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# Factors Affecting Automobile Fuel Efficiency

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## ABSTRACT

*This paper briefly discusses the development of modern automotive technology. Factors affecting the recent changes in automotive technology are also identified. A qualitative discussion about the future of automobiles is made in the light of various technological, environmental, economic and social factors. The impacts of these changes on the private transport sector of developing countries especially Bangladesh, are highlighted.*

## INTRODUCTION

The history of the automobile dates back to as early as 1876 when Nicolaus A. Otto (1832-1891) first ran his prototype spark-ignited four-stroke cycle engine. The engine developed 2 brake horse power (bhp) at 160 revolutions per minute (rpm). It had an overall efficiency of 14% and expansion ratio of 2.5 [Heywood (1988)]. Since then, many important developments were made to automobile engines in a steadily growing automobile market.

At the end of the nineteenth century, another technological breakthrough was achieved by Rudolph Diesel. He invented the first compression ignition engine. Both spark-ignition and compression-ignition engines are still being used in automobiles in a modified form. Nevertheless, Otto engine always maintained their popularity in the automobile industry and to consumers because of their better performance and low weight to power ratio as compared with diesel engines.

During the last thirty years, automobile industries all over the world have been subjected to increasing pressure and criticisms for their role as one of the leading polluters in the energy sector. After the oil crises in the 1970s, this challenge became harder. Governments, on one hand, wanted them to increase the efficiency of future passenger cars whereas environmentalists, maintained pressure on them to reduce emissions. In view of these conflicting goals, there seem to be a great potential for improvement in automobile technology.

This paper discusses the recent development and future potentials of automotive technology. It is divided into two major parts. The first part deals with the historical trends of car fuel efficiency.and the second part discusses qualitatively various factors that affected recent changes and possible changes in the future automobile technology. Effects of these changes in the private tranport sector of developing countries, especially in Bangladesh, are highlighted in the concluding remarks.

## HISTORICAL TRENDS OF CAR FUEL EFFICIENCY

OECD[1] countries manufacture more than 85% [Hallwag (1990)] of the total number of cars produced in the world each year. In addition to that, most major R&D works in automobile technology are carried out in these countries. Since almost all these countries practise free market economy, any improvement of fuel economy in one country automatically forces car manufacturers in other countries to follow suit to stay in competition. For example, in the early 1980s, Japanese car manufacturers were forced to improve fuel economy of their cars in order to retain market share in the US car market. Under this assumption, one can say that the car fuel efficiency in the developing countries, generally net importers of cars, are largely determined by that in the OECD countries.

Prior to 1973, the general tendency of consumers was to buy bigger, more powerful and high-performance-engined cars. Consumers put little emphasis on car fuel efficiency mainly because of very low fuel prices. Car manufacturers, in the absence of any legislation, acted according to consumers' demands. As a result, in 1973, the fleet fuel efficiency in the United States went down to its lowest level after the Second World War to about 5.7 kilometres per litre (kpl) compared to well above 6 kpl before 1960. In

1 OECD - Organisation for Economic Cooperation and Development.

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European Community countries, on the other hand, fleet fuel efficiency remained more or less constant in the range of 8.5 to 9.5 kpl over the same period of time. The reason for this difference is quite obviously the difference in gasoline prices in two continents. Historically, the average gasoline price in the USA has been half that in other major OECD countries. Therefore, European car users have always opted for more fuel-efficient cars.

After the 1973/74 oil price rise, the trend in automobile efficiency changed almost abruptly towards an increase, particularly in the United States. Oil price hike in the late 1970s further accelerated this growth rate (see Figure 1). Growth rates of new car fuel efficiency, and hence fleet fuel efficiencies in Western European countries, have been sustained mainly through voluntary agreements between governments and car manufacturers. Only the United States government imposed a mandatory target for new car fuel efficiency, for both cars locally produced and those imported into the United States, for each year from 1977 to 1985. The legislation, known as the US Energy Policy and Conservation Act (EPCA) of 1975, sets a corporate average new car fuel economy target of 11.69 kpl (27.5 mpg) to be attained by 1985. Considering the US new car fuel efficiency in 1977, the 1985 target was an improvement of more than 55%. In other IEA[2] countries, the improvement target was set voluntarily at around 10% to 12% from its generally high initial value (compared to that in the USA) in 1977. Improvements of fuel economy in these countries were attained by improving the overall automobile technology, while in the USA, a significant portion of the change was due to consumers' shift from larger to smaller cars. For example, the percentages of new cars having engine capacity of more than 2000 cc registered in 1978 in the USA, the UK and Japan were 82%, 11% and 2% respectively and in 1981, these figures were 65%, 6% and 3% respectively [OECD(1984), OECD(1991)].

It is interesting to note that until 1984 the average fuel economy of new cars has always exceeded the targets set by the US EPCA of 1975. The reason has been purely economic. The act prescribed a huge penalty on not meeting the standard. It states that if a manufacturer fails to achieve the target for a particular year, he has to pay fifty dollars for each mile per gallon for each car manufactured. That means, if a manufacturer produces one million cars in a particular year, and falls short of the standard for that year by only 0.5 mpg, he would have to pay a fine of $25 million. As a result car manufacturers always exceeded the standards to allow for errors in sales forecasting. This proves that if sufficient incentives and/or penalties are introduced by the government it might be possible to see more improvements in the fuel economy of new automobiles.

Data on fleet fuel efficiencies in developing countries are generally poor and unreliable. Fleet fuel efficiencies in these countries are probably slightly lower than those in developed countries. To justify this assumption, four reasons can be given. Firstly, most developing countries are net automobile importers. They mainly import smaller cars from Japan and Western Europe. But because of the low capital costs of these cars, they usually lack new fuel saving technologies. Secondly, due to the absence of proper and adequate safety and fuel economy standards in most of these countries, a significant proportion of imported cars are cheap "reconditioned"[3] cars. Thirdly, due to the high purchasing costs of automobiles relative to personal incomes, automobile users tend to operate their vehicles beyond their operating/economic life. This in turn lowers the average fleet fuel efficiency. And lastly, technical expertise in automobile maintenance and repair in these countries is relatively poor. As a result, automobiles consume more fuel than they should, had they been properly maintained and tuned. In addition, poor road conditions and inappropriate traffic management systems also decrease fuel economy of automobiles in these countries.

## RECENT DEVELOPMENTS AND FUTURE POTENTIALS OF AUTOMOBILE TECHNOLOGY

Recent developments in fuel-efficient automobiles have been started since the early 1970s due to two driving factors, viz., market forces resulting from high fuel prices and global environmental concerns. The effect of market forces on car ownership and car use have already been discussed in previous chapters.

2 IEA - International Energy Agency.

3 Reconditioned cars are generally 3 to 5 year old cars fitted with either new cylinder blocks or sleeved cylinders and renovated exterior.

Their effect on technology can be best described by the following statement by Seiffert and Walzer [Seiffert et al (1985)]:

> *"If no demands are made on technology, only little progress usually results and many good ideas are put on the waiting list."*

Demands on technology were made after the oil crises, both by governments and consumers, which resulted in a significant improvement in automobile efficiency in the last ten years. On the other hand, environmental concerns over automobile emissions in governments of various countries have put pressure on manufacturers to try to reduce pollution. These pollution control measures are, in general, detrimental to efficiency improvements. For example, a three-way catalytic converter reduces the engine power output by about 3-5%. Therefore, manufacturers have always been trying to strike a balance between emission reduction and fuel efficiency.

In order to fulfil requirements, development tasks for future automobiles must incorporate the following factors. They are: fuel economy, consideration about ecology and the environment, safety, reliability and comfort and most of all, vehicle cost. Simultaneous compliance of these requirements is hard to achieve. For example: vehicle safety can not be improved without adverse effects on vehicle costs; vehicle performance is very difficult to improve without surrendering an extent of fuel economy characteristics, etc.

The automobile power-plant is one area where considerable improvements can be made in order to increase efficiency and to reduce emissions. Efficiency can be increased significantly by increasing the compression ratio of the engine. But, in practice, the compression ratio of SI engines is severely limited by the anti-knock characteristics of fuel. For conventional automobiles run by regular gasoline (Research octane number (RON) more than 96), the compression ratio is in the range 8.0:1 and 11.0:1 (see Figure 2). Tetra-ethyl lead has been used as an additive to gasoline to improve its anti-knock properties from early this century. But the risk to health from lead emissions brought back unleaded gasoline. Nowadays, more than 70% of the gasoline consumed in the US is unleaded. At the same time, legislations for emission control necessitate the use of catalytic converters, which can run only on unleaded gasoline engines. The effects of these changes are twofold. Firstly, the octane rating of unleaded gasoline is generally lower than leaded gasoline, and therefore, the compression ratios of engines operated by unleaded gasoline are lower. This in turn reduces the thermal efficiency. The RON of unleaded gasoline can be improved by catalytic reforming and isomerization and blending with oxygenates like methanol, ethanol, tertiary butyl alcohol (TBA), and methyl tertiary butyl ether (MTBE). Although expensive, these processes can upgrade the RON of unleaded gasoline to about 95, compared to 98 for 4-star gasoline. Secondly, the use of catalytic converters (three-way, as required by all cars having engines bigger than 2.0 litres manufactured in European Community by 1989) reduces the fuel economy by about 3% - 8%. Moreover, the manufacturing costs of catalytic converters are rather high, viz., of the order of US $ 200 to US $400 per car.

The decrease in fuel economy due to catalytic converters and octane requirements (OR) of engines can be minimised by using lean-burn and/or stratified charge engines (SCE). Usually the OR of an engine is variable in the operating range of the engine. It also varies between individual cylinders and with the throttle opening. SCEs provide a solution to these problems. These engines operate on a wide-open-throttle (WOT) throughout their operating ranges. Fuel is injected directly into the cylinder in such a manner that the fuel-air mixture is always richer around the spark-plug than in other part of the cylinder. The fuel requirements for individual cycles and cylinders are measured and monitored by microprocessors. The advantages of these engines over conventional engines are high fuel economy, low emissions and multi-fuel capability. The major drawbacks of SCEs are high cost and relatively low performance.

A considerable fuel economy gain at part load can be obtained by substituting conventional constant compression-ratio engines by variable compression-ratio engines. At a relative load of 20%, fuel economy improvements can be as much as 10%. Combined with variable timing, thereby reducing charge cycle loss, these engines can even be more efficient.

In the past ten years, significant developments have been made in the basic engine technology. One such development is the introduction of engines having more than the conventional two valves per cylinder. Four-valve engines are more countries, inferior performance compared with gasoline engines and reduced gasoline price in real terms in the past two to three years which reduced its comparative advantage over gasoline engines. Therefore, it is highly unlikely that diesel engines can capture a significant share of the auto market in the near future.

One of the most important, as well as difficult, tasks of motor vehicle designers is to match the vehicle speed to engine speed at various loads. Not only do the engine and transmission systems need be efficient individually, they must be efficient synergistically. In order to achieve this goal, transmission systems are matched in such a way that the engine operates at a high average load, i.e., high load and low speed, most of the time. Ideally, cars should be fitted with infinite number of gear ratios for perfect matching. But in practice, they are fitted with a finite number of gears, generally four or five in case of manual transmission systems. As a result, they run at less than the optimum efficiency at a given speed and load.

Usually, the gears are designed in such a manner that on first gear the fully loaded car is able to climb a gradient of 30$^{o}$ and on top gear it can achieve the theoretical maximum speed. Intermediate gear ratios are arranged in a geometric progression for best acceleration. It should be noted that in the case of manual transmission, too many gear ratios would actually reduce the overall fuel economy and driveability, because of excessive operation of the accelerator pump as well as the impracticability of too many gear changes in a given distance. Moreover, in practice, fuel economy gains tend to diminish with increasing gear ratios. Because the addition of one more gear ratio would reduce the efficiency due to the weight of the gear, the addition of a fifth gear to a four-speed manual transmission can achieve gain in fuel economy of about 3 to 4%, while a sixth gear would achieve a smaller gain and more complexity in gear-box design.

On the other hand, automatic transmission systems which have been widely used in American cars since 1950s are less efficient and have a smaller number of gear ratios than manual transmission systems. The overall loss due to a three-speed automatic transmission is in the range of 12 to 15% compared to a four-speed manual transmission. In the case of a four-speed automatic this loss is a little less. One inherent drawback of automatic transmission systems is the use of torque converter and fluid couplings. Losses due to slippage in these components are significantly higher than in toothed gears.

Ideal matching of engine and wheel speed can theoretically be obtained by an automatic continuously variable transmission (CVT). By means of automatic control, CVTs operate in a narrow range around the optimum efficiency level. An on-the-road experiment was carried out by the Volkswagen Motor Company of Germany with two 1.50-litre Golf cars, one fitted with a CVT and the other with a manual four-speed plus economy gear. The fuel economy results showed that on an ECE[4] cycle, the car fitted with CVT consumed 18.4% less fuel than that fitted with manual transmission [Sieffert et al (1984)]. Performance characteristics were also better for the automatic. However, this technology is very new and still in an experimental stage. Only a very few cars fitted with CVT, mostly European and Japanese, have been marketed. Demand for them was very low because of their high costs. In the USA, about 70% of the car fleet are fitted with conventional automatic transmission, the rest being manual. It has been projected that only about 2% of 1995 model cars in the USA will be fitted with CVT [Smerk (1981a), Smerk (1981b)].

Another important component in the automobile transmission system is the final drive assembly which includes the propeller shaft and the differential. Until about the late 1970s almost all passenger cars had a longitudinal front engine with rear wheel drive (RWD). Even now most six-cylinder or bigger cars have the same arrangement, because of design restrictions[5]. On the other hand, more than 80% of the total cars[6] produced in the world in 1989 were equipped with transverse or longitudinal front engines with front wheel drive (FWD). Advantages of FWD over RWD are many. First, the absence of a drive-shaft and universal joints in FWD vehicles reduces losses due to friction and transmission. Second, fuel economy is improved because of the reduction

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4 ECE - Economic Commission for Europe.

5 In the case of bigger front engined cars, little room is left for transmission systems under the bonnet. If they are both to be accommodated under the bonnet, then the height of the car should be increased with possible reduction in fuel economy, driveability and comfort.

6 Cars with less than 2.0 litres, 4-cylinder engines.

in weight. Finally, the interior space of the passenger compartment is increased by a significant amount. It is estimated that about a 1 to 3% gain (direct) in fuel economy can be achieved by the shift of the drive train from the rear wheel to front wheel. RWD to FWD has led to an important decrease in weight (approximately 125 pounds in a sub-compact and 250 pounds in a full-sized vehicle). All this is being achieved at a cost penalty of approximately $125 per car measured in 1980 dollars.

One of the easiest and effective methods of increasing fuel economy is the reduction of the weight of the vehicle. As a rule of thumb, every 100 kg extra weight means 1 litre more fuel consumption per 100 km [Förster (1983)]. There are several ways of achieving this objective, two of them are: material substitution, down-sizing the vehicle. But there are other criteria as well, some of which have negative effects on weight reduction. These are safety, roominess and comfort. For example, vehicle down-sizing as a means of weight reduction must also ensure adequate passenger and luggage capacity at a reasonable cost and good driveability.

In the late 1970s, weight reduction in American cars was achieved mainly by down-sizing. The development of systems engineering and improved digital computers along with CAD/CAM made it possible to keep the internal passenger space and luggage volume almost the same. In the case of already compact European and Japanese cars, little down-sizing was possible. Instead, weight reduction was achieved by substituting heavy metallic parts with lighter metals or plastics and major changes in basic structural design. One of the main structural changes was the concept of unibody or integral body-frame design in place of separate body-frame design. This led to secondary weight savings and better driveability and comfort. Materials constitute more than 50% of the car cost and are an important area where drastic weight reduction is possible. Some of the alternative materials which are becoming increasingly popular are high-strength steel, aluminium, plastics (both reinforced and non-reinforced) and ceramics. The use of ceramics in high temperature areas has already been discussed.

High-strength low-alloy steel is a suitable and often a good substitute for the conventionally used mild-steel and cast iron as a structural and body material. The thickness and therefore the weight can be reduced significantly, keeping an equivalent structural rigidity. Aluminium-alloy with its specific gravity of 2.720 compared to 7.860 of mild steel and only a slightly lower tensile strength (43 ksi compared to 65 ksi for mild-steel), has always been considered as a good substitute for steel. But its production cost and even the recycling cost is still too high and energy intensive for it to be considered as a replacement for mild steel in the near future. As an example, aluminium wheel-rims can save 16% to 40% weight at an extra cost of 190% to 290% [Seiffert et al (1984)].

The use of plastics, both in the interior and exterior has increased dramatically since 1975. This is particularly true of Japanese cars, where the use of plastics has gone up from 5% by weight in 1975 to more than 15% in 1985. Apart from its advantage of being lightweight, there are several other advantages which mean plastics can be expected to be one of the major materials in car industry. For example the cost of manufacturing plastic components is comparatively lower than metal components. Also, they are easier to manufacture as well as safer to use in the interior than most other metals. If properly reinforced, plastic parts may as well be used as the oscillating masses in the engine. In that case, not only the weight, but also the unbalanced mass, would be reduced.

The inter-relationship between weight reduction and fuel economy is very complex. Secondary weight reduction makes it even more complicated. As a result, there is no theoretical equation involving these two quantities. But an empirical relationship, established by regression analyses by various investigators, showed that a fuel economy gain of $1.4 \times 10^{-5}$ gal per mile can be achieved by reducing the weight by 1 pound [Hillard et al (1984)]. Another result showed that fuel savings of 3 to 4% in the ECE and EPA cycles are possible for a weight reduction of approximately 10% [Seifferd et al(1984)]. The data on fuel efficiency for more than 150 different makes and models of cars produced around the world in 1989 are plotted against vehicle gross weight and presented in Figure 3. The graph shows an almost linear relationship between the fuel efficiency and the vehicle weight.

Intensified research on vehicle aerodynamics has been going on for the last two decades or so. A significant reduction of the drag coefficient has been achieved during this time. The 1992

Audi 100 model, a commercially marketed car, attained a $c_D$-value of 0.30 and Nissan 300 ZX attained a $c_D$-value of 0.31. The integrated research Volkswagen (IRVW) car Auto 2000 has a drag coefficient of only 0.25. The improvement potential in vehicle aerodynamics is still enormous. A well-streamlined driveable vehicle can be expected to have a $c_D$-value as low as 0.15. However, a drag coefficient of 0.25 for almost all models of passenger cars is a more realistic value which can be achieved within the next twenty years. Translated into a fuel economy value, it means about 15% improvement in ECE or EPA[7] mixed cycle.

Other factors which have a considerable impact on automobile fuel economy are, the characteristics of driving cycle, vehicle maintenance and the driving pattern. A significant fuel economy gain is possible, of the order of 15 to 20%, together with lower pollution, by the so-called "stop-start systems". The basic concept of these systems is to stop the engine when power is not required, i.e., when the car is stalling, and operate the engine only when power is required. Research is under way in a number of countries to develop various methods of achieving this goal. With the increasing use of electronics in automobiles these systems are conceivable by early next century.

The two factors mentioned above depend solely on car users. Engine tuning and tire pressure are the two most important areas of vehicle maintenance. Decreased tire pressures increases the area of contact of tire and road. This results in increased rolling resistance and tire wear. A badly tuned engine is a major source of higher fuel consumption. For example, in a six-cylinder engine, only one misfiring spark plug can reduce the fuel economy by about 20% {Hillard et al (1984)]. An estimate made from a survey carried out by Champion Plugs (UK) Limited in 1975 on 5000 cars showed that the UK car fleet had been consuming 5% more fuel than was necessary [Department of Energy (1981)]. A more recent analysis estimated an 18% reduction of fuel consumption by the UK fleet if all cars had been tuned properly [Department of Energy (1981)].

7 EPA - Environment Protection Agency (United States Government).

Table 1 summarizes the above discussion about the possibilities of fuel economy improvements in future automobiles due to the improvements in engine technology.

## CONCLUSIONS

Factors affecting automobile fuel efficiency have been identified from the main historical trends of the car producing developed countries. In the ten years from the mid-1970s to the mid-1980s, almost all countries experienced a significant rise in fleet fuel efficiencies. This happened for two main reasons: firstly, the increasing price of fuel led car users towards using smaller and more efficient cars and secondly, governments intervened in car markets. However, the change in fleet fuel efficiencies in developing countries, especially in Bangladesh, was less significant. The reasons were: firstly, very little down-sizing was possible in a fleet already consisting of small cars and secondly, due to long lead time for replacement and relatively slow growth in the economy and hence the automobile market, new energy saving technologies did not penetrate into the fleet. If, the trend of importing reconditioned cars continues it will restrict the advanced automotive technology to come into the Bangladesh market until atleast the late 1990s.

It should be noted that environment pollution control technologies and increasing awareness about the safety standards could decrease the fuel efficiency of future cars. But the available technology can cope with the loss if sufficient incentives are provided to the car manufacturers. It was identified that these incentives can be either higher gasoline prices or stricter government legislation. These seem to be equally effective. Judging from the recent international debates about the environment pollution control measures, the former is more likely. The resulting effects of such measures on the developing countries will be a slow increase of fleet fuel efficiencies at first, then a decline for some time followed by a steady increase. The timing of these changes are likely to vary from one country to the other depending on the economic situation of the respective country. But, one should hope that in the interest of oil-importing developing countries like Bangladesh, the fleet fuel efficiency should change as it did in the USA in the 70s decade.

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Table 1 Possibilities of improvement of future passenger cars[13]

| Possible areas of improvement | Percent fuel saving from 1985 base |
|---|---|
| **Engine** | |
| • Thermal efficiency | |
| – Combustion chamber | 1 to 2% |
| – Air-fuel mixture (lean burn, SCEs, etc.) | 2 to 3% |
| • Reduction of loss | |
| – Heat loss | 1 to 2% |
| – Engine friction loss (piston ring, bearing, etc.) | 2 to 4% |
| • Other improvements | |
| – Variable displacement engines | 5 to 10% |
| – Better engine control (valves, fuel system, etc.) | 3 to 16% |
| **Transmission system** | |
| • Automatic transmission | |
| – 4 speed (change over 3 speed) | 2 to 4% |
| – 5 speed (change over 4 speed) | 3 to 4% |
| – Continuously variable transmission | 10 to 15% |
| • Front wheel drive | 5 to 10% |
| **Weight reduction** | |
| • Development of lightweight materials | 5 to 10% |
| • Structural design of the body | 6 to 8% |
| **Reduction of running resistance** | |
| • Aerodynamic drag | 5 to 12% |
| • Rolling resistance | 0 to 2% |
| **Other improvements** | |
| • Improvement of tyre material and design | 0 to 1% |
| • Lubricants and fuel | 1 to 5% |
| • Alternative fuel | –10 to –4% |
| • Electrical/electronic system | 2 to 6% |
| • Driving pattern (speed, stop-start, tuning, etc.) | 4 to 8% |
| • Emission control | –6 to –10% |
| • Safety equipments | –3 to –7% |

Note: The figures shown in the table are not additive. The percentage fuel savings shown here are based on the author's judgement and in speculation about the future car market in the developed countries.

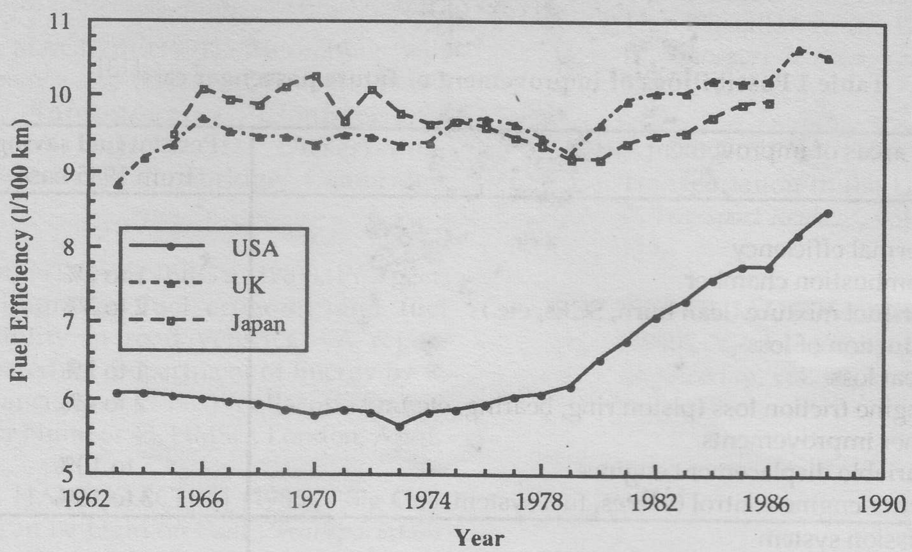


**Figure 1 Fleet fuel efficiencies in the developed countries**
Source: National Statistical Abstracts of respective countries.

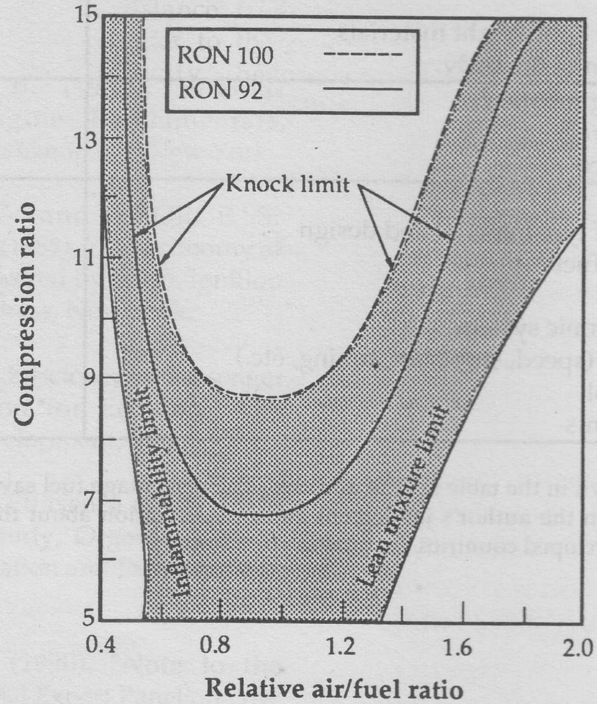


**Figure 2 Knock limits in SI engines as function of compression ratio**

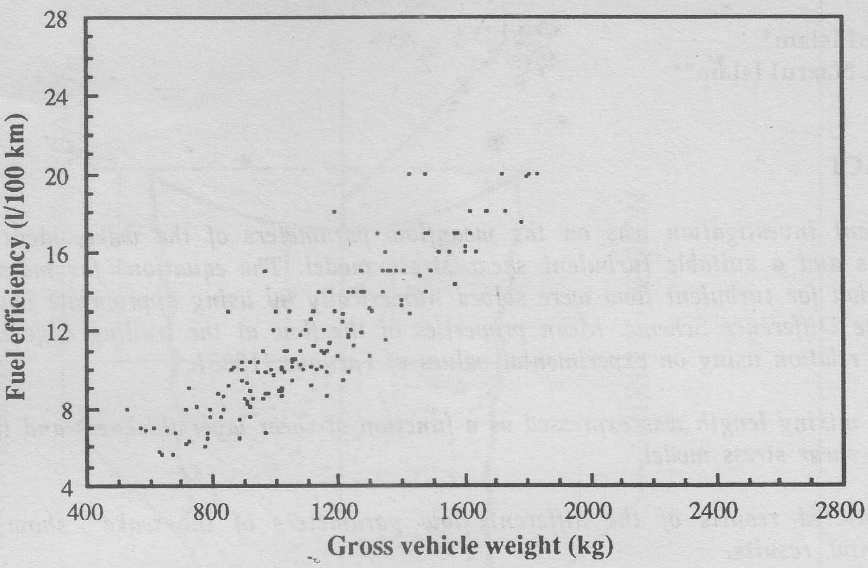


**Figure 3 The relationship between fuel efficiency and gross vehicle weight [Hallwag (1990)]**