Engine Remanufacturing and Energy Savings

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1 Introduction

As per [9], the United States Transportation sector consumed 28.5% of the total 101.5 quadrillion BTUs of energy consumed in the US in 2007. This fraction has been consistently rising at more than 1% over the last couple of decades. It is also true that the United States on-road transportation energy use is dominated by Passenger Cars, as shown in the figure 1 [1]. The total energy used by on-road transportation (by cars, trucks, motorcycles and buses) in 2007 is 22,393 trillion BTUs.

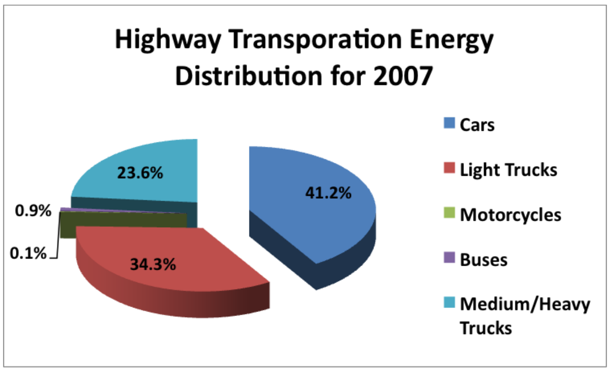


Figure 1: Transportation Energy Use break-up for different vehicle categories [1].

On a per vehicle basis, heavy-duty trucks consume the most energy due to their extensive driving cycles and low fuel economy. [9] reports that heavy trucks consumed on an average consumed over 23,000 BTUs per vehicle in 2006, while passenger cars and light-trucks consumed approximately 5,500 and 6,900 BTUs respectively. As a result, the need to reduce transportation energy consumption, especially by passenger cars and heavy trucks is very apparent. To do so it is important to understand the characteristics of the vehicle population on-road as well as of the new ones purchased every year. The Bureau of Transportation Statistics [10] estimates the average new vehicle (passenger cars and light trucks) sales in 2008 to be 10,933 while used vehicle sales to be 36,530. The same for 2007 were 12,631 and 41,418 respectively. This shows the prevailing presence of customers interested in choosing used vehicles and their components over new ones. Though this characteristic does not completely represent the vehicle population, it seems to be highly prevalent and thus demands investigation. This report thus undertakes the task to evaluate the energy saving potential of reusing/remanufacturing the largest-energy-consuming component of a vehicle - its engine. When these engines reach their end of life, they can either be land-filled or they can be recycled which would conserve only the original materials, or they can be remanufactured and resold in a like-new workable condition which would not only conserve the materials but also the value-added during the manufacturing processes, like casting, molding, machining etc. Intuitively, remanufacturing seems to be the most viable option. Remanufacturing of automobiles engines has been practiced since 1920s. As per the PERA (The Production Engine Remanufacturers Association), engine remanufacturing in the U.S. alone is a $2.5 billion industry with approximately 2.4m engines remanufactured every year [2].

In this report we would like to focus on remanufacturing of passenger car gasoline engines and heavy duty combination truck diesel engines and calculate their benefits with reference to energy savings. Along with energy, economic assessments are also presented for comparison.

2 Gasoline Engines for Passenger Cars

2.1 Introduction

The gasoline engine considered in this analysis is from the report by Keoleian et. al [2]. It is a 3.5L internal combustion gasoline 60°V-6 engine with a 5.2L engine oil capacity. For the analysis let us consider a base year, which is assumed to be 1987 for this report. This means that the consumer considered is the owner of a car originally manufactured in 1987. This consumer on an average drives the car for 120,000 miles, which adds up to 1999 [5], and then has the following choices shown in Figure 2

In reality, the consumer has another option of buying a second-hand car of a range of years as well. Since this range (of the age of second-hand cars) is fairly large, and the fraction of them containing remanufactured engines is also unknown, this option is not considered in our analysis.

In the above figure (Figure 2) Option 1 refers to extending the life of the original car/engine system of 1987 by remanufacturing the engine. For being in favor of remanufacturing, this engine is assumed to be like-new, that is, it is as good as it was when it was brand-new. Option 2 involves keeping the same car but replacing the engine with a new state of the art engine of 1999, assuming that the new engine is compatible with the existing car system. Option 3, another very popular option, is of abandoning the existing car/engine system of 1987 altogether, and purchasing a new passenger car of 1999. Note that the engine in Option 2 and 3 are the same but the energy consumed by them will be different. This is explained in detail later.

With respect to the engines being studies, there are 2 kinds:

- An engine originally manufactured in 1987 and remanufactured and put back into use in 1999. Lets just call this "Remanufactured Engine" for simplicity.

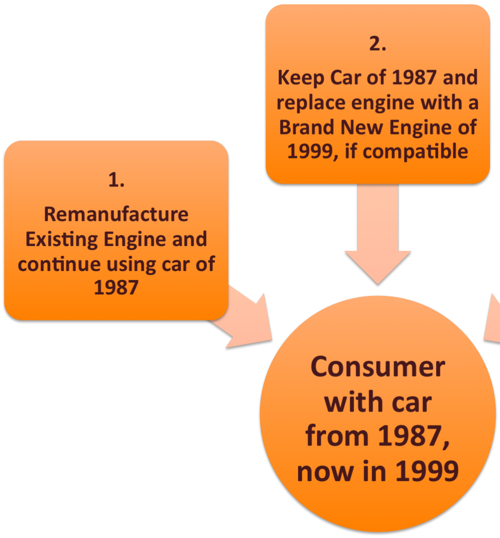


Figure 2: The average decision choices for a consumer who has used his car (bought in 1987) for 120,000 miles and now in 1999 is considering changing the vehicle or remanufacturing its components.

- An engine newly manufactured in 1999 and put into use instantly. Lets just call this "New Engine."

2.2 Life Cycle Inventory

2.2.1 Raw Materials Production

New Engine - The energy used to produce the raw materials, which are required to manufacture the above described gasoline engine, was derived from the following bill of materials (figure 3)[2].

It can be seen, that the major contributors are expectedly steel, iron and aluminum. The total weight of the engine is ~150Kg. The data for specific energy has been taken from the report by Keoleian et al [2] and compared with data from Smil [11].

Remanufactured Engine - Though remanufacturing involves bringing back the used components to a like-new condition, sometimes components are damaged beyond repair and have to be replaced with new ones. Along with this, other materials used in cleaning, refurbishing etc comprise of the raw material inputs that go into remanufacturing an engine. From [2], the energy consumed in the production of raw materials that are used to remanufacture a gasoline engine is ~1.386GJ.

Material	Energy Intensity (MJ/Kg)	Weight (Kg/engine unit)	Imbedded Energy Contributions (MJ/engine unit), upto raw material stage
Aluminum (average)	143	0.8	114.400
Aluminum (cast)	57	27.5	1567.500
Aluminum (extruded)	190	0	0.000
Aluminum (rolled)	183	1.7	311.100
Total Aluminum		**30**	**1993.000**
Asbestos	31	0.2	6.200
Bronze	127	0.2	25.400
Ethylene propylene diene monomer	209	0.2	41.800
Iron (cast)	34	66.6	2264.400
Iron (cast, forged)	94	2	188.000
Total Iron		**68.6**	**2452.400**
Polyamide (PA 66)	175	0.5	87.500
Polyporpylene	71	0.5	35.500
Rubber	116	0.7	81.200
Total Polymer			**204.200**
Steel (average)	24	10.2	244.800
Steel (cast)	34	9.1	309.400
Steel (cast, forged)	94	20.6	1936.400
Steel (cold rolled)	28	4.7	131.600
Steel (electric arc furnce)	9	0	0.000
Steel (galvanized)	32	2.7	86.400
Steel (hot rolled)	26	2.7	70.200
Total Steel		**50**	**2778.800**
Tin	249	0.1	24.900
Totals		**151**	**7526.700**

Figure 3: Bill of Materials for Gasoline Internal Combustion Engine [2].

2.2.2 Manufacturing

New Engine - The energy consumed during manufacturing of the engine, which is exclusive of raw material production is 4.374 GJ [2].

Remanufactured Engine - The manufacturing, rather remanufacturing stage, primarily entails disassembly, cleaning, checking for defects, repairing/refurbishing, replacing (if need be), re-assembling and testing. These steps all require energy which is taken to be ∼1.409 GJ from [2].

2.2.3 Use Phase

The energy consumed while the engine is in use is dependent on a number of factors like the total time of use, the fuel consumption rate, the percentage of fuel energy consumed by the engine itself etc. The fuel economy data available [12] is only for new cars with new engines or for average on-road vehicles. However if you mix and match cars and engines (like in the case of Option 2), the fuel economy is likely to change since different cars have different aerodynamic drag, different transmissions etc. Explicit data for the fuel economy in such cases is not available. Remanufactured engines can often be deployed into various car systems (as long as the car and the remanufactured engine are compatible), thus making it difficult to estimate the resulting fuel economy. While the same engine when installed in different cars can result in different fuel economies, it is true that the energy consumed per unit fuel input by the engine itself would be fixed. In other words, the efficiency of the engine (our system) remains fixed irrespective of which car the engine is deployed into (which is outside the system).

Remanufactured Engine, Option 1 - Let us first analyze the homogeneous system of Option 1 (car and engine of the same year, 1987, allowing us to use the available fuel economy literature data). To calculate the energy consumed by the engine of 1987 (base year), we will calculate the fraction of total energy utilized by a car and engine of 1987, that corresponds to the engine alone. Note that the MPG of a car is for the car as the system and not the engine alone.

The life of a passenger car vehicle was referred from [2] and considered to be 120,000 miles, as described before. The fuel economy (mpg, fuel consumption rate) of a new car of 1987 was taken from [12] since the remanufactured engine is expected to perform like new. The specific energy of Gasoline Fuel was taken from [9]. These statistics can be used to calculate the energy used by the entire vehicle during it total use, since the fuel economy is the performance metric of the entire vehicle. However, what is needed is the energy used by the vehicle engine alone. The contribution of fuel that goes or is consumed by the engine, was adopted from [3, 4], and was taken to be 80%. The distribution of fuel energy in a passenger car is shown in the figure 4.

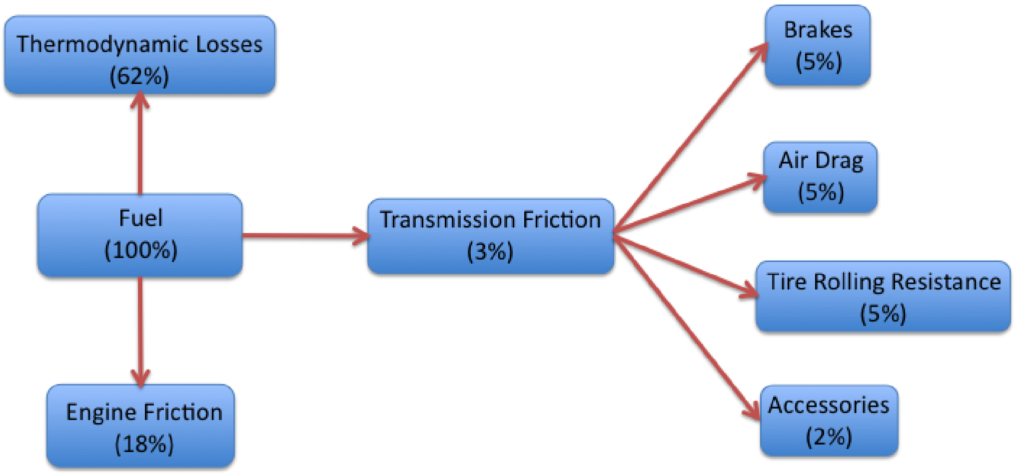


Figure 4: Fuel Energy Distribution in a Passenger Car [3, 4].

The thermodynamic efficiency of a gasoline engine (typically 38%) and engine frictions are used to calculate the engine contribution to the use phase energy of a vehicle (80% of the total fuel energy). In other words, the efficiency of this engine is roughly 20%.

It should be noted that the fraction of total energy consumed by the vehicle that can be attributed to the engine alone is called the Contribution Factor of the engine. With technological advances in drive-train efficiencies, vehicle aerodynamics, tire friction, this Contribution Factor is expected to vary in time. Since no data was found which indicated these changes, the 80% [3] statistic, that originally comes from a reference published in 1994, was assumed to be valid for a new average passenger car manufactured in this study's base year, 1987.

Using the above statistics and approximations, the use phase energy for a new average engine for passenger cars in 1987 was estimated to be 443,149 MJ. A better understanding for the calculations in shown in the table below in Figure 5

Thus an engine manufactured in 1987, on an average consumes 443 GJ of absolute energy during the 120,000 mi of driving. Since we assume like-new condition for the remanufactured engine and since the car remains the same, this is also the energy consumed by the remanufactured engine or with Option 1.

New Engine, Option 2 - The Option 2 considers continuing with the same car of 1987, after replacing the installed engine with a new state-of-

				Value	Units
Energy contained in 1 gallon of Gasoline				**132**	**MJ**
Fuel Economy (mpg)				**28.60**	**mpg**
Contribution Factor for a gasoline engine				**80%**	
Total Energy consumed by the vehicle (MJ)	=	120,000*132/28.6	=	553,923.63	MJ
Energy Consumed by the Engine (MJ)	=	553,923.63*0.80	=	443,138.90	MJ
Energy Consumed by the rest of the car (MJ)	=	553,923.63*(1-0.80)	=	110,784.73	MJ

Figure 5: Engine Use phase calculation for a new engine of 1987.

the-art engine of 1999. As mentioned before that the fuel economy for such a vehicle is not available. However we do know, from Lutsey et al [13], about the change in fuel economy for the vehicle caused by replacing an engine of one particular model year with an engine of another model year, keeping everything else the same. So if we put a 1999 new engine into the old 1987 car from above, we know that the fuel economy will rise from 28.4 mpg to 29.161 mpg [2]. Using this, the total energy consumed by the vehicle to travel 120,000 miles is 543,196 MJ. Also known from above is that everything but the engine consumes 110,784.74 MJ of energy during the 120,000 mile travel. Thus the energy consumed by the 1999 engine is simply the difference between these two numbers which is 442,412 MJ.

New Engine, Option 3 - Option 3 considers the energy consumed by a new engine of 1999 when installed in a new car of 1999. We know again from [12] that the fuel economy of such a vehicle is 28.48 mpg. Thus the total energy to travel 120,000 miles for such a vehicle is 556,121 MJ. Also we know that the engine considered in this case is the same as the engine considered in Option 2. That is, both the engines have the same efficiency. So let us calculate the efficiency of the engine in Option 2.

Let η_{87} be the efficiency of the engine in 1987, which we know is 20%. Similarly let η_{99} be the efficiency of the engine of 1999, considered in Options 1 and 2. Let $E_{T,87in87}$ and $E_{T,99in87}$ be the total energy consumed by the vehicles in Option 2 and 3 respectively. Since the energy consumed by the rest of the vehicle is the same (everything but the engine),

$$\eta_{87} \times E_{T,87in87} = \eta_{99} \times E_{T,99in87} \tag{1}$$

[2] Lutsey et al give the change from 1987 to 2004 to be 0.6 mpg, and we just assume this change to be linear, so that the change from 1987 to 1999 is 0.6*12/17. Also Lutsey et al give this change for the entire drive train, and since the contribution factor for the transmission is only 0.03, Figure [?], the change is assumed to be entirely for the engine

Using this the efficiency of the New Engine of 1999 was calculated to be 20.395%. That is the newer engine is more efficient by 0.395%.

Using this and knowing that the total energy consumed by a new car of 1999 is 556,121 MJ (calculated above), the energy consumed by the engine in Option 3 is 442,700 MJ, not very different from Option 3.

2.2.4 Transportation

Transportation has been estimated to be 3-5% of the Manufacturing and Processing phases alone by ([2]). By including the use phase (which has been show above to be severely dominating), the impact of transportation would certainly be negligible. As a result transportation energy was not included in the analysis.

2.3 Life Cycle Assessment

Combining all calculations and data above for a new and remanufactured gasoline engines for a passenger car, the life cycle assessment can be charted out in figure 6.

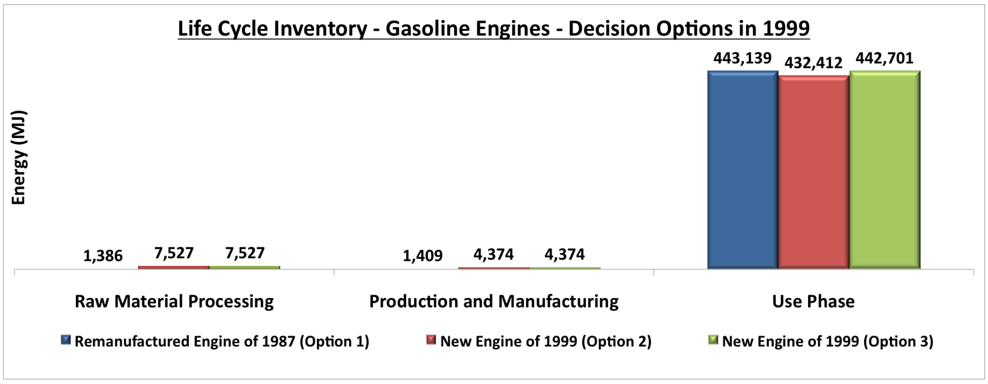


Figure 6: Life Cycle Assessment of a New (1999) and Remanufactured (1987) Gasoline Engine.

The first point to grasp is the predominance of the use phase over the life cycle of the products. The use phase of an engine consumes over 99% of the life cycle of the remanufactured engine and over 97% for the new engine, for both options (2 and 3). It can also be seen that the new engine provides marginal savings in the use phase but at the same time consumes more energy in both the raw materials and production phase. The similar use phase of the new and remanufactured engines could be because the CAFE standards did not change significantly between 1987 and 1999. This is further diagnosed later. It is also worth noting that the above LCA is based on a process-based model. A hybrid-model (using both process-based and economic input-output models) which includes the building, office, electricity, retail, motor, wholesale, truck transport, and rail transport etc. will estimate a much higher energy requirement to manufacture gasoline engines. For instance, authors of [14] estimate it to be close to 33,862 MJ, which is considerably higher than the process-based-model-estimate used in this study. Similar statistics for the remanufactured engines is 17,102 MJ, which again is considerably higher than the process-based-model-estimate used in this study.

2.4 Remanufacturing Energy Saving Potential

Remanufacturing energy saving potential refers to the relative savings obtained by choosing to remanufacture over new. Remanufacturing is feasible only if the energy consumed during its life is less than that for a new engine. A remanufactured engine consumes lesser energy than a new engine during the (re)manufacturing stage, but due to technological innovations, a new engine may consume lesser energy in the use phase than a previous-technology-based remanufactured one. Thus there is a trade-off which needs to be analyzed. The break even point is when the savings of a remanufactured engine, during the remanufacturing stage relative to the sum of the manufacturing and raw material stages of a new engine, are exactly lost in the extra energy used in the use phase of a remanufactured engine because of being of a relatively out-dated technology.

However, realistically, remaufacturability of an engine or for that matter any product can be deterred by two major factors:

(a) Obsolescence - which is the inferiority of the performance metric of a remanufactured product relative to the current new one. Technological changes cause new products to offer more, may it be in terms of energy efficiency or capacity (volume, speed etc).

(b) Degree of Degradation - The goal of remanufacturing is to revive the discarded product to a like-new condition. However, since the components have already lived one entire life before being remanufactured, their performance could be little inferior to what it was when it was manufactured for the first time. Note, this degradation is expected to be little, since before being sold, remanufactured products are expected to have passed all the tests that a new products undertakes.

Let us first deal with obsolescence assuming the there is no performance degradation in the remanufactured engine, in other words, an engine originally manufactured in 1987, and the same engine after being remanufactured and used again starting 1999, have the same fuel economy (remanufacturing resumes the engine to like-new condition).

Once the engine is remanufactured and resold, it competes with new engines (in other words Option 2 vs 1 or Option 3 vs 1, as explained above), which may or may not be performing better. One way to gauge the performance of an engine is to look at the average fuel economy of an on-road passenger car and of a new passenger car (domestic and international)[5, 6, 12], which has been graphed out below in Figure 7.

In 1975, after the 1973 oil embargo, the US government enforced the the Corporate Average Fuel Economy (CAFE) standards (came into effect in 1979) under which all vehicles (new) with a gross weight less than 8,500 lbs were to provide a fuel economy above a certain minimum standard set for that year. The impact for this is evident in the graphs. The second graph exhibits the reaction of this standard from new passenger car manufacturers. For remanufacturing energy saving potential, what is important is the annual change in the performance metric (figure 8).

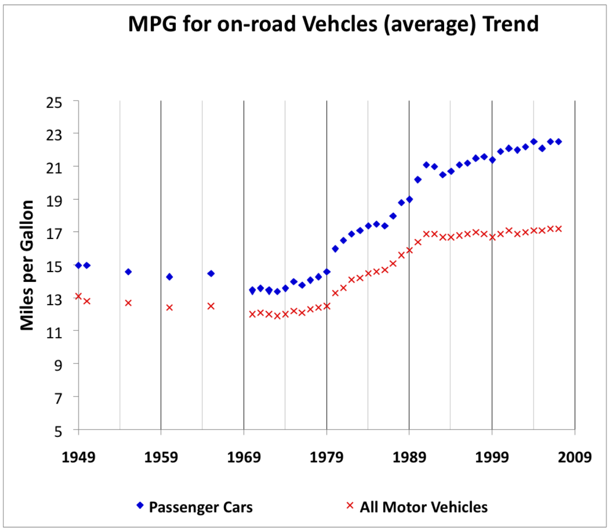
Since, the CAFE standards came into effect in 1979, the bar chart shows a evident spike in 1980, where the fuel economy of an average on-road vehicle increased by $\sim$1.4 mpg. Though such changes do indicate the expected improvements in engine efficiency, but they are not a direct indicator since these improvements are the the comprehensive effects of improvements in engine efficiency, rolling resistance, transmission efficiency, aerodynamics etc. As a result, repeating the calculation conducted above between a 1999 new engine and a 1987 remanufactured engine, for a 1987 new engine and a 1975 remanufactured engine (note this period contains the enforcement of the CAFE standards) gives a better understanding for the remanufacturing energy savings potential for the engine alone, and the trend exhibited. The results are shown in Figure 9.

Clearly, improvements in engine efficiency have helped reduce the use phase energy requirements by over 46% from 1975 to 1999, primarily because of the enforced CAFE standards (since there is a greater change between 1975 and 1987 (compare first two columns) , when the CAFE standards were enforced, than between 1987 and 1999 (compare the 3^{rd} and 4^{th} columns)). Also note the striking difference between the energy consumed by placing a 1987 Engine in a 1975 car and a 1987 engine in a 1987 car. Since the engines are primarily the same, this hints of the improvements in efficiency of the other components of the car as well, between 1975 and 1987. Lutsey et al [13] support this result. Another interesting inference is that the 1999 engine consumes lesser energy in the 1987 car than in the 1999 car. This is again supported by [13] which shows how the increase in the size of the car has a big role in explaining this.

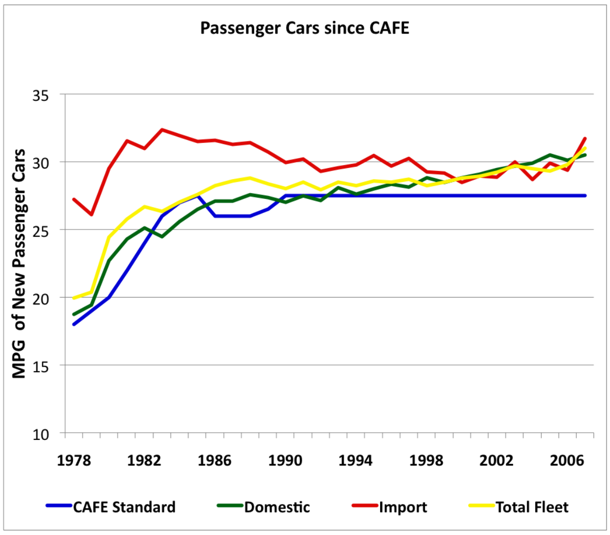
Using these calculations and the data available for manufacturing and remanufacturing gasoline engines from Keoleian [2], the life cycle energy comparisons between new and remanufactured engines was made (Figure 10).

Two years of comparison - 1987 and 1999 are shown.

1. 1987: The year of consideration is 1987



(a) On-Road Vehicles



(b) New Vehicles

Figure 7: Fuel Economy Trend for Passenger Cars[5].

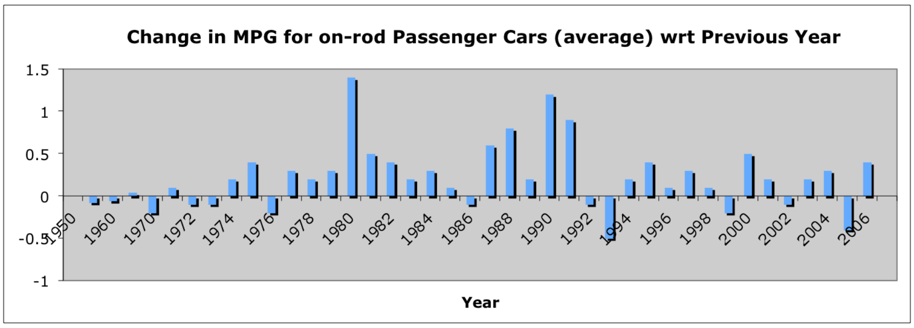


Figure 8: Annual Fuel Economy change for on-road Passenger Cars[6].

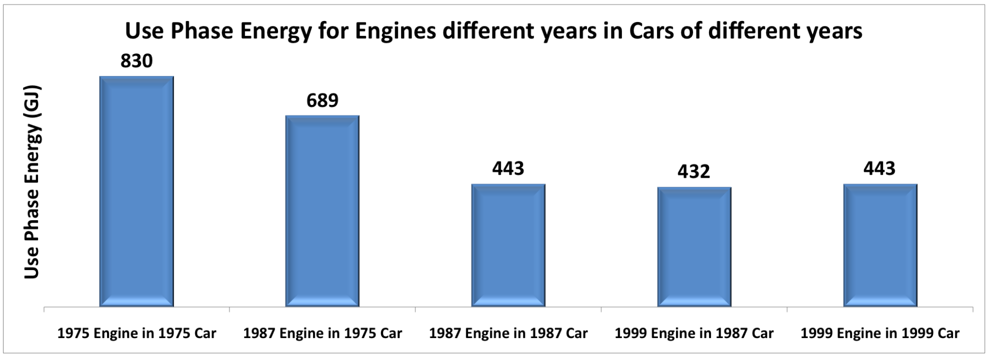


Figure 9: Use phase energy consumption for engines of different generation to travel 120,000 miles.

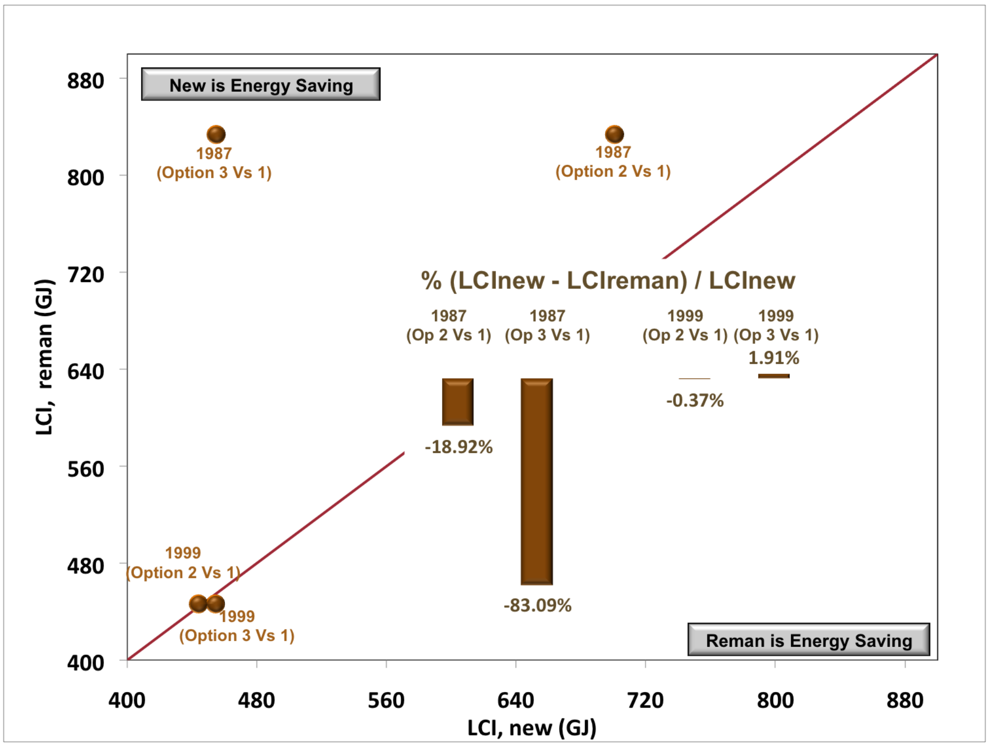


Figure 10: Car Engine Remanufacturability Trend.

- Option 1: A new engine of 1975 gets remanufactured and put back into the old car of 1975
- Option 2: A new engine of 1987 is placed into the old car of 1975
- Option 3: A new car (with a new engine) is bought in 1987 and used

2. 1999: The year of consideration is 1999

    - Option 1: A new engine of 1987 gets remanufactured and put back into the old car of 1987
    - Option 2: A new engine of 1999 is placed into the old car of 1987
    - Option 3: A new car (with a new engine) is bought in 1999 and used

Since we are comparing a new engine with a remanufactured engine, for each of the years of consideration we have two comparisons - Option 2 Vs 1 and Option 3 Vs 1. The data point labeled 1999, compared a new (Option 2 or 3) and remanufactured engine (Option 1) in 1999. The remanufactured engine has lived through one life of 120,000 miles and date back to the manufacturing date of 1987. Similarly the data point of 1987 compares a new (Option 2 or 3) and remanufactured engine of 1987 (Option 1), where the remanufactured engine was originally manufactured in 1975. Again, we have not yet considered any degradation for the remanufactured engine and assume it to be like it was when it was brand new.

The graphs shows that for the year of 1987 where the new engine performed much better than the remanufactured engine from before the CAFE standards, there are life cycle energy savings by choosing the new engine. This means that the relative energy expenditure to manufacture the new engine is easily overcome by the use phase energy savings of the new engine, which is also evident in Figure 9. It is also clear that replacing the old engine of 1975 with a new car of 1987 (Option 3) gives much larger savings (over 83%) than by only replacing the engine with a new engine of 1987 (Option 2), which gives savings of close to 19%. This is because of the substantial improvements in the efficiency of other components of the car as well apart from the engine. As a result there is lesser energy required by the other components and thus lesser absolute losses by the engine.

For the year of 1999, the two engines (new and remanufactured) almost perform equivalently over the life cycle making the comparison nuanced with energy savings of close to around 1%. This, as explained before, could be because the CAFE standards have not changes significantly between 1987 and 1999. [13] have shown that though the efficiency of the vehicle has improved over these years as well, it has been diverted away from the fuel economy and utilized to provide different functions to the passenger like improved air-conditioning, larger size etc.

The overall big conclusion from the analysis is that the savings in the production phase by remanufacturing gasoline engines for passenger cars can be overwhelmed by the relative energy expenditure in the use phase (since gasoline engines have a dominating use phase over their life cycles) because of technological obsolescence causing the new engines to be more efficient. This has been analyzed for remanufacturing without any degradation (that is assuming like-new) and any degradation could further favor the use of new in such scenarios. Absence of efficiency improvements in the engine will make the use phase between the new and remanufactured engine to be equivalent and thus the savings in the production phase can create a net savings for the remanufactured engine over the life cycle.

2.5 Economics (Answer to Why Car Engines are Remanufactured!)

Remanufacturability can be analyzed from either the environmental perspective or from the point of view of economics. The most economical option is not always the most environmental friendly. The economic feasibility of remanufacturing is well know and it is common for remanufactured products to sell at 40-60% of the price of a new product [15]. Hence we first looked into the environmental effects of remanufacturing passenger car gasoline engines, by comparing the energy consumed during the entire life cycle of a new and a remanufactured engine. We found that in earlier years of 1987, remanufacturing was not the energy saving option and choosing new leads to greater savings. For recent years like 1999, the analysis is nuanced. While these estimations are assuming that the remanufactured engine performs like-new and has negligible performance degradation compared to how it was when it was brand-new, adding any kind of degradation will only further promote the use of new engines over remanufactured one from the energy savings perspective. However still, remanufacturing of automobile engines is a popular activity and a number of independent manufacturers and OEMs practice it. The reason for this can be understood by overlooking the environmental calculations above and concentrating on the economics alone. As per the survey conducted by Keoleian et al [2], a new gasoline engine costs ∼\$5,700. On the other hand when buying a remanufactured engine, one can either purchase it from the remanufacturer itself (∼\$2,700) or from a dealer (∼\$4,000) [2], who adds his commission within the total price. Thus the monetary savings for a customer can range from \$1,700-\$3,000. However, this initial monetary saving is expected to be lost (at least partially) by the extra gasoline consumed during the use phase of a remanufactured engine.

Until now we have assumed only obsolescence, but let us now also assume that remanufacturing might fail to completely bring back the like-new condition and that the quality of a remanufactured engine is slightly degraded, compared to what it was when it was first manufactured. Let us represent this degradation in terms of the percentage lower fuel economy offered by the remanufactured engine. This analysis is exhibited in Figure 11.

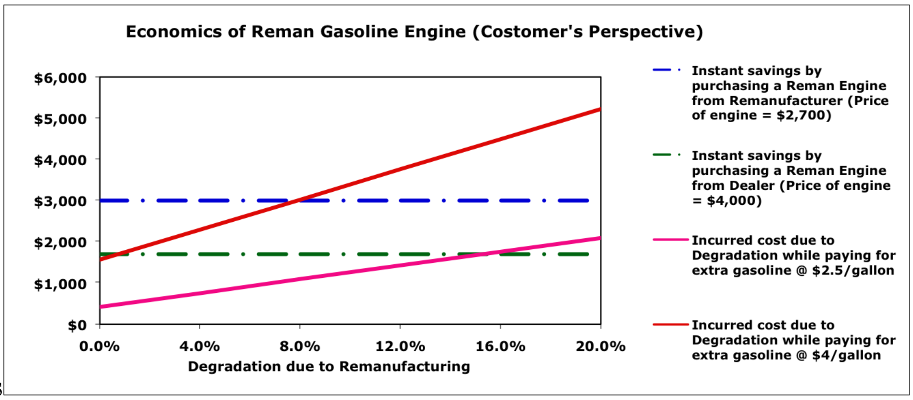


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Figure 11: Economic Analysis of Passenger Car Engine Remanufacturing.

Two prices of gasoline have been considered - $2.5 per gallon and $4 per gallon. The horizontal dashed lines are the savings in the two ways of purchasing a remanufactured engine - from a dealer or from the remanufacturer itself. The total cost of extra gasoline consumed (over the use phase) increases linearly with the relative degradation of a remanufactured engine. It is inferred, that except for the case with a high price of gasoline and buying the remanufactured engine from the dealer, the allowable degradation is more than 5%, which is quite unexpected with the critical testing and advanced remanufacturing techniques used today. Thus remanufacturing appears to be profitable to the customer from the economics point of view, though it ends up being detrimental from an energy savings stand-point.

Another way to conduct economic analysis, is the way done in [2]. This analysis is for the year of 1995, where the consumer has the choice to either buy a new engine of 1995 or a remanufactured engine, originally manufactured in 1983. The price of the new engine like above was $5,700, while for the remanufactured engine was $3,350 (average price between purchasing through a dealer or from a remanufacturer). The price of gasoline for the subsequent 12 years was taken from [16]. Using these, the real life cycle energy cost of a new engine is $13,178, while for the remanufactured is $11,100, calculated in 2000 dollars. Thus in terms of 2000 real dollars, purchasing a remanufactured gasoline engine in stead of a new engine in 1995, lead to a savings of approx. 16%. Thus again, economically, remanufacturing a gasoline engine is favorable.

3 Diesel Engines for heavy duty combination trucks

3.1 Introduction

The engine chosen is from the report by Sutherland et al [17], which is a six-cylinder, 15L diesel engine with the application of heavy-duty semi tractor-trailers (class 8 combination trucks). The consumer choice in this case is same as that shown in Figure 2 for gasoline engines. Once again let us use the labels of ”Remanufactured Engines” and ”New Engines.”

3.1.1 Raw Material Production and Manufacturing

New Engine - The bill of materials for a conventional engine for a heavy duty truck was used along with specific energies from [11] to estimate the energy for materials production for a heavy duty engine to be 54,818 MJ. The energy for the manufacturing phase was obtained from the Keoleian report [2] and scaled up using the energy of the raw material processing. Though the manufacturing energy could also be scaled up by weight, the composition of the gasoline and diesel engines was found to be slightly different - The gasoline engine has 45% Iron, 33% Steel and 20% Aluminum, while the diesel engine comprises of 62% Iron, 31% Steel and 4% Aluminum. Thus scaling by energy in the raw materials ((Energy to Manufacture Gasoline Engine) * (Energy in the Raw Materials for the Diesel Engines) / (Energy in the Raw Materials for the Gasoline Engine)) seems more appropriate. Doing this gives the energy to manufacture the Diesel engine to be 31,855 MJ. Thus the total energy embodied in the Diesel Engine, which includes raw materials and manufacturing is 86,673 MJ.

Remanufactured Engine - The value of the embodied energy after manufacturing, has been used from the report by Sutherland et al [17]. Their calculations reveal a savings of 16.25 GJ relative to a new engine just prior to sale (embodied energy of a remanufactured engine is 1.85 GJ). This estimate is again for the main components of the engine (engine block, cylinder head, connecting rods, pistons and crank shaft), and not for the complete engine. By using it, the analysis becomes slightly in favor of directing remanufacturing to be more energy saving that using new.

3.1.2 Use Phase

New Engine - The estimated life time was referred from [18] and taken to be 750,000 miles. The average mileage was taken to be 60,000 miles [8]. Thus the average life-time of a truck was also estimated to be $\sim$12 years. Thus the years of consideration were again 1999, 1987 and 1975. [8] gives the average fuel economy for combination trucks of these years to be 5.1, 5.7 and 5.4 mpg respectively. Clearly the changes in fuel economy have not been that substantial. To calculate the use phase energy, the energy intensity values (MJ/vehicle mile) for combination trucks was used [8]. The year 1999 was again chosen for the production of a new engine. This data enables the calculation of energy consumed during the life of a combination truck. To calculate the fraction of this energy used by the engine [7] was referred. The distribution of fuel energy use by different parts of the vehicle is shown in Figure 12.

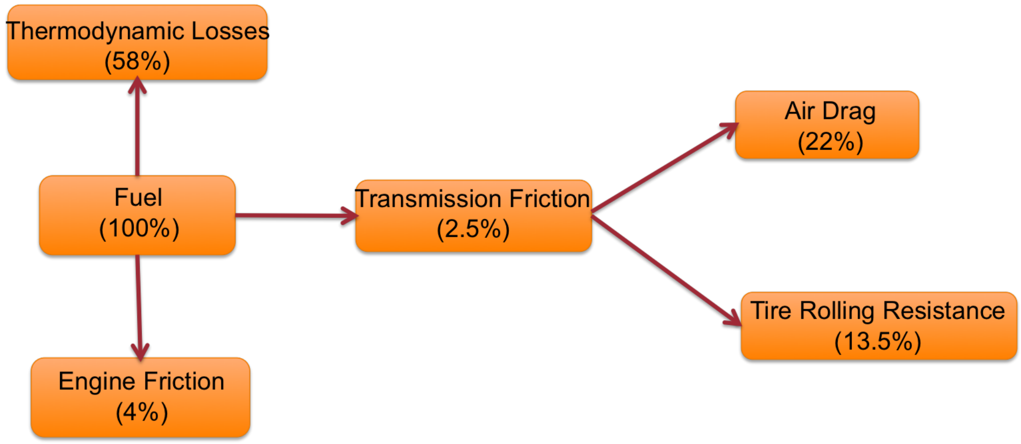


Figure 12: Fuel Energy Distribution in a Combination Truck[7].

Hence, ∼62% of the fuel energy is consumed by the engine (contribution factor for the engine in heavy duty trucks is 62%). In the case of Heavy-Duty Trucks (combination trucks as considered in this study), the fuel economy has not exhibited any considerable change and after discussing with the Federal Highway Administration it was learnt that most of the fluctuation can be attributed to the data gathering methodology [19]. This could primarily be because there was no major regulation imposed for heavy duty trucks like the CAFE standards for passenger cars. As a result the contribution factor for engines in trucks has been assumed to be constant for the years of consideration. In the case of passenger cars, the sharp improvements in the fuel economy were intentional and thus researchers like Lutsey et al [13] had diagnosed the factors that had helped improve the fuel economy. In the case of combination trucks on the other hand there is no data that explains what fraction of the fluctuations in the fuel economy can be attributed to changes in engine efficiency, if any. As a result, unlike the case of passenger cars there is not enough to estimate the fuel economy for truck having an engine from another year. Hence, Option 2 could not be evaluated for trucks. This means that we will consider only two options for the consumer:

- a remanufactured engine installed back into the old truck that has already been driven for 750,000 miles.

- a new engine in a new truck

Thus the use phase energy for the new engine of 1999 is simply 62% of the total energy consumed by the old truck during the 750,000 miles of driving. Using this and the above values (MJ/ vehicle mile values from [8]), the use phase energy of a diesel engine of a combination truck is estimated to be $\sim$ 12.612 TJ.

Remanufactured Engine - In the year of 1999, the remanufactured engine, which would be one lifetime old would be from 1987. Since the contribution factor is assumed to remain the same, the same calculation can be done for the remanufactured engine (which is like-new) as well to estimate the use phase energy of a remanufactured diesel engine of a combination truck to be 11.97 MJ.

3.1.3 Transportation

Like in the case of gasoline engines, transportation energy is expected to be negligible since its percentage contribution is expected to be similar for diesel engines as it is for gasoline engine. Thus the transportation phase energy is neglected from the analysis.

3.2 Life Cycle Analysis

Combining all calculations and data above for a new diesel engine for a combination truck, the life cycle assessment can be charted out as shown in Figure 13.

Clearly the use phase energy consumption dominates tremendously over the prior stages, making the bar for "raw materials + manufacturing" hardly visible. Also it is interesting to note how a small difference of 0.3 mpg between the two generations creates an enormous difference in the use phase.

3.3 Remanufacturing Energy Saving Potential

To assess the remanufacturability of truck engines, like in the passenger car case, fuel consumption trends were derived [8]. The CAFE standards were only imposed for light-duty vehicles with gross weight of $\leq$ 8,500 lbs. This partially explains why the fuel economy of trucks has remains more or less constant over the years. Another reason for this could be the monotonous increase in the payload of trucks (not applicable to passenger cars) negating the increase of engine capability to provide a better fuel economy. To check for this the historical trend of the national average payload (in tons) of a class 8 combination truck obtained from the Federal Highway Administration [20]

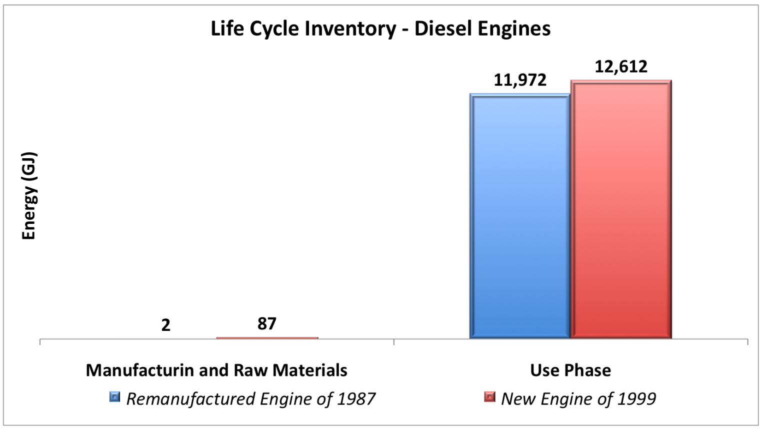


Figure 13: Life Cycle Assessment of a New (from 1999) and Remanufactured (from 1987) Diesel Combination-Truck Engine.

has been plotted below. Figure 14 shows this along with the fuel economy trend for combination trucks.

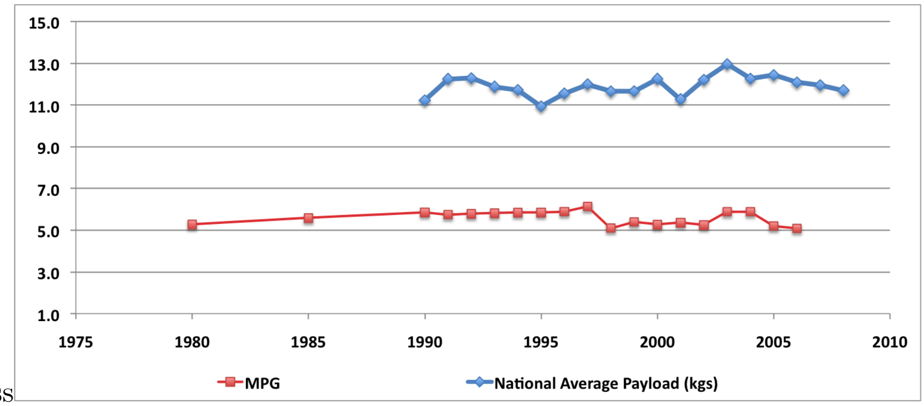
ss

Figure 14: Average Fuel Economy and Payload for a Combination-Truck[8].

Both the payload and average fuel economy for combination trucks have roughly been the same over the past. The slight fluctuations in both are attributed to the way data is recorded and procured by the Department of Transportation [19]. Figure 15 better exhibits the changes in fuel economy over the years. The average absolute change is for the years under consideration is only 0.18 mpg.

Using Figure 15 and 14, it is accepted that the performance in terms of fuel economy for combination truck engines has remained more or less the same over the past years. If anything, fuel economy of engines has

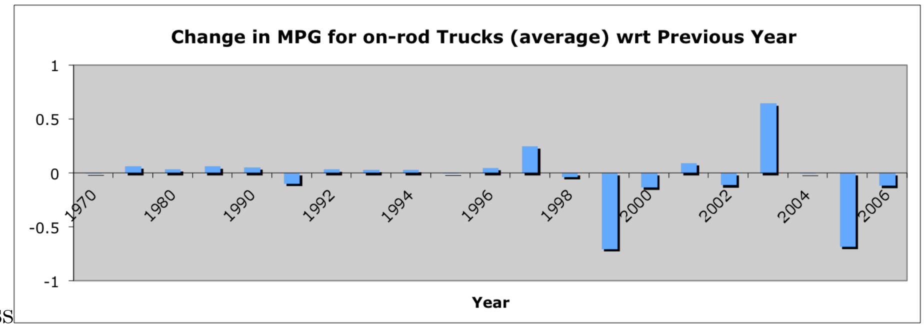


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Figure 15: Annual Fuel Economy change for on-road Combination Trucks.

slightly decreased partially due to the SOx and NOx regulations. Using this data and making calculations similar to those for 1999, the remanufacturing energy savings potential of truck-engines in 1987 was also estimated. In this case the new engine was of 1987 while the remanufactured one was originally manufactured in 1975. The results have been plotted in Figure 16.

Interestingly, the plot shows that combination-truck engines in 1987 should not be remanufactured, while those in 1999 should. In fact the respective savings can be around 10% and 5.7% respectively. However, these results are deceiving. The truth is that there has not been substantial change in the fuel economy of heavy trucks and the fluctuations that exist are likely to be because of the data gathering methodology. The key point to take is that these fluctuation, even though small in magnitude (0.6 mpg between 1975 and 1987 and 0.4 mpg between 1987 and 1999), are large enough to turn the conclusion significantly. This emphasizes the predominant impact of the use phase and its high sensitivity to the fuel economy of combination trucks. Since small fluctuations are expected to exist between engine to engine, it seems that the remanufacturing energy saving potential can vary from unit to unit. Thus a case by case calculation is required to make sure that the strategy chosen - new or remanufactured, is the energy saving strategy. This poses a big question on the generally believed energy savings ability of the Truck Engine remanufacturing industry.

4 Conclusion

Remanufacturing energy savings potential for both gasoline and well as diesel engines has been evaluated. Policy intervention for gasoline engines has caused gasoline engines to progressively provide better fuel economy over the years. As a result new engines perform much better (in terms of energy consumption) than remanufactured engines, giving use phase energy savings far superior to the manufacturing energy savings of remanufactured engines.

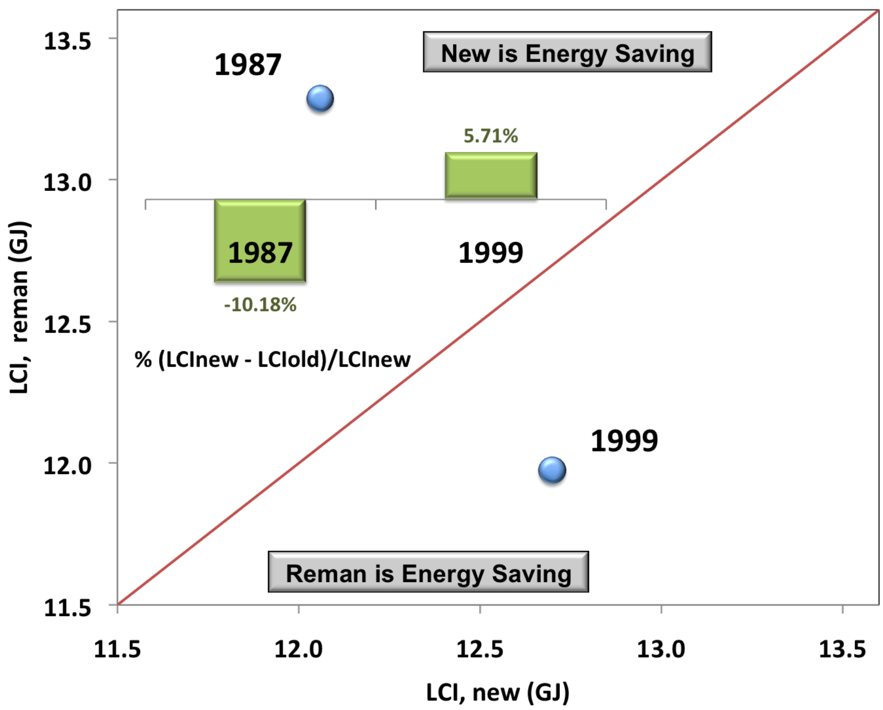

Figure 16: Truck Engine Remanufacturability.

Hence, choosing new engines was concluded to be the energy savings strategy for the years around 1987 when the CAFE standard were progressively becoming stricter. Over the past decade or more, the CAFE standards have not changed and thus there has not been as significant an improvement in engine technologies as in the 80s. Thus for the years around 1999, it was estimated that the total life cycle energy consumption for the new and remanufactured engine was roughly similar. If new CAFE standards are to be enforced in the near future, the scenario will again be like the 80s, and use of the newer, more efficient engine is likely to be the energy saving strategy.

On the other hand diesel engines for combination trucks have not had any standards imposed as a result of which the fuel economy for them has roughly remained the same, historically. Thus the initial savings during the manufacturing phase for a remanufactured engine relative to new, are expected to be the net energy savings over the life cycle. Thus remanufacturing for diesel engines for combination trucks seems to be the viable energy savings strategy. The fuel economy data used from the Department of Transportation, by itself has some inherent fluctuations which have been observed to impact the conclusions significantly. Overall, it was concluded that even minor fluctuations (less than 1 mpg) in fuel economy are significant enough to reverse conclusions. This is because of the dominance of the use phase over the life cycle of the product. The use phase for the diesel engine consumes close to 99.4% of the total life cycle energy. Such small variation is expected to exist from driver to driver, and from one driving condition to another, and especially from one engine unit to the other. Thus accurate estimation of fuel economy is essential, on a case by case analysis, so as to estimate the remanufacturing energy savings potential for diesel heavy duty engines.

5 Assumptions

In the above analysis a number of assumptions were made, primarily due to data unavailability. They are listed below:

- In reality, many reclaimed engines have lived a shorter life (e.g. from abandoned cars or from car crashes where the engine survives) or even longer (some from the 1950s, as informed by local engine remanufacturers), and since it is hard to know the average age of cores, a remanufactured core is assumed to be 1 lifetime old, on an average.

- Energy to manufacture and remanufacture engines for the various years considered could not be found, and thus the same manufacturing and remanufacturing energy was used for all the years. Hence, manufacturing and remanufacturing energies for the two types of engines obtained from [2] and [17] were used for all years under consideration.

At this point it should be understood that the manufacturing phase has been shown to have a minimal impact on the total life cycle energy consumption and thus the impact of this assumption is not expected to be severe.

- The fuel economy of a vehicle for its entire life time has been taken to be the average off all new vehicles of its class (passenger car/class 8 truck) and model year.

- It was assumed that the average fuel economy of a car does not deteriorate with use, and during the entire life the average fuel economy of an engine is what it was to start with.

- The two primary reports for this study, [2, 17], base their analysis and conclusions on a single engine each and not an average of multiple engines, as ideally desired. This report does the same, again due to lack of average data availability.

- The percentage contribution of the engine to the total fuel consumed by a vehicle is assumed to be constant for all years under consideration for the truck. This assumption has been justified in the text.

- For the case of Gasoline Engines, Lutsey et al give the change from 1987 to 2004 to be 0.6 mpg, and we just assume this change to be linear, so that the change from 1987 to 1999 is 0.6*12/17. Also Lutsey et al give this change for the entire drive train, and since the contribution factor for the transmission is only 0.03, Figure 4, the change is assumed to be entirely for the engine.

- An engine dissipates a fraction of its energy as heat, when it consumes fuel. This fraction is taken to be constant in the above study. However, [21] have indicated that this fraction could vary from 10 - 40 % depending on the engine torque, RPM (revolutions per minute) etc. The estimations used above (38% for gasoline engines and 42% for diesel engines) are close to the upper limit indicated by them. This means that the use phase energies estimated above are on the conservative side and that the impact of use phase can be even more pronounced.

- Transportation has been estimated to be 3-5% of the Manufacturing and Processing phases alone by ([2]). By including the use phase (which has been show above to be severely dominating), the impact of transportation would certainly be negligible. As a result transportation energy was not included in the analysis.

References

[1] Stacy C. Davis, Susan W. Diegel, and Robert G. Boundy. Transportation energy databook edition 28. *Prepared by the Oak Ridge National Laboratory for the US Department of Energy*, 2009.

[2] Vanessa M. Smith and Gregory A. Keoleian. The value of remanufactured engines: life-cycle environmental and economic perspectives. *Journal of Industrial Ecology*, 8(1-2):193–221, 2004.

[3] Cutler J. Cleveland (Editor in Chief). Vehicles and their power plants: energy use and efficieny. *Encyclopedia of Energy*, 2004.

[4] Marc Ross. Fuel efficiency and the physics of automobiles. *Contemporary Physics*, 38(6):381–394, 1997.

[5] US Energy Information Administration. April 2009 monthly energy review. 2009.

[6] Automotive Fuel Economy Program. Annual update fy 2003. 2003.

[7] Energy Efficiency US Department of Energy and Renewable Energy. Roadmap and technical white papers: 21st century truck partnership.

[8] Bureau of Transportation Statistics. Internet Source: $http : //www.bts.gov/publications/national_transportation_statistics/html/table_04_14.html$. Table 4-14: Combination truck fuel consumption and travel. National Transportation Statistics 2009.

[9] Stacy C. Davis, Susan W. Diegel, and Robert G. Boundy. Transportation energy databook edition 28. *Prepared by the Oak Ridge National Laboratory for the US Department of Energy*, 2008.

[10] National Transportation Statistics 2008 Bureau of Transportation Statistics. Table 1-17: New and used passenger car sales and leases. 2008.

[11] Vaclav Smil. *Energy in Nature and Society*. MIT Press, 2008.

[12] US Department of Energy. Table 7. transportation sector key indicator and delivered energy consumption, annual energy outlook 2009. 2009.

[13] Nicholas Lutsey and Daniel Sperling. Energy efficiency, fuel economy and policy implications. *Transportation Research Record: Journal of Transportation Research Board*, (1941):8–17, 2005.

[14] E.R. Venta and A. M. Wolsky. Energy and labor cost of gasoline engine remnanufacturing. *Department of Energy, ENergy and Environmental Systems Division*, 1978.

[15] William Hauser and Robert T. Lund. The remanufacturing industry: Anatomy of a giant. 2003.

[16] U.S. Department of Energy. Internet Source: *http : //www.eia.doe.gov/emeu/aer/txt/ptb*0524.*html* Annual Energy Review 2008. Table5.24retailmotorgasolineandon-highwaydieselfuelprices,1949-2008. 2009.

[17] John W. Sutherland, Daniel P. Adler, and Vishesh Kumar Karl R. Haapala. A comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production. *CIRP Annals - Manufacturing Technology*, 57(5-8), 2008.

[18] Linda Gaines, Frank Stodolsky, Roy Cuenca, and James Eberhardt. Life cycle analysis of heavy vehicles. *Air & Waste Managent Association Annual Meeting*, 1998.

[19] Department of Transportation. Personal conversation with the us federal highway administration, office of policy information.

[20] US Department of Transportation. Vehicle travel information system (vtris) - by the federal highway administration (fhwa). *Internet Source: https://apps.fhwa.dot.gov/VTRIS/.*

[21] Jerome Barrand and Jason Bokar. Reducing tire rolling resistance to save fuel and lower emissions. *SAE World Congress and Exhibition, April 2008. Internet Source: http : //www.sae.org/technical/papers/*2008 − 01 − 0154, 2008.