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CASE STUDY OF THE INNOVATION PROCESS CHARACTERIZING THE DEVELOPMENT OF THE THREE-WAY CATALYTIC CONVERTER SYSTEM

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16. Abstract
This report traces the development of the three-way catalytic converter system from its origins in automaker and chemical firm research in the 1950s, to present plans preparing the system to be the auto exhaust emission control device most widely used on American cars in the 1980s. Multiple forces led to the decision by major automakers in the late 1970s to adopt the system. Among these forces were tightening exhaust emissions regulations; the development of low-cost, mass-producible system components; and institutional factors including strong system advocates, internationalization of the auto industry, and the desire of certain technology-oriented automakers to defend their U.S. market shares by adoption of the system. The paper concludes that the three-way converter system may become the dominant auto exhaust emission control device for American-market cars in the 1980s if problems relating to adoption of the system to 6 and 8 cylinder engines, reduction in requirements for precious metals, and the development of secure sources of supply for those metals are resolved.

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PREFACE

In the future, further reductions in fatalities, fuel consumption, and emissions associated with automobile use will be needed. To ensure that these goals are achieved the process by which the development, implementation, and adoption of innovative automobile technology occurs is being assessed as part of the Implementation of Innovation in the Motor Vehicle Industry Program, at the Transportation Systems Center. The current study, focussing on the development and adoption of the three-way catalyst, provides an important link in addressing these questions. It examines the impact of tightening fuel economy and emissions regulations, corporate strategies, the international nature of the automobile market, and the advocacy role played by the catalyst suppliers.

This work was conducted under the Implementation of Innovation in the Motor Vehicle Industry Program (HS-928), at the Transportation Systems Center, with the sponsorship of Mr. Sam Powel, III, Office of Research and Development, National Highway and Traffic Safety Administration. The contract technical monitor was Dr. Bruce Rubinger.

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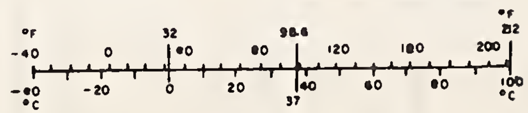
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

1. INTRODUCTION

The development of the three-way catalytic converter is an important technological response to the tightening of auto exhaust emission regulations in the United States. The three-way catalytic converter is the only device currently available on production cars that can meet the toughest emissions standards ever promulgated: The original standards for model year 1976 set forth in the Clean Air Act of 1970. Also, three-way converter systems allow cars to meet stringent pollution control standards while maintaining fuel economy and performance superior to that permitted by most other emission control technologies.

The core technology of this innovation was developed by non-automotive firms, with the catalyst manufacturers in the forefront. This occurred despite the heavy investment in catalytic converter development by such automakers as Ford and General Motors.

The international nature of the auto industry in the mid-1970s was essential to the development of this system. The U.S. auto industry did not initially seem receptive to three-way converter technology; General Motors' vice president of environmental affairs termed it, in early 1975, simply "a theoretical possibility." Had foreign producers not been a dynamic force on the American market, it is quite possible that mass production practicality would not have been demonstrated for this system, and exhaust emissions standards weakened.

The worldwide nature of the automobile market gave Volvo and Saab an incentive to employ the three-way converter system. Soaring labor costs in Sweden, and the rise of the Swedish Krona against the dollar, were hurting the sales of these companies. To defend their U.S. market share, both firms turned to innovation as their competitive strategy. In this context it is noteworthy that Volvo, and especially Saab, had a prior history of stressing their technological achievements.

2. BACKGROUND

2.1 SYSTEM OPERATION

The three-way catalyst functions as part of a system which includes: the catalyst located on the end of the exhaust pipe; an oxygen sensor; and a fuel injector or modified carburetor. The system controls the mixture of air and fuel in the exhaust, maintaining it close to a proportion of 14.5:1. Only at that ratio will the catalyst efficiently perform its function of reducing HC, CO, and NO_x into harmless gases. The system provides for good fuel economy and performance by eliminating the need for other emission control devices which hinder engine efficiency.

The three-way converter (TWC) stands in contrast to the earlier oxidation catalytic converter, which could reduce HC and CO, but not NO_x, to harmless gases. Before the model year 1977, all production automobile converters were the simpler oxidation converters, and most emission control devices still are of that variety.

2.2 SYSTEM DEVELOPMENT

Catalytic conversion for the elimination of harmful auto exhaust pollutants was first suggested by the auto industry itself in the 1950s. Makers of chemical catalysts for non-automotive uses (e.g. mining machinery) became interested in developing a device for automotive applications. In 1964, the California state government certified that some chemical firms had converters available for mass production, (i.e. oxidation catalysts), capable of meeting that state's new auto exhaust emissions standards; the automakers chose instead to meet the standards without converters. Converters were not put on mass production cars until after passage of the Clean Air Act of 1970. To meet the interim 1975 standards, most passenger cars sold in the U.S. utilized for the first time catalytic converters which could oxidize HC and CO. However, NO_x was still being reduced by the use of other devices which, as standards on NO_x exhaust emissions grew tighter, would increasingly hinder fuel economy and performance. In late 1976, the first three-way converter system was introduced on some Volvo lines sold in California under that state's unusually tough standards. In 1977 GM and Ford introduced similar systems in limited production.

The demand for the three-way catalyst was a result of progressively tighter federal and California auto exhaust emissions standards which were increasingly crippling the performance and fuel economy of vehicles equipped with conventional emission control systems.

3. STATUS OF INNOVATION

Volvo, Saab, GM, and Ford are currently selling cars equipped with three-way converter (TWC) systems on the California market. General Motors and Ford are planning nationwide installation of the systems on some cars in the next few years. Starting with model year 1981, GM plans to put three-way catalysts on all of its cars. Implementation of this program is predicated on success in adapting the system to six-cylinder and eight-cylinder engines; this has not yet been done, and all current TWC systems are installed on four-cylinder engines.

The future outlook for TWC systems is quite good. It appears that by the early 1980s the three-way catalyst will be placed on most autos sold in the U.S. market. No other technology appears to be able to meet both the emissions and fuel economy standards mandated for the next few years. Present research efforts appear to be focused on refinements of the existing technology and development of a base metal catalyst.

4. REMAINING BARRIERS TO ADOPTION

The only economic barrier to adoption is increased initial cost to the consumer. However, the promise of improved fuel economy and performance may effectively mitigate this. The primary technical barriers to adoption are: 1) effectively scaling up the TWC system for use on 6-cylinder and 8-cylinder engines,* and 2) reducing the amount of precious metals used in each converter to a point where aggregate demand can be supplied without exhausting world reserves in the near future.

The major institutional barrier to adoption is the need for secure sources of supply for the platinum group metals used in the three-way converter. At present the only significant reserves of such metals are located in the Republic of South Africa and the USSR, neither of which is such a source. Platinum group metals used as catalysts by the U.S. auto industry are supplied from South Africa.

Regulatory action has acted as an incentive, not a barrier, to adoption of this technological innovation.

*This report covers the period to September 1978. Since then, TWC systems have been marketed on 6- and 8-cylinder-engine passenger cars sold in the U.S. (Sources: 1979 MVMA Specifications Form: Passenger Car--Volvo 240, 260, p. 10; 1980 MVMA Specifications Form: Passenger Car -- Ford Lincoln Versailles, p. 10)

1. INTRODUCTION

This case examines the development of the three-way catalytic converter as a device for controlling the exhaust emissions of passenger automobiles sold on the U.S. market.

The three-way converter is the most sophisticated device designed around the observation that hazardous pollutants, when exposed to the appropriate materials in the extremely hot environment of an automobile's exhaust system, can be chemically catalyzed into harmless gases. The three-way converter is so named because it reduces three noxious pollutants - hydrocarbons, carbon monoxide, and nitrogen oxides-into such gases.

In the 1950s, when widespread concern first arose about automotive exhaust pollutants, catalytic converters were already commercially available for the control of non-automotive pollutants. Automaker research in the 1950s indicated that the use of catalytic converters was the most promising approach for the control of important automotive pollutants. However, not until the late 1960s did the automakers seriously consider the devices for mass production as pollution control devices on passenger cars for the U.S. market.

In 1968, the U.S. Government set the first mandatory exhaust emissions standards for all new passenger cars sold in the United States. As time progressed, these standards grew increasingly tough, and automakers again turned to catalytic converter technology. Beginning in model year 1975, catalytic converters designed to reduce hydrocarbons and carbon monoxide to harmless gases were put on most new passenger cars sold in the U.S.

In 1976, a Volvo passenger car equipped with a three-way converter was certified to have met not only the tough 1977 California standards but also the toughest standards ever promulgated, the 1976 standards originally set forth in the Clean Air Act of 1970. The device was made available on some 1977 Volvo and Saab autos sold in California. In model year 1978, General

Motors and Ford began equipping some of their California passenger cars with three-way devices, and GM announced that it would equip all of its model year 1981 passenger cars with three-way converters.

The story of this rise to prominence for the three-way catalytic converter is the subject of this case.

2. DISCUSSION

1951-1970: The Stage is Set

Smog Discovered: Early Research

In 1951, Professor A.J. Haagen-Smit of the California Institute of Technology demonstrated that "motor vehicle emissions were key contributors to photochemical smog"[1] in Southern California. Within a few years, automotive exhaust emissions were seen as a significant and nationwide problem.[2]

In 1955, Congress vastly expanded the federal air pollution research program.[3] Also in 1955, American Motors, Chrysler, Ford, and General Motors, with other firms, formed a joint committee under the aegis of the Automobile Manufacturers Association to study automobile air pollution.[4]

Among the research groups formed by this committee, one was given the task of investigating exhaust emissions controls. In 1957, the researchers of this Exhaust System Task Group presented a paper at the National West Coast Meeting of the Society of Automotive Engineers. In this paper, the researchers described their work on "various methods of treating automotive exhaust to remove hydrocarbons."[5] Hydrocarbons had been singled out as the pollutant to be dealt with because of their key role in the formation of photochemical smog.[6] As for other pollutants,

> separation of inorganic compounds such as lead components, sulphur dioxide, oxides of nitrogen has not been investigated.[7]

Nor were carbon monoxide emissions an object of the research.[8]

The conclusion of the research group was that the use of oxidizing catalytic converters was the most promising approach available for the reduction of hydrocarbons in auto exhaust emissions.[9] However, the group also concluded that:

> The casual reader is warned not to expect to see catalytic converters (or other exhaust treating devices) on automobiles at an early date, even though one of the oxidation catalysts tested in the industry program has shown some promise. Numerous engineering problems have been observed while testing the device.[10]

Of the problems, the researchers specifically noted those of engine noise, converter warmup efficiency, converter heat, and converter size. Also, the researchers noted the problem of lead in commercial gasoline.

> Lead components in exhaust are important to the designers of catalytic converters, since these compounds are notorious catalyst poisons. At the present time it seems more practical to develop a lead resistant catalyst than to attempt to remove lead from the exhaust.[11]

<u>California Initiatives</u>

In 1961, pursuant to new California standards, automakers began to install positive crankcase ventilation devices (the now famous PCV valves) on all new cars sold in California, "and in 1963 the devices were installed on all new cars nationwide."[12] These devices weren't exhaust emissions control devices, but rather devices to prevent emissions from crankcases - emissions which accounted for 25% of the HC emissions of uncontrolled cars.[13]

The California legislature wanted, in addition, exhaust emissions controls. In 1963 it authorized the state government to mandate that HC and CO exhaust emissions control systems be installed on all new cars sold in California no later than one year after the state had certified that systems were practical and available at a reasonable cost.[14]

> In March, 1964, the auto companies told the state the 1967 model year was the earliest that they would be able to install exhaust control devices.[15]

In June 1964, the state certified 4 devices as practical and available at reasonable cost. Three of these devices were oxidizing catalysts, each of which had been submitted by a team of non-automaker "independent" firms. The three teams were American

Cyanamid and Walker Manufacturing, W.R. Grace and Norris Thermador, and Universal Oil Products and Arvin Industries.[16]

> In August, 1964, the auto companies announced that they would, after all, be able to provide exhaust control devices - of their own manufacture - for the 1966 model year.[17] (for the California market, only).

None of the automakers' devices were catalytic converters. Chrysler chose to meet the California standards by making changes in the carburetor and in distributor calibration, retarding spark time, and altering the air/fuel mixture to a leaner than usual ratio. General Motors, Ford, and American Motors similarly altered spark timing and the air/fuel mixture, and also added an air pump to inject extra air into the engine. The Chrysler system alone was cheaper than the devices offered by the independent suppliers; the others cost the same as the suppliers' devices. Nonetheless it was the automakers' and not the suppliers' systems which were added on to model year 1966 California cars.[18]

Federal Initiatives

In 1965, the U.S. Congress directed the Department of HEW to set standards, effective January 1, 1968, on HC and CO emissions from new automobiles.[19]

To meet the 1968 standards, which limited exhaust emissions on MY 1968 cars to 3.3 grams/mile HC and 33 grams/mile CO, air pumps and lean air/fuel mixtures and carefully controlled ignition timing were used. Tougher standards for 1970 were met (actually, unmet) with more timing adjustments and carburetor changes.[20]

Passage of the Clean Air Act of 1970

Standards Set

However, it was widely perceived that the Congress, responding to the growing political might of the environmental movement, would in 1970 pass legislation setting federal auto exhaust emissions standards far tougher than those extant.[21] The standards that were set by the Clean Air Act of 1970 were certainly that (see Table 1).

Under the new law, model year (MY) 1975 autos sold in the U.S. would be allowed maximum exhaust emissions of 0.41 grams per mile (gm/mi) HC, 3.4 gm/mi CO and 3.1 gm/mi NOx (.41/3.4/3.1) for the first 50,000 miles. MY 1976 autos would have to conform to a limit of .4/3.4/.4.[22]

TABLE 1. FEDERAL AUTO EXHAUST EMISSIONS STANDARDS SET FORTH IN THE CLEAN AIR ACT OF 1970 (figures in gm/mi)

Year	HC	CO	NO_x
70/71	4.1	34	-
73/74	3.0	28	-
1975	0.41	3.4	3.1

Source: Progress in the Implementation of Motor Vehicle Standards Through June 1973. Annual Report of the Administrator of Environmental Protection Administration to the U. S. Congress, pp. 3-3,3-5.

Automakers File for Extension

Under the law, the Administrator of the federal Environmental Protection Agency could give an automaker or all automakers extensions of one year on the standards if a determination were made that the automaker or automakers filing for the extension were unable to meet the standards despite "all good faith efforts."[23] By early 1972, five firms had applied for the extension: GM, Ford, Chrysler, International Harvester, and Volvo.[24]

Hearings Held

Pursuant to the law, public hearings were held in the spring of 1972. During these hearings, the automakers said that the technology to meet the Clean Air Act's standards for 1975 and 1976 was not available for mass production.[25]

Debate on Catalysts

Several manufacturers of catalytic converters disagreed. One, Engelhard Minerals and Chemicals, said that it had road tested an oxidation converter capable of meeting the 1975 emissions standards for 25,000 miles, and saw no reason that the device could not last the full 50,000 miles required by law. Ford, with whom Engelhard had been developing this device (trademarked PTX), replied that Engelhard had used lead sterile gasoline and ash-free lubricating oil in its converter test, neither of which would be commercially available in 1975 and both of which improved the durability of the catalysts.[26]

EPA administrator Ruckelshaus refused to grant a delay of standards in spring, 1972.

Further Debate

Later in 1972, Engelhard again caused "another eruption of the catalytic converter controversy"[27] when it announced that it had run an oxidizing catalytic converter the full 50,000 miles required by the law, and still met the 1975 standards. Ford officials, who by this time had placed a contract with Engelhard to supply "up to 60%" of Ford's catalytic converter needs for model years 1975-77, were again skeptical.[28] In addition to repeating the criticism of the use of lead sterile gasoline and ash-free lubricant, Ford officials also noted that Engelhard had not followed the exact driving cycle required by the EPA, and that the tests were therefore invalid.[29]

Chrysler vs. Engelhard

According to the testimony of Engelhard officials, prepared for the EPA, the Chrysler Corporation leadership was more than skeptical. Chrysler, the Engelhard officials said, cut off Engelhard as a supplier of catalytic converters and switched to another major catalytic converter maker, Universal Oil Products, in order to punish Engelhard for publicly contradicting Chrysler's position on the technological feasibility of catalytic converters. Chrysler officials denied this charge, saying that the supplier switch was for economic reasons. EPA administrator Ruckelshaus suggested that Chrysler just might have perjured itself, and also that Chrysler may have failed to make a good-faith effort to meet the 1975 emissions standards.[30]

1973: Extensions Granted

In the meantime GM, Ford, Chrysler and International Harvester had placed a suit before the U.S. Court of Appeals in Washington, D.C. asking for a judicial order requiring a one-year extension of the 1975 standards set by the Clean Air Act of 1970.[31]

In February of 1973, the court ordered the EPA to reconvene hearings on the automakers' plea for an extension; "the 3 judge panel asserted the agency hadn't properly explored the automakers' contentions."[32]

The EPA held this second round of hearings, and on April 11, 1973, granted the one-year extension allowed under the law for HC and CO standards. In July 1973, it granted the one-year extension also allowed for the NO_x standards. In each case, the EPA administrator set interim standards.[33]

TABLE 2. INTERIM EMISSIONS STANDARDS ESTABLISHED IN 1973

The Original Standards Were (gm/mi)				The Original Standards Were (gm/mi)		
HC	CO	NO_x	Model Year	HC	CO	NO_x
.41			74	3.4	28	-
.41	3.4	3.1	75	1.5	15	3.1
.41	3.4	.41	76	.41	3.4	2.0
.41	3.4	.41	77	.41	3.4	0.40

Source: *Progress in the Implementation of Motor Vehicle Standards through June 1974*. Annual Report of the Administration of Environmental Protection Administration to the U.S. Congress, p. I-4.

Standards to Encourage Converter Use

The interim standards were set so as to strongly encourage the use of oxidizing catalytic converters, especially on cars sold in California, which was allowed to set emissions standards tougher than those for the rest of the United States.[34]

Congress Sustains the Catalytic Converter

Ford and Chrysler Go to Congress

Ford and Chrysler were not satisfied with the EPA ruling, and decided to present the case for weaker standards to Congress, specifically a freezing in place for several years of the MY 1974 standards.[35]

Honda

The Ford and Chrysler case faced major obstacles. Honda Motor Company, for instance, had developed a mass production, four cylinder, stratified charge engine that the EPA, in December 1972, certified as meeting the original 1975 standards without the need for a catalytic converter.[36] The availability of such an engine, especially since Chrysler and Ford had both procured a license from Honda for its production, hardly aided the Ford/Chrysler case.[37]

GM Defends Converters

General Motors also presented an obstacle to the Ford/ Chrysler case; GM officials testified before Congress that catalytic converters were ready to go on MY 1975 cars and that the devices would save enough fuel to offset their $150 price tag.[38] This fuel saving resulted from the converter's permitting engines equipped with the device to meet current exhaust emissions standards while being tuned for higher combustion efficiency than was previously possible.[39,40]

For GM, the fuel saving was especially helpful. Its MY 1974 auto fleet suffered from terrible gas mileage, worse in fact than that of any other American producer (see Appendix, Sec III).[41] Also important to General Motors was the need to recoup its enormous investment in oxidizing catalytic converter development,[42] which one observer estimated in 1975 was on the order of $215 million.[43] According to Business Week, General Motors officials in 1973 planned to put catalysts on some of its 1975 cars even if Congress has frozen the standards.[44]

Chrysler Arguments

Chrysler argued against the catalytic converter, suggesting that catalytic converters "would raise costs, not help fuel economy, and not affect pollution."[45] Ford was less negative towards catalytic converter technology than Chrysler, but was still in favor of freezing the 1974 standards in place.[46]

The 1974 Clean Air Act Amendment

Congress supported the catalytic converter, and EPA's interim 1975 and 1976 standards remained in place. The original 1975 standards were to go into effect in model year 1977. As with the 1970 Clean Air Act, Congress made a provision for the EPA to grant a one-year extension of the 1977 standards.

Automaker Response

General Motors put oxidation catalytic converters on all of its MY 1975 cars, even those small cars whose engine systems could have met the 1975 standards without the devices. Chrysler was forced to put converters on 75% of its MY 1975 auto production, though the corporation was pushing efforts to develop engine technology which would allow its cars to meet EPA standards without the use of converters.[47] Ford put catalytic converters on 70% of its auto production, and AMC on one-third of its production. Most of AMC's autos were sufficiently light so that their emissions stayed within EPA standards without catalysts.[48]

Supplier Position

For the catalyst suppliers, this meant volume production. Big beneficiaries included Engelhard Minerals and Chemicals, which supplied Ford and General Motors as well as six foreign manufacturers (Daimler-Benz, Nissan, Peugeot, Renault, Toyo Kogyo, and Volvo);[49] Universal Oil Products, which had a sole source supplier contract with Chrysler[50]; and Matthey Bishop which, along with Engelhard, supplied Ford.[51] General Motors supplied fully built converters to American Motors, being AMC's sole supplier.[52] According to one report, GM also signed a contract to supply Ford with millions of converters for Ford's MY 76 autos.[53] However, there was no other report of this contract, thus it is safe to conclude the contract probably fell through. The use of oxidation catalytic converters increased the sticker price of cars so equipped by $110.[54]

Oxidation Converters as Dominant Design

Alternatives

In MY 1975 oxidizing converters were put on most passenger cars sold in the U.S. market. However, some auto firms were not satisfied with this development. Honda's autos with CVCC engines didn't need to be so equipped, and Chrysler was working on the development of the lean-burn engine.

Chrysler's lean-burn engine was designed to meet extant exhaust emissions control standards without the use of catalytic converters or air pumps.[55] The "Lean Burn" design was simply a conventional Otto cycle engine with a sophisticated electronic spark control that allowed for very complete combustion. This greatly cut HC and CO emissions, and provided good engine performance at a fuel saving air-fuel ratio of 18:1. (The conventional ratio in the mid-1970s was 15:1). The system that made this possible was a feedback unit that linked oxygen sensors (in the cylinder, apparently) to a microprocessor which then fired each spark on command.[56]

However, both the Honda and the Chrysler technology faced a serious barrier in the form of tighter NO_x standards. With the imposition of the first nitrogen oxide standards in MY 1973, most autos were equipped with exhaust gas recirculation (EGR), and spark retard. These cut NO_x emissions, but at the cost of decreased fuel economy and performance ("driveability"), for NO_x

is a product of the high temperatures usually accompanying complete combustion and the NO_x reduction solutions made engines less efficient. Highly efficient engines, such as Honda and Chrysler developed, could not meet the most stringent NO_x standards without possibly crippling add-on devices.[57]

Train Extension

In early 1975, citing concern that had arisen over the possible emission of dangerous quantities of sulfates by catalytic converters (a possibility which never materalized),[58] EPA Administrator Russell Train granted a one-year delay in meeting the federal standards that had been set for MY 1977. Train set interim standards, and proposed that Congress permit the interim standards he set to be extended through MY 1979; tougher interim standards would be set for MY 1980 and 1981, with the standards originally proposed for MY 1977 being set for MY 1978.[59] (See Table below.)

TABLE 3. EMISSIONS STANDARDS ESTABLISHED IN 1974

1974 Congressional Standards (gm/mi)				1975 Train Extension (gm/mi)		
HC	CO	NO_x	Model Yr.	HC	CO	NO_x (Train)
1.5	15	3.1	1975	1.5	15	3.1
1.5	15	2.0	1976	1.5	15	2.0
0.41	3.4	2.0	1977	1.5	15	2.0
0.41	3.4	0.4	1978	0.41	3.4	0.4
			Model Yr.	Pres. Ford/Chrysler Rec.		
Train Recommendations			1976	1.5	15	3.1
1.5	15	2	1977	1.5	15	3.1
1.5	15	2	1978	1.5	15	3.1
1.5	15	2	1979	1.5	15	3.1
			1980	1.5	15	3.1
			1981	1.5	15	3.1

Source: Progress in the Implementation of Motor Vehicle Standards Through June 1975. Annual Report of the Administrator of Environmental Protection Administration to the U.S. Congress, p. 1,3.

Chrysler Corporation was happy with that aspect of the EPA decision which set the lower limit of NO_x at 2 gm/mi - though the corporation urged Congress to set the standard at 3.1 gm/mi instead, as President Ford had suggested.

As the Wall Street Journal article put it, "The No. 3 auto maker added that a decision to freeze standards through 1979 could 'open new doors for emissions control technology',"[60] specifically lean-burn.

Regulatory Action

However, Congress had to act before this freeze could be granted. This did not happen in 1975. Also, Congress passed and President Ford signed into law mandatory auto fuel efficiency standards - standards which would require automakers to drastically raise the fuel efficiency of their fleets while at the same time meeting tougher exhaust emissions standards.[61] Also in 1975, California set 1977 exhaust emissions standards of .4/9/1.5. Chrysler delayed introduction of its lean-burn engine system from fall, 1975 to late January, 1976, and cut the number of MY 1976 vehicles to be so equipped from 200,000 to 65,000. The New York Times reported that "some observers of the industry" suspected that Chrysler trimmed back its lean-burn plans not so much because of technical difficulties but rather because of the regulatory environment.[62] It also became apparent that Chrysler's lean-burn system would not by itself be able to keep NO_x emissions down to the MY 1977 standards on its MY 1977 autos.[63]

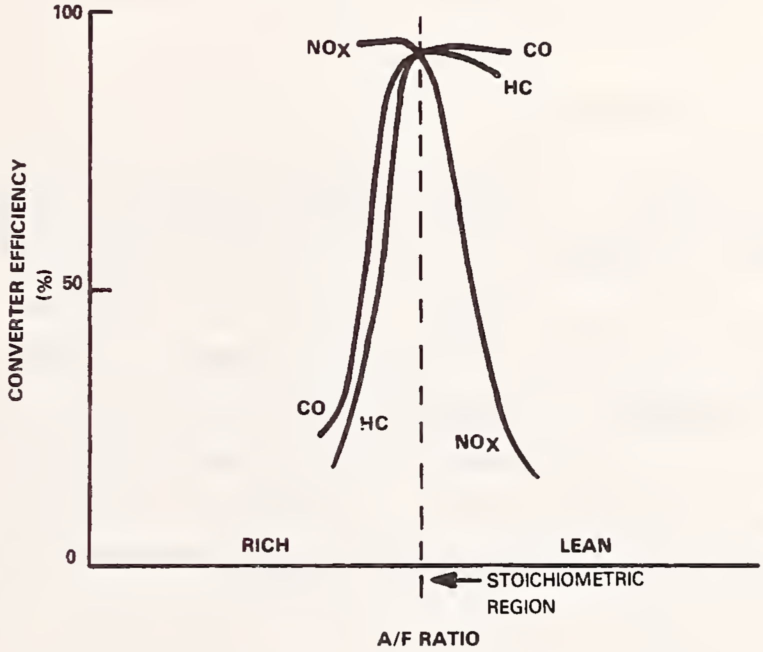
Meeting NO_x Standards

NO_x Catalysts

As it happens, nitrogen oxides could be effectively catalyzed by converters containing rhodium in addition to platinum, or both platinum and palladium. This had been known for some years. Universal Oil Products (which in 1975 changed its name to UOP) proposed such a device - a three way converter (TWC) back in 1973, before even the first extension of the 1975 standards.[64]

However, NO_x presented the same problem for the designers of three-way converters that it did for the designers of the Chrysler or Honda engine systems. No_x is a product of the high temperature combustion associated with high efficiency engine operation,[65] the same operation which is so efficient at reducing HC and CO output.

For the catalyst designer, there was an added problem. For the three way converter to simultaneously facilitate the reduction of HC, CO, and NO_x to a harmless state, the air/fuel ratio has to be closely controlled at a proportion around 14.5:1.[66] As the air/fuel mixture becomes leaner (less fuel per unit air) than this stoichiometric mix, NO_x conversion efficiency falls off sharply, while CO and HC conversion efficiencies remain high. As the air/fuel mixture grows richer (more fuel per unit air), HC and CO conversion efficiency falls off sharply while NO_x efficiency remains high (see figure 1).



Source: (AE 6-77, p. 39)

FIGURE 1. A NARROW WINDOW OF OPERATION: EFFICIENCY OF THREE-WAY CONVERSION AS A FUNCTION OF AIR/FUEL RATIO

To maintain the air/fuel mix in the stoichiometric region (see Glossary of Terms), one technique is to set up a feedback system that hooks an oxygen sensor in the exhaust system to a microcomputer which controls, either through fuel injection or an electronically controlled carburetor, the mixing of air and fuel in the cylinders.

California Introduction

It was this technique that Engelhard, Volvo, Saab-Scania, and Robert Bosch GmbH used in developing their λ-Sond TWC system. Volvo and Saab were already using the Bosch Jetronic electronically controlled mechanical fuel injection system on some of their production cars, and Bosch had developed an oxygen sensor that would last 15,000 miles. Engelhard Minerals & Chemicals developed a suitable catalyst containing platinum and a platinum group metal rhodium, in a ratio of roughly 5 parts platinum to one part rhodium.[68]

These firms presented a λ-Sond equipped MY 1977 Volvo 240 series passenger car to the California Air Resources Board (CARB) for testing. On June 2, 1976, CARB released a statement saying that the λ-Sond-equipped Volvo not only met the 1977 California standards but also the toughest standards proposed by the Clean Air Act of 1970 (which in 1976 had become the Federal MY 1978 standards) which the U.S. auto industry was fighting as impossible to meet.[69] It even met the MY 1978 standard after 50,000 miles of road testing.[70] Not only that, but the λ-Sond Volvo got better gas mileage than more polluting MY 1976 "49-State" Volvos; and the λ-Sond Volvo even met the U.S. 1980 fuel economy standard of 20 mpg (See Table 4).[71]

TABLE 4. CALIFORNIA AIR RESOURCES BOARD EXHAUST EMISSIONS AND FUEL ECONOMY TEST RESULTS FOR THE LAMBDA-SOND VOLVO

	Exhaust Emissions (grams/mile)			Fuel Economy (miles/gallon)		
	HC	CO	NO_x	City	Hwy	Combined
Average of 4 Volvo Test Cars, including 50,000 mile deterioration factor	0.20	2.8	0.17	18.2	28.1	21.6
Clean Air Act Goals	0.41	3.4	0.40			
1977 California Standards	0.41	9.0	1.50			
Current (1976) Federal Stds.	1.50	15.0	3.10			

SOURCE: CARB Fact Sheet, June 2, 1976.

These fuel economy gains were attributed to the removal of EGR and the spark retard system, which with the use of a TWC system were no longer necessary.

The test results received enormous publicity because they were released at a time when Congress was debating whether or not to push the 1978 standards back to 1985 and perhaps "entirely remove the requirement for control of oxides of nitrogen."[72] CARB itself did not recommend retention of the 1978 standards, but instead:

> To permit an orderly phase-in of the technology now available to meet the Clean Air Act goals, the ARB is recommending the following standards be adopted by the Congress.

Model Year	HC	CO	NO_x
1978	0.9	9	2
1979-80	0.41	9	1.5
1981	0.41	3.4	0.4

> Cars sold in California have met the standards recommended nationally for 1978 since 1975, and 1977 California cars will all meet the standards recommended nationally for 1979-80.[73]

Attached to the CARB statement was a letter from California Governor Jerry Brown asking that Congress support the emissions standards proposed by CARB.

Many in the auto industry were furious at the way CARB interpreted the implications of the Volvo test data. Howard Freers, Ford chief of car engineering, called the CARB statement "half a press release."[74] Industry officials muttered darkly about Jerry Brown's presidential ambitions.[75]

There were technical criticisms of the λ-Sond certification: that the λ-Sond TWC system was tested under California procedures-procedures less stringent than those used by the EPA; that the Bosch oxgyen sensor had to be replaced every 15,000 miles (if it were deemed "major equipment" by the EPA, under federal regulations it would have to last 50,000); that at the ratio of rhodium to platinum in the λ-Sond TWC (rhodium and platinum are mined together), the supply of rhodium would be quickly exhausted (CARB said that an effective TWC could be manufactured using the rhodium-to-platinum ratio that occurred in nature and in quantities small enough to pose no shortage problem);[76] that the system would not work well with a 6-cylinder engine (the Volvo engine is a 4-cylinder unit); and that the system only worked with expensive ($150 over the cost of carburetor system) fuel injection systems.[77]

The final Congressional action on the Clean Air Amendments, which were passed in the summer of 1977, established a schedule of standards somewhere between the CARB proposal and earlier industry hopes (see Table 5).

TABLE 5. 1977 AMENDMENTS TO CLEAN AIR ACT

Year	HC	CO	NO_x
1977	1.5	15	2
1978	1.5	15	2
1979	1.5	15	2
1980	0.41	15	2
1981	0.41	7	1
1982-85	0.41	3.4	1

Source: Public Law 95-95 "Clean Air Act Amendments of 1977," as recorded in United States Code/Congressional and Administrative News, 95th Congress - 1st Session p. 91 Stat. 751-52.

Diffusion of TWC

Saab/Volvo

In the spring of 1977, Saab had introduced λ-Sond-equipped Saab 99's in West Coast and high altitude areas; 4000 of them would, it was hoped, be sold in the first year.[78] That number was equivalent to one-half of Saab's MY 1976 U.S. sales.[79]

Volvo planned to sell 10,000 of its MY 1977 λ-Sond-equipped autos.[80] Apparently, Volvo was successful, because for MY 1978 Volvo expanded production of λ-Sond systems in order to install them on Volvo's full engine lineup in the Western states, making the system standard on its 242GT and 262 model autos.[81]

Chrysler

Other auto firms were also deciding to work with TWC systems. Chrysler announced very early in 1977 that it would be studying not only the use of TWC systems employing platinum and rhodium as the catalysts, but also the use of systems employing cheaper ruthenium or base metal catalysts.[82]

Ford

Very early in 1977 Ford also announced that it would be installing a TWC system employing a newly developed electronically controlled carburetor as standard equipment on its 30,000 MY 1978 California Ford Pintos and Mercury Bobcats, using 2.3 liter, 4 cycle engines.[83] The converter itself was a two-staged device with a UOP[84] - and perhaps Engelhard supplied catalyst. This system also contained a Bosch oxygen sensor (apparently the EPA decided that the sensor, which needed to be replaced every 15,000 miles, at a cost of $10-$15, was not a major component). The new carburetor had been developed by the Holley Division of Colt Industries.[85]

In early 1978, Ford announced that some 80,000 full-sized MY 1979 Mercury Marquis and Ford LTDs would be equipped with a similar system as part of a new engine control system called EEC II. Apparently, the EEC II engines would also use exhaust gas recirculation.[86]

GM

General Motors has also begun a TWC installation program, the most comprehensive yet announced by a U.S. automaker.

The first stage began with GM's announcement that MY 1978 California Chevrolet Monzas, Pontiac Sunbirds, and Oldsmobile Starfires equipped with the four cylinder 151 CID engine would have a TWC system called "Phase II", which again employed the Holley electronically controlled carburetor. Twenty-two hundred of the cars were equipped with the systems, which added $165 to $185 to the cost of each car, and $100 to the price ($25 above the usual CA emissions package). On the other hand, with the installation of the TWC systems came the removal of the EGR and spark retard devices, and General Motors proudly noted that now its California Pontiac Sunbirds would provide better performance than previously, and fuel economy would equal that of Pontiac Sunbirds in the rest of the country (see Appendix for data on fuel economy impact of several TWC systems).[87]

GM's Buick division also installed a phase II TWC system on some MY 1978 California Buick Skylarks equipped with a 231 CID V-6. The V-6 system uses a Rochester Products Division dual carburetor which had to be partially redesigned. This held up introduction of the V-6 system until mid-1978; this MY 1978 production run will apparently be around 200 systems. Nonetheless, in 1979 "Buick expects to supply some 40,000 to 50,000 V-6 engines for use with the Phase II emissions system in California."[88]

By the beginning of 1978, General Motors had decided that all of its future U.S. passenger cars would be equipped with the Phase II TWC systems, starting with all California cars in MY 1980 and all other cars sold in the U.S. in MY 1981. In MY 1979, Phase II electronic controls will become digital, as opposed to the present analogue design.[89] GM's catalyst supplier for the Phase II TWC system is new to the U.S. market, Degussa Wolfgang of Germany. Degussa will be supplying GM with pellet catalysts, that is, ceramic pellets coated with the platinum-rhodium mixture. (The pellets themseles will be supplied by Rhone-Poulenc).[90]

Pellets

GM has consistently favored the use of the more expensive pellet catalysts over the design which has the catalyst coating a monolithic honeycomb - the design favored by Volvo and Saab. The advantage of the pellet catalyst is that unlike the cheaper alternative design, the actual canister does not have to be replaced when the worn-out catalyst needs replacing. Both Engelhard and UOP have the facilities to produce both varieties of substrates.[91]

GM supplies its own sensors and, like Ford, apparently its own electronic equipment.[92]

Others

Other automakers are also planning to use TWC systems on California or other U.S. cars within the next few years. (One report suggests that AMC may already be selling an 8-cylinder engine system equipped with a TWC system). UOP also holds many other supply contracts, though it is unclear whether or not these contracts are for three-way or oxidizing catalysts. UOP has sole source contracts with Chrysler, Toyo Kogyo, Nissan (Datsun) and Fiat, and multiple-source contracts with Ford and Porsche.[93] The Chrysler contract runs until MY 1982,[94] so that contract may involve three-way catalysts at some point.

The status of the TWC systems of other foreign automakers is at present unclear, although the technology is diffuse enough (Bosch, the leading and perhaps only TWC oxygen sensor supplier - supplying Volvo, Saab, and Ford - is German, as is Degussa Wolfgang) that it should be available to most automakers. For instance, Johnson-Matthey (UK) has in a recent annual report[95] a picture of a British Leyland TR-7 on a test stand. This vehicle was marked "three-way catalyst." Also, Nissan, Toyota and Toyo Kogyo have developed three-way catalysts to meet toughened Japanese 1978 auto exhaust emissions standards.

Secure Supplies of Noble Metals

One problem which needs mentioning is that of rhodium and platinum supply. Though GM has high hopes for its program to reduce the proportion of rhodium to platinum in TWC's to the material "mine-mix" of 1:19, even at that ratio the metal must still be supplied.[96] The only reserves of platinum group metals large enough to supply the U.S. auto industry are found in the USSR and South Africa,[97] neither of which can be considered secure sources of supply. All of the platinum group metals now going into GM, Ford, Chrysler, and AMC converters, whether oxidizing or three way, are mined by two companies, Rustenberg Mines (which has close ties to Johnson-Matthey of the UK, a converter maker) and Impala Platinum Ltd., in South Africa.[98]

South Africa reserves of platinum group metals will be sufficient to supply the U.S. industry's converter need if the amount of rhodium in converters can be brought down from its present high level. If not, Soviet and Canadian supplies will be needed as well. Canadian reserves are totally insufficient by themselves. They are far too small to meet U.S. automaker needs. The size of Soviet reserves is unknown.[99] Also, the USSR has not shown a great willingness to sell large quantities of platinum group metals in the past, at least not on cost-effective terms or in long-term contracts.[100] Given the rising pressure for economic sanctions against South Africa, this supply problem warrants further attention. Perhaps base metal catalysts, despite their tendency to be poisoned by sulfur in gasoline, may need to be reevaluated.

Concluding Observations

The development and implementation of emissions technology has been a central issue in automotive technology throughout the 1960s and 1970s. What observations can be made about factors bearing on the very successful introduction to the marketplace of the particular technology that is the subject of this case study?

First, the core technology of the three-way converter system was developed largely by non-automotive firms, with the catalyst manufacturers being its most important champions, despite the heavy investments in money and personnel made in catalytic converter development by such automakers as General Motors and Ford. Even Volvo and Saab apparently contributed comparatively little to the actual technical development of the λ-Sond system. The fuel injection system had been perfected and introduced by Robert Bosch GmbH. (According to some industry sources, the Bosch system was preceded by earlier development done by Bendix in the U.S.) Bosch also developed the electronic control system and oxygen sensor. Engelhard supplied the catalysts.

Indeed, from the 1950s, it was the catalyst manufacturers who were in the forefront of the development of the automotive version of the converters. It was the catalyst manufacturers whose converters were certified by California in 1964. It was a catalyst maker, Engelhard, which, in 1972, took the risk of publicly contesting its customers' positions on the efficacy of converter technology.

That this was the case is not surprising. The development of catalytic converter technology is essentially a solution to problems in chemistry and involves the metallurgy of precious metals. To win a market among the automakers, the catalyst suppliers had to convince those firms that converter technology was superior to competing alternatives and convince federal regulators that converters could meet implementation schedules the automakers said were impractical. The catalyst makers could do this because they had no other automotive products that would be put at risk by their role of champion, and because they had much to gain by entering a large industry.

Second, the three-way converter system, as opposed to just the converter, is the product of the worldwide automotive industry. Key work was carried out in the U.S., West Germany, and Sweden, and of course, by those miners in South Africa who made it all possible by supplying the crucial precious metals.

The international nature of the auto industry in the mid-1970s was essential to the development of this system. The U.S. auto industry did not initially seem receptive to three-way converter technology. General Motors' Vice President of Environmental Affairs termed it, in early 1975, simply "a theoretical possibility."[101]

Had foreign producers not been a dynamic force on the American market, it is quite possible that auto exhaust emissions standards would have been much weaker than they actually were, because no mass production practicality would have been shown for the three way converter system.

As it was, the worldwide nature of the market gave Volvo and Saab an incentive that they might not otherwise have had, to employ the three-way converter system. Because labor costs in Sweden were soaring, and the Swedish krona rising in value against the dollar, both firms were faced with the task of defending their U.S. market share as the auto industry became more international. Both turned to innovation to aid in the defense. Volvo, and especially Saab, frequently characterized themselves as makers of technically superior automobiles; that is, innovation was a basic element of their competitive strategies. Both firms saw more innovation as an effective counter to the rocketing price of their autos.

Third, U.S. and California regulations on auto exhaust emissions provided tremendous market pull for the introduction of new technologies. The three-way catalytic converter was especially favored by the regulations, since it showed promise of meeting the tighter emissions standards earlier than competing alternatives.

Since the regulatory agencies tracked technological developments, and since the regulatory process was flexible, it seems safe to say that the availability of a mass-producible TWC system partially contributed to the maintenance of timetables for implementing auto exhaust emissions; standards so tough that only equipment with TWC systems would allow most autos to meet them.

Fourth, it can be said that the successful introduction of the three-way catalytic converter was the result of a fortuitous mix of circumstances. Not only the international structure of the industry, but also the strategies of individual firms, and the regulations of many levels of government favored the introduction of the technology. In addition, the particular mixture of firm size, market position, and the strategies of the catalyst firms were centrally important to the diffusion success of the catalytic converter.

For years chemical firms had been championing catalytic converters. For instance, UOP began its converter research program in 1957. However, the catalyst maker responsible for introducing the TWC system, and one of the most forceful champions of the oxidizing catalytic converter was Engelhard, a firm which reported that it only began its own automotive converter research in 1964, the year that U.S. automakers declined to utilize converters on their California cars.[103]

UOP, the other major catalyst supplier, is a moderate sized (about $700 million a year in sales), seemingly very entrepreneurial firm (one which shows its pride in developments by listing the number of patents it receives each year in its annual reports). It was vulnerable enough for a debtor's bankruptcy to cause such a cash flow crisis that UOP found itself in 1975 suddenly a subsidiary of Signal Corp., (which makes turbochargers for autos among other things).

Engelhard, on the other hand, has many times the sales and many more times the return on equity that UOP has. Engelhard's hallmark did not seem to be innovative entrepreneurship but rather quite successful participation in the extractive industries. While UOP became involved with automotive catalysis through its work with catalysts in oil refining (one of UOP's major areas is refinery construction), Engelhard's prior experience was with precious metals (as was that of Matthey-Bishop and Degussa Wolfgang).

One could perhaps attribute an almost symbiotic relationship to firms such as Engelhard and those such as UOP. The former, large, profitable, and secure in its other markets, could safely champion the new technology against auto industry opposition; while the latter, also possessing the technology, could win automaker favor for its product by providing a dependent and able supplier.

Volvo and Saab provided an outlet for the introduction of the technology because of their corporate commitment to a policy of technological innovation as the preferred method of meeting market problems brought about by cost difficulties. General Motors and Ford had the resources to adopt the technology for their own use, but not the incentive to take the lead in innovation. The Swedish producers had the incentive. Motor Trend magazine made the observation of Volvo (equally applicable to Saab) that

> as a comparatively small foreign manufacturer, Volvo could not expect to influence decisions made on Capitol Hill. (104)

After Volvo and Saab led the way in California, the U.S. firms also began equipping California cars with the new technology. Competing technologies capable of meeting the tight standards have been unable to capture a large fraction of the U.S. market. The lean-burn technology pioneered by Chrysler and the CVCC engine pioneered by Honda have remained innovations on vehicles of the innovator's company only.

Then, regulations in California were tightened, for non-technological reasons, to the point at which in 1976 the benefits of the TWC system in fuel economy and driveability became so great compared to that offered by the traditional approaches, that it seemed to be almost a regulatory necessity. Also, the success of the TWC system in meeting the California standards probably was a major factor in keeping the federal standards as tough as they were. This in turn furthered the advantage of the TWC over its competitors in the rest of the U.S.

The confluence of regulatory and economic pressures may well be leading to a dominant design for exhaust emissions control for the familiar internal combustion engine. The writers of _Ward's Automotive Yearbook 1978_ feel that the three-way converter system will follow the path of the oxidizing converter and become standard equipment on all new cars within the next few years.[105]

It is important to ask whether or not the success of the three-way converter has negatively affected the development of alternative exhaust emission control technologies which are not currently competitive but which might eventually prove superior. In this respect, does the three-way converter represent the ascendancy of a dominant design in auto exhaust emissions control technology?

Time will tell.

3. SUMMARY HIGHLIGHTS

ROLE OF ADVOCATES/CORPORATE PERSONALITIES

It is safe to say that the TWC system would not have been adopted without the initiative of the catalyst makers, chiefly UOP and Engelhard Minerals & Chemicals. The personalities of these key advocates were very different. UOP was a technologically innovative and daringly entrepreneurial company looking for an automotive bonanza; Engelhard was a conservatively run firm with diverse operations looking for new markets to insure profitable use of its ample cash flow.

ROLE OF MARKET PULL/ROLE OF REGULATION

The demand for the TWC system was a result of progressively tightening federal and California auto exhaust emissions standards which were increasingly crippling the performance and fuel economy of vehicles equipped with conventional pollution control systems. This situation provided an opportunity for two technologically oriented Swedish automakers, Saab-Scania and Volvo, to adopt the TWC system in order to defend their US market share in the face of severe cost difficulties.

SOURCES OF THE INNOVATION

The TWC system was a derivative of the automotive catalytic converter technology that had been in development since the late 1950s. The major catalyst makers had long been involved in this development, and participated in the mass production of the oxidizing catalytic converter beginning in 1974.

GESTATION PERIOD/RESOURCES

Serious work on the TWC system apparently began in the early 1970s, when it became clear that major innovation would be needed to meet the tight pollution control standards just voted into law, and when the electronic equipment necessary to the operation of the system became widely and cheaply available. Quantitative data on resources applied to the development of the TWC system itself are not available, but it is assumed that TWC system development accounted for a significant fraction of the hundreds of millions of dollars and the thousands of workers known to have been allocated to overall catalytic converter development.

BARRIERS TO ADOPTION

Regulation was not a barrier to adoption. Technical problems facing the adoption of the TWC system were the difficulties in the use of the system with 6 and 8 cylinder engines (these difficulties have apparently now been overcome, at least for the 6 cylinder engine) and the durability of the oxygen sensor (this problem was overcome by administrative action). The insecurity of sources of supply for key materials could become a major barrier to adoption, but thus far it has not been. A major barrier to adoption was the reluctance of the American automakers to take the lead in employing the TWC system on their cars.

CURRENT STATUS

Saab, Volvo, Ford and General Motors offer the TWC system on many cars sold in California. All of these firms are expanding employment of the system, with GM looking towards use of the system on all of its cars sold in the US beginning in MY 1981. Other automakers besides these four are investigating the technology; several should be offering it on their cars in the next few years as tighter federal and California emissions standards are implemented.

4. GLOSSARY OF TERMS

Air/fuel mixture (a/f mix). The mixture of air and fuel found in the cylinders of internal combustion engines. The quantity and proportion of pollutant in the exhaust as it leaves the cylinder varies as the proportion of air to fuel in this mixture.

Lean air/fuel mixture means low proportion of fuel to air.
Rich air/fuel mixture means high proportion of fuel to air.

Air pump. "Device which cuts emissions of CO and HC by injecting air into hot exhaust gases just leaving the cylinder which speed further combustion of unburned hydrocarbons and converts the carbon monoxide into harmless carbon dioxide."[a]

Catalytic converter. Device which facilitates the reaction of certain constituents of hot exhaust gases with each other in order to reduce the constituents to a harmless state.

Oxidizing converter - device which reduces HC and CO.
Three-way converter - device which reduces HC, CO, and NO_x.

Exhaust Gas Recirculation (EGR). "Technique to cut NO_x emissions in which a portion of the exhaust emissions are sent back to the carburetor, where they mix with the incoming air/fuel mixture to reduce both oxygen concentration and the combustion temperatures."[b]

Lean-Burn. Engine technology which permits internal combustion engine to run at very lean fuel mixtures (see lean air/fuel mixture).

Positive Crankcase Ventilation (pcv) device. "The first auto pollution control device, the pcv unit prevents HC from escaping into the atmosphere from the crankcase, thus cutting 20% of the HC emissions given off from a car before control."[c]

Stoichiometric region. The proportion of air-to-fuel in the air/fuel mixture at which optimal conversion to harmless gases of HC, CO, and NOx can take place. The ratio is around 14.5:1.

Stratified Charge Engine. Otto cycle engine structured to create a rich a/f mix at the top of the cylinder and lean a/f mix at the bottom. This permits more complete combustion than would otherwise be possible, improving fuel economy and decreasing the amount of HC and CO in the exhaust.

(a) "Detroit Bets it Can Clean Up its Engines," Business Week, September 23, 1967, p. 89.

(b) Ibid.

(c) Edwin Mills and Lawrence White, "Auto Emissions: Why Regulation Hasn't Worked," Technology Review, March/April 1978, p. 36.

GLOSSARY OF TEXTUAL AND BIBLIOGRAPHIC ABBREVIATIONS

AE - Automotive Engineering

AI - Automotive Industries

AN - Automotive News

CARB Fact Sheet - California Air Resources Board Fact Sheet, "1977 Volvo Three-Way Catalyst Automobile"

CO - Carbon Monixide

HC - Hydrocarbons

IW - Industry Week

NO_x - Nitrogen Oxides (Oxides of Nitrogen)

NYT - New York Times

O&G Jour - Oil & Gas Journal

Priest - Joseph Priest, Problems of Our Physical Environment, Reading, MA: Addison Wesley Publishing Co., 1973.

Pt - Platinum

Rh - Rhodium

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WSJ - Wall Street Journal

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90. "GM to Buy Materials for Pollution Device from German Concern," Wall Street Journal, June 13, 1977, p. 2.

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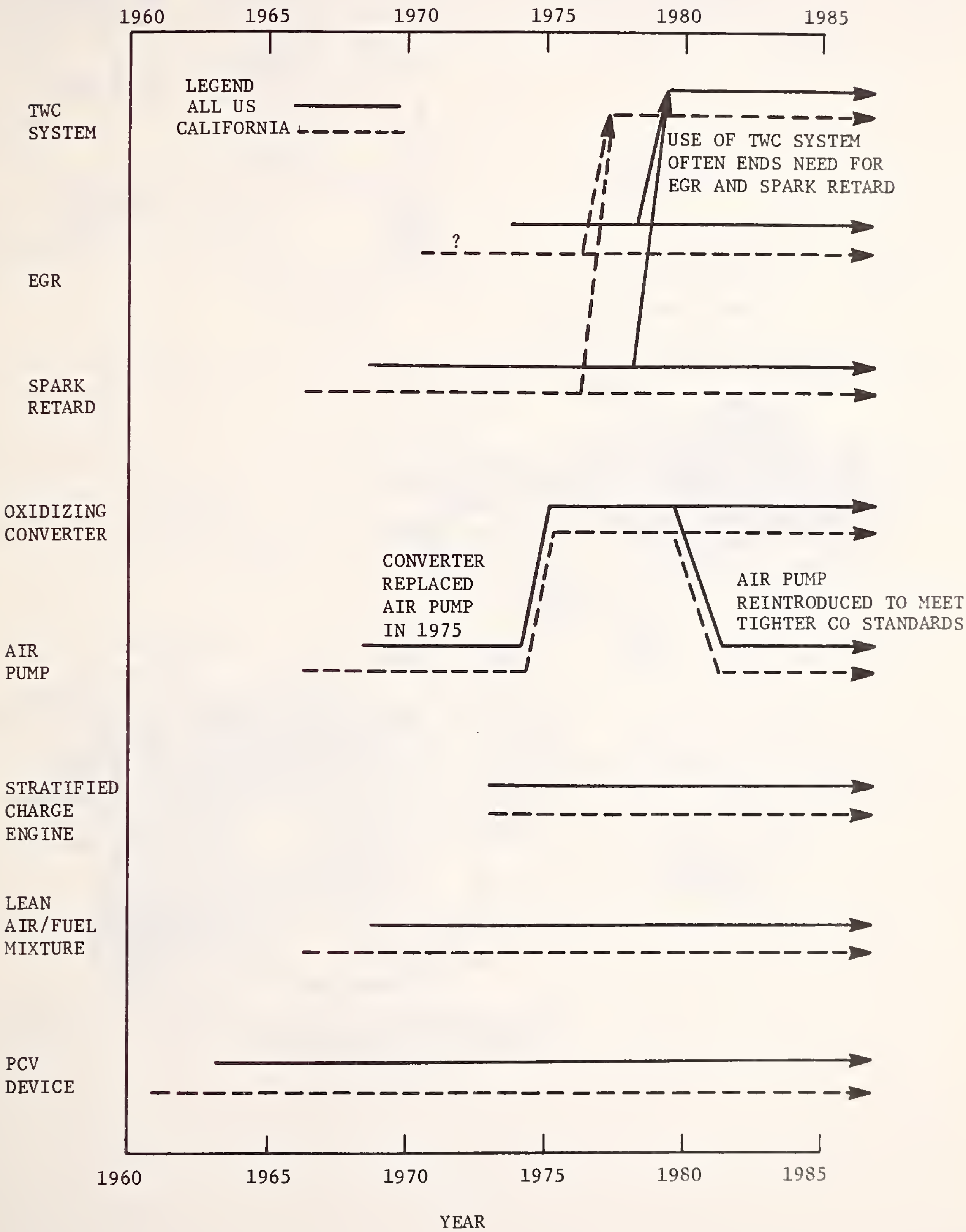
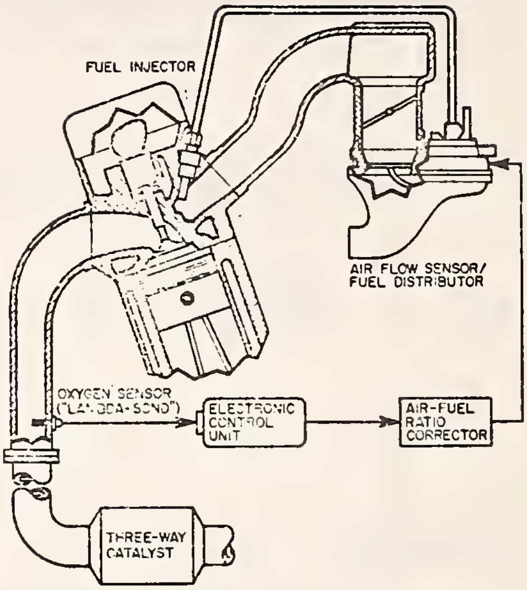
APPENDIX

AUTO POLLUTION CONTROL DEVICE INTRODUCTION SCHEDULE

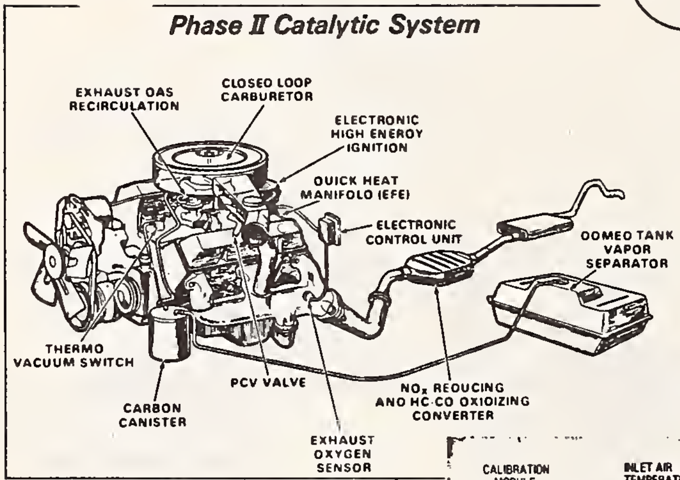


MAJOR CURRENT THREE-WAY CATALYTIC CONVERTER SYSTEMS



LAMBDA-SOND
(VOLVO/SAAB)

SOURCE: AE 85:2 p. 43
February 1977

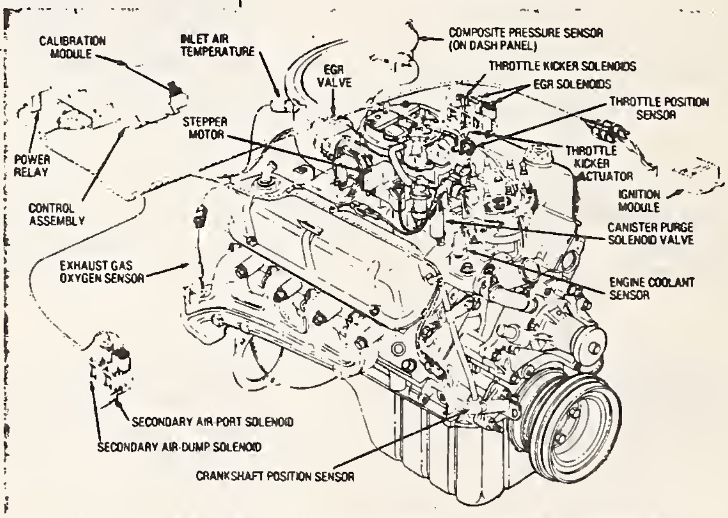


PHASE II
(GENERAL MOTORS)

SOURCE: AI p. 20
Feb. 1, 1978

EEC II
(FORD)

SOURCE: WARD'S
Auto World p. 71
May 1978



Ford's second generation electronic engine controls electronically coordinate air/fuel ratio, spark advance and exhaust gas recirculation.

TENTATIVE SUPPLY NETWORK FOR TWC SYSTEMS

AUTOMAKER	SUBSTRATE	SUPPLIER OF CATALYST	CARBURETOR OR FUEL INJECTION SYSTEM	OXYGEN SENSOR
VOLVO/SAAB	CORNING GLASS	ENGELHARD	BOSCH	BOSCH
CHRYSLER[1]	"	UOP	-	-
FORD	"	UOP?	HOLLEY	BOSCH
GENERAL MOTORS (AND POSSIBLY AMC)[2]	RHONE POULENC	DEGUSSA WOLFGANG	HOLLEY	GENERAL MOTORS

[1]This is if Chrysler actually has a TWC system; the listed data could refer to oxidizing converter components.

[2]Since GM supplied fully-built oxidizing converters to AMC, it is possible that this arrangement would also apply to TWC systems, if indeed AMC is actually equipping cars with them.

SOURCES: Annual Reports of Corning Glass, Engelhard Minerals and Chemicals, General Motors, Ford, and Volvo; and Ward's Auto World, April 1978, pp. 40-43.

FUEL ECONOMY AND EMISSIONS OF VEHICLES WITH ADVANCED CONVENTIONAL ENGINE SYSTEMS

Manuf.	Model	Inertia Weight	Emission Standard	Engine	Emission Control System	Emissions, g/mi HC	CO	NO_x	Fuel Economy, mpg City	Highway
Saab	99	3000	C-78	Gasoline, L4 121 CID, TC	FI, 3-way catalyst	0.23	2.5	0.74	19.7	27.2
	99	3000	C-78	Gasoline, L4 121 CID, N.A.	FI, 3-way catalyst	0.21	3.9	0.14	22.2	29.7
	99	3000	F-77	Gasoline, L4 121 CID, N.A.	FI, 3-way catalyst EGR	0.89	8.0	1.7	21.9	31.0
Volvo	240	3000	C-77	Gasoline, L4 130 CID	FI, 3-way catalyst	0.2	2.7	0.18	18	28
	245	3500	C-77	Gasoline, V6 163 CID	FI, oxid. Cat., EGR	0.2	1.1	1.25	14	26
	244	3500	C-78	Gasoline, V6 163 CID	FI, 3-way catalyst	0.35	3.6	0.85	15.6	26
	264	3500	F-76	Gasoline, V6 163 CID	FI, air inj., EGR	1.3	13.0	2.6	15.0	27
	244	3500	F-26	Gasoline, L4 130 CID	FI, air inj., EGR	0.80	9.1	1.9	18	25
GM	Sunbird	3000	C-77	Gasoline, L4 151 CID, A3	Carb., oxid. cat, EGR	0.25	2.5	1.3	20	27
	Sunbird	3000	C-78	Gasoline, L4 151 CID, A3	Carb., 3-way cat.	0.38	5.7	1.2	23	31
	Sunbird	3000	F-77	Gasoline, L4 151 CID, A3	Carb., oxid. Cat., EGR	0.5	7.0	1.1	22.5	30.5
Ford	Pinto	2750	C-77	Gasoline, L4 140 CID	Carb., oxid. cat., EGR	0.22	1.1	0.75	22	34
	Pinto	2750	C-78	Gasoline, L4 140 CID	Carb., 3-way catalyst	0.39	3.8	0.90	22.6	31

SOURCE: SAE Paper 780347, "The Moving Baseline of Conventional Engine Powered Passenger Cars", March 3, 1978

SOME ABBREVIATIONS USED IN ABOVE CHART

C - California
F - Federal
FI - Fuel Injection
TC - Turbocharger

FIFTY-STATE FUEL ECONOMY FIGURES FOR VARIOUS MANUFACTURERS

Manufacturer		1974	1975	1976	1977
GM	MPG_u	10.54	13.49	14.50	15.95
	MPG_h	14.55	18.67	20.28	21.87
	MPG_c	12.03	15.41	16.64	18.16
Ford		12.67	11.64	15.19	14.91
		18.62	17.11	20.96	20.72
		14.80	13.60	17.34	17.07
Chrysler		11.89	13.45	14.27	14.29
		17.00	19.20	20.03	20.58
		13.75	15.54	16.39	16.57
AMC		14.46	16.77	16.15	16.87
		19.52	22.57	21.83	22.27
		16.37	18.96	18.29	18.93
VW		22.61	23.04	22.95	25.88
		35.05	35.62	34.38	38.49
		26.91	27.39	26.98	30.35
Toyota		19.19	18.92	21.19	24.74
		28.59	28.17	31.87	35.65
		22.52	22.17	24.95	28.69
Nissan		20.69	21.46	22.46	23.81
		30.00	31.09	31.87	32.72
		24.05	24.94	25.90	27.13
Volvo		16.55	16.35	16.45	17.01
		24.66	24.42	24.75	25.25
		19.42	19.21	19.37	19.94
Audi		19.14	20.33	21.89	22.14
		29.67	31.58	30.83	32.77
		22.78	24.21	25.17	25.92
Fiat		18.89	19.00	19.94	19.88
		27.01	27.12	29.78	30.16
		21.85	21.96	23.05	23.48
Triumph (BLMI)		19.3	20.35	20.83	22.60
		27.7	29.22	29.44	31.82
		22.3	23.57	23.98	25.99
Saab		18.41	21.15	20.00	20.64
		21.91	25.23	27.59	28.95
		19.84	22.81	22.82	23.70
Fuji		22.5	23.20	26.46	26.17
		31.0	32.11	35.02	37.08
		25.7	26.51	29.78	30.16
Daimler-Benz		13.30	15.03	16.32	17.16
		18.76	21.25	22.52	22.48
		15.30	17.35	18.63	19.20
Honda		26.05	27.16	28.47	31.31
		36.99	38.36	39.69	42.59
		31.11	31.27	32.62	35.55
Toyo Kogyo		11.69	14.36	18.93	24.58
		17.07	20.97	27.19	33.90
		13.62	16.73	21.93	28.05

Manufacturer	1974	1975	1976	1977
Porsche	17.5	16.56	17.14	16.01
	27.3	25.89	26.90	27.74
	20.9	19.76	20.48	19.78
R.R.	8.2	9.03	10.03	9.97
	10.9	12.03	13.22	12.93
	9.2	10.17	11.25	11.11
Alfa Romeo	20.6	19.44	19.48	20.59
	26.8	25.26	26.90	30.42
	23.0	21.69	22.24	24.09
Jaguar (BLMI)	9.4	10.95	10.83	11.37
	13.9	16.18	15.57	15.93
	11.0	12.81	12.55	13.05
Renault	19.6	23.52		23.25
	26.9	32.33		37.75
	22.3	26.81		28.11
Peugeot	16.58	19.98	19.73	24.14
	23.05	27.51	26.23	30.12
	18.98	22.79	22.21	26.15
BMW	16.69	15.45	16.52	17.71
	24.79	22.93	22.94	25.15
	19.54	18.11	18.90	20.43
Austin-Morris (BLMI)	21.6	20.37	18.42	17.75
	30.2	28.60	31.87	29.67
	24.8	23.40	22.74	21.67
Checker		14.90	15.70	15.54
		19.49	20.36	20.94
		16.70	17.50	17.58
BLMI (all)	17.3	18.48	18.16	18.4
	24.8	28.50	27.40	27.7
	20.1	21.39	21.41	21.7
All Companies MPG_c		15.58	17.76	18.64

Legend:

MPG_u - Urban cycle fuel economy

MPG_h - Highway cycle fuel economy

MPG_c - Composite fuel economy figure

Source: EPA. Automobile Emission Control, 1976
NTIS # PB 267-865, p.4-3

Production sales values used for 1974 whenever possible; 1975, 1976, and 1977 estimate based on estimated sales.

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