ/kg)	
Part Material	2005	2030	New	Recycled
Steel	87	90	65	52
Cast iron	87	90	r[b]	37
Wrought aluminum	93	93	231	52
Cast aluminum	90	90	r[b]	44
Reinforced plastics	8	15	56	37
Un-reinforced plastics	20	35	79	14
Copper	76	85	140	35
Zinc	5	30	112	8
Powder metal	0	0	93	n/r[c]
Rubber	0	0	88	n/r[c]
Other	0	0	88	n/r[c]
Fluids	0	0	88	n/r[c]

[a] Under a maximum aluminum-substitution scenario.

[b] Assumed produced from recycled scrap.

[c] Assumed not recycled.

Table 2 Weight of Baseline vs. Aluminum-Intensive Vehicle[a] (kg)

Material	Baseline Vehicle Weight[b]	Aluminum–Intensive Vehicle Primary Weight	Secondary Wt. Savings[c,d]	Net Weight
Steel	790	186	(33)	153
Cast iron	185	54	(10)	44
Wrought aluminum[e]	17	215		215
Cast aluminum	66	252	(45)	207
Reinforced plastics[f]	14	14		14
Un-reinforced plastics	98	98		98
Other	271	271	(21)	250
Total	1441	1090	(109)	981
Weight reduction		351	109	460

[a] Under a maximum aluminum-substitution scenario.

[b] Baseline vehicle uses a cast-iron engine block and aluminum cylinder head.

[c] Assumes savings of 0.5 kg per kg of "body-in-white" weight reduction for engine and chassis components (steel, cast iron, cast aluminum).

[d] Due to 20% smaller fuel tank capacity and 3% less mass of copper, zinc, glass, and rubber.

[e] Includes 14.5 kg for radiator and other small components.

[f] Remains the same on a total mass basis, because most plastics (by mass) are used in interior components, which are assumed to remain unchanged from the baseline.

assumed to reach near-total levels for steel, cast iron, wrought and cast aluminum, and copper. Thus, by 2030, new AIVs should account for manufacturing as well as operational energy savings.

Figure 3 shows the evolution of fleet-wide, life-cycle energy savings of AIVs using the above-described market-penetration, weight-reduction, and fuel-efficiency assumptions, along with utilization and scrappage assumptions typical for conventional light-duty vehicles.

Operational energy savings[1] begin to accrue almost immediately, offsetting increases in manufacturing energy for the first few years. However, by 2016, scrap-wrought aluminum becomes sufficiently plentiful (and the technology for recycling it sufficiently mature) that the energy required to manufacture AIVs becomes essentially equivalent to that required to manufacture CVs. Throughout the period, AIVs continue to cost more because of their higher material cost.

As shown in Figure 3, the full benefit of aluminum substitution is not realized for over 15 years. Not only are savings delayed by vehicle turnover and the lack of recycling infrastructure, but manufacturing energy actually increases in the early years.

Analysis 2: Energy Savings Potential of Transitional Technologies

Although impressive progress has been made in virtually all of the technologies under development by the Partnership for a New Generation of Vehicles (PNGV), a production-ready prototype has not yet achieved tripled (3X) fuel economy. Recognizing this, the National Research Council's Standing Committee to Review the PNGV Research Program has suggested making a transition from double (2X) fuel economy vehicles to triple (3X) fuel economy vehicles. In its fourth report, the PNGV peer review committee stated that "a strategy of accelerated implementation of the technologies leading to an approximately 60+ mpg non-hybrid vehicle, coupled with an expanded research plan to reach the 80 mpg target seems both prudent and feasible" (NRC 1998). Clearly, tripling saves more energy than doubling fuel economy (although the drop in energy use declines from successive efficiency

[1] The curve labeled "vehicle use" includes upstream savings from reduced fuel production and distribution.

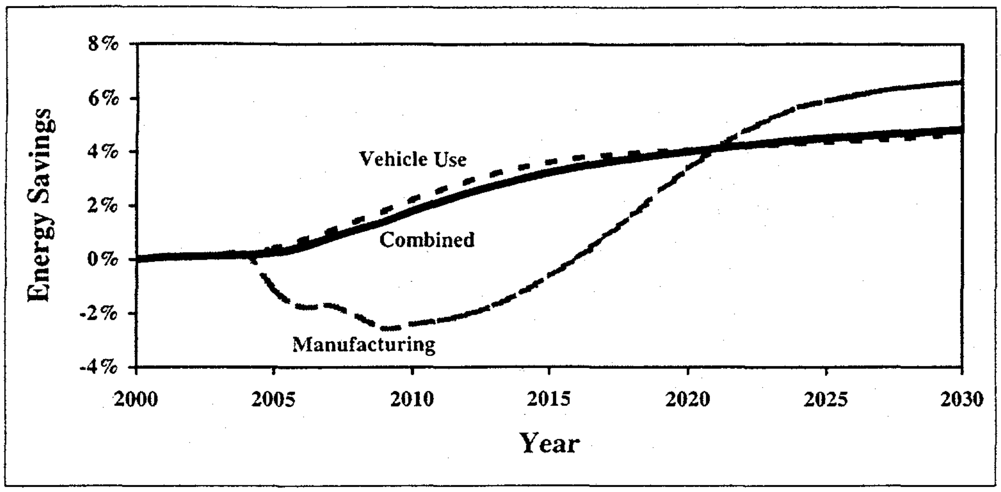

Figure 3 Reduction in LDV Energy Use with Aluminum-Intensive Vehicles

increases).[2] However, if 2X vehicles are introduced sooner, *even at a slower rate of market penetration*, not only will energy savings begin to accrue while research continues on more advanced technologies, but savings will continue to augment the savings from 3X vehicles once they are introduced.

Following this line of thinking, a reference case and two market-penetration scenarios (a transition and a 3X-only scenario) were devised (see Figs. 4 and 5). The reference case is based on the *1997 Annual Energy Outlook* published by the U.S. Department of Energy's Energy Information Administration (1996). The transition scenario assumes that 2X vehicles are introduced in 2004 and that their share of the new light-duty-vehicle (LDV) market rises to 16% in 2016 and then becomes asymptotic; 3X vehicles are introduced in 2012 and account for 52% of new sales by 2030 (in addition to the 17.5% sales share held by 2X vehicles). By contrast, in the 3X-only scenario, no dramatic improvement in fuel efficiency occurs until 2010 when 3X vehicles are introduced. However, in the absence of competition from 2X vehicles, 3X market-share grows to 60% of new LDV sales in 2030.

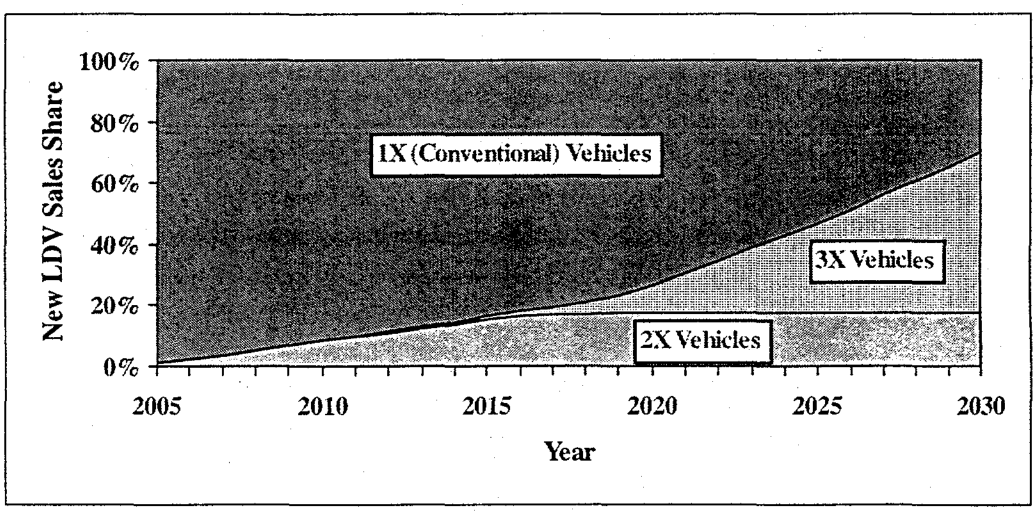

Figure 4 Market Shares under a Transition Scenario

[2] For example, doubling baseline fuel-economy results in an increase from 27 to 54 mpg, while tripling produces 81 mpg. Expressed in terms of fuel savings potential, doubling yields 50% savings and tripling yields 66.5%, an incremental increase of only 16.5%.

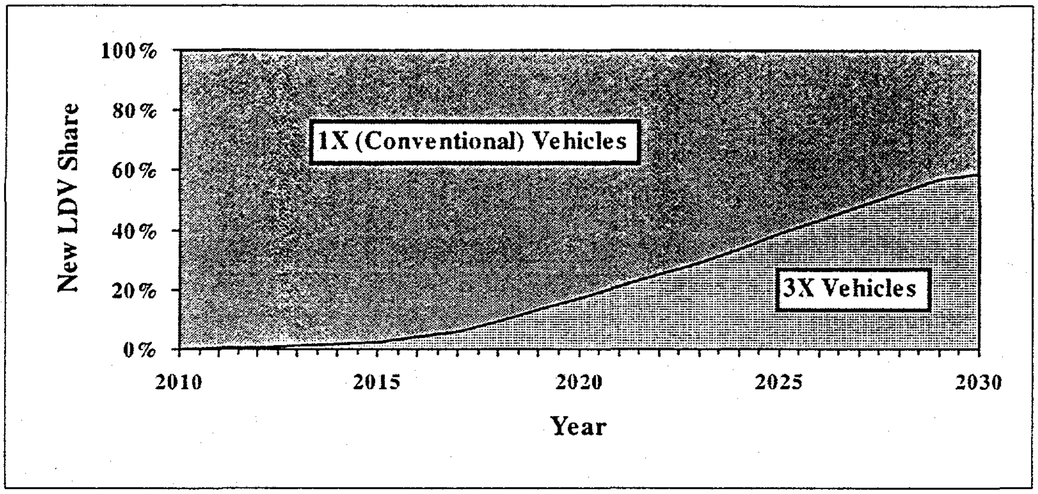

Figure 5 Market Shares under a 3X-Only Scenario

Note that because propulsion-system efficiency is assumed to account for most of the gain between 2X and 3X vehicles, the scope of this analysis was limited to the fuel cycle (i.e., energy savings from vehicle operation and fuel production and distribution). As shown in Figure 6, by delaying the introduction of 3X vehicles, energy savings do not begin to accrue until the second decade of the century. For example, in 2017, the transition scenario reduces LDV energy use by approximately 5% from reference case levels (compared with less than 2% under the 3X-only scenario). This benefit (roughly an additional 3% savings under the transition scenario) peaks around 2018, but it continues close to that level throughout the forecast period. Even in 2030, the transition scenario continues to have significant energy reductions. Put differently, equivalent savings occur seven years earlier if transition vehicles are introduced and continue to exceed savings (albeit at a diminishing rate) from 3X vehicles alone throughout the forecast period. Through 2030, the transition scenario saves 1.7 billion bbls of petroleum as compared with the 3X-only scenario (5.5 billion bbls as compared with the reference case). By 2030, the transition scenario reduces reference-case fuel use by over 23%, as compared with approximately 21% under the 3X-only scenario.

The effect of the transition scenario on greenhouse gases (GHGs) is similar (see Figure 7). As compared with the reference case, 3X vehicles alone reduce GHGs by over 300 million MT of CO_2-equivalent in 2030 (a combination of 2X and 3X vehicles reduce GHGs by 330 million MT). Note that none of the GHG reduction in the 3X-only scenario occurs by 2012, the final year of the U.S.-Kyoto commitment. However, in the transition scenario, GHGs decline by 30 million MT in 2012 (relative to the reference case).

The implication of these findings is that waiting for a "leap-forward" technology may be counterproductive. Early introduction of intermediate or transitional technology offers an important "bridge" to the future, as well as short-term energy savings (and reductions in GHGs). However, this conclusion is based on the assumption that investment in the transitional technology and its associated infrastructure will be sufficient to permit it to achieve its market potential. This is far from certain. If the technology is clearly transitional (as in the 2X case), investment may not be forthcoming unless it offers some longer-term advantage vis a vis the eventual market winner. In this line of thinking, investors will "sit on the fence" until it becomes clear which propulsion technology and (especially) which fuel will be the ultimate market winner. Conversely, the transitional technology could enhance the prospects for one or more "leap-forward" candidates by encouraging infrastructure investment that is more readily adapted to that alternative.

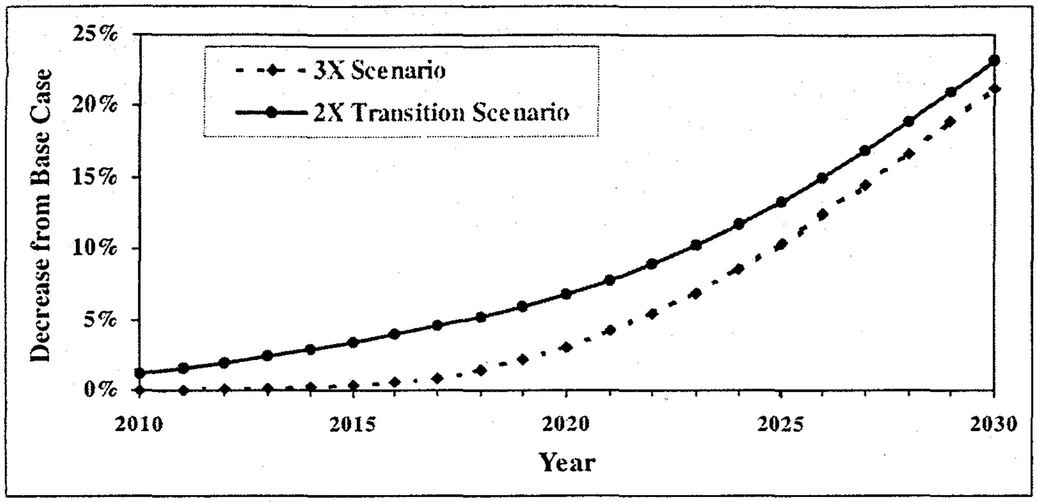

Figure 6 Energy Savings of Transition vs. 3X-Only Scenario

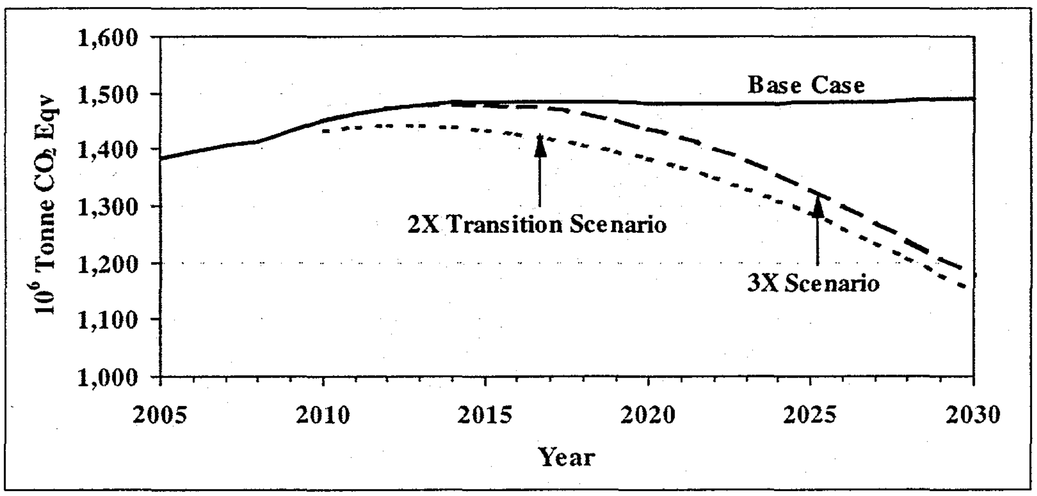

Figure 7 Greenhouse Gas Reductions under Transition and 3X-Only Scenarios

Modeling Approach

Both analyses used the IMPACTT model to track vehicle stocks, scrappage, rated fuel-economy, and utilization by vintage, which then provided the means to calculate fuel use by all vehicles (advanced and conventional) expected to be on the road in a given forecast year (Mintz et al. 1994, Mintz and Saricks 1998). The IMPACTT model estimates annual energy consumption and emissions production by conventional and advanced-technology vehicles as they move through the light-duty fleet. IMPACTT incorporates a stock module that adds new vehicles (AIV, CV, 3X, or 2X) and retires old vehicles from an initial vehicle population to produce annual profiles of the auto and light-truck population by age and technology; a usage module to compute auto and light-truck travel and fuel use by technology; and an emissions module to compute upstream and operational emissions of criteria pollutants and GHGs for autos and light trucks, again by technology. The usage module computes the quantity of petroleum that would have been consumed by CVs in the absence of advanced technologies (reference case); the quantity of petroleum-equivalent consumed by 3X, 2X, conventional (1X), and aluminum-intensive vehicles in the particular scenario under investigation; and the net savings due to the presence of advanced-technology vehicles in the fleet. Upstream energy use is computed post hoc, as a function of operational energy use and a series of rates developed by the Greenhouse gases, Regulated Emissions, and Energy use in Transportation

(GREET) model (Wang 1996, Wang 1999). For additional discussion of the linkage between IMPACTT and GREET, see Wang et al. (1998).[3]

IMPACTT may be envisioned as a stack of worksheets, one for each technology being examined. Each worksheet includes the stock, usage, and emissions modules shown in Figure 8. Since stock modeling is a key component of IMPACTT, annual travel, fuel use, and emissions of conventional- and advanced-technology vehicles are the sum of vintage-level estimates. This detail is particularly useful for dealing with issues related to fleet turnover, including recycling and comparing alternative market-penetration scenarios.

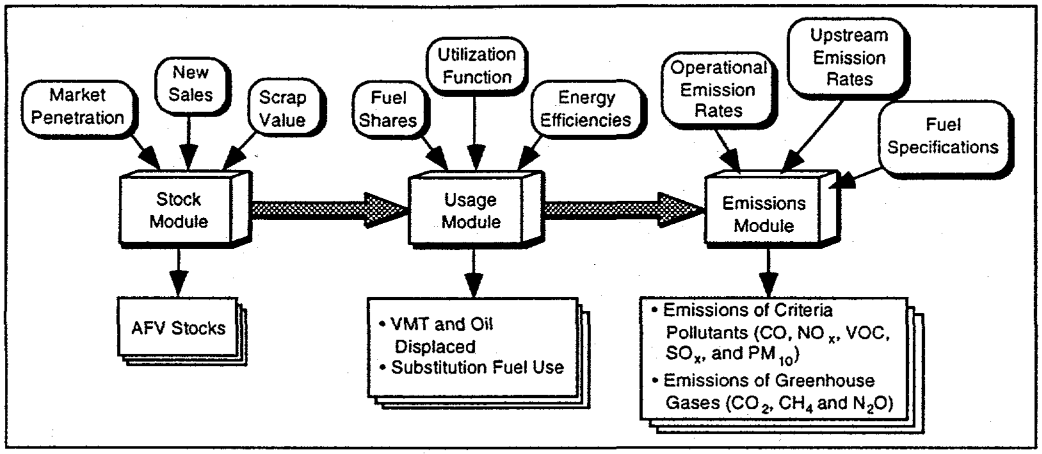

Figure 8 Structure of IMPACTT Model

CONCLUSIONS

This paper reports findings of two separate analyses in which the energy benefits of advanced technologies are systematically estimated by using market penetration and stock modeling. The latter produces more conservative estimates than in many other analyses, and by taking the subjective element out of the equation, the end result is a more defendable estimate. Stock modeling is an essential element in estimating the speed with which advanced technologies can yield benefits and in quantifying the magnitude of those benefits. Rising market shares can provide a misleading impression that new technologies are rapidly replacing conventional technologies when, in fact, conventional vehicles are and will continue to be the norm for some time to come. In life-cycle analysis, stock modeling is doubly important — to accurately estimate energy use in vehicle operation and to account for material recovery and recycling, which, in turn, affect energy use in vehicle manufacture. Although analysis of historical precedents can, in some cases, substitute for stock modeling per se, the latter is generally more transparent, more reproducible, and more defendable to technical and non-technical audiences.

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[3] Unlike GREET, IMPACTT's fuel-use module computes only downstream or operational energy use. Upstream energy use is computed as the product of operational energy use and a GREET-supplied rate.

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