Emission Control and Fuel Economy

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Extended Abstract

For at least the near term future, the conventional piston engine will continue to be the dominant automobile power plant. The two major factors to which it must respond are emission standards and fuel economy. Since these two factors are closely linked, we have made a theoretical and experimental study of fuel economy as a function of emission standards for a variety of catalytic and thermal control systems applied to the piston engine.

Theoretical Considerations

Factors affecting fuel economy and emissions can be divided into those external to the engine and those internal. For this paper, all external factors will be assumed constant, with vehicle weight, the most important of these, held at 4000 lbs.

Internal factors having significant effects include air-fuel ratio, compression ratio, spark timing, exhaust gas recycle, and load factor. Each will be discussed in turn and the entire discussion summarized by relating fuel economy to emission standards for several emission control systems.

Peak fuel economy is obtained at air-fuel ratios slightly leaner than the stoichiometric value. The region of 16-16.5 lbs. of air per lb. of fuel generally is the optimum. Richer mixtures release less of the fuel's available heat of combustion while leaner mixtures are increasingly difficult to burn at the optimum time. Additionally, dilution with fuel or air lowers peak flame temperature. Maximum production of nitrogen oxides occurs at about the same air-fuel ratio as maximum fuel economy, since both are functions of peak flame temperature. Carbon monoxide and unburned hydrocarbon emissions decrease with increasing air-fuel ratio, although a practical limit is reached with conventional systems at about 18, where mis-fire begins and hydrocarbon emissions turn up again.

Increasing compression ratio allows more efficient use to be made of the heat energy in fuel. For example, at constant performance, an increase in C. R. from 8:1 to 9:1 would improve fuel economy 5 - 6 %. However, the higher peak flame temperatures associated with this change would also produce an increase in nitrogen oxide production.

Engine load is another important parameter affecting fuel economy. The greatest relative economy is obtained at wide open throttle operation. At any reduced load (reduced intake manifold pressure) the engine must work harder to pump the air-fuel charge into the cylinders. These pumping losses are a minimum at full-load operation. In practice, maximum fuel economy is not obtained at a vehicle's top speed, since increased wind resistance and road friction losses more than compensate for increased engine efficiency. However, for a given vehicle weight at a given speed, a small engine operating closer to full load will have better fuel economy than a large engine throttled back.

Exhaust gas recycle is commonly used to reduce nitrogen oxide formation. It functions by lowering peak flame temperatures and thus might be expected to harm fuel economy. However, because EGR requires an increased intake manifold pressure (wider throttle opening) to maintain constant power output, the engine has less pumping and throttling losses and can compensate for most of the efficiency lost by lower peak flame temperatures. In order to take maximum advantage of this trade-off, it must be borne in mind that EGR also decreases flame speed. Therefore, spark timing must be advanced to allow proper combustion time. Spark timing must also be adjusted for changes in air-fuel ratio as flame speed also changes with this parameter.

The foregoing has discussed peak flame temperature as related to fuel economy and nitrogen oxide formation. It is also necessary to consider a related parameter, exhaust gas temperature, and its relation to emission control. Generally, the higher the peak flame temperature, the more heat energy which can be extracted from the combustion chamber, hence the lower the exhaust gas temperature. However, in order to control emissions by homogeneous or heterogeneous reactions outside of the engine, high temperatures are desirable. Thus we must examine the balance between temperature and emission control.

Thermal reactors require temperatures in excess of 1500°F to achieve satisfactory homogeneous control of carbon monoxide and hydrocarbons to the most stringent statutory levels. Normal exhaust gas temperatures are in the 1000°F range. Therefore, a substantial increase in exhaust temperature or in available heat of combustion in the exhaust is required for these devices. The most fuel economical method of supplying the needed heat is to richen the air-fuel ratio. This will supply excess carbon monoxide and hydrocarbons, which, when combusted in the reactor, will maintain it at its operating temperature.

Practical considerations militate against using this approach solely, so a combination of enrichment and spark retard, which also increases exhaust temperature, but at a greater fuel economy penalty, is necessary. A third method, lowering the compression ratio, imposes a still higher fuel penalty. Fuel economy debits of 20 - 25% compared to uncontrolled cars are typical for thermal reactors controlling emissions to the stringent statutory levels of 3.4 g/mi. of CO and 0.41 g/mi. of HC.

On the other hand, catalytic oxidation of carbon monoxide and hydrocarbons proceeds efficiently at temperatures associated with normal exhaust temperatures. Thus fuel economy debits of the type associated with thermal reactors are not necessary. The engine can be tuned for maximum operating efficiency without regard to exhaust temperatures. Therefore, oxidation catalysts allow decoupling of emission control from engine operation.

Unfortunately, catalytic reduction of nitrogen oxide is not as independent of engine operation as is catalytic oxidation of carbon monoxide and hydrocarbons. The reduction catalyst requires a reducing atmosphere, hence the engine must be run at an air-fuel ratio richer than stoichiometric. This means a fuel penalty will be incurred compared to an uncontrolled car even if all other engine parameters are optimized. In addition, most reduction catalysts require operating temperatures in excess of normal exhaust levels, so further inefficiencies would be necessary. It would be desirable to have a reduction catalyst capable of efficient conversion at normal exhaust gas temperatures. Ruthenium-containing catalysts have this potential, but to date neither they nor their high temperature base metal counterparts have exhibited satisfactory durability.

In summarizing all of these considerations, we can compare a pre-control, 1967, 4000 lb. vehicle in fuel economy with that predicted for vehicles equipped with thermal or catalytic control systems to meet several emission standards. First, a 1974 vehicle relying on engine modifications only, including a compression ratio of 8.2:1, to meet this year's standards shows approximately a 14% debit in fuel economy. Thermal reactor vehicles, which can tolerate leaded fuel and therefore operate at compression ratios of 10:1, could meet the 1974 standards with about a 6% debit and the 1975 United States interim standards for carbon monoxide and hydrocarbons with about a 12% debit. In meeting the more stringent California interim and future U. S. standards, rich thermal reactors are required and the debit should rise to the 20 - 22% level. Finally, if the statutory 1977 nitrogen oxide level of 0.4 g/mi. is to be achieved with a thermal system, the debit should reach approximately 25%.

Catalytic systems on the other hand, cannot use leaded fuels. They will therefore be designed with compression ratios in the range of 8:1 to accomodate lower octane unleaded fuels. Even so, their lower operating temperatures should result in better fuel economy. Thus the 1975 interim standards for carbon monoxide and hydrocarbons should be achievable at a fuel economy debit of only about 6% from pre-controlled levels. The more stringent 1976 standards should cause a rise to only about 8%, and even the 1977 standard for nitrogen oxide will produce only about a 12% debit.

Experimental Results

The relationship between fuel economy and exhaust emissions has been studied with two types of systems. The first uses a noble metal monolithic oxidation catalyst to control hydrocarbon and carbon monoxide emissions and exhaust gas recycle to limit nitrogen oxide emissions. The second system is a dual catalyst configuration, with a reduction catalyst for nitrogen oxide control followed by the oxidation catalyst. Air is injected between the two catalysts to convert the exhaust gas to a net oxidizing composition.

The oxidation catalyst-EGR system was mounted on a 1973 vehicle with a 350 in^3 displacement engine. The stock vehicle, equipped with a non-proportional EGR system, gave emissions, in g/vehicle mile as tested on the 1975 Federal Test Procedure, of 21.4 CO, 1.3 HC, and 3.3 NO_x. Its fuel economy over the same test cycle was 10.40 miles per gallon. As modified with oxidation catalysts and a proportional EGR system, that is one responding directly to the exhaust gas flow rate, the test vehicle easily met the 1976 statutory CO and HC standards of 3.4 and 0.41 g/mile respectively. With the timing advanced for good fuel economy, not only was the stock NO_x emission level matched, but a 7% gain in fuel economy was achieved. Retarding the timing lowered NO_x emissions further, but at some cost in fuel economy. Work is continuing in an effort to optimize the factors influencing the NO_x emission-fuel economy trade-off with this system.

The dual catalyst system was mounted in a 1973 vehicle similar to the base car described above. In this case, no EGR was used on the modified car. The reduction catalyst was the GEM reinforced Ni-Cu material made by Gould, Inc. With the dual catalyst configuration, as described earlier, catalyst temperature is the primary determinant of fuel economy and NO_x emissions. The temperature was varied by a combination of air-fuel ratio and spark timing control. The statutory 1976 standards for CO and HC emissions were met at all temperatures, but NO_x was dependent on catalyst temperature. At an average catalyst temperature around 1100°F,, an emission level of 1.7 g/mile was achieved, with fuel economy comparable to the unmodified vehicle. At 1200°F., NO_x emissions were controlled to 0.9 g/mile, but a fuel economy debit of 4% was incurred. Finally, the 1977 statutory standard of 0.4 g/mile was reached at 1300°F., with a fuel economy debit of 10%.