Love the Way You Move: Energy Savings in Transportation

Moving people on the ground is the single greatest use of transportation energy.

Most passenger trips in the U.S. are made by automobile. People looking for a chance to bash ordinary Americans often sneer at the "American love affair with the automobile". I have to admit there is an element of that; automobiles do have attractiveness beyond their functionality. But in point of fact there are plenty of rational reasons Americans prefer cars to other forms of passenger transport in most cases.

An overwhelming one is that journeying by transit often takes longer. For example, work travel using public transportation takes about twice as long as private transportation though there is only a slight difference in travel distance[193].

There are comfort issues as well. Due to load management requirements the odds are you will have to stand part of the way if traveling during rush hour. There is always the chance of harassment or criminal victimization. Incidentally, most transit buses (as opposed to long distance coach buses) get **fewer** passenger miles per gallon than most automobiles[147].

We have already discussed a transit system that does not have these problems - which offers the convenience and comfort of automobiles at a reasonable cost – CyberTran which would attract a lot of the passenger miles currently spent in automobiles. Cars would still have advantages for physically heavy shopping, for work requiring significant equipment, and for certain types of recreation - among others. 75% of passenger miles traveled by auto in the U.S. are NOT subject to this limitation[194]. Allowing for a certain amount of pure automobile love, it would not be unreasonable to guess that a superior passenger transit system could attract 70% of the miles now traveled by automobile, light truck, van or SUV. Many of the remaining miles could be part of car sharing or other rental arrangements.

A reminder: the small light Cybertan cars run on cheaper tracks, keeping the total capital cost of an CyberTran urban (or suburban) system (including elevated rail and guideways) at about a tenth or less of the per seat cost of conventional light rail. The same light cars also mean energy costs per passenger mile are better than conventional light rail as well.

CyberTran is a computer automated driverless system; routes are calculated on the fly, meaning that passengers that will travel with either no or very few stops between their departure and destination, and that transfers will be uncommon, and without long waits or missed connections. Passengers will not need to wait more than five minutes for a car, which will be available 24 hours per day, seven days a week. Seating is guaranteed; passengers never need to stand. CyberTran may easily be made bicycle, wheelchair, baby stroller, and package friendly.

Given the combination of greater convenience to attract more passengers, and on the fly optimization of routes it would not be unreasonable to assume that CyberTran cars in operation will use a higher percent of their capacity than buses, maintaining an average of four passengers per vehicle.

CyberTran cars consume about .106 kWh per passenger mile[195]. If that electricity comes from hydropower, wind or other non-combustion sources (with a 20% loss to allow for increased line losses), this is the equivalent of 330 passenger miles per gallon. Cars and personal trucks combined averaged around 32 passenger miles per gallon in 2000[147]. CyberTran would transport passengers around 10 times more efficiently than automobiles.

The way to implement CyberTran would be to begin replacing bus routes where it would provide cheaper, faster, more comfortable more convenient and more energy efficient transport for bus riders – then lure auto riders into the now far superior mass transit system.

One thing that may ultimately help CyberTran succeed is its resemblance to a giant penis. Probably, painting it any type of flesh tone would be too obvious. But surely a marketing person could do something with the fact CyberTran is bigger than a car, but can tirelessly keep thrusting forward much longer.

Superior transit could replace all regular route city and suburban buses and about 70% of automobile mileage. The other 30% won't go away; there are all the functions mentioned at the beginning of this article that transit won't work well for. There are people in rural areas where demand is too scattered to support even the far less expensive transit CyberTran represents. And there are people who simply will prefer cars to trains.

There are two solutions for them.

A four passenger electric sedan (running at the equivalent of above 200 mpg if the electricity had come from wind, water or other non-combustion sources with a 20% transmission loss) was demonstrated in 1997 that had a range of 210 miles at normal highway speeds before needing recharging and could have retailed for as little as $20,000[196].   That is a lot of money; but it was also at the mid, rather than high end for a new car –even in 1997. There are people for whom that mile range would not be enough; but there are also plenty who would never drive more than 210 miles in a single day, not even on vacation. Note that that battery lifespan and cost are not an obstacle to this in mass production[197].

What about people who need greater range – whether in an occasional rental or for their daily driving needs? There is a solution for that too - the Hypercar[198].

As with green buildings, this is a case where whole system thinking is the key - where doing several things at once works better than doing any one of them singly.

Hybrid autos gain efficiency three places.

First, a gasoline-powered generator produces electricity that in turn drives the car motor. This is more efficient than burning gasoline to drive motor directly. Heat converts into electricity more efficiently than high torque mechanical power if weight must be kept low. Electricity, in turn converts, into high torque mechanical power with almost no loss.

Second, manufacturers have made slight weight reductions.

Third, some use regenerative braking to recover mechanical energy lost in stopping and slowing.

Hybrid engines alone only increase performance by 30% on average. But, the combination of all these factors has been known to double mileage for some models.

There have also been prototypes of ultra-light cars - using carbon fiber/fiberglass composites to produce bodies much lighter than normal cars, with the same or better strength.

These are much, much more expensive than conventional autos and get double or triple the mileage.

But if you combine the two technologies various synergies occur.

With the lighter weight the hybrid engine and batteries can be smaller and lighter - decreasing weight much more than the simple substitution of carbon and silicon for steel would suggest. The regenerative breaking gains much more stopping power - so much more that manual brakes feel like, and are as responsive as power brakes, so power brakes are not needed. Similarly manual steering is as responsive as power steering.

This increases mileage to the point that the gas tank size can be reduced, decreasing weight more. Using electric axle motors eliminates the need for a transmission and a lot of other standard auto parts.

At this point something interesting happens to cost. Even though carbon fiber is about 1000 times as expensive per pound as steel, you are using a lot fewer pounds. And much of cost of steel parts is shaping the steel; with carbon fiber/fiberglass composites, parts are extruded pre-shaped. The car uses ten to twenty composite parts vs. hundreds of steel parts. Paint is baked in, so the painting step that can represent as much as 15% of the manufacturing cost of a car is eliminated.

As a result, this ultra-light weight, ultra-efficient car costs less to manufacture than a comparable conventional car. Savings in labor, capital equipment, and manufacturing energy more than make up the increased material cost.

You end up with a better car too. Safety in even a small hyper-car far exceeds that of the best SUVs. Carbon fiber (and passengers enclosed by it) will survive collisions a lot better than steel. (This doesn't mean that you can't make a hypercar SUV as well.) A Hypercar can be expected to last much longer than a conventional car. (Carbon fiber lasts longer than steel -even when diluted with fiberglass.) Fewer parts mean that maintenance is simpler - both diagnosis of problems and their repair are easier.

They can have any feature any other car has - air conditioning, power windows, sunroofs or whatever.

No one has actually built one commercially for a number of reasons - including the fact that it would make every existing auto manufacturing plant obsolete, and cannibalize sales of existing models - forcing the write-off of unamortized capital equipment. U.S. auto makers might have done it anyway as a blow against their competition, but the American auto industry does not sacrifice short-term profits to gain market share. The manufacturers of other nations might have considered it. But US free trade principles tend to be for other nations to follow. There are already informal (but enforced) quotas on Japanese automobiles. A foreign manufacture making a radically better car than U.S. manufacturers would face significant risks of exclusion from the U.S. market.

Someone in another industry might have considered it. But there is more to the auto industry than making a good product. You need distributors, suppliers, and a unique type of marketing. So for someone other than an auto company to take this on would require a deep-pocketed risk taker with an appetite for a fight - not the world's most common animal. In short there are plenty of reasons besides practicality for auto makers to resist Hypercars.

Gasoline powered hypercars would use around one third the energy per mile compared to conventional automobiles. Battery powered hypercars would do better; the Solectria Sunrise discussed above was essentially a hypercar EV; the 210 MPG efficiency was better than a hydrogen car driven by fuel cells.

All of these, CyberTran, electric cars and Hypercars will take time to implement. Is there something that may be done immediately?   Hybrid cars are growing in sales, and already run to some extent off batteries. Increase that battery capacity, and add a plug so that you can charge them from the grid; the result is PHEV (Plugin Hybrid Electric Vehicle). You can get much of the thermodynamic efficiency improvement you could get with a 100% electric car, and still have the range of gasoline engine. You don't have the improvement you would get with a true Hypercar or electric car, because you don't have the ultra-light weight, the other improvements such as good aerodynamics and low rolling resistance, and you have the mass and complexity of both a larger battery and a fuel tank. But carbon (and other) emissions are half of those generated by a conventional car[199], and they are a minor modification of automobiles on the market now. We could build them now in our current factories. In fact conventional hybrids have been customized into PHEVs[200].

This another way take advantage of batteries that may be superior to a pure electric hypercar - plugin hybrid hypercars. The could give us almost the efficiency of electric cars, all the carbon reductions we need, and the convenience of a conventional range and a 400 mile range with instant refills.

Imagine a hypercar PHEV70 with a seventy mile battery - in the Solectria Sunrise that would have been ten kWh. You have saved 2/3rds of the weight of the batteries, so you can spend them on a tank and engine to drive the electric motors when the battery is discharged the maximum that is safe for it, enough to get about 70 miles. Usually it is considered that 85% of miles driven by Americans are driven on trips of less than 60 miles in a day, so it is safe to assume that a 70 mile range will let at least than much of the mileage be driven by batteries. A hypercar should get 75 miles to the gallon, so a four gallon tank will extend your range to 375 miles, with the ability to refill in any gas station - reasonable even on long trips. If the grid you charge from is mainly wind, water and sun charged , you are getting 200 MPG for 85% of your driving, 75 MPG for 15% and ending up with 181 MPG in energy efficiency (better incidentally that the 5X efficiency Lovin's claims for hydrogen based hypercars). With a low carbon grid, you are getting the same carbon reduction an all gasoline car would get at 300 MPG. But if we can really produce sustainable, carbon neutral biomass, we can do better. Fill that tank up with 85% biofuel and 15% fossil fuel. The lowest energy biofuels have about half the BTU value of gasoline or diesel, so as a worst case scenario we need double our tank size to 8 gallons. But we do have 15% dead dinosaurs in the mix - reduce it back to 6.8 gallons. Also, the lowest energy density biofuels can also generate 30% more power per Btu in than fossil fuels, because they can be burned more completely. So reduce the tank back to under five gallons. We have not increased the auto weight substantially, but if the biofuel came from truly carbon neutral (or carbon negative) biological sources, we have reduced carbon by another ~74% - due to fossil fuel displacement (more for energy denser fuels). Carbon emissions and oil use have been reduced 98% per mile compared to a 25 MPG gasoline car.

There is one last possible efficiency gain in transportation. Assuming that heavy grocery trips would continue to be done by automobile, there is one other already existing technology that could greatly reduce energy for this purpose – internet ordering of groceries to be delivered from local suppliers. A Finnish study showed that if people had refrigerated reception boxes to hold the groceries such deliveries (so they could be delivered with an eight hour window, and stores could optimize their delivery schedules) this would save around 76% of energy use compared to individual trips to the grocery store[201].

Aside from technology, there is a policy that could win us occasional drops in emissions. A percentage of the automobiles on the road are old beater cars, worth from $400-$1,800. They are near or past the end of a conventional automobile lifetime, kept alive as the only transportation alternative for many of the poor. They mostly get very poor mileage, and generate high emissions. Periodically, offer the owners of such cars even trades of them for new or decent used cars with better mileage, lower emissions; most will be glad to accept them. Or, for a lower cost option, Europe has found that a straight buy-out (at a premium) of junk cars a very effective way to increase average mileage, and reduce emissions for the actual on-the-road fleet.

The following table summarizes selected transportation alternatives[155]: (note – percentages calculated from year 2000 table quads)

Transport Mode	Transport Percent	Efficiency Improvements	CyberTran	Other Electric	Fueled	Total
Cars	33.34%	70% of miles CyberTran factor 10 reduction /25% to electric hyper cars factor 5.8 reduction/5 % to fueled Hypercars factor 3 reduction	2.33%	1.44%	.56%	4.33%
SUVs & Light Trucks	24.22%	70% of miles CyberTran factor 12 reduction /10% electric SUV factor 7 reduction/20 % to HyperSUVs factor 3 reduction	1.41%	.35%	1.61%	3.37%
Motorcycles	0.10%	Savings unanalyzed, modeled as unchanged			0.10%	0.10%
Transit Buses	0.35%	CyberTran - factor 10	0.04%			0.04%
Inter-City Buses (currently very efficient[202])	0.12%	Hyperbuses 40% reduction			0.07%	0.07%
School Buses	0.29%	No significant change.			.29%	0.29%
Smart Growth (fewer subsidies for sprawl[203]) very long term – can make unknown contribution over next 30 years						
Medium/Heavy Trucks	17.65%	85% to Rail factor 10[204], 15% to Hypertrucks 20% reduction (increased use of rail requires more rail infrastructure, and changes in tax policies that subsidize trucks)			3.62%	3.62%
Construction vehicles	1.40%	20% savings replace standard diesel with hybrid			1.12%	1.12%
Agricultural vehicles	2.05%	20% savings replace standard diesel with hybrid			1.64%	1.64%
Air General Aviation	0.64%	Savings unanalyzed, modeled as unchanged			0.64%	0.64%
Air Domestic Carriers	7.34%	High speed CyberTran replaces short trips (20% of energy use[i]) + videoconferencing replaces 42% of business miles (42%[205] of 26%[206]). For remainder, operational efficiencies such as turning off engines and towing planes to runways, doing air replacement and other power requiring services on the ground, and better optimization of scheduling and traffic control also can save fuel[207]. The planes themselves can be gradually replaced with 20% more efficient models[208]; the combined savings is thus a 29.6% efficiency gain	0.14%	0.04%	2.79%	2.97%
Air International	1.35%	29.6% savings from immediately prior entry.			0.95%	0.95%
Water Freight	4.43%	25 % efficiency gain[209] non-barge traffic – ~50%. (Barges already efficienct[210])			3.88%	3.88%
Water Recreation	1.14%	25% efficiency gain (same as non-barge freight)			0.86%	0.86%
Pipeline	3.33%	75% volume reduction, + 14%[211;212] efficiency gain			0.72%	0.72%
Rail Freight	1.89%	Change unanalyzed			1.89%	1.89%
Rail Transit	0.17%	Unchanged		0.17%		0.17%
Rail Commuter	0.09%	Unchanged		0.09%		0.09%
Rail Intercity	0.07%	Unchanged			0.07%	0.07%
Tonnage Reduction		Rail, Truck, and Water freight ton miles reduced by 40%			-3.54%	-3.54%
Total			**3.92%**	**2.09%**	**17.27%**	**23.28%**

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[i] See appendix "How CyberTran May Replace Short Domestic Flights".

We have an 77% per capita reduction in transit energy – at somewhere between no additional costs and a saving - a slightly higher percentage of which is electricity than at present. CyberTran is cheaper than cars, light trucks, SUVS and planes even before energy cost is taken into consideration. Hypercars are about the same cost or a bit cheaper than normal cars – ditto hypertrucks and Hyperbuses. Electric cars, if mass produced, would be comparable in cost to conventional cars, though with a more limited range. Heavy rail freight capital costs and maintenance are lower per ton-mile than roads and trucks, even before energy savings are considered. Telecommuting pays for itself many times over in fuel costs. Improved water shipping efficiency, and more efficient airplanes are pretty much break even propositions when it comes to fuel cost.

Logically it would seem that the substantial capital savings in ground transit, ground freight, short term air flights, and substantial fuel savings from telecommuting substituting for some air travel, will more than make up for the small capital costs of slightly improved shipping and planes. That the 77% per capita transportation energy savings is free, rather than a net capital savings is a highly conservative assumption. The conservative assumption that the 77% savings is free, that the costs of the savings are completely paid for by other capital savings, means we can afford to pay five times the current cost of fossil fuel to run transportation on renewables.

One note on all this: unfortunately one assumption that is normally good falls down badly here - that fossil fuel consumption roughly tracks emissions. Airplanes, sadly, produce warming far out of proportion to their carbon emissions. The problem here is water vapor.

Normally, water vapor causes greenhouse heating only in response to increases in other greenhouse gases. The troposphere (where we live) mostly is saturated with all the water it can hold. Put more water in the air and it will precipitate out within a short time - maybe a great distance from where it was absorbed. However, if we add carbon dioxide equivalents to the air, that heats it just a little. The small temperature rise lets the atmosphere absorb water vapor in greater amounts. In other words, while carbon dioxide forces the temperature up words, water vapor increases temperature as feedback mechanism. The way climate scientists often put this is that "water vapor is a feedback, not a forcing".

The trouble with jet airplanes is that they emit water in the lower stratosphere, not the troposphere. They fly above the clouds, where the air is NOT saturated with water. Water emitted at the level is a forcing, not a feedback. If airplanes were infrequent this would not matter. Water, even at that level, is not a long term feedback. As a one time thing, it would soon mix with the troposphere and precipitate out quickly. Unfortunately, airline schedule are pretty regular from day to day. So jet planes add water to the stratosphere faster than nature regulatory mechanism can keep up with. We won't have a choice but to reducing flying even after all "no regrets" reductions are made. This is not a terrible thing. A luxury configured CyberTran (six people per car - configured with bathrooms, water, drinks and snacks) could get you 3,000 miles in under two days. (It could actually travel that distance in 20 hours, but we are assuming stops for meals , stretch breaks, and an overnight stop for sleeping.) For long journeys like this, if we can get Maglev or other very highs speed electric trains to work, we could end up coming close to airplane speed, and simply eliminate air travel for any trip that does not cross large bodies of water. Ultra high speed trains are not particularly energy efficient. (Maglev is especially egregious due to the embedded energy in Maglev tracks.) But energy efficiency is not (for a change) the point; even if high speed rail consumes more energy than planes, the global warming effect is still lower. And if the electricity for this purpose comes from solar or wind energy than the global warming effect is near zero.

At any rate flying won't have to be zero. We may, due to having delayed so long to tackle a problem that was widely foreseen in the 1970's, have to drastically reduce it for a while. There will be more replacement of international travel with long distance communication. Most long distance travel over land will be by trains. Most long distance travel over water will be by ship. We will find higher speed versions of both trains and ships; but overall long distance travel will be slower. The world won't be quite as small for a while. But in the long run, if we survive otherwise, we will find a solution to this as well.

End Notes

[193]"Journeys-to-work using public transportation continued to take twice as long as private transportation, though there is only a slight difference in travel distance."
 Ibid 147 p11-15.

[194]Ibid 147 p11-12.

[195] John A. Dearien (Junior), "Ultralight Rail and Energy Use," in *Encyclopedia of Energy*, ed. Cutler J. Cleveland (Elsevier Publishing, March 2004), 255-66.

[196] Energy Conversion Devices, Inc., *Energy Conversion Devices, Inc. 1997 Letter to Stockholders - Commercializing Technologies That Enable the Information and Energy Industries.* Dec 1997, Energy Conversion Devices, Inc., 26/Sep/2005 <http://www.ovonic.com/PDFs/LtrstoShldrs/ecd97ltr.pdf>.p3.

[197]Mark Duvall et al., *Advanced Batteries for Electric-Drive Vehicles : A Technology and Cost-Effectiveness Assessment for Battery Electric, Power Assist Hybrid Electric, and Plug-in Hybrid Electric Vehicles*, Preprint Report, Version 16. 25/March 2003, Electric Power Research Institute (EPRI), 03-Jan-2007 <http://www.epri.com/corporate/discover_epri/news/downloads/EPRI_AdvBatEV.pdf>.
Page v. - Battery cycles are over 2,000 cycles with almost no loss of capacity with deep discharge, even better with shallow discharge in actual use. So we can conservatively estimate 1,000 cycles, which would last longer than the lifetime of the car.

Page vi - NiMH cost can reach $320 per kWh capacity in volumes of 100,000 or more. (Remember that an automobile needs more than one)

So battery cost, interest, and electricity at 14 cents per kWh will still cost less than $2.50 per gallon gas.

[198]Rocky Mountain Institute, "The Hypercar® Concept," *Transportation*, 2004, Rocky Mountain Institute, 19/Aug/2004 <http://www.rmi.org/sitepages/pid386.php>.

[199] IAGS-Institute for the Analysis of Global Security, *Plug-in Hybrid Vehicles*. 14/Jan 2006, IAGS-Institute for the Analysis of Global Security, 17/Mar/2006 <http://www.iags.org/pih.htm>.

[200] CalCars - The California Cars Initiative - 100 MPG Hybrids, *Plug-In Hybrids: State Of Play, History & Players.* 17/Mar 2006, 17/Mar/2006 <http://www.calcars.org/history.html>.

[201]Hanne Siikavirta et al., "Effects of E-Commerce on Greenhouse Gas Emissions: A Case Study of Grocery Home Delivery in Finland,". *Journal of Industrial Ecology* 6, no. 2 - E-commerce, the Internet, and the Environment Spring 2002, MIT Press, 19/Aug/2004 <http://mitpress.mit.edu/journals/jiec/v6n2/jie_v6n2_83_0.pdf>.Pp 83-97.

[202]Ibid 147 Table 2.11 Passenger Travel and Energy Use in the United States, 2000

[203]Gerrit Knaap et al., *Government Policy and Urban Sprawl*. 2000. *Illinois Department of Natural Resources*, University of Illinois at Urbana-Champaign, 29/Jun/2005 <http://dnr.state.il.us/orep/c2000/balancedgrowth/pdfs/government.pdf>.

[204]Ibid 147 p2-19.
Table 2.14 - Intercity Freight Movement and Energy in the United States, 2000

[205]Cathy Keefe, "Business and Convention Travelers' Habits Tracked in New Survey," *Press Releases*, 8/Feb 2005, Travel Industry Association of America (TIA), 23/Sep/2005 <http://www.tia.org/pressmedia/pressrec.asp?Item=359>.

[206]Charles River Associates Incorporated;Polaris Research & Development, "A Summary of Key Statistics Across Airports," *AIR PASSENGERS FROM THE BAY AREA'S AIRPORTS, 2001 & 2002 - Final Report Volume 1:OVERVIEW AND METHODS*, CRA No. D03144-00. Sept 2003. *Metropolitan Transportation Commission*, 23/Sep/2005
<http://www.mtc.ca.gov/maps_and_data/datamart/survey/APS_report_volume_1.pdf>.p7.
 (Note statistics are bay area statistics only.)

Inbound International travel 26%-30% primarily for business purposes. So 26% remains a conservative estimate at international level.
Bureau of Transportation Statistics, *BTS - U.S. International Travel and Transportation Trends - Overseas Travel Trends*. 2004, Inbound Overseas Travel;, Bureau of Transportation Statistics, 23/Sep/2005
<http://www.bts.gov/publications/us_international_travel_and_transportation_trends/overtrends.html>.

21% of RPM business and first class. Since an increasing percent of business air travel is economy, that is consistent with 26% estimate.
Jim Corridore, "Industry Profiles - Industry Trends," *Standar & Poor's Industry Surveys: Airlines*. 25/Nov 2004. *Standards & Poor's Division of McGraw Hill*, 23/Sep/2005
<http://libsys.uah.edu/library/mgt301/spairline.pdf>.p11.

[207]D. Dimitriu et al., *Aviation and the Global Atmosphere -(Chapter 8) Air Transport Operations and Relations to Emissions - Executive Summary*. Apr 1999, GRID-Arendal Official United Nations Environment Programme (UNEP) Centre, 19/Aug/2004
<http://www.grida.no/climate/ipcc/aviation/119.htm>.

[208]Boeing World Headquarters, *Boeing 787-3 Dreamliner Facts*. 2003, Boeing Company, 21/Aug/2004
<http://www.boeing.com/commercial/7e7/facts_sr.html>.

[209]William R. Moomaw et al., *Climate Change 2001 - Mitigation -Working Group III: Mitigation - 3.4.4.8 Waterborne Transport*. 2001, Intergovernmental Panel on Climate Change, 19/Aug/2005
<http://www.grida.no/climate/ipcc_tar/wg3/103.htm>.

[210]U.S. Army Corp of Engineers | Rock Island District | Mississippi Valley Division, *Transportation Mode Comparison - Energy Environment- Efficiency*. Jan 2002. *U.S. Army Corp of Engineers | Rock Island District | Mississippi Valley Division*, 26/Sep/2005 <http://www2.mvr.usace.army.mil/UMR-IWWSNS/documents/tr-comp.pdf>.p1.

[211]I'm conservatively estimating compressor change potential to be only a 1% savings though more probably between 2% and 4% of compressor energy could be saved in the U.S. through such means.

Compresser efficiency can vary from 50% to over 90% in natural gas pipelines.
Southwest Research Institute (SwRI), *18-Services for the Pipeline Industry Brochure*. 2005, Southwest Research Institute (SwRI), 27/Sep/2005 <http://www.swri.edu/3pubs/brochure/d18/pipeline/pipeline.htm>.

We have an aging fleet of compressors 20-50 years old. While most the efficient gas compressors are about 91%, new electric compressor 92-95% efficient. (Note: these percents are comparisons to the thermodynamic limit, not to a theormodynamically impossible 100% efficiency. And yes, the gas used to generate the electricity for the electric compressors is taken into consideration; it is like hybrid cars; in some cases using heat to generate electricity to produce mechanical power can be more efficient that using heat directly to generate mechanical power).

Michael Crowley and Prem Bansal, *Development of an Integrated Electric Motor Compression System*. 3/Oct 2004, Gas Machinery Research Council | DOE NETL Research Review, 27/Sep/2005

<http://www.gmrc.org/gmrc/2004finalpapers/Development%20of%20an%20Integrated%20Electric%20M otor%20Driven%20Compressor.pdf>.

Although older less efficient compressors were more rugged and lasted up to 50 years, more typically a pipeline compressor lasts 30 years. Most U.S. compressors are under 90% efficiency, and almost none are above 91%. So even if the "compressor fleet" was new we could expect just about every compressor to be replaced over the next 30 years with one that is a percent or two more efficient. But in fact, as documented above we have a lot of old compressors, which are probably more in 75%-80% efficiency range. They will need to be replaced soon; replacing them with the most efficient compressors will save a lot more than a few percent. So actually 4% savings from compressor improvements would still be a conservative estimate. 1% leaves a huge margin of error.

[212]Phil Ferber et al., *Gas Pipeline Optimization. 31st Annual Meeting - October 20-22, 1999 | St. Louis, Missouri.* Oct 1999, Pipeline Simulation Interest Group, 27/Sep/2005 <http://www.psig.org/papers/1990/9905.pdf>.p16.

This documents a 13.26% savings from just better (and very simple) software control. That cumulated with a 1% savings from improved compressors gives you better that 14% savings. And that does not even consider leaks: better controls can detect leaks more quickly and pinpoint them more accurately. More modern compressors cause fewer leaks to begin with. (Compressors are a major cause of leaks.) So that gives you an additional margin of error in an already very conservative estimate.