TRADE-OFFS BETWEEN FUEL EFFICIENCY AND EMISSIONS

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The trade-offs between fuel economy and emissions and improvements in fuel economy that allow elimination of add-on devices are addressed. The cold-start emission problem for conventional engines is also discussed. This paper provides some background and estimates on fuel economy for various emission constraints and some estimates of the percentage of fuel economy improvement necessary to eliminate add-on devices. The conclusions are that add-on devices cannot be eliminated by the projected fuel economy gains and that improved carburetor designs and manifold systems have their largest impact on the cold-start problem.

This paper examines the trade-offs between fuel economy and emissions, improvements in fuel economy that allow the elimination of add-on devices, and the cold-start emission problem for a conventional spark-ignition engine system. It provides some background and estimates on fuel economy for various emission constraints and some estimates of the fuel economy improvements necessary to eliminate add-on devices.

It must be stressed strongly at the outset that to include the emission constraints rigorously is not currently possible since the data available are completely inadequate for that task. In addition, the detailed data for lean-burn engine concepts that are optimized for fuel economy and that do not employ some degree of spark retard and exhaust reactions are not readily available. These data are necessary in determining the source of the cold-start problem. Other constraints such as fuel octane requirements and manufacturing lead times are equally important and difficult to assess.

The system nature of the vehicle optimization procedure is emphasized by indicating that vehicle weight, transmission design, aerodynamic performance, and engine design are interrelated in the vehicle optimization procedure. Teams of experts will be required if fully optimized vehicles are to become a reality. Such teams will be assembled only when realistic emission standards are set and guaranteed not to change for 5 to 10 years.

To provide an indication of the potential for improved brake-specific fuel consumption (BSFC) through engine redesign and improvements in engine control, three concepts that bracket the range of interest are discussed in more detail: a lean, high-turbulence, high-compression ratio engine, with first a manifold reactor and then an oxidation catalyst, and a close-to-stoichiometric engine with exhaust gas recirculation (EGR) and secondary air for engine nitric oxide (NO_x), hydrocarbon (HC), and carbon monoxide (CO) emission control and with catalysts for additional exhaust clean-up. This improvement in fuel economy from the engine is estimated at 20 percent. It is deduced that the estimated 40 percent improvement in fuel economy by 1980 will be a result of a reduced vehicle weight and some improvements in vehicle design in addition to engine improvements.

Estimates of the fuel economy improvements necessary to eliminate add-on devices point out the impossibility of this method of control. The use of spark retard and exhaust manifold reactors will be necessary to meet the hydrocarbon standard of 0.25 g/km (0.4 g/mile) in even the best lean-burning systems, and a reducing catalyst will be necessary for NO_x control at the 0.25-g/km 0.4-g/mile) standard.

The final topic covered is the cold-start and warm-up problem. This problem is basically a fuel distribution and atomization problem. Improved carburetors and new carburetors combined with improved intake systems will greatly alleviate this problem. Experimental lean-burn systems have shown good HC and CO control. Although detailed emission data are not available on these systems, it is postulated that the emission improvements from these lean-burn systems are largely due to the improvements in their cold-start emissions and fuel economy.

BACKGROUND

In this section the engine variables that affect emissions are reviewed, and the trade-offs between fuel economy and emissions are discussed. The engine parameters that govern the fuel economy are also important in determining the emissions from an engine. In some instances improvements in fuel economy result in improved emissions. However, as is most often the situation in systems engineering, the improvement in one output results in the degradation of another, and an overall optimization must be attempted. The optimization procedure occurs not only between fuel economy and emission but also among the various pollutants themselves.

The experimental results in Figure 1 show the classical behavior of the three pollutants, NO, HC, and CO, with air-fuel ratio, EGR, and spark retard (1). In general, BSFC, BSNO, BSCO, and BSHC all improve for lean operation. However, the emissions levels attained by running lean without any other controls are not sufficiently low to meet federal standards. Hence, other control parameters such as EGR and spark retard must be used to control NO and HC emissions. As indicated by the results shown in Figure 1, CO emissions do not change substantially with EGR and spark retard and are primarily a function of the air-fuel ratio. The trade-offs involved in optimizing BSNO, BSHC, and BSFC are clearly shown. For small amounts of EGR, some NO_x control is gained with no apparent loss in fuel economy or control of HC emissions. For higher EGR rates, the NO_x is reduced substantially while HC and specific fuel consumption increase.

Many investigations have shown the trade-offs of NO_x and HC and BSFC. Figure 2 is the result of one such investigation at Nissan (2). As is the situation in most of these studies, combustion duration varied with EGR and air-fuel ratio since the engine geometry is fixed. This study indicates that, for a large reduction in NO_x, either HC emissions or fuel economy must be sacrificed.

A 5 percent loss in fuel economy due to EGR resulted when HC emissions were held constant and NO_x emissions were reduced 60 percent. If fuel economy was maintained, HC emissions increased for any reduction in NO_x.

A recent investigation performed at Mobil (3) studied the interrelations of fuel economy, BSNO, BSHC, air-fuel ratio, and compression ratio (CR) for a cooperative fuels research (CFR) engine. Some of the results are shown in Figures 3, 4, and 5. In Figure 3, $BSNO_x$ is plotted versus BSFC for various compression ratios and spark timings. The addition of 10 percent EGR results in a 50 to 60 percent reduction in NO_x emissions because of the increase in brake power. The results shown in this figure would indicate that specific NO_x emissions could be reduced by a factor of 7 with a BSFC improvement of 7 percent by changing operating conditions from maximum break torque (MBT) spark at 7.5 compression ratio and no EGR to MBT spark at 10.5 compression ratio with 20 percent EGR. This example did not place any constraint on HC emissions, which will increase according to the results shown in Figures 1 and 2. According to the results shown in Figure 5, BSHC can be constrained if a 15° spark retard is used at 10.5 compression ratio with a resultant 6 percent loss in BSFC. Obviously the control philosophy will depend heavily on the emission constraints that are set by the efficiency of the clean-up devices used in the after-treatment process. Also, as part of this study, the NO_x emissions were constrained at a level of 3 kg/kW·h (5 g/bhp·h) and HC emissions were varied. For these constrained conditions, both the minimum fuel consumption and minimum octane number for trace knock were achieved at the lowest compression ratio studied (CR = 7.5). Also, overall minimum fuel consumption was attained at the leanest air-fuel ratio studied (A/F = 15.4) for controlled HC and NO_x emissions. These data show that the historically accepted improvement in engine efficiency may not result when HC and NO_x must be constrained because of emission requirements.

The degree of complication is already substantial with only the consideration of EGR, spark retard, and air-fuel ratio. The parameters of mixture homogeneity and distribution, proportional EGR, intake air and coolant temperature, ignition system, combustion chamber design, engine speed and load, valve timing, and transient operation have not been discussed. In this paper the effects of mixture homogeneity in emissions will be discussed because of its relevance to the cold-start problem. A discussion of the effects of the other parameters is given in another paper (4).

The effect of mixture homogeneity on specific fuel consumption is shown in Figure 6 (5). Figure 6 also shows the decrease in HC and NO emissions with better mixture preparation, which occurred as a result of extending the lean misfire limit. The homogeneity of the fuel-air charge can also have an effect on CO emissions especially if the operating point is near stoichiometric.

Small-scale variations in the local equivalence ratios are one cause of the higher than theoretical values of CO observed at stoichiometric operation. Cylinder-to-cylinder distribution can also cause anomalously high CO and NO_x emissions when the operating point is lean of stoichiometric. Figure 7 shows a typical spread in the individual air-fuel ratios delivered to a four-cylinder engine (6). Also shown in this figure is the air-fuel ratio distribution when a special mixture generator is used. Figure 8 shows the resultant pollutant levels from each cylinder as well as those that result from a uniform air-fuel distribution. The CO and NO_x show the expected result. The HC emissions do not change since they are a quench phenomenon and the NO and CO emissions are generally bulk gas related.

A test was conducted in this experiment to determine the transient nature of the NO_x emissions for the carbureted system versus the mixture generator. Figure 9 shows the results of this test. The resultant decrease in NO_x is dramatic. However, it probably cannot be attributed to cylinder-to-cylinder distribution alone. A likely cause for this dramatic result is the transient operation of the carburetor system versus the mixture generator. The transient response of the carburetor system could have led to an air-fuel ratio change during accelerations and decelerations whereas the mixture generator probably maintained a constant air-fuel ratio. The more frequent use of the single plane intake manifold for lean engine systems indicates that a large plenum manifold with short runners to the cylinders gives good transient response and cylinder-to-cylinder distribution.

SUMMARY OF INTERACTIONS

The discussion in the previous section shows that changes in almost all engine design and operating variables that affect BSFC also affect engine emissions (especially HC and NO_x). Many of these variables also affect the engine fuel octane number requirement to avoid trace knock at part or full load. Also, changes in a number of these variables would require changes in other engine variables to achieve satisfactory engine operation. For example, substantially leaner carburetor calibration would, at a minimum, require improvements in mixture quality and an improved ignition system for adequate drivability.

To underline the complexity of these interactions the effect of changes in the most important variables on BSFC, BSNO, BSHC, and octane requirements (OR) is given in Table 1. The assumptions made in drawing up the table are that each change is made one at a time to a conventional spark ignition (SI) engine with the air-fuel ratio calibrated lean of stoichiometric (15 to 16:1) and with the engine operated at maximum brake torque spark timing. Most of the changes that improve BSFC have a detrimental effect on HC or NO_x emissions or both or on octane requirement.

Some of the changes given in Table 1 have by themselves limited direct impact on BSFC; however, their

Figure 1. Effect of input variables on emissions and efficiency.

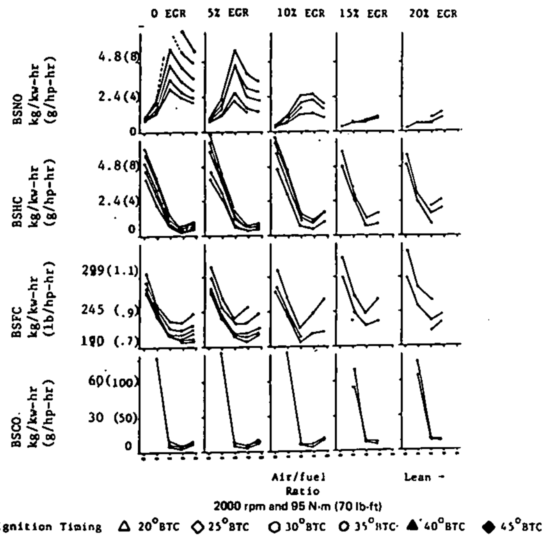


Figure 2. Trade-off due to exhaust gas recirculation.

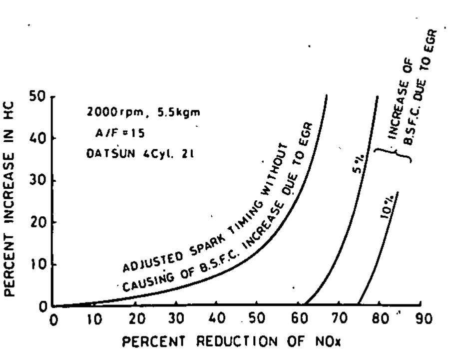


Figure 3. Effect of exhaust gas recirculation, spark timing, and compression ratio on the relation between $BSNO_x$ and BSFC.

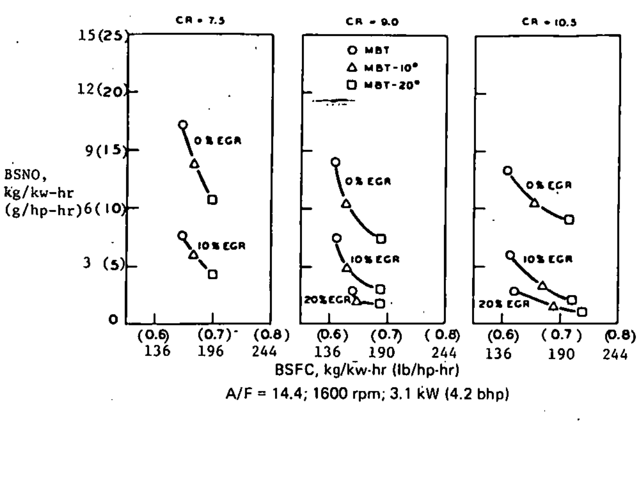


Figure 4. Effect of exhaust gas recirculation and compression ratio on relation between $BSNO_x$ and BSFC.

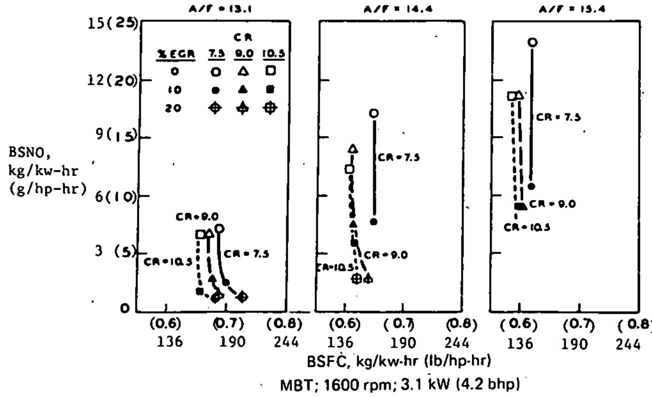
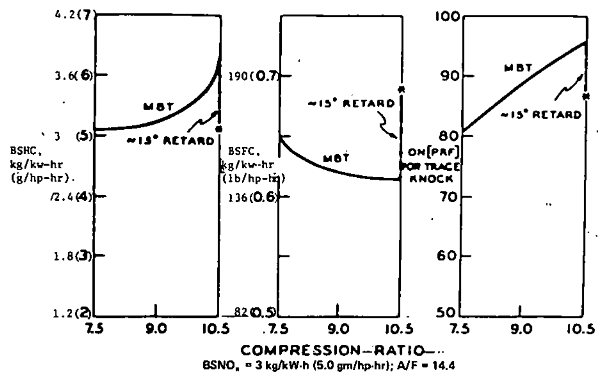


Figure 5. Effect of maintaining constant NO_x and HC emissions with change in compression ratio (interpolated and extrapolated data).



*Interpolated and Extrapolated Data.

Figure 6. Mixture preparation and fuel effects on exhaust emissions and fuel consumption.

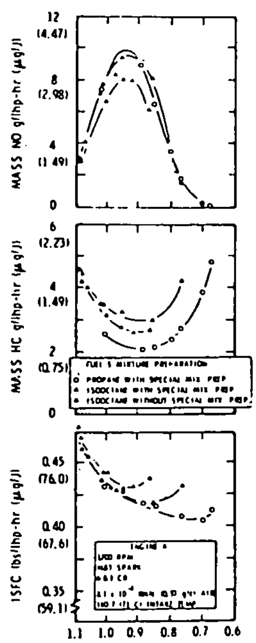


Figure 7. Distribution of air-fuel ratio.

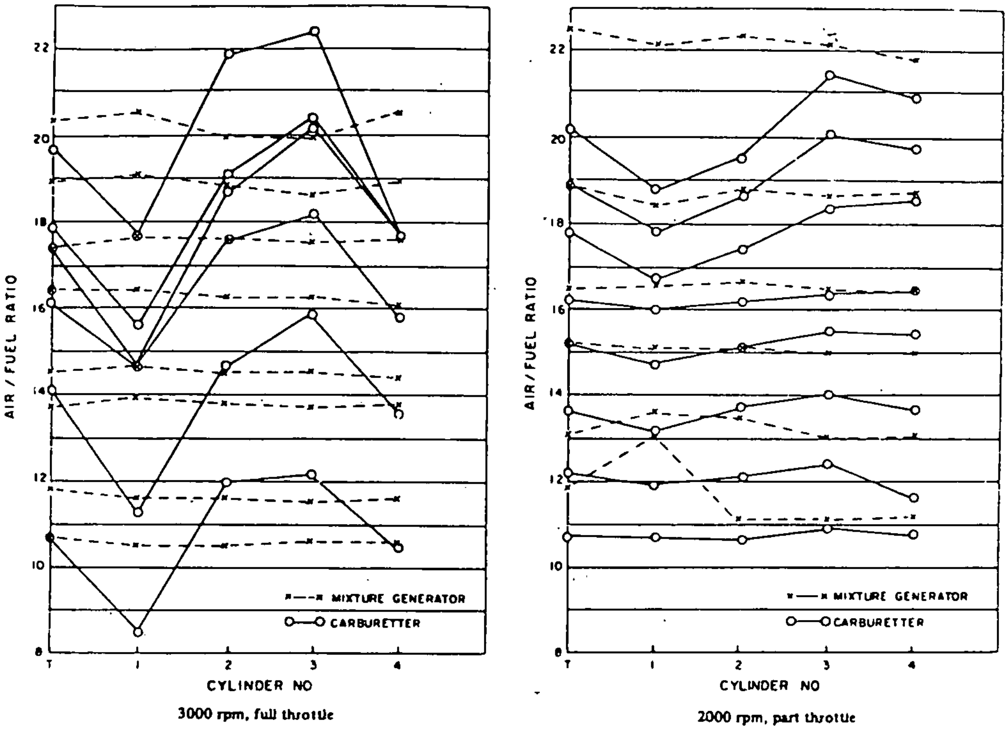


Figure 8. Pollutant levels.

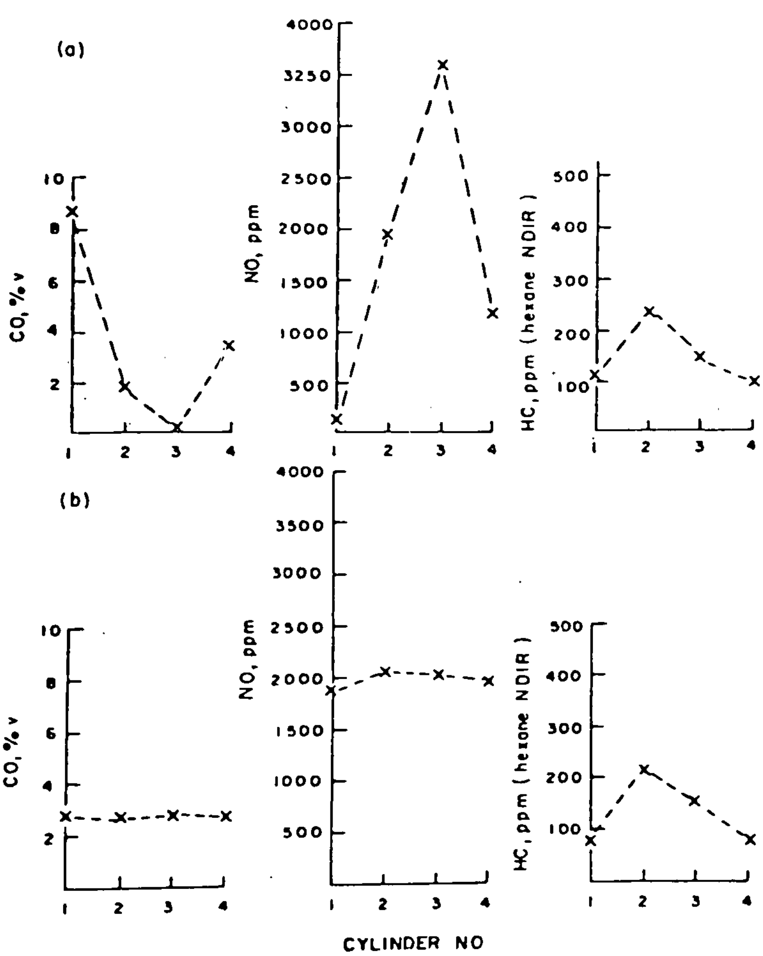
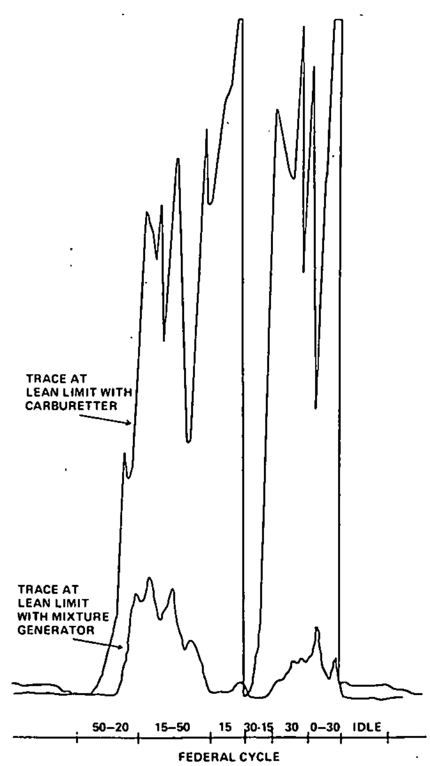


Figure 9. Comparison of NO_x traces at lean limits of carburetor and mixture generator.



indirect impact may be significant. Changes in engine design or operating conditions that improve the degree of emission control achieved may allow other changes that improve BSFC while maintaining emission levels constant. Such fuel economy gains may be especially important if spark retard has to be used to control HC emissions. A reduction in exhaust heat losses (for example through the use of exhaust port liners) will allow advances in spark timing toward MBT to be made while HC emission levels are held constant. Thus, an indirect BSFC gain can be obtained.

So far in this paper, I have attempted to show the interrelations of the engine variables with respect to emissions and fuel economy. Because of these interactions, the optimization of an engine system is a difficult task. Each engine and emission control system must be optimized as a system concept and not on a component-by-component or variable-by-variable approach. It is important to understand that a general operating philosophy of the entire vehicle-engine-drive train system must be formed before the optimization procedure can begin. The vehicle weight and transmission characteristics are important design considerations for the engine developer. A true optimization will come only when teams of experts cooperate to design a vehicle. But before any optimization procedures can commence, the constraints must be known, and for the level of effort necessary for a complete vehicle design these constraints must be firm and relatively long term.

EFFECT OF FUTURE EMISSION STANDARDS ON FUEL ECONOMY

The emission standards likely to be in effect in the 1980 to 1985 period can only be guessed at this stage. Unfortunately, the values of these standards are especially important because they dictate the type of conventional engine emission control systems that will have to be developed and are the major constraints with respect to fuel economy. For example, the so-called lean-burn system and the HC/CO oxidation catalyst system with EGR may have the potential of reaching the following vehicle emission standards (0.62 g/km = 1 g/mile) (7):

Emission	Lean Burn (g/km)	Catalyst (g/km)
HC	0.25	0.56
CO	2.11	5.59
NO_x	1.24	0.62

But these two systems do not appear to have the potential for reaching lower NO_x emission values. The current 1978 NO_x standard of 0.25 g/km (0.4 g/mile) can only be approached with a dual catalyst or three-way catalyst system. The mixture control requirements for these four systems are all quite different (quite modest for the HC/CO catalyst system; extremely stringent for the three-way catalyst system), as is the most desirable carburetor calibration.

Other potential emission constraints are sulfate standards and particulate standards. The type of sulfate standard now being proposed for 1979 may constrain the air-fuel ratio of lean engine systems with oxidation catalysts and make EGR rather than very lean air-fuel ratios the preferred approach. Little is known about the impact of sulfate standards on engine and emission control technology, however. Although there is some discussion of particulate automobile emission standards, there is also little that can be said of their potential impact except that the use of lead in fuels would probably be limited to levels below today's regular leaded gasoline.

Since these constraints must be included in any optimization analysis, the following methodology is suggested for examining fuel economy gains through improved conventional engine design and control of operating variables. To make an estimate of fuel economy of engines in the 1980 to 1985 time period relative to today's engine technology, one must first select values for the emission standards that have to be met and then select those engine and emission control systems that have the best potential of meeting those standards. (Best in this context includes judgments about manufacturability, marketability, reliability, and serviceability, which are difficult to quantify but are important indeed.) At lower emission levels than those of today [0.93 g/km (1.5 g/mile) HC, 9.32 g/km (15 g/mile) CO, and 1.93 g/km (3.1 g/mile) NO_x], and with engine and control technology available in the short term (say, 1975 to 1980), there will be a fuel economy penalty for all the conventional engine systems now considered practicable. The question then becomes, For a given set of emission standards and for a given engine and control system, to what extent can improvements in engine and control system technology offset this penalty?

A number of estimates have been made of the effect of different standards on vehicle fuel economy due to changes in engine and emission control systems alone. The fuel economy penalties associated with several different sets of standards are shown in Figure 10 (8). Although the magnitude of the estimates on the decrease in fuel economy varies, there is general agreement that fuel economy will decrease. In addition, the rate of decrease is generally agreed on. These projections were made assuming current emission control technology. Without significant improvements in technology, engine fuel economy will be between 5 and 13 percent worse than the former 1977 levels shown in Figure 10 and between 10 and 23 percent worse (depending on vehicle weight and details of the control system) than the current 1978 levels. The fuel economy penalties at 0.62 g/km (1 g/mile) NO_x level would depend on whether EGR (or air in the lean engine case) or reduction or three-way catalysts are used for NO_x emission control. I have seen no convincing evidence that these emission levels are achievable with technology available in the short term with any lesser fuel economy penalties.

Further reductions below today's emission control levels of both NO_x and HC emissions contribute to these fuel economy penalties, but to different degrees at different emission levels. Figure 11 shows the effect of an optimized air-fuel ratio, EGR rate, and spark timing on engine HC and NO_x emission and fuel economy. Currently engine HC emissions (in systems with oxidation catalysts) are in the 1.24 to 1.86-g/km (2 to 3-g/mile) range with NO_x emissions of about 2 to 2.5. At these operating conditions, fuel economy is not especially sensitive to small changes in emission levels. However, reduction in engine HC emissions by a factor of 2 to 3 at constant NO_x or reduction in NO_x by a factor of 2 to 3 at constant HC both result in significant fuel economy penalties (primarily because spark retard must be used to raise exhaust temperatures to reduce HC emissions or prevent their increasing as EGR does). It would be rash to predict that anything less than a factor of 2 to 3 reduction in engine HC emissions will be required by 1985. A reduction in NO_x emissions below 1.24 g/km (2 g/mile) will likely be required, too.

POTENTIAL GAINS IN FUEL ECONOMY

Engine Fuel Economy

Much of the following discussion of the recovery of con-

Table 1. Interactions of engine control variables on fuel economy, emissions, and octane requirement.

Variable and Direction of Change	BSFC	$BSNO_x$	BSCO	BSHC	OR
Improve mixture quality	0	+	-	-	0
Calibrate carburetor lean	-	-	-	+/-	-
Retard spark from MBT	+	-	-	-	-
Increase EGR percentage	+/-	-	0	+	?
Increase compression ratio	-	+	0	+	+
Increase burn rate	-	+	0	+	-
Reduce exhaust heat losses	0	0	-	-	0
Improve ignition system	0	0	0	-	0

Note: + = increase; - = decrease; ? = impact unclear; +/- = may increase or decrease; and 0 = no change.

Figure 10. Projected losses in fuel economy to meet more stringent exhaust emission standards.

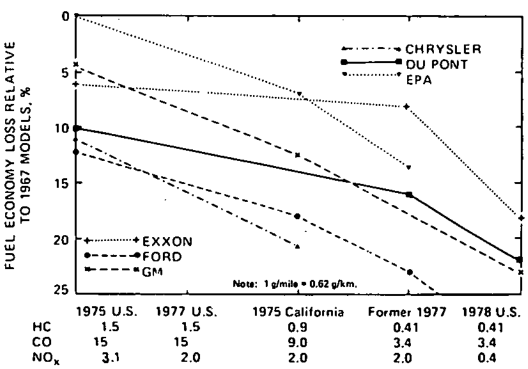
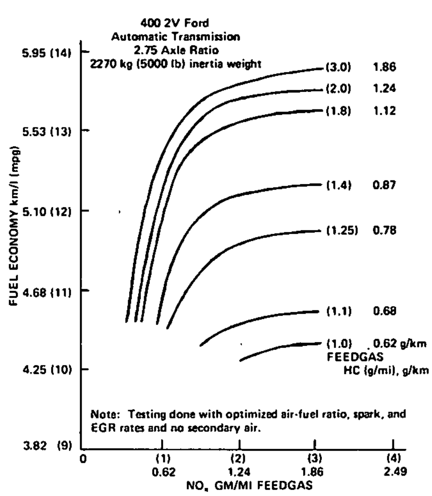


Figure 11. Effect of various factors on emission and fuel economy.



version losses is speculation because adequate data on the effects of design and operating variable changes at appropriate emission levels are not available. However, such a discussion provides a useful, if approximate, quantification of the maximum gains in thermal efficiency that can be realized through improvements in technology. These improvements would offset the reductions in efficiency due to tighter emission control, which were described in the previous section.

Incomplete combustion within the air-fuel flammability limits is generally a loss of the order of 3 percent. Even if a 50 percent improvement in combustion efficiency is accomplished, only a net gain of 1.5 percent in thermal efficiency will result. As the limits of inflammability are approached, the gains that might be realized could be larger than those gained with close to stoichiometric operation.

The specific heat of the gas can be decreased by leaner operation or by more dilute operation with EGR. The gain in efficiency is of the same order for leaner operation as for dilute operation even though the air has a greater ratio of specific heat. Dilute operation produces a gain due to lower combustion temperatures, which result in less dissociation and lower specific heats. If the operating air-fuel ratio can be changed from 16/1 to 19/1, a 5 to 10 percent gain in indicated thermal efficiency will result. Likewise if the use of EGR reduces the burned gas temperatures by almost 200 K, a gain of 5 to 10 percent will result. However, EGR is more effective on a percentage basis than air in reducing NO_x. Thus, at the same NO_x emission level, less dilution with EGR is required.

Long burning times and heat losses to the combustion chamber walls also contribute to the loss in thermal efficiency as compared with the ideal Otto cycle. Cleveland and Bishop (9) estimate that it may be possible to recover 5 percent in thermal efficiency by improvements in burning rates and reduced heat losses. Although increased burning rates would decrease exhaust temperatures and reduce HC and CO burn up, reduced heat losses would have the opposite effect.

Pumping losses cannot be eliminated from a carbureted engine except through the use of unthrottled stratified charge or variable compression ratio devices. These two techniques are viewed as long term (i.e., 20-year time scale) for the entire vehicle population. The maximum gain in thermal efficiency attainable at road load by using an unthrottled engine is of the order of 40 percent. For a throttled engine, lean or dilute operation would decrease the pumping losses and a gain of 5 to 10 percent would result. Similarly intake valve timing and gear ratios can be chosen to reduce the part load pumping losses. However, maximum engine power at wide-open throttle would be reduced.

An increase in compression ratio increases the available energy that can be extracted from the engine. By increasing the compression ratio from 8 to 10 the thermal efficiency increases from 5 to 8 percent, depending on load and air-fuel ratio. Full advantage of this increase in compression ratio can only be realized if spark timing can be held at advance for best torque. Whether this is possible depends on the octane rating of the available fuel, the engine octane requirement, the degree of HC emission control required, and the effectiveness of the exhaust treatment device.

Table 2 gives our estimate of the "minimum" possible gains that may be attained over the 1975 vintage engines for three engine systems. The first is a lean-burn engine with an exhaust thermal reactor and spark retard for HC control. The second is a lean-burn engine with a catalyst for HC and CO control. Both of these concepts would have difficulty meeting NO_x emission standards below about 0.93 g/km (1.5 g/mile) at the HC and CO emission standards anticipated for 1980 to 1985. The third concept is a slightly lean or stoichiometric engine with EGR for engine NO_x control, and with an HC and CO catalyst and secondary air at NO_x levels down to about 0.93 g/km (1.5 g/mile) or with a three-way catalyst at lower NO_x levels (assuming that durable three-way catalysts and sensors can be developed). I stress again that these are estimates of the maximum gains for these systems. Some of the assumptions made in preparing these estimates and some qualifications are given below.

Table 2. Estimate of maximum percentage of increase in thermal efficiency for three engine systems.

Engine Control Variable	System 1[a]	System 2[b]	System 3[c]
Increased compression ratio	5 to 8	4 to 6	3 to 4
Air-fuel ratio or EGR	5 to 10	5 to 10	4 to 8
Improved combustion	1½	1½	1½
Faster burning and lower heat losses	5	5	5
Pumping work	5 to 10	5 to 10	4 to 8
Spark retard for HC control	-5 to -10	—	-3 to -5
Total gain	17 to 25	21 to 33	16 to 22
Allowance for nonsynergistic effects	11 to 17	14 to 22	11 to 15

[a]Lean burn engine with spark retard and manifold reactor for HC control.
[b]Lean burn engine with catalyst system for HC and CO control.
[c]Slightly lean engine with EGR for engine NO_x control and with catalysts.

Figure 12. Effect of levels of future exhaust emission standards on potential improvements in fuel economy.

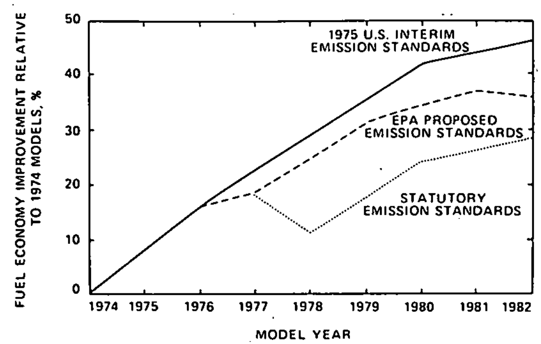
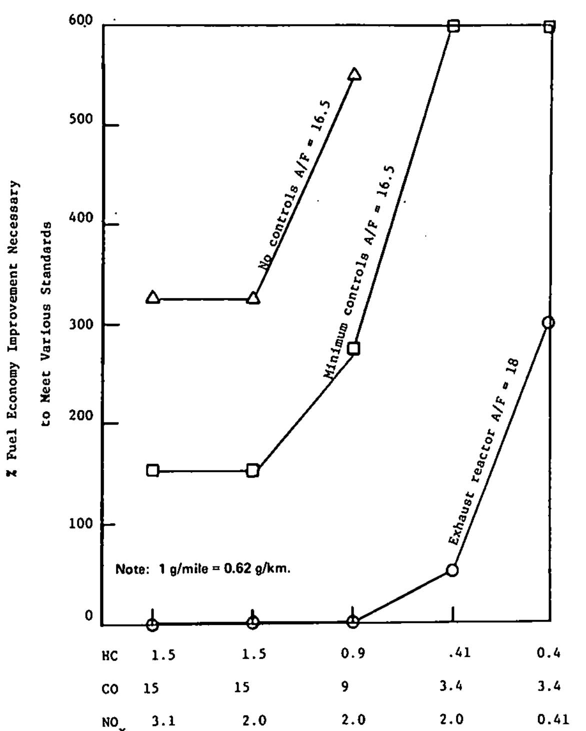


Figure 13. Fuel economy improvements necessary to eliminate add-on devices.



1. Possible compression ratio increase depends on octane rating of available fuel, HC emission standard, and so on. We have assumed leaded fuel and CR increases from 8 to 10 for system 1, unleaded fuel and CR increases from 8 to 9.5 for system 2, and unleaded fuel and CR increases from 8 to 9 for system 3;
2. Less dilution occurs with EGR than with air for equivalent NO_x control, so thermal efficiency gains are lower; and
3. Total gain is reduced by one-third because almost all these parameter changes interact.

If such gains in fuel economy result, it should now be obvious that these gains will not be a result of any single idea or invention. New developments in single components such as carburetors, fuel injectors, manifolding, and valve timing will not in themselves produce an improvement in the 15 to 30 percent range. Gains in thermal efficiency of this magnitude will be the culmination of concentrated research and development of all facets of engine design and integration in a vehicle. The attainment of more efficient engine vehicle combinations will be the result of the 2 and 3 percent improvements in individual components that have been systematically incorporated into the vehicles.

Vehicle Fuel Economy Gains

In addition to gains in fuel economy attributable to the engine, other variables such as vehicle weight, power transmissions, aerodynamic drag, and rolling friction can contribute significantly to gains in fuel economy. The largest single factor is probably the vehicle weight. A shift to a higher percentage of small automobiles has taken place during the past several years. According to Ward's Automotive Yearbook and Weekly Reports, the proportion of the market taken by small automobiles grew from 16 percent of all automobiles in 1966 to 36 percent in 1972 to more than 45 percent in 1974. The results of a study by Cantwell, Kinnear, and Russell (8) are shown in Figure 12. Fuel economy of the vehicle population is improved 40 percent by 1982. Approximately 50 percent of this gain is due to engine improvements and 50 percent is due to a shift to smaller, lighter vehicles and transmission improvements. The study points out that the gains to be expected in small vehicles would not exceed 20 percent. This is in agreement with our estimate given in Table 2.

SUMMARY OF FUEL ECONOMY-EMISSION TRADE-OFFS

A comparison of the expected losses in fuel economy due to emission controls and the expected gains due to improved engine design shows essentially no gain if the statutory standards are to be met. Only through design changes such as improved transmission, reduced aerodynamic drag, and reduced vehicle weight will the fuel economy be improved, as shown in Figure 12.

One of the questions for discussion at this workshop was, Will improved engine efficiencies meet EPA standards for emissions without add-on devices? Figure 13 shows the fuel economy improvements necessary to eliminate add-on devices. Three cases are presented. Table 3 gives the base lines for the calculations. For case 1 the engine is optimized for fuel economy and there are no add-on devices. This vehicle was essentially built for the European market and has very little in the way of pollution control (7). Case 2 assumes that by using better combustion chamber design and small amounts of spark retard the hydrocarbon levels could be reduced by a factor of two and the NO_x levels may be

Table 3. Calculations for cases shown in Figure 12.

Case	Vehicle (kg)	Emissions (g/km) HC	CO	NO_x	Fuel Economy (km/liter)	Air-Fuel Ratio
1[a]	1133	2.48	3.67	0.93	9.6	16.5/1
2[b]	1133	1.55	1.86	0.75	9.6	16.5/1
3[c]	2041	0.50	2.49	0.93	4.7	18/1

Note: 1 g/km = 1.61 g/mile; 1 km/liter = 2.35 mpg; 1 kg = 2.2 lb.
[a]No controls.
[b]Estimate based on case 1 with improved mixture preparation and some spark retard.
[c]Test results with some oxidation in exhaust, some spark retard, and improved mixture preparation through using a sonic carburetor.

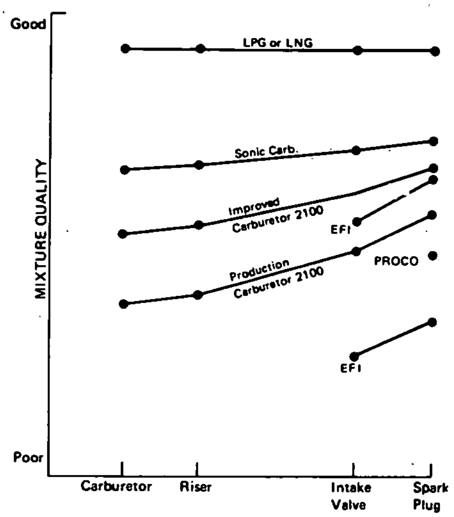


Figure 14. Estimates of mixture quality trends of induction system under hot-operating conditions.

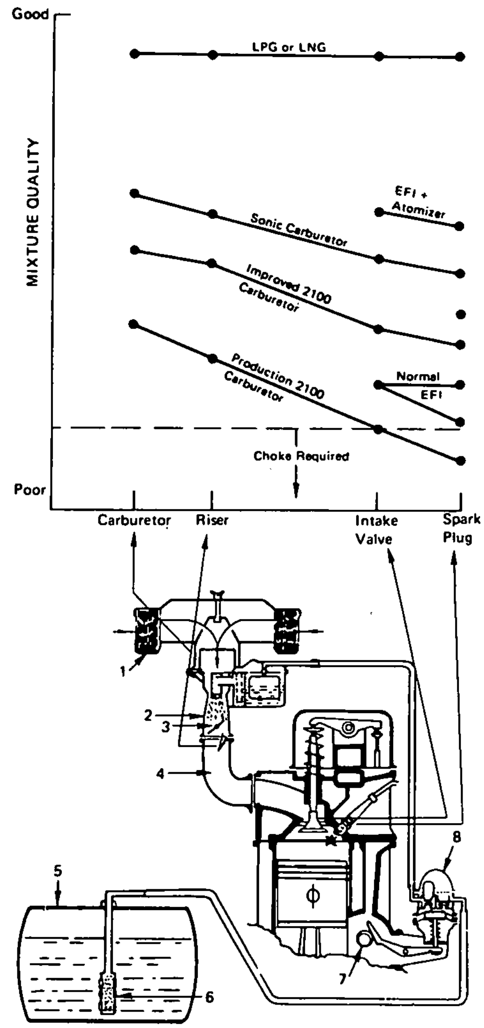


Figure 15. Estimates of mixture quality trends of induction system under cold-start and drive conditions.

reduced slightly with small amounts of EGR. Case 3 represents results of tests in which a sonic carburetor and an exhaust manifold reactor were used (7). This engine concept is an experimental system and is not near production. However, we feel that it represents a lower bound on a production lean-burn system that would not use a catalyst. Figure 13 shows the percentage increase in fuel economy necessary to meet various standards for these three cases. It is clear that some spark retard and a thermal reactor are necessary to maintain low HC levels in the absence of a catalyst converter. It is also clear that there is no possibility of meeting the 0.25-g/km (0.4-g/mile) NO_x standards without the use of a reducing catalyst and that tremendous improvements in fuel economy are needed to attain the 0.25-g/km (0.4-g/mile) HC standard.

COLD-START POLLUTION PROBLEM

The success or failure of many emission control systems lies in their ability to cope with the cold-start pollution problem. This problem arises from the inability of the induction system and carburetor system to provide a homogeneous, vaporized fuel-air mixture to the engine cylinders. During cold start, most carburetors produce droplets of fuel that are too large to follow the air stream and condense on the walls of the intake manifold. As a result a rich air-fuel mixture must be supplied to the engine cylinders so that an ignitable air-fuel mixture in the vapor state is present in the cylinder at the time of spark. High fuel consumption, CO emissions, and HC emissions generally result. Early fuel evaporization systems have been developed by most of the automobile manufacturers. These systems generally use exhaust heat and high shear velocities to help vaporize the fuel. They have the disadvantages of a finite warm-up time and a control system to divert the exhaust heat after a certain intake temperature is reached so that overheating of the charge does not result. This technique essentially tries to correct a problem created by poor carburetion.

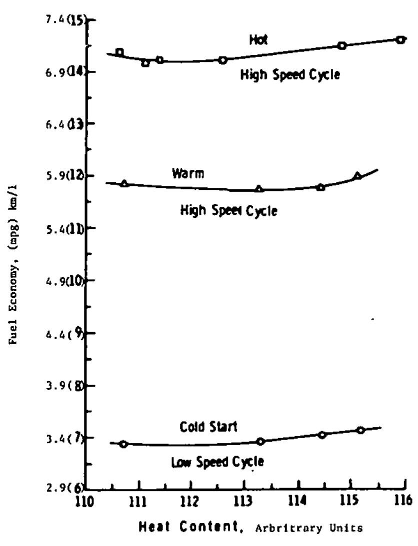
A second aspect of this problem is the distribution of the fuel-air charge to the individual cylinders. If a large maldistribution in fuel-air ratio exists from cylinder to cylinder, then richer carburetor settings are necessary for all cylinders to have ignitable mixtures at the time of spark. If large amounts of fuel condense on the walls of the intake system, it becomes difficult to design an induction system. If a carburetor can be designed to give fine droplets that follow the air stream, then the mixture distribution problem reduces to the design of an intake system that equally distributes the mass or air to each cylinder.

The mixture quality trends for various carburetor-induction system combinations are shown in Figures 14 and 15 for hot- and cold-operating conditions respectively (7). The results of the hot test show that all the systems tested had average mixture quality, and there was only a small improvement over the improved conventional carburetor when a sonic carburetor was used. The cold test results show quite a different trend. In the hot tests the mixture quality improved as the charge went from the carburetor to the spark plug. This is probably a result of the improved evaporization due to a hot air stream and heated intake system. Conversely, a decrease in mixture quality is observed in the cold tests as the charge travels from the carburetor to the spark plug. Hence, the production carburetor, which starts out with an average mixture quality at the carburetor, fails to maintain this level and has a poor mixture quality at the time of spark. Here the intake air and manifold are cold, and fuel condensation and lack of fuel evaporization are the likely causes of the downward trend. It is necessary to begin with a relatively good mixture quality at the carburetor (i.e., droplets that can follow the air stream) if an acceptable mixture is to result at the spark plug. The improved production carburetor and the sonic carburetor are successful in providing acceptable mixture quality at the time of spark. However, the difference between the improved production carburetor and the sonic carburetor is greater in the cold tests than in the hot tests.

Cylinder-to-cylinder distribution of the fuel-air charge is as important as obtaining good mixture quality for improving both cold-start and ultra-lean operation. In both these situations the carburetor is calibrated for ignitability of the leanest cylinder, and hence rather richer operation can occur in the other cylinders. The spread in air-fuel ratios for full throttle and part throttle was shown in Figure 7 for a four-cylinder engine. This spread can be even greater during cold-start operation. It is important that the carburetor with its induction system be designed to maintain a relatively constant air-fuel ratio during transient operation and during cold start in order to maintain fuel economy and emission levels.

The effect of warm-up on fuel economy is shown in Figure 16. The differences in fuel economy between cold operation and fully warmed-up operation are dramatic. These differences can only be explained by poor mixture preparation and distribution that necessitate overly rich carburetion. The emissions of CO and HC are higher for rich operation on a concentration basis and coupled with the poor fuel economy results in a severe problem on a grams-per-kilometer basis.

Figure 16. Effect of warm-up on fuel economy (averages of four cars).



There is a strong possibility that sonic carburetors or improved production carburetors will be available in the near future. The improvements in emissions and fuel economy demonstrated by these systems (especially the sonic carburetor system) are most likely due to their superior mixture quality during cold start and warm-ups. My opinion is that the cold-start emission problem will slowly be alleviated as these new carburetor systems are put into production.

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