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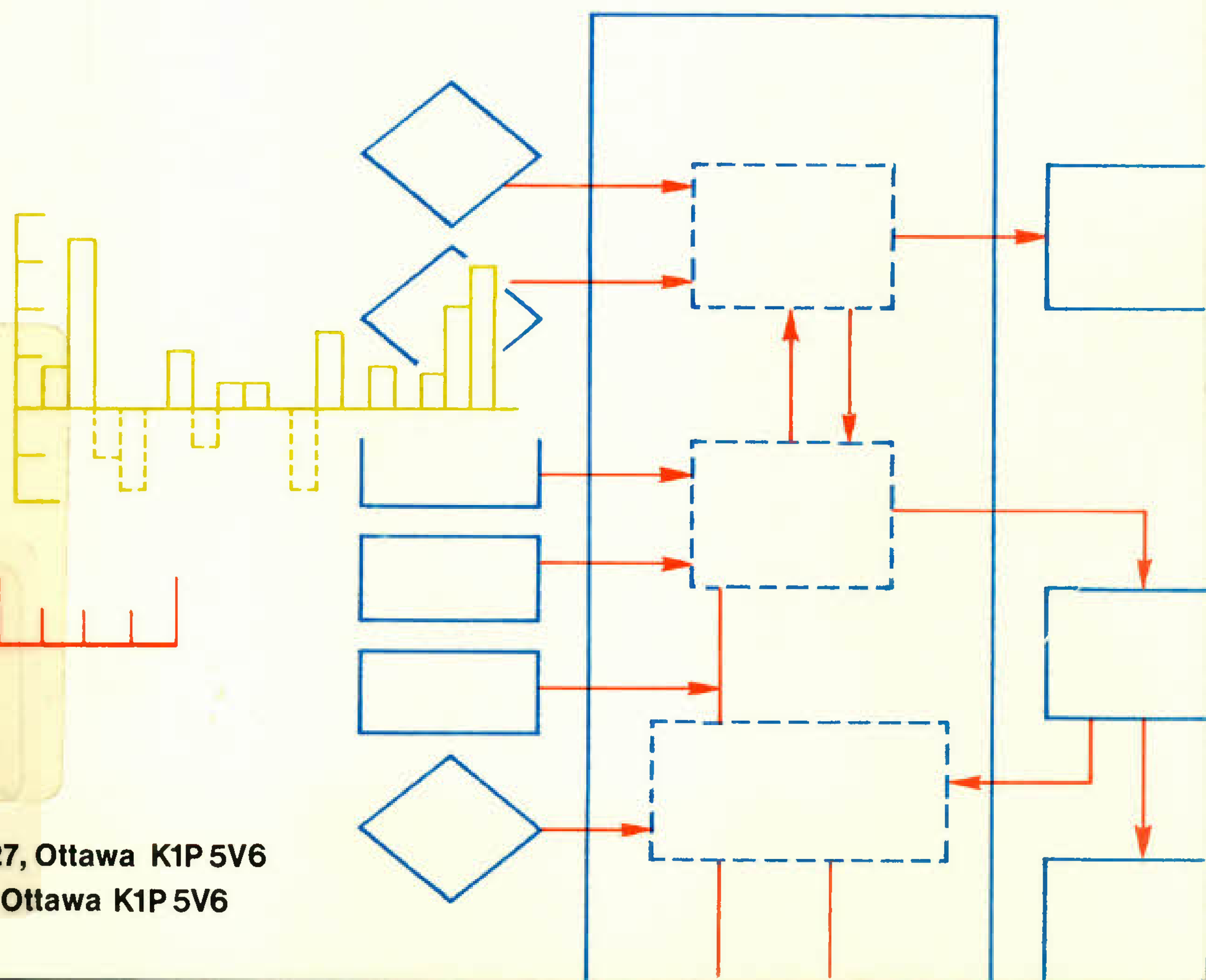

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DISCUSSION PAPER NO. 41

Automobile Emission Control: Means and Costs

by Julian R. Walker

October 1975

RÉSUMÉ

Ce document porte sur la technologie et les coûts du contrôle des émissions de polluants par les automobiles. Il vise à présenter au profane diverses méthodes de contrôle et à décrire les techniques en usage de même que celles qui seront probablement mises au point d'ici quelques années. Mentionnons, notamment, des modifications à la conception même du moteur à combustion interne, l'utilisation d'accessoires externes, ou le traitement des gaz d'échappement, ainsi que d'autres possibilités, comme le moteur diesel et le moteur à combustion généralisée.

L'auteur calcule les coûts des diverses techniques en tenant compte de deux types de réglementation, soit le maintien des normes d'émission en vigueur en 1975 et l'adoption des normes plus sévères envisagées pour 1977 aux États-Unis. Il estime et extrapole jusqu'à 1985 les coûts des immobilisations, du carburant et de l'entretien, en se fondant surtout sur des données de la U.S. National Academy of Sciences. Il montre que le coût total du programme de contrôle des émissions pour les années 1966 à 1985, sous l'hypothèse du maintien des normes actuelles, est comparable à celui d'autres grands projets entrepris ou envisagés au Canada, comme celui de la baie James et la construction du pipe-line de la vallée du MacKenzie.

Abstract

This paper examines the technology and costs of automobile emission control. A layman's guide to various approaches to emission control describes the technology currently in use as well as that likely to appear in the medium-term future. Approaches involving design or "bolt-on" modifications to the conventional internal combustion engine and/or the treatment of exhaust gases are described, as are certain alternative engines -- in particular, the diesel and the stratified charge engine.

Costs are developed for the various technologies under two regulatory environments -- maintenance of the present 1975 emission standards and adoption of the stricter proposed U.S. 1977 standards. Capital, fuel, and maintenance costs are estimated, based largely on U.S. National Academy of Sciences data, and extrapolated to 1985. The total cost of the emission control program from 1966 to 1985, assuming maintenance of the present standards, is shown to be of the same order of magnitude as other large projects undertaken or proposed in Canada, such as the James Bay project and the MacKenzie Valley pipeline.

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Chapter 1

INTRODUCTION

The automobile plays a central role in the lifestyle of the people in most developed countries. Not only does it perform the obvious function of a means of transportation, but the car also provides an opportunity for expression of individuality and is often regarded as a symbol of socio-economic status. From an environmental viewpoint, the automobile is enormously energy-intensive and an important source of airborne pollutants. This paper is largely concerned with the automobile in the latter context. The material presented here was undertaken as part of the work of the Social Indicators Group on environmental indicators and trends.[1]

The automobile is an important direct contributor to atmospheric concentrations of three pollutants: these are carbon monoxide, hydrocarbons, and nitrogen oxides. In 1970, the Federal Department of the Environment estimated that gasoline and diesel powered motor vehicles accounted for about 75 per cent, 65 per cent, and 55 per cent, respectively of the total nationwide emissions of these three pollutants.[2]

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[1]See, for example, D. M. Paproski and J. R. Walker, "Air Quality in Canadian Urban Areas", Economic Council of Canada, Discussion Paper No. 18 (December 1974).

[2]Environment Canada, *A Nationwide Inventory of Air Pollutant Emissions 1970*, Ottawa, 1973.

Carbon monoxide emissions are, *by weight*, by far the most important of the three, comprising some 14 thousand tons in 1970. In terms of negative effects on human health, however, this pollutant may represent a relatively small problem. The principal health threat posed by carbon monoxide arises when individuals are exposed to extremely high ambient concentrations. Carbon monoxide is more readily absorbed into the blood than is oxygen, leading in extreme situations to oxygen starvation and death. At typical ambient levels, however, any effects are likely to be limited to a slight headache. Recovery from exposure to even considerable levels is extremely rapid, with no apparent chronic effects.

The negative impact of hydrocarbons emitted by automobiles lies mainly in their role in oxidant formation. Oxidants, principally ozone, are the product of a photochemical reaction in the atmosphere, requiring the presence of hydrocarbons and nitrogen oxides. Oxidants are generally thought to represent a fairly serious health threat in the form of aggravation of latent infections of the respiratory system, though they may affect other parts of the body as well.[3]

The oxides of nitrogen, of which nitrogen dioxide is the most important, have a dual impact. First, in their own right, they cause irritation of the respiratory system. Second, as noted above, they are necessary for oxidant formation.

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[3]For a summary of negative effects of oxidants (and other pollutants) and corroborating epidemiological evidence, see D. M. Paproski and J. R. Walker, "Air Quality in Canadian Urban Areas".

Consequently, oxides of nitrogen are probably the most important by-product of automobile use from the viewpoint of air pollution, and their abatement warrants the highest priority.

The strategy adopted by governments to reduce emissions of these three pollutants has been to establish equipment standards applicable to new automobiles, in the form of maximum allowable emissions per mile driven. The first standards were aimed at reducing both the evaporative emissions of hydrocarbons and the emissions of hydrocarbons and carbon monoxide from the crankcase, but since 1970, exhaust emission control for these pollutants has been required. Finally, in 1973, Canadian emission standards were established for nitrogen oxides.

The question of whether such a strategy is an efficient way to reduce emissions is beyond the scope of this paper. Nonetheless, some observations may be made in passing. Such an approach, as presently applied, provides no incentive to the industry for success in achieving the level of control required by the standards, except in the negative sense that failure could lead to considerable problems for the manufacturer. This environment is likely to result in conservative engineering innovations and modest research efforts. A second difficulty is that there may be little incentive for the car owner to maintain the integrity of his or her vehicle's emission control equipment. This may be a particularly severe problem in the case of the new oxidation catalyst systems fitted to some 1975 cars: degradation of the catalyst cannot be detected without testing, and will not affect the operation of the car at all.

The remainder of this paper is concerned with the technical means and costs of automobile emission control. Chapter 2 provides a brief description of the approaches now being used, or likely to appear in the next few years, to the reduction of emissions from the conventional internal combustion engine through design or "bolt-on" modifications and/or through the treatment of exhaust gases; there is also a discussion of alternative engines, and the extent to which they emit pollutants and consume energy relative to the conventional engine. In Chapter 3, estimates of capital and operating costs of these various possibilities are presented, and some aggregate estimates developed for the costs of automobile emission control up to 1985.

Chapter 2

THE TECHNOLOGY OF EMISSION CONTROL

Various means of reducing emissions have been developed by the automobile industry in response to specific maximum allowable emission levels established by governments for hydrocarbons, carbon monoxide, and nitrogen oxides. Emission standards for Canada and the United States are shown in Table 1 and can be compared to an estimate of the (relatively) uncontrolled average emissions for the Canadian automobile fleet in 1970. It should also be noted that California sets its own emission standards, which are stricter than the so-called "49-state" or "Federal" U.S. standards. One result of this has been that most automobile manufacturers produce two or three versions of the same model, and some models are not available in California.

Table 1

AUTOMOBILE EMISSIONS

		Hydro-Carbons	Carbon Monoxide	Nitrogen Oxides
		(grams per mile)		
Canada -- 1970 fleet average		19.0	125.0	6.0
Standards				
(1) Canada	1973	3.00	28.00	3.10
	(percentage reduction relative to 1970 fleet average)	(84.2)	(77.3)	(48.2)
	1975-76	2.00	25.00	3.10
	(percentage reduction relative to 1970 fleet average)	(89.4)	(79.8)	(48.2)
(2) United States	1975	1.50	15.00	3.10
	1977 (originally 1976)	0.41	3.40	2.00
	1978	0.41	3.40	0.40
(3) California	1975	0.90	9.00	2.00

Sources: *A Nationwide Inventory of Air Pollutant Emissions 1970*, Environment Canada, Ottawa, 1973; and *Report by the Committee on Motor Vehicle Emissions*, National Academy of Sciences, Washington, D.C., 1974.

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Although the strategy that has been adopted to date by most automobile manufacturers involves "bolt-on" or relatively minor design modifications of the conventional internal combustion engine, and/or treatment of the exhaust gases, it has now become apparent that this strategy will not necessarily enable manufacturers to meet the anticipated U.S. emission limits for 1978.[4] This has focused considerable attention on alternative engine designs such as the stratified charge,[5] diesel, Stirling, and Wankel engines. This chapter describes the emissions problem, and then discusses the hardware presently in use or likely to be used in the future, and finally, evaluates the alternative engine types mentioned above.

The Emission Problem

There are three main sources of pollutant emissions in a conventional automobile: blow-by gases from the crankcase, evaporation of hydrocarbons from the fuel system, and exhaust gases. The first two of these sources have been virtually eliminated since 1968: crankcase gases are recycled through the engine by the "positive crankcase ventilation (PCV)" system, and evaporative emissions are filtered and returned to the carburetor. Exhaust emissions, on the other hand, remain a significant source of airborne pollutants, in spite of the

[4]The conventional internal combustion engine refers to the multi-cylinder four-stroke or Otto-cycle overhead-valve engine which powers most automobiles and some motorcycles and trucks.

[5]For the purposes of this study, the stratified charge engine is regarded as an alternative engine design. Although, in principle, it is an Otto-cycle engine, it represents a modification of the conventional design which is sufficiently different that it can be considered in the alternative category. The diesel can also, in principle, be regarded as a type of stratified charge, but it is treated separately in this document.

substantial reduction of emissions from new cars,[6] and this paper will be concerned exclusively with this aspect of the automobile.

The conventional internal combustion engine consists of one or more reciprocating pistons in relatively airtight cylinders. An air-fuel mixture is introduced into the cylinder through the intake manifold and intake valve. When the piston has reached the top of its motion and compressed the mixture, a spark from the spark-plug ignites this mixture, and the resulting rapid expansion of gases forces the piston back down the cylinder. When the piston returns to the top of the cylinder, the spent gases are forced out of the exhaust valve and the cycle starts again. The reciprocating motion of the piston is translated into rotary motion by the crankshaft, which, in turn, provides power to the drive wheels through the transmission and driveshaft. The first practical engine of this type was built by a German engineer, Nikolaus Otto, in 1876 and consequently is usually referred to as the Otto engine.

The fuel burned in the Otto engine is a mixture of hydrocarbons refined from crude oil. Under ideal conditions, this fuel could be burned in oxygen, producing heat, carbon dioxide (CO_2) and water (H_2O). In practice, however, the fuel is burned in ambient air which contains a high proportion of nitrogen, which, at typical combustion temperatures, undergoes some oxidation to form oxides of nitrogen (NO_x). In addition,

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[6]See Environment Canada, *Automobile Emission Trends in Canada, 1960-1985* (Ottawa, 1973): however, one problem is basically that vehicle miles travelled is increasing fast enough to eventually offset reductions in per-mile emissions.

the hardware required to accurately control the air-fuel mixture over the wide range of operating conditions typically required of automobile engines is expensive; the conventional venturi carburetor represents a trade-off between cost and efficiency which results in less-than-perfect mixture control. As a result, the fuel is never completely oxidized, and the incomplete combustion produces hydrocarbons (HC) and carbon monoxide (CO).

Finally, since the formation of the nitrogen oxides is greater at higher temperatures, and, other things being equal, more complete combustion results in higher temperatures, there tends to be an inverse relationship between emissions of the nitrogen oxides and those of carbon monoxide and hydrocarbons as the air-fuel ratio is altered around the stoichiometric point.[7] Although the emission of nitrogen oxides drops off as the air-fuel ratio increases beyond a certain point of leanness (the dilution lowers the combustion temperature), not only does the emission of hydrocarbons, in particular, increase concurrently, but, as well, the fuel consumption rises and the power output drops notably. These relationships are described graphically in Chart 1.

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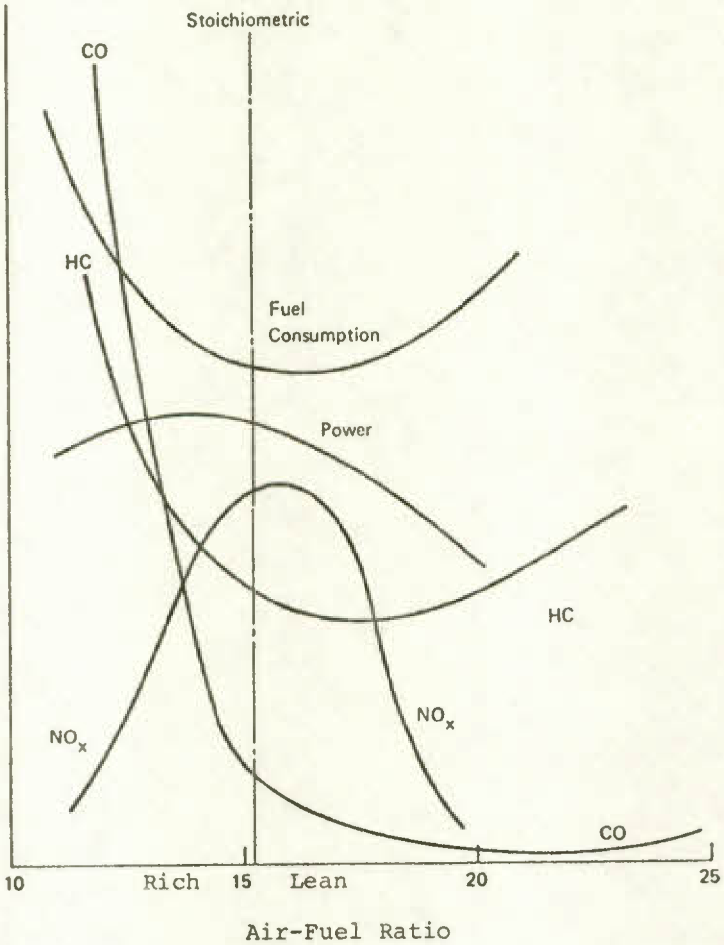
[7]The first emission limits for automobiles controlled only carbon monoxide and hydrocarbons. The effect of this was that emissions of the nitrogen oxides actually increased in new cars before 1970.

Chart 1

THE RELATIONSHIP OF TYPICAL ENGINE EMISSIONS AND PERFORMANCE TO THE AIR-FUEL RATIO[1]



[1]The vertical scale is linear and shows relative rather than absolute values for each parameter.

Source: *Report by the Committee on Motor Vehicle Emissions*, National Academy of Sciences, Washington, D.C., November 1974.

As the foregoing discussion implies, automobile emission control is not simply a matter of ensuring more complete or efficient combustion. Rather, it is necessary to control the combustion so that hydrocarbons are oxidized as completely as possible, and yet gas temperatures are kept low enough to prevent the formation of nitrogen oxides. Automobile manufacturers have, by and large, been able to achieve this, at least to the extent required by the (shared) Canada-United States 1973 emission standards, largely by means of combustion modification. Basically, this has entailed more precise mixture control and a lean air-fuel ratio (more air than stoichiometric) to control hydrocarbons and carbon monoxide, and *exhaust gas recirculation* and lower *compression ratios*[8] to prevent nitrogen oxide formation. However, the U.S. 1975 standards have led to a basic change in approach: most engines in common use require a *catalytic converter* to oxidize hydrocarbons and carbon monoxide in the exhaust system so as to meet the standards.[9] Finally, the even more restrictive 1977 U.S. standards have led to interest in the use of more radical variants of the internal combustion principle, such as the stratified charge engine, and to renewed interest in the use of diesel engines to power passenger cars. In the remainder of this section, the hardware required in these three approaches will be described under the headings of *combustion modification*, *exhaust gas treatment*, and *alternative engine types*.

Combustion Modification

The goal of combustion modification is more complete combustion at lower temperatures. There are three main engine parameters that can be altered to achieve this: the fuel delivery system, the ignition system, and the physical attributes of the combustion chamber.

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[8] The compression ratio is the ratio of the volume of the combustion chamber when the piston is at the bottom of its motion to the volume when it is at the top.

[9] Because of the different standards in different jurisdictions, the use of actalytic converters is not general. Virtually all California cars, many "Federal" U.S. cars, and some Canadian cars are equipped with converters for 1975. The Canadian standards for 1975 are less restrictive for carbon monoxide and hydrocarbon emissions than the U.S. 1975 standards, and the former standards are met in some cases without the application of a catalytic converter. However, the adjustments necessary in the absence of a converter have an adverse effect on fuel economy.

(a) *Fuel Delivery Systems*

Most North American automobiles are equipped with carburetors. Ambient air is drawn through the carburetor barrel by a partial vacuum in the intake manifold, which is induced by the downward movement of the piston. A section of the barrel is constricted, causing increased air velocity. This venturi effect draws gasoline up from the float chamber through one or more jets into the air flow. This air-fuel mixture then passes into the intake manifold where further mixing takes place, and then into the cylinder through the intake valve.

The lean mixture required for emission control can be obtained by means of a simple adjustment to allow less gasoline to mix with the airflow. However, unfortunately, the carburetor must deliver the required mixture over a wide range of air temperatures, throttle openings and engine speed. This problem is further compounded by the fact that automobile engines have more than one cylinder and mixture control at the carburetor does not imply mixture control in each cylinder: the latter requires uniform distribution of the fuel charge in the intake manifold. The effect of these considerations has been that although carburetor development in the past few years has achieved mixture control at the carburetor of ± 5 per cent, the charge in the cylinders varies by much more than this (as much as ± 20 per cent).[10]

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[10] *Report by the Committee on Motor Vehicle Emissions*, National Academy of Sciences, Washington, D.C., 1974, p. 47.

Fuel injection provides better mixture control and uniform cylinder-to-cylinder charge distribution. Each cylinder head is fitted with an injector nozzle which squirts the required amount of gasoline into the combustion chamber. The size of the "squirt" is determined by either electronic or mechanical sensing of the mass of air flowing into the cylinder. However, in spite of the superior mixture control characteristics of fuel injection, its use in automobiles manufactured in North America is unlikely in the immediate future because there is no large-scale domestic producer of fuel injection systems.[11]

The development of more controllable carburetors and the potential use of fuel injection make possible the use of continuous *feedback control systems*. In such a configuration, electronic sensors monitor the composition of exhaust gases in the tail pipe and relay this information to the fuel delivery system, which adjusts the mixture accordingly. This control is required because the effectiveness of dual and three-way catalytic converters is critically dependent on the composition of exhaust gases. This will be discussed in more detail in a later section.

The hardware described above facilitates the control of hydrocarbon and carbon monoxide emissions through effective delivery of lean air-fuel mixtures to the combustion chambers.

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[11]It is interesting to note that in the early 1960's, Rochester mechanical fuel injection was offered as an option on the Chevrolet Corvette. Production was discontinued in 1965.

However, moderately lean mixtures tend to result in higher combustion temperatures, and hence, the increased formation of the oxides of nitrogen. This can be attenuated if exhaust gases are introduced into the ambient air with which the fuel is mixed. This technique, known as *exhaust gas recirculation* (EGR) is in use on most cars produced since 1973. The proportion of exhaust gas in the mixture (usually about 15 per cent) is varied according to engine operating conditions and is controlled by the degree of manifold vacuum. Unfortunately, at the levels required to control nitrogen oxide emissions, EGR has detrimental effects on driveability and fuel economy.[12]

Finally, attempts have been made to increase the homogeneity of the fuel charge. Most 1975 model cars have some type of fuel evaporation device to preheat the mixture. In addition, more radical systems are in the experimental stage, such as the *catalytic fuel reformer* which transforms gasoline to hydrogen and carbon monoxide, promoting the combustion of lean mixtures.

(b) *The Ignition System*

The air-fuel mixture is ignited in the combustion chamber by a spark which is caused by the sudden application of a high potential difference (25,000 volts is common) across the gap of a spark plug. The potential difference is produced by the *coil* and the timing of the spark is achieved by a

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[12]At very low levels, EGR acts as an anti-knock agent and actually increases fuel economy.

cam-operated switch (the points). The spark is sent to each cylinder successively, according to the firing order of the engine, by the distributor. Finally, the degree of spark advance -- that is, the extent to which the spark precedes the arrival of the piston at "top dead centre" -- is typically controlled by manifold vacuum: the degree of advance is increased when the engine is running faster, and when the throttle is opened.

From the viewpoint of emission control, there are two problems related to ignition. First, occasional misfiring results in large emissions of unburned hydrocarbons, and second, full spark advance at low engine speeds also increases hydrocarbon emissions and, through higher temperatures, nitrogen oxide formation.

Misfiring is caused by wear and tear of the points, and by spark-plug fouling. Both these problems have been eliminated by the adoption of high-energy *capacitor discharge ignition* systems (CDI) -- an entirely electronic system with no moving parts, which delivers a higher potential difference across the spark-plugs, preventing fouling. It should be noted that CDI is the only device developed (at least in part) to reduce emissions, which actually improves the efficiency of the internal combustion engine.

Finally, spark advance is prevented at low engine speeds by overriding the automatic vacuum mechanism. This results in a loss in fuel economy and driveability. Fortunately, the advent of catalytic converter systems has rendered the spark advance "stopper" unnecessary on converter-equipped cars.

(c) *Physical Attributes of the Combustion Chamber*

Placement of valves and spark-plugs, and the shape of the top of the piston can affect the extent of combustion because of their effect on cylinder gas turbulence and flame propagation. Within the constraints of the conventional overhead valve spark ignition engine, these parameters have already been optimized. However, the stratified charge engine, which is discussed in a later section, is a recent development of this aspect of engine design.

The extent to which the air-fuel mixture is compressed in the cylinder is an important determinant of cylinder gas temperature, and, hence, nitrogen oxide emissions. This aspect of engine design is measured by the compression ratio defined earlier. Basically, raising the compression ratio increases the specific output of the engine and combustion temperatures, and improves fuel economy. High compression engines also require higher-octane, "leaded" gasoline to prevent knocking. To reduce nitrogen oxide emissions, and also to permit the use of low-lead gasoline (thereby reducing lead emissions) compression ratios have been substantially reduced since 1969.[13] It should also be mentioned, in passing, that lead in gasoline acts as a cushioning lubricant on valve seats: the use of low-lead fuel has made induction hardening of valve seats necessary.

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[13]The average compression ratio now is probably about 8:1, compared to pre-1970 levels of at least 9:1, with some as high as 12:1.

In summary, the combustion modification devices discussed above have enabled automobile manufacturers to meet the 1973 standards, resulting in a reduction of emissions from new cars of at least 84 per cent, 77 per cent and 48 per cent for hydrocarbons, carbon monoxide, and oxides of nitrogen, respectively, from the uncontrolled average levels (see Table 1). However, this reduction in emissions has been obtained at the expense of fuel economy and driveability. The former is a direct and quantifiable cost to the car operator -- gas mileage has been reduced by about 20 per cent for an average North American-produced car. The latter also imposes a cost in the form of stumbling and hesitation on acceleration as a result of lean mixtures, difficult starting, and substantial power loss. These "convenience" losses are not directly quantifiable,[14] but are real costs nonetheless.

Exhaust Gas Treatment

The object of exhaust gas treatment is to eliminate pollutants in the exhaust system, allowing retuning of the engine for better performance and fuel economy. However, while this has been achieved to some extent with air injection and oxidation catalysts, the very low U.S. emissions limits for 1977 require hardware whose effectiveness is critically dependent on the composition of exhaust gases, and hence, on mixture control.

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[14]For an example of how these costs might be measured, at least in the case of horsepower reductions, see D. N. Dewees, *Economics and Public Policy: The Automobile Pollution Case*, MIT Press, Cambridge, Mass., 1974.

The devices discussed below oxidize unburned hydrocarbons and carbon monoxide in the exhaust system, leaving water and carbon dioxide. In addition, reduction and "three-way" catalysts reduce oxides of nitrogen to elemental oxygen and nitrogen.

Air Injection

A compressor pump is used to force air into the exhaust manifold where it reacts with the hot exhaust gases, reducing hydrocarbon and carbon monoxide emissions. The pump is driven by a belt, in the same manner as the fan and alternator on a conventional engine. The only drawback of air injection is that the air pump may require as much as five horsepower to operate, reducing the net output of the engine.

Thermal Reactor

The thermal reactor is a chamber in the exhaust system which encourages the spontaneous oxidation of hydrocarbons. The efficiency of the thermal reactor is greatly increased if it is used in conjunction with air injection, and while originally it required mixtures with low (rich) air-fuel ratios, new designs have enabled its use with high (lean) air-fuel ratios.

Catalytic Converters

Three types of catalytic converters have been developed: oxidation converters increase the reaction rate of oxidation of hydrocarbons and carbon monoxide in exhaust gases, reduction converters reduce oxides of nitrogen, and three-way converters perform both functions. All three consist of a chamber through which exhaust gas flows, passing over a catalyst bed.

(i) <u>Oxidation converters</u> are in use on many 1975 automobiles in the United States, and on some (mainly General Motors) cars in Canada. The catalyst uses a mixture of platinum and palladium and is in one of two forms: General Motors and American Motors use catalyst-coated aluminum oxide pellets, while Chrysler and Ford use a coated ceramic honeycomb structure. Both types have been demonstrated to yield reductions of carbon monoxide and hydrocarbon emissions of about 83 per cent and 90 per cent respectively, when used in conjunction with conventional emission control devices.

Converter-equipped cars can tolerate richer mixtures and do not require low-speed spark retard. As a result, driveability and fuel economy are substantially improved. However, these cars must use only unleaded gasoline: otherwise lead is deposited on the catalyst, destroying its effectiveness. Engineers are divided on the amount of leaded fuel which the catalyst will tolerate, but some estimate that as little as two or three tankfuls would destroy the converter. As a result, the United States Environmental Protection Agency requires all service stations with annual sales in excess of 200,000 gallons to stock unleaded gasoline, and provides for a maximum fine of $10,000 if a station puts leaded gas into a converter-equipped car. In addition, cars fitted with converters have a valve on the gas filler pipe which will only accept the smaller unleaded pump nozzle.

The catalyst can also be destroyed by excessive heat. In fact, under some circumstances, the catalytic reaction itself can generate enough heat to ruin the converter. This can occur if the exhaust gases contain too high a proportion of unburned hydrocarbons, which can result from engine misfiring or poor timing, and sudden mixture richening resulting from rapid deceleration. Electronic (CDI) ignition virtually eliminates the possibility of ignition failure, but the second problem has required the addition of a deceleration valve to prevent the carburetor from returning to the idle position too quickly when the throttle is released.

(ii) Reduction converters require rich air-fuel mixtures and tight mixture control: excess air in exhaust gases can result in overheating and catalyst failure. The 1977 U.S. standards will probably require the use of a dual catalyst configuration in most North American-produced automobiles. The simplest version consists of a reduction catalyst near the exhaust manifold, followed by air injection and an oxidation catalyst. The mixture control necessary for reduction and dual catalyst systems will require better carburetors or fuel injection, possibly with sensors and continuous feedback control. As a result of the richer mixture needed, fuel economy is reduced compared to the oxidation catalyst alone.

(iii) Three-way converters remove all three pollutants from exhaust gases by simultaneous oxidation and reduction. The composition of exhaust gases must be very precisely controlled -- again, feedback to electronic fuel injectors is required. At the present time the three-way converter is the only system which enables a conventional internal combustion engine to meet the very strict 1978 U.S. standards.

In summary, catalytic systems seem to offer the only means of reducing emissions from the conventional engine much below 1975 levels. The inability of converters to tolerate leaded gas poses a serious practical problem in terms of simple availability of lead-free gas. Unleaded gas is also more expensive than regular grades: to achieve a sufficiently high octane rating without lead additives requires a purer feedstock oil or more complex procedures in the refining process. The result of these two factors is likely to be that many catalyst-equipped cars will use leaded fuel, and average emissions will rise. This problem is compounded by the fact that emissions testing procedures to check the effectiveness of the catalysts are expensive and complicated. As a result, not only is there no incentive for the car owner to maintain the effectiveness of his catalyst system, but he also has no simple way of knowing whether it is even working.

Alternative Engine Types

The foregoing discussion suggests that the technological limits of emission control have been reached with the advent of catalytic converter systems, at least in terms of reasonable cost and convenience. However, while this is true for the conventional Otto-cycle overhead valve engine, a number of alternative engine types have emerged which are fundamentally cleaner than the traditional configuration.

Two such engines, the diesel and stratified charge, are currently in at least limited production and consequently will be discussed in this paper. There are, in addition, a number of other designs which have received some attention in the media, some of which may reach the production stage in the 1980's and consequently deserve mention here, at least in passing. The *gas turbine*, in its present form, is too inefficient when scaled down to automobile size. The *Stirling engine*, an external combustion engine roughly comparable to the steam engine, shows some promise because of its high thermal efficiency, but present versions have a very low power-to-weight ratio. The *steam* engine itself has attracted renewed attention, and Saab (the Swedish automobile and aircraft manufacturer) is working on a nine-cylinder swashplate engine which may be in production by 1985. *Electric* motors are already in use in short-range urban vehicles, but the limitations of current storage batteries prevent its consideration as a serious short-run alternative. Finally, the *Wankel* or *rotary* engine has been widely publicized as the engine of the future, primarily because of its high power-to-weight ratio. However, from an environmental standpoint, the rotary engine appears to be a step backwards: its fuel economy is poor in relation to power output, and its emissions are high because of its highly irregular combustion chamber and the rich mixture required. In fact, in the face of substantially higher fuel prices in 1974, Mazda, the only firm committed to the Wankel, suffered a large decline in sales, and General Motors indefinitely postponed its Wankel development project.

The stratified charge engine and the diesel are discussed below in more detail.

Stratified Charge

The stratified charge engine achieves low emissions of carbon monoxide and hydrocarbons by burning an extremely lean mixture. Nitrogen oxide formation is prevented by slower propagation of the flame-front through the compressed mixture, resulting in lower temperatures.

The stratified charge principle, as the name implies, involves the use of a non-homogeneous fuel charge. The charge at the bottom of the combustion chamber is so lean that it could not be ignited by a spark, while the mixture at the top, near the spark-plug, is very rich, and ignites readily. The burning of the rich mixture in turn ignites the lean main charge, resulting in complete combustion and a long, cooler power pulse.

There are a number of practical configurations in various stages of development which make use of the stratified charge principle, but the only such engine currently in production is the Honda CVCC.[15] In the Honda engine, two intake valves are used: one admits a rich mixture to a small prechamber in which a spark-plug is fitted, and the other admits the main lean charge to the combustion chamber. Carburetion is provided by a single three-venturi unit: two barrels provide the mixture for the main charge and the third feeds the prechamber. The more

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[15]Compound Vortex Controlled Combustion, so called because early versions relied on turbulence of the mixture to obtain more complete oxidation of the fuel.

complicated valve gear and carburetor are somewhat more expensive to produce than those of a conventional engine, but this is more than made up for by the fact that with no "bolt-on" modifications or exhaust gas converters, this engine has been shown to meet the proposed U.S. 1977 standards even after 50,000 miles. The addition of exhaust gas recirculation yields a further reduction in nitrogen oxide emissions, but at some cost (roughly 15 per cent) in fuel economy.[16]

Diesel

The diesel differs from the Otto-cycle engine in that ignition is achieved by the heat generated when the mixture is compressed -- no coil, distributor, or spark-plugs are necessary. To generate the necessary heat, a very high compression ratio is required (20:1 is common, compared to about 8.5:1 for a conventional spark ignition engine) and the extra strength needed on the engine block and cylinder heads results in a lower power-to-weight ratio. This factor, coupled with highly visible emissions of particulates, has contributed to preventing general market acceptance of diesel automobiles in North America.

With respect to the three pollutants for which standards exist, the diesel is remarkably clean. In fact, the Mercedes-Benz 240D meets the proposed U.S. 1977 standards with no emission control equipment at all. As in the stratified charge engine, this characteristic of the diesel is a result of an extremely lean air-fuel mixture. The lean mixture also

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[16]*Report by the Committee on Motor Vehicle Emissions*, National Academy of Sciences, p. 67.

gives good fuel economy: the 240D achieved 29.5 miles per gallon with an automatic transmission, using number 2 fuel oil which is typically slightly cheaper than regular grade gasoline.[17] Finally, because no ignition system is used, the diesel exhibits excellent reliability and low maintenance costs.

From the technical point of view, the only disadvantage of the diesel is that although emissions of nitrogen oxides for existing engines is in the range of 1 to 1.5 grams per mile, control to the U.S. proposed 1978 level of .4 grams per mile has not been demonstrated.

Comments

The Canadian 1975 standards can be and are being met with relative ease by a variety of approaches to emission control. Ford Motor Company is employing air injection and a thermal reactor (the "thermactor" system), exhaust gas recirculation, lean mixture and spark retard on most engine options available in Canada. General Motors uses a catalytic converter system and EGR. Finally, some European manufacturers have met the standards by the superior mixture control afforded by fuel injection. In short, Canada has clearly benefited from the emission control technology developed in other countries.

Stricter standards in the future (such as the proposed U.S. 1977 levels) would require the more complex, and expensive dual and three-way converter systems, or a switch to alternatives such as the diesel or stratified charge engines. In this

[17] *Report by the Committee on Motor Vehicle Emissions*, National Academy of Sciences.

context, it is important that policy-makers and the public be aware of new developments in emission control technology that may have a beneficial effect on ambient air quality, and of the costs associated with these developments. In the following chapter, costs are developed for two options: continuation of the present standards, or imposition of the 1977 U.S. levels.

Chapter 3

THE COST OF EMISSION CONTROL

In this chapter, the cost of automobile emission control is estimated by first estimating the cost of achieving the appropriate standard for a "typical" car in a given year (1966 through 1985). This cost is then multiplied by the actual (for 1966 through 1974) or anticipated (for 1975 through 1985) new car sales for the year in question to obtain the total cost of the emission control program. In the interest of simplicity, demand effects resulting from new car price increases are ignored; the analysis also does not take into account such market trends as the move to smaller cars and the continuing increase in price of fossil fuels.

Two regulatory scenarios are investigated. First, costs associated with a continuation of the Canadian 1975 emission standards until 1985 are estimated. Second, costs are estimated for four systems which meet, or may be expected to meet with further development, the proposed U.S. 1977 standards, and these costs are extended over the market until 1985. In all cases, the costs estimated are the extra costs associated with the reduction in emissions.

Methodology

The average cost per car of emission control in a given year depends on the system or mix of systems under consideration, and consists of three components. These are the capital costs, the additional maintenance costs, and the extra fuel costs associated with the approaches being used to reduce emissions. The point of reference is the pre-1966 automobile which is considered to be uncontrolled, and therefore to have no capital or maintenance costs associated with the reduction of emissions.

All costs are reduced to a present value basis. Capital costs are already in present value terms, but fuel and maintenance costs must be converted. To achieve this, a car is assumed to last eight years, and to be driven 10,000 miles per year on average. Annual maintenance costs associated with the reduction of emissions are then discounted to the time of purchase. Fuel costs are obtained by deriving consumption in gallons from average fuel economy and an assumed price for the type of fuel required by the engine under consideration. The extent to which this annual fuel cost exceeds the fuel cost of an uncontrolled pre-1966 automobile is, after correction for vehicle weight, the fuel cost attributable to emission control.[18] This annual cost is then discounted to the time of purchase.

The total cost of emission control for any one model year is obtained by multiplying the sum of capital, fuel and maintenance costs for the "typical" car by the number of new cars sold that year. New car sales for the years 1975-85 were estimated on the basis of an assumed constant growth of 3.34 per cent per annum; this rate affords the best fit for the preceding

[18] The fuel costs for an uncontrolled pre-1966 automobile are estimated from the costs experienced over the period 1957 to 1965.

eleven years. For the scenario involving the imposition of the proposed 1977 U.S. standards, the total market for 1977 and thereafter was split among the four systems which meet or may be expected to meet these standards (the dual catalyst or three-way catalyst treatment of exhaust gases from a conventional engine, the stratified charge engine, and the diesel), and account was taken of the respective costs and anticipated market acceptance of these systems.

Finally, all costs are evaluated in constant 1972 Canadian dollars, and a discount rate of 5 per cent per annum is used. Although this discount rate may seem low, it should be borne in mind that since costs are in constant dollars, this is a real rate; with a rate of inflation of 10 per cent per annum, this corresponds to a nominal rate of 15 per cent per annum.

Capital Cost

(a) *1966-1976 automobiles*

The capital costs of emission control equipment commonly used to meet standards over the period 1966-75 are shown in Table 2; the total accumulated costs for 1976 are assumed to be the same as for 1975.[19] These estimates are based on those reported by the U.S. National Academy of Sciences.[20] They include neither federal nor provincial taxes, and have been converted to Canadian dollars (see Appendix A for details of the estimation of the differential between U.S. and Canadian car prices).

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[19]The capital costs discussed here are for a six-cylinder car. These are intended to serve as a proxy for all engine sizes.

[20]*Manufacturability and Costs of Proposed Low-Emmission Automotive Engine Systems*, National Academy of Sciences, Washington, D.C., 1973.

Table 2

EMISSION CONTROL CAPITAL COSTS PER AUTOMOBILE, 1966-75

(1972 Canadian dollars)

		Costs[1]	Total Additional Costs for Year	Total Accumulated Cost Over Uncontrolled Car[2]
1966	*PCV system	3.16	3.16	3.16
1968	*Evaporative control	15.82	15.82	18.98
1970	*Transmission control	4.22		
	*Compression ratio change	2.11		
	Ignition timing change	1.05		
	Carburetion change	1.05		
			8.43	27.41
1971-72	Carburetion change	8.86		
	*Idle control solenoid	5.27		
			14.13	40.49[3]
1973	*Air injection system	48.07		
	Exhaust gas recirculation	10.55		
	*Hardened valve seats (4-, 6-cylinders)	2.11		
	*Transmission changes	1.05		
	Spark advance control (ignition system)	1.05		
			62.83	102.27[4]
1974	*Cam, bore and piston changes	4.22		
	Hardened valve seats (V-8)	2.11		
			6.33	106.49[5]
1975	Catalytic converter	60.74		
	Proportional exhaust gas recirculation	33.32		
	Carburetion changes	26.36		
	Electronic ignition	13.71		
	Miscellaneous changes	10.54		
			144.67	230.70[6]

*Added to 1975 items to obtain 1975 cost over the cost of an uncontrolled pre-1966 car.

[1]These costs exclude the 12 per cent Canadian federal manufacturers' sales tax.

[2]Where the same factor is treated more than once (e.g., carburetion) only the cost of the latest change in this factor is included in the accumulated total to that date.

[3]Obtained by adding the costs for the 1971-72 changes to the accumulated total for 1970 and subtracting the cost of the earlier carburetion change ($1.05).

[4]Obtained by adding the cost for the 1973 changes to the accumulated total for 1971-72, and subtracting the cost of the earlier change in the ignition system ($1.05).

[5]Obtained by adding the cost for the 1974 changes to the accumulated total for 1973 and subtracting the cost of the earlier hardening on the valve seats ($2.11).

[6]Obtained by adding the cost for the 1975 changes to the accumulated total for 1974 and subtracting the cost of the earlier exhaust gas recirculation ($10.55 in 1973), the cost of the most recent carburetion change ($8.86 in 1971-72), and the cost of the most recent change to the ignition system ($1.05 in 1973).

Sources: *Manufacturability and Costs of Proposed Low-Emission Automotive Engine Systems*, National Academy of Sciences, Washington, D.C., 1973, and estimates by the author.

Note that the "total accumulated cost over uncontrolled car" for any one year is not necessarily the total of total additional costs for previous years. This is because only the cost of the most recent of repeated adjustments to the same system (e.g., carburetion or ignition) is included. Because the 1975 standards are to some extent more restrictive for the

United States than for Canada, more 1975 model cars have been equipped with catalytic converters in the former country than in the latter. However, in the interest of simplicity, the costs for Canada have been estimated, as a first approximation, as if all 1975 models were equipped with converters.[21]

As a final note on the reliability of these cost estimates, the figures by model year in Table 2 are broadly consistent with those reported in another study done in the United States.[22]

(b) *Configurations meeting the 1977 U.S. standards*

As mentioned earlier, costs are available for four systems which are expected to, or currently meet, the U.S. emission standards originally proposed for 1976. These are the stratified charge engine and diesel, both currently in production, and two systems using catalytic converters -- a single three-way catalyst with feedback-controlled fuel injection, and a dual catalyst system.

Capital costs for these four systems, relative to a conventional uncontrolled engine, are shown in Table 3.[23] These costs are further disaggregated by number of cylinders.

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[21]Certain models from U.S. manufacturers have met the 1975 Canadian standards by adjustments that tend to have an adverse effect on fuel economy. Some European manufacturers, on the other hand, have met these standards by making use of the superior mixture control and distribution afforded by fuel injection.

[22]*The Economic Impact of Pollution Control, A Summary of Recent Studies*, prepared for the Council on Environmental Quality, Department of Commerce and Environmental Protection Agency, Washington, D.C., March 1972.

[23]These capital costs include, besides the additional costs associated with the systems themselves, the costs these systems incur in terms of necessary design changes in the rest of the car.

However, the market shares of four-, six- and eight-cylinder engines has remained relatively stable over the past five years (see Appendix B). Consequently, in the final calculations for the scenario involving the imposition of the 1977 U.S. standards a weighted average, employing average market shares as the weights, is used as the capital cost of a "typical" car.

Table 3

EMISSION CONTROL CAPITAL COSTS PER AUTOMOBILE TO MEET PROPOSED U.S. 1977 STANDARDS[1]
(1972 Canadian dollars)

	Engine Size		
	4-cylinder	6-cylinder	V-8
Dual catalyst	220	354	501
3-way catalyst, EFI	172	239	312
Stratified charge	201	232	--
Diesel[1]	285	355	--

[1]These costs exclude the 12 per cent Canadian federal manufacturers' sales tax.

Sources: *Report by the Committee on Motor Vehicle Emissions*, National Academy of Sciences, Washington, D.C., 1974; *Manufacturability and Costs of Proposed Low-Emission Automotive Engine Systems*, National Academy of Sciences, Washington, D.C., 1973; and estimates by the author.

The dual catalyst system is the most expensive of the two systems employing a conventional engine because of the extra cost of the second reducing catalytic converter. The high capital cost of the diesel reflects the extra strength required to withstand the higher pressures resulting from a very high compression ratio. As will be seen later, however, the high capital cost of the diesel is more than made up for by low maintenance and excellent fuel economy. Finally, note that there are no cost estimates given for a stratified charge or diesel V-8 engine. This is because in the former case, no data were available, while in the latter, no manufacturer, as far as is known, has plans to build a diesel in this configuration.

Maintenance Costs

The annual additional maintenance costs per automobile associated with emission control are based on data reported by the National Academy of Sciences. These costs are shown for the model years 1966 to 1976 in Table 4.

Table 4

ADDITIONAL ANNUAL MAINTENANCE COSTS PER AUTOMOBILE ASSOCIATED WITH EMISSION CONTROL FOR THE MODEL YEARS 1966-76[1]

(1972 Canadian dollars)

	Engine Size[2]		
Model Year	4-cylinder	6-cylinder	V-8
1966-72	--	2	--
1973	--	7	--
1974	--	7	--
1975	4	3	4
1976	4	3	4

[1]These represent the annual maintenance costs for each year of the assumed eight year life span of an automobile. These costs are put on a present value basis when the total additional maintenance costs are calculated (see Table 8).

[2]The annual maintenance costs for the typical six-cylinder engine over the period 1966 to 1974 are related to the capital costs for this period shown in Table 2, and are intended to serve as a proxy for the average additional maintenance costs for all engine sizes.

Sources: *Manufacturability and Costs of Proposed Low-Emission Automotive Engine Systems*, National Academy of Sciences, Washington, D.C., 1973; and estimates by the author.

The annual additional maintenance costs per automobile for the four systems that meet, or are expected to be able to meet, the 1977 U.S. standards are shown in Table 5. Once again, the costs associated with the dual catalyst system are higher, reflecting the cost of periodically replacing the extra converters.

The stratified charge engine exhibits costs only slightly higher than average, due to its more complex valve gear. Finally, the diesel's well-known reliability and simplicity result in maintenance costs lower than those of a typical uncontrolled spark ignition (conventional) engine.

Table 5

ADDITIONAL ANNUAL MAINTENANCE COSTS PER AUTOMOBILE ASSOCIATED WITH THE CONTROL OF EMISSIONS REQUIRED TO MEET THE PROPOSED 1977 U.S. STANDARDS[1]

(1972 Canadian dollars)

System	Engine Size		
	4-cylinder	6-cylinder	V-8
Dual catalyst	27	30	39
3-way catalyst	5	4	3
Stratified charge	10	5	--
Diesel	(8)[2]	(9)[2]	--

[1]These represent the annual maintenance costs for each year of the assumed eight year life span of an automobile. These costs are put on a present value basis when the total additional maintenance costs are calculated (see Table 8).

[2]The figures in parentheses represent a net reduction in costs.

Sources: *Manufacturability and Costs of Proposed Low-Emission Automotive Engine Systems*, National Academy of Sciences, Washington, D.C., 1973; and estimates by the author.

Fuel Costs

At the outset, it must be recognized that emission control is only one of several factors determining fuel economy. In fact, in an urban driving environment involving frequent acceleration and deceleration caused by traffic conditions, stop signs, and traffic lights, total vehicle weight is by far the most important determinant of fuel consumption. For this reason, much of the increase in consumption which is popularly thought to be the result of emission control is in fact the result of the increase in average vehicle weight as a result of government safety regulations (for example, 5 mph safety bumpers) and the trend towards more luxurious, and hence heavier, standard automobiles. Automatic transmissions, which are now standard equipment in most automobiles, may impose a penalty as high as 5 per cent due to the unavoidable constant slippage resulting from fluid drive.

Nonetheless, emission control has also contributed to the increase in fuel consumption, both because of the reduced efficiency of controlled combustion (lean mixtures and spark retard) and the increased weight of the emission control equipment itself.

The fuel economy estimates and additional fuel costs associated with emission control reported here for uncontrolled cars and 1970-74 models[24] are derived from U.S. Environmental Protection Agency data. These data are disaggregated by weight class, affording control of this critical factor. The estimates for the configurations meeting the 1975 and 1977 standards are based on National Academy of Sciences data. The estimates from the two sources were rendered comparable by a simple conversion derived from overlapping model years.

Fuel economy estimates for 1970-74 models and the resulting cost increases associated with emission control are shown in Table 6. These calculations are based on the assumptions that a "typical" car is driven 10,000 miles per year and

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[24]Control of crankcase and evaporative emissions before 1970 is assumed to have no effect on fuel economy.

that these cars use "regular" grade gasoline at a price of 43 cents per imperial gallon (before tax). This table shows an average overall decrease in fuel economy of about 2.3 miles per gallon for the period 1970-74, resulting in an average fuel cost increase of almost $19 per year.

Table 6

ADDITIONAL FUEL COSTS PER AUTOMOBILE ASSOCIATED WITH EMISSION CONTROL FOR THE MODEL YEARS 1970-74

(1972 Canadian dollars)

Model Year	Fuel Economy (Miles per imperial gallon)	Annual Fuel[1] Costs ($)	Annual Increase in Fuel Costs Associated with Emission Control ($)
Pre-1970 uncontrolled	24.4	176	--
1970	22.7	190	14
1971	21.7	198	22
1972	22.4	192	16
1973	22.0	196	20
1974	21.7	198	22

[1]Assuming annual mileage of 10,000 miles and price of 43 cents per gallon over this period (taxes are excluded).

Sources: *A Report on Automobile Fuel Economy*, U.S. Environmental Protection Agency, Washington, D.C., 1973; and estimates by the author.

The corresponding calculations for the systems that are intended to meet the 1975 and proposed 1977 U.S. standards are shown in Table 7. Here, fuel economy is disaggregated into three classes, chosen to roughly correspond to the four-, six-, and eight-cylinder divisions used earlier. Once again, the dual catalyst is the most expensive of the configurations that meet, or may be expected to meet, the proposed 1977 U.S. standards, while the excellent fuel economy of the diesel results in an actual decrease in costs relative to an uncontrolled gasoline engine.

Table 7

ADDITIONAL ANNUAL FUEL COSTS PER AUTOMOBILE ASSOCIATED WITH THE CONTROL OF EMISSIONS REQUIRED TO MEET THE 1975 AND PROPOSED 1977 U.S. STANDARDS

(1972 Canadian dollars)

Emission System	Fuel Economy (miles per imperial gallon)			Annual Fuel Costs ($)[1]			Annual Increase (decrease) in Fuel Costs Associated with Emission Control ($)		
	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large
	(engine size)[2]			(engine size)			(engine size)		
Uncontrolled	34.2	24.4	18.7	126	176	230	--	--	--
1975 standards									
Typical model[3]	30.7	24.4	18.0	147	185	250	21	9	20
1977 proposed U.S. standards									
Dual catalyst	23.5	19.2	11.9	192	234	378	66	58	148
3-way catalyst, EFI	27.3	23.0	15.4	165	196	292	39	20	62
Stratified charge	27.3	23.0	--	157	187	--	31	11	--
Diesel	37.5	31.6	--	112	133	--	(14)	(43)	--

[1]Assuming annual mileage of 10,000 miles and prices (excluding taxes) as follows: regular grade, 43 cents per gallon; No. 2 diesel, 42 cents per gallon; unleaded, 45 cents per gallon.

[2]The small, medium, and large engine sizes correspond roughly to the four-, six-, and eight-cylinder categories, respectively.

[3]The same figures are assumed for 1976.

Sources: *A Report on Automotive Fuel Economy*, U.S. Environmental Protection Agency, Washington, D.C., 1973; *Manufacturability and Costs of Proposed Low-Emission Engine Systems*, National Academy of Sciences, Washington, D.C., 1973; and estimates by the author.

This decrease in costs is aided by the slightly lower costs of No. 2 diesel fuel (assumed to cost one cent per gallon less than regular grade gasoline). Note that the catalyst systems suffer an additional penalty in that they require unleaded gasoline, which is assumed to cost two cents per gallon more than regular gasoline.

Total Costs of Emission Control

The total annual additional costs per "typical" automobile associated with emission control are presented in Table 8 for 1966 to 1976. They are the sum of the capital, maintenance, and fuel costs necessary to meet the actual standards that were or are in force. Also shown in this table are the comparable estimated annual costs for each of the four systems that meet, or may be expected to meet, the proposed 1977 U.S. standards. Where the capital, maintenance, or fuel costs are available separately for four-, six-, and eight-cylinder engines,[25] the aggregate cost figure for each of these elements of the annual total is calculated using the average market shares for the period 1970-74. In all cases, as explained earlier, the annual maintenance and fuel costs have been converted to a present value basis by discounting at 5 per cent over the assumed eight year lifetime.

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[25]For example, the maintenance and fuel costs for 1975 and 1976, and the capital, maintenance, and fuel costs for the dual catalyst and 3-way systems are available by engine size.

Table 8

TOTAL ADDITIONAL COSTS PER AUTOMOBILE ASSOCIATED WITH EMISSION CONTROL[1]

(1972 Canadian dollars)

Year	Capital Costs	Maintenance[2] Costs	Fuel[2] Costs	Total Costs per Automobile
1966	3	13	--	16
1967	3	13	--	16
1968	19	13	--	32
1969	19	13	--	32
1970	27	13	90	130
1971	40	13	142	195
1972	40	13	103	156
1973	102	45	129	276
1974	106	45	142	293
1975	231	25	121	377
1976	231	25	121	377
Dual catalyst	400	222	722	1,344
3-way catalyst	262	24	319	605
Stratified charge[3]	217	48	136	401
Diesel[3]	320	(55)[4]	(184)[4]	81

[1]The costs given for 1975 and 1976 are those associated with meeting the 1975 standards, while the costs given for the four systems that meet, or are expected to be able to meet, the proposed 1977 U.S. standards are for the scenario in which these latter standards are imposed over the period 1977-85.

[2]Annual costs discounted at 5 per cent over eight year lifetime.

[3]Costs available only for 4- and 6-cylinder engines.

[4]Figures in parentheses indicate a decrease.

As can be seen from the table, higher degrees of emission control have been attained at ever-increasing unit costs. While this increase was considerable over the period 1966-76, the annual costs are moderate relative to those associated with the catalytic converter systems intended to meet the proposed 1977 U.S. standards. The costs for a 3-way catalyst equipped car and for a dual-catalyst equipped car are 60 per cent and 260 per cent greater, respectively, than those for a car meeting the 1975 standards.[26] In the light of these costs, the 1977 configurations employing catalytic converters would appear to represent the limit of the "bolt-on" approach to emission control.

[26]More than half the cost associated with the dual catalyst system is because of severely reduced fuel economy.

On the basis of costs alone, the alternative engine systems -- the stratified charge and diesel -- compare very favourably with the dual and 3-way catalyst systems.[27] However, the diesel has traditionally enjoyed little popularity, partly because of its low power-to-weight ratio.

To convert these costs per automobile to total annual emission control costs, it only remains to multiply the cost per automobile for each year by the number of cars sold in that year. For the years up to 1975, this poses no problem, since accurate statistics on new car sales are readily available. Projection to 1985, however, requires two further steps. First, car sales for each year must be obtained by projecting present trends over the next ten years. Second, the regulatory environment must be simulated.

With respect to the first step, the simplest assumption is that of a constant exponential rate of growth of new car sales. Although this approach neglects cyclical swings, over a period as long as ten years these variations may reasonably be expected to cancel each other, leaving only the underlying trend. In Appendix B, an exponential growth rate is fitted to data for the period 1964-74, and this is then extrapolated until 1985.

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[27]While the costs for the stratified charge engine and diesel are based on data for four- and six-cylinder engines only, rough estimates indicate that one might expect the costs to increase only marginally for the stratified charge engine and to remain comparatively low for the diesel when the hypothetical costs of an eight-cylinder engine are considered in the estimation of the total costs per automobile in each case. In these estimates the market shares for the four-, six-, and eight-cylinder engines are assumed to be the same as over the period 1970-74.

Predicting the regulatory environment is straightforward. The Canadian Government has announced that the 1975 standards will be extended indefinitely. However, considering Canada's unique position with respect to the United States, it is also interesting to speculate on the effects of adopting the proposed U.S. emission standards for 1977. Consequently, two alternatives are evaluated: first, the continuation of present Canadian standards, and second, the imposition of the U.S. standards from 1977 on.

(a) *Continuation of 1975 standards*

The Canadian 1975 standards can be met with the present catalytic converters, or by strict mixture control and thermal reactors. As explained earlier, the converter-equipped car is taken as being representative of the various approaches. Table 9 shows the effect of extrapolating the 1975 technology until 1985, and also provides an estimate of costs incurred to the end of 1974. The total cost of emission control to 1985 is some $5.3 billion, of which $937 million had been spent by 1974.

To put these figures in perspective, it is useful to estimate the total lifetime expenditures of all types for the automobiles sold in a particular year. If we assume that a "typical" car costs $3,000 in 1972 dollars (including emission control equipment), achieves 22 miles per gallon, lasts eight years, is driven 10,000 miles per year, and costs $50 per year for maintenance of all forms, the total lifetime expenditures for such a car in present value terms (using a 5 per cent per annum discount rate), would be \$4,590.[28] For a year in which one million new cars are sold, total expenditures would therefore be about \$4.6 billion. Consequently, the total emission control costs for the twenty-year period (1966-85) shown in Table 9 are of a magnitude roughly similar (a differential of about 15 per cent) to the total lifetime expenditures for the new cars sold in one year.

Table 9

TOTAL EMISSION CONTROL COSTS WITH 1975 STANDARDS IN FORCE FROM 1975 TO 1985, CANADA, 1966-85

(1972 Canadian dollars)

Year	New Car Sales	Costs per Automobile of Emission Control	Total Emission Control Costs
	(thousands)	(\$)	(\$ millions)
	Actual		
1966	684	16	11.0
1967	668	16	10.7
1968	738	32	23.6
1969	756	32	24.2
1970	636	130	82.7
1971	745	195	145.3
1972	813	156	126.8
1973	936	276	258.3
1974	869	293	254.6
			937.2
	Projected		
1975	894	377	337.0
1976	924	377	348.3
1977	955	377	360.0
1978	987	377	372.1
1979	1,020	377	384.5
1980	1,054	377	397.4
1981	1,090	377	410.9
1982	1,126	377	424.5
1983	1,164	377	438.8
1984	1,203	377	453.5
1985	1,243	377	468.6
Total emission control costs, 1966-85			5,332.8

(b) *Adoption of Proposed U.S. 1977 Standards: Two Scenarios*

In this alternative new car sales would be spread over the four systems which meet the proposed 1977 standards. Consequently, in order to estimate the total cost from 1977 to 1985,

[28]This excludes taxes, such as the federal manufacturers' sales tax, and the tax on gasoline. The costs of automobile insurance are also excluded.

market shares must be determined for each engine type. The shares assumed for a scenario involving a strong reliance on alternative engines are shown in Table 10, and are in accord with the following suppositions:

(i) The dual catalyst system will cause the least dislocation for North American manufacturers -- hence this configuration will have the largest share initially.

(ii) New car buyers will rapidly move away from the higher-cost catalyst systems to the lower cost substitutes.

(iii) The diesel will enjoy only modest popularity because of a low power-to-weight ratio and particulate emissions.

(iv) There will be a gradual move towards smaller cars and more modest engines.

Table 10

ASSUMED MARKET SHARES IN SCENARIO INVOLVING HEAVY RELIANCE ON ALTERNATIVE ENGINES TO MEET 1977 STANDARDS, CANADA, 1977-85

Year	Dual Catalyst	3-way Catalyst	Stratified Charge	Diesel
		(per cent)		
1977	60	15	15	10
1978	40	21	25	14
1979	20	26	35	19
1980	0	30	48	22
1981	*	29	49	22
1982	*	28	50	22
1983	*	27	51	22
1984	*	26	53	21
1985	*	25	55	20

*Less than 1 per cent.

Applying these shares to the total sales projections for 1977-85, and multiplying by the appropriate total annual additional costs per automobile associated with the control of emissions, yields the figures shown in Table 11. For this scenario, the total emission control costs of adopting the 1977 U.S. standards are some $6.6 billion over the period 1966-85. This represents an increase of about $1.3 billion over the costs of continuing the 1975 standards to 1985.

Table 11

TOTAL EMISSION CONTROL COSTS FOR SCENARIO INVOLVING HEAVY RELIANCE ON ALTERNATIVE ENGINES TO MEET 1977 STANDARDS, CANADA, 1977-85[1]

(Millions of Canadian dollars)

Year	Dual Catalyst		3-Way Catalyst		Stratified Charge		Diesel[2]		Total Emission Control Costs
	Thousands of Cars	Total Costs	Thousands of Cars	Total Costs	Thousands of Cars	Total Costs	Thousands of Cars	Total Costs	
1977	573	770.1	143	86.5	143	57.3	96	7.8	921.7
1978	395	530.9	207	125.2	247	99.0	138	11.2	766.3
1979	204	274.2	265	160.3	357	143.2	194	15.7	593.4
1980	*	*	316	191.2	506	202.9	232	18.8	412.9
1981	*	*	316	191.2	534	214.1	240	19.4	424.7
1982	*	*	315	190.6	563	225.8	248	20.1	436.5
1983	*	*	314	190.0	594	238.2	256	20.7	448.9
1984	*	*	313	189.4	638	255.8	252	20.4	465.6
1985	*	*	311	188.2	684	274.3	249	20.2	482.7
Total emission control costs 1977-85									4,952.7
Total emission control costs 1966-76 (Table 9)									1,622.5
Total emission control costs 1966-85									6,575.2

*Negligible.

[1]The total new cars sales assumed are shown in Table 9.

[2]The total costs for the diesel do not take account of potential production change over costs.

The second scenario assumes a much heavier reliance on catalytic converters than on alternative engines to meet the 1977 standards. In this scenario, the dual catalyst system dominates briefly, and then is replaced by the less expensive 3-way catalyst system. The alternative engine systems occupy only a small portion of the market between 1977 and 1985. The assumed market shares are shown in Table 12.

Table 12

ASSUMED MARKET SHARES IN SCENARIO INVOLVING HEAVY RELIANCE ON CATALYST SYSTEMS TO MEET 1977 STANDARDS, CANADA, 1977-85

Year	Dual Catalyst	3-Way Catalyst	Stratified Charge	Diesel
1977	60	30	10	*
1978	45	45	10	*
1979	30	60	10	*
1980	15	75	10	*
1981	*	90	10	*
1982	*	90	10	*
1983	*	90	10	*
1984	*	90	10	*
1985	*	90	10	*

*Less than 1 per cent.

For this scenario, the total emission control costs for the period 1966-85 are about $8.5 billion (Table 13). This represents an increase of about $3.2 billion over the costs of continuing the 1975 standards to 1985. A slower evolution from the dual catalyst system to the 3-way catalyst system would exert a significant upward pressure on the total emission control costs. Thus, to meet the proposed 1977 standards, a heavy reliance on catalytic converters would appear to be a more expensive option than a significant shift to alternative engine systems.

Table 13

TOTAL EMISSION CONTROL COSTS FOR SCENARIO INVOLVING HEAVY RELIANCE ON CATALYST SYSTEMS TO MEET 1977 STANDARDS, CANADA, 1977-85[1]

(Millions of Canadian dollars)

Year	Dual Catalyst		3-Way Catalyst		Stratified Charge		Diesel		Total Emission Control Costs
	Thousands of Cars	Total Costs	Thousands of Cars	Total Costs	Thousands of Cars	Total Costs	Thousands of Cars	Total Costs	
1977	573	770.1	287	173.6	95	38.1	*	*	981.8
1978	444	596.7	444	268.6	99	39.7	*	*	905.0
1979	306	411.3	612	370.3	102	40.9	*	*	822.5
1980	158	212.4	791	478.6	105	42.1	*	*	733.1
1981	*	*	981	593.5	109	43.7	*	*	637.2
1982	*	*	1,013	612.9	113	45.3	*	*	658.2
1983	*	*	1,048	634.0	116	46.5	*	*	680.5
1984	*	*	1,083	655.2	120	48.1	*	*	703.3
1985	*	*	1,119	677.0	124	49.7	*	*	726.7
Total emission control costs 1977-85									6,848.3
Total emission control costs 1966-76 (Table 9)									1,622.5
Total emission control costs 1966-85									8,470.8

*Negligible.

[1]The total new car sales assumed are shown in Table 9.

Clearly, these estimates are critically dependent on assumed market shares. If, for example, the majority of cars were equipped with diesel engines after 1977, the costs might well be below those resulting from a continuation of the 1975 standards. However, a heavy reliance on the diesel for passenger automobiles would necessitate, among other things, a large and expensive shift in production in the oil refining industry, away from gasoline towards diesel oil.

Chapter 4

CONCLUSIONS

The automobile has reached a crisis point in its history. Society is becoming increasingly aware of the negative impact on land use patterns, energy reserves, and ambient air quality resulting from reliance on the automobile as the king-pin of our transportation system. This paper has explored the extent to which impacts on the last area of concern can be minimized.

From the point of view of technology, cleaner automobile engines are available now, and continuous improvements in efficiency are to be expected in the future. There exists, however, the danger that concern over dwindling energy supplies may compromise further development.[29] Most automobile manufacturers are using catalytic converters on their 1976 models because exhaust gas treatment offers a fuel economy advantage over combustion modification in conventional engines, even though technically, the converter approach has serious drawbacks, in the form of intolerance of leaded fuel and uncertainty about the effective lifetime of catalytic systems.

On a more positive note, there are reports that Toyota will be offering a two-litre stratified charge engine in some of the small sedans, and that General Motors may offer a diesel engine as an option in some 1977 Oldsmobile models.

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[29]There has been some pressure recently in the United States for a moratorium on emission and safety standards so that manufacturers can concentrate on improving fuel economy.

In addition, Chrysler has developed a lean burn system incorporating superior mixture control to reduce emissions and improve mileage without a catalyst.

As a final comment on the technology of emission control, it should be emphasized that the objective of pollution abatement programs is a permanent reduction in emissions, not merely successful certification of equipment. The potential divergence between these objectives is underlined by a confidential report of the U.S. Environmental Protection Agency which states that in spite of certification of pre-production models, the output of regular production runs do not meet present new car emission standards.[30]

With respect to the cost of automobile emission control, the estimates developed in Chapter 3 indicate that Canadians spent about $1 billion in 1972 dollars over the period 1966-74, and that under the present regulatory environment this will grow to more than $5 billion by 1985.

If Canada were to adopt the proposed U.S. standards for 1977, the total cost would be increased, within the context of the alternatives discussed, to about $6.6 billion or more in 1972 dollars. But, as noted in Chapter 3, this figure is critically dependent on the assumed mix of technologies that the market selects to meet the stricter standards. In present value terms, adoption of the 1977 U.S. standards imposes an additional investment cost of about $1.3 billion or more on the Canadian economy.

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[30]Reported in *Car and Driver* magazine, October 1975, pp. 86-87.

The issue of whether the benefits of automobile emission control are worth the size of the investments required[31] has been left aside so far, and it seems fitting to conclude this paper with some reference to this question.[32] If it is accepted that the primary impact of a deterioration of urban air quality lies in the resulting effect on human health, then the value of pollution abatement is measured by, first, a reduction in deaths related to air pollution, second, a reduction in demand for the services of doctors and hospitals, and third, a reduction in the cost of mild respiratory conditions, in terms of discomfort, absenteeism and reduced job efficiency. No effort will be made here to quantify these impacts, though effects of the second and third types are, at least in principle, measurable. It remains, however, to say that it is a measure of humanistic values in our society that even one death attributable to air pollution is one too many.

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[31]As a rough benchmark to assess the cost of emission control, it will be remembered that the original estimated of the total cost of the MacKenzie Valley pipeline and the James Bay project were each in the range of $5 billion (though, of course, substantial escalation has subsequently occurred).

[32]There is a brief discussion in Appendix C of the factors influencing the efficacy of direct government regulation as a strategy to control emissions.

Appendix A

CANADA-U.S. CAR PRICES

In spite of the Auto Pact regulating trade in automobiles between Canada and the United States, there remains a substantial price differential between the two countries. The cost estimates in Chapter 3 rely heavily on data expressed in U.S. dollars, and consequently an estimate of the average differential was necessary to convert these figures to Canadian dollars. The price differential, expressed in terms of the percentage by which the Canadian price exceeds the U.S. price (taking account of the Canada-U.S. exchange rate), is given in Table A-1 for the years 1969-73. Since all calculations are on a "before tax" basis, factory list price is used to estimate the differential. Factory list price is the manufacturer's suggested retail price less handling charges and excise taxes. The figures for each year in Table A-1 are based on averages of differentials for several different models. Based on this data, an average differential of 11 per cent was used to convert U.S. to Canadian prices (for the purposes of estimating future prices, the Canadian and U.S. dollar are assumed to be equivalent).

Table A-1

CANADA-U.S. AUTOMOBILE PRICE DIFFERENTIAL, 1969-73

Year	Average percentage by which the Canadian price exceeds the U.S. price[1]
1969	7.0
1970	10.3
1971	11.7
1972	12.6
1973	12.8
1969-73 average	10.9

[1]Based on factory list price, corrected for the Canada-U.S. exchange rate.

Source: *Seventh Annual Report of the President to the Congress on the Operation of the Automotive Products Trade Act of 1965*, Committee on Finance, United States Senate, Washington, D.C., 1974.

Appendix B

THE CANADIAN AUTOMOBILE MARKET

A brief study of the Canadian automobile market was made to determine the rate of growth of new car sales and to attempt to discover any trends in the composition of the market which should be taken into account when making sales projections to 1985. Data on new car registrations, by manufacturer, model, and engine size (number of cylinders) was obtained from R. L. Polk and Co. Ltd. of Toronto for the period 1970-74. In addition, total registrations were obtained for 1964-70 from the Department of Industry, Trade and Commerce.

These data have been aggregated in various ways. Table B-1 summarizes the data by size class, giving market shares for each year from 1970 to 1974. This table shows a slow movement towards the mid-size car, primarily at the expense of the full-size group. This is somewhat misleading, however, since these groupings are only relative -- in fact, a 1974 mid-size car is similar in size to the full-size car of ten years ago. Thus, the apparent trend away from full-size cars was not judged to be sufficiently meaningful to warrant explicit incorporation in estimates of emission control costs.

Table B-1

MARKET SHARES BY SIZE CLASS 1970-74, CANADA

(Per cent)

Size	1970	1971	1972	1973	1974
Small					
subcompacts, foreign compacts, sports	27.2	31.8	31.9	29.7	25.8
Medium					
compacts and intermediate sports (e.g., Mustangs)	18.8	17.9	18.4	21.2	25.0
Mid-Size	18.2	15.8	18.8	20.8	22.7
Full-Size					
(and luxury)	35.8	34.5	30.9	28.3	26.5
Total	100	100	100	100	100

Source: Polk Canadian New Vehicle Registration Service, R. L. Polk and Co. Ltd., Toronto, Ontario.

Engine size is probably more important from the viewpoint of emission control than is vehicle size. However, a breakdown by engine displacement was not available. Fortunately, classification by number of cylinders was possible, and this is used as a proxy for engine size. This breakdown, for 1970-74, is shown in Table B-2. As can be seen, there is very little change in the market shares over this period, and no evidence of a clear trend. Consequently, all total cost estimates are based on the unit costs of a "typical" car; where costs are available separately by number of cylinders, the cost of a "typical" car is calculated using average (1970-74) market shares as weights. These weights are .282, .142, and .572 for four-, six-, and eight-cylinder cars, respectively.

Table B-2

MARKET SHARES BY NUMBER OF CYLINDERS, 1970-74, CANADA

(Per cent)

	1970	1971	1972	1973	1974
4-cylinder	26.6	31.3	31.1	28.3	24.7
6-cylinder (including the V-6)	14.6	14.2	12.7	12.9	16.9
V-8	58.8	54.5	56.2	58.8	58.4
Total	100	100	100	100	100

Source: Polk Canadian New Vehicle Registration Service, R. L. Polk and Co. Ltd., Toronto, Ontario.

Appendix C

SOME NOTES ON DIRECT GOVERNMENT REGULATION AS AN EMISSION CONTROL STRATEGY

Emission control is fundamentally a technical problem, not an economic one: cleaner automobile engines will be developed by engineers, not economists. The economist's role is limited to the development of an environment in which innovation in emission control technology is rewarded in the economic sense, either directly, by success in the market place, or indirectly, through an artificial market, such as the proposed emission charge system.[1]

Direct government regulation, in the form of maximum allowable emissions, is the basic approach employed in reducing automobile emissions. However, it is unlikely that such an approach would produce the most cost-effective solution. Nonetheless, there would appear to be a number of factors which would determine the degree of success of a regulatory strategy.

First, the industry concerned must be highly concentrated -- that is, consist of a small number of firms. Otherwise, the cost of testing and certifying the product is prohibitive. The North American automobile industry certainly meets this requirement -- General Motors, Ford, Chrysler, and American Motors accounted for 75 per cent of new car sales in Canada in 1970 and a further 17 per cent were produced by Renault, Volvo,

[1] D. M. Paproski, "Environmental Management in a Canadian Context", Economic Council of Canada Discussion Paper (forthcoming).

Volkswagen, Datsun and Toyota. This degree of concentration is of course a very mixed blessing; the social and economic costs of an oligopolistic market structure may be considerable.

Secondly, the industry must be innovative. Since the regulatory approach does not provide economic incentives to technological advance, the desire to innovate must already be present. In the case of the automobile industry, emphasis on innovation, as measured by expenditure on research and development as a percentage of sales, is relatively high. The transportation industries group in Canada spends about 4 per cent of gross sales on research and development. The evidence also suggests, however, that much of the effort is directed at development which is intended to improve esthetic aspects of automobiles: such things as "quieter, smoother ride", interior trim, and so on. For example, the two innovations which enjoyed the greatest market acceptance in the last two years were vinyl roofs and "opera" windows.

Automobile manufacturers are, of course, not wholly to blame for this. The typical North American automobile buyer is notoriously unsophisticated. The purchase of a $5,000 automobile is often made in a state of almost complete ignorance as to its mechanical attributes, and in some areas, brand allegiance is so strong that an individual may be classified as a "Chevy man" or a "Ford man" in the same sense as he may be labelled according to his political allegiances. In such an environment, it is not surprising that components of proven superiority such as disc brakes, radial tires, and fuel injection may not necessarily enjoy more than limited market acceptance.

This lack of predilection for technological innovation on both the demand and the supply side of the automobile market strongly suggests that, in the absence of incentives, an efficient solution to the emission control problem is unlikely to emerge. It should be noted, of course, that penalties for failure to comply with standards cannot properly be considered incentives since there is no reward for a successful development effort, and concern for the risk of legal sanctions can be expected to result in conservative engineering.

A third determinant of success of the regulatory approach is the nature of the emission source itself. Specifically, if a large proportion of emissions of a particular pollutant is accounted for by a small number of large sources, centralized regulation is comparatively straightforward from the viewpoint of administration and surveillance, both in terms of certification of new equipment, and ensuring that standards continue to be met throughout the lifetime of this equipment. As noted above, the concentration of the automobile industry makes certification relatively easy, but once an automobile is sold, ensuring that it continues to meet the standards is a formidable problem (in 1973 there were over ten million motor vehicles registered in Canada, of which 78 per cent were passenger cars). In fact, the individual automobile owner experiences a certain disincentive to maintain his or her car's emission control equipment, in part because of the costs of such repairs. Ensuring that the standards are met is further complicated because the condition of the emission control devices has, in general, no noticeable effect on the performance of the car. This is particularly true of the catalytic converter. The driver has no way of knowing, without special tests, whether the converter is working or not.

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