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THE DEVELOPMENT AND INTRODUCTION OF THE AUTOMOTIVE TURBOCHARGER
A Case of Innovation in Response to Fuel Economy Regulation

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16. Abstract

This case study examines the evolution of the turbocharger from its invention in 1905 by Dr. A. J. Buechi, to its use on passenger cars in the late seventies. The case makes a number of points. The market for turbochargers has changed over time. In the fifties, suppliers developed a commercial turbocharger for compact, light, high-speed diesel engines which found a large and growing market. Application to the automotive field was slow in coming. Turbochargers found use in competitive racing. Aside from a brief period in the early sixties, the automobile industry did not seriously consider turbochargers for passenger cars until the mid-seventies. Down-sizing and the attendant reduction in engine horsepower in response to the mandated fuel economy standards have created a market for turbochargers. Suppliers played an important role in the success of this innovation.

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PREFACE

In the future, further reductions in fatalities, fuel consumption, and emissions associated with automobile use will be needed. To insure that these goals are achieved, it is necessary to understand more thoroughly the process by which the development, implementation, and adoption of innovative automobile technology occurs. The current study, focusing on the development and commercialization of the turbocharger, provides an important link in addressing these questions. It assesses the impact of market pressures created by the fuel economy regulations, the advocacy role played by suppliers, and the changing perceptions of barriers to adoption.

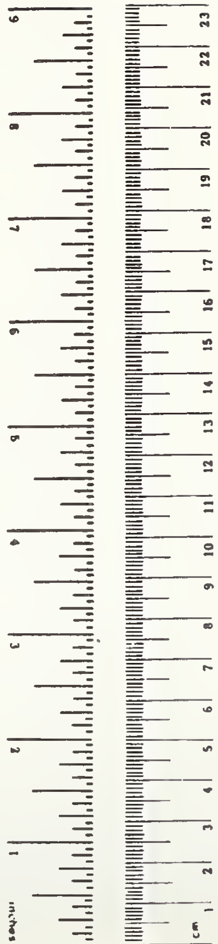
The turbocharger was selected for study due to its demonstrated ability to significantly improve automobile fuel economy without compromising vehicle performance. However, until recently, wide scale adoption of this innovation was thwarted by technical and economic barriers. The manner in which these barriers were overcome has important policy implications which may be projected to other sectors.

This work was carried out as part of the Implementation of Innovation in the Motor Vehicle Industry Program (HS-929), at the Transportation Systems Center, under the sponsorship of Mr. Sam Powel III, Office of Research and Development, National Highway Traffic Safety Administration.

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	36	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

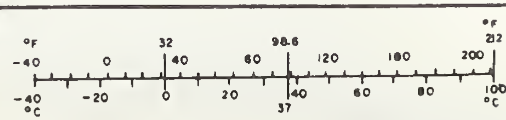


TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

EXECUTIVE SUMMARY

Mandated corporate fuel economy standards in the late seventies have led to the downsizing of passenger cars and the development and introduction of compact, lighter, and higher rpm four- and six-cylinder gasoline engines. Downsizing and the attendent reduction in engine horsepower have created a market for turbochargers. The use of a turbocharger on a reduced displacement engine offers the possibility of achieving the twin goals of improved fuel economy without loss of power and performance.

This case study examines the evolution of the turbocharger from its invention in 1905 by Dr. A.J. Buechi to its use on passenger cars in the late seventies. The case makes a number of points. The market for turbochargers has changed over time. Prior to World War II, the turbocharger's principle markets were in the aviation, marine and heavy-duty diesel engine fields. However, in the early fifties, suppliers undertook the development of commercial turbochargers for compact, light, high-speed diesel engines. The result of their work was a unit which was simple, rugged for road service, easy to install, impervious to weather, lightweight, fast in response to engine needs, inexpensive and easy to service. This unit found a large and growing market in commercial diesel engines for trucks both in the U.S. and abroad. Turbocharged diesel engines for trucks was a natural point of entry for mass-produced turbochargers because of the truck industry's need for increased fuel efficiency and horsepower.

Application to the automotive field was slow in coming. Suppliers had been experimenting with turbochargers for automotive engines since the late fifties. Turbochargers for automobile engines first found use in competition racing. Their success in racing was important to the overall development and adoption of turbocharger technology by automakers. The success of turbocharged competition engines served to establish that good acceleration characteristics and power output could be obtained from turbocharged engines by paying proper attention to design characteristics and by properly matching the performance characteristics of the turbocharger to those of the engine.

With the exception of a brief period in the early sixties, the automobile industry did not seriously consider turbochargers for passenger cars until the mid-seventies. There were technical problems including manufacturability, inertia lag, engine realibility, noise maintenance, engine knock, and cost. But most studies concluded that these problems were not insurmountable barriers to adoption. The industry's reluctance to use turbochargers in the sixties had more to do with market conditions and the trend towards bigger engines. The industry perceived the turbocharger as a low-volume performance option; at the time, automakers gained performance through the addition of more engine horsepower, rather than by the use of supercharging.

With the concern for fuel economy in the mid-seventies, the industry's perception of the turbocharger changed. Having once viewed turbochargers as a performance option restricted to the aftermarket, the industry now saw them as possible, but partial solutions to the new mandated fuel economy standards. Turbochargers offered the possibility of doubling the output of a smaller displacement engine without raising fuel consumption and, in some cases, with appreciable gains in fuel economy. By 1977, most major automakers in the U.S. and many foreign manufacturers expected to market turbocharged passenger cars. By 1978, these plans were confirmed, and many manufacturers announced the availability of turbochargers on upcoming models.

The turbocharger has proven its capability to increase the specific output of the reciprocating engine in an economical way so that it is safe to predict that in the future turbochargers will find increased application in passenger cars.

1. SUPERCHARGING AND ITS POTENTIAL

There are two traditional methods of raising power output in a piston engine: raise the engine's compression ratio or pump more fuel mixture into the engine. With the former method, fuel quality and combustion chamber design set a practical limit on how high a compression ratio can be used. The second method, pumping more mixture, can be accomplished in several ways. One way is to increase engine displacement. This has the drawback of increasing the engine's size and weight. Another way is to run the engine faster, thus pumping more mixture through it in a given time. There is a physical limit, though, to the rpm any engine can run without suffering extensive damage to its valve gear, bottom end, and pistons.

The final and best way to increase the mixture in an engine utilizes the 75 year old concept of forced air induction or supercharging. Most simply, supercharging is fitting an air compressor to blow into the manifold. The practical supercharger has been around for over 50 years and was an indispensable part of Grand Prix racing cars from 1927 to 1950.

Supercharging provides the engine with high-flow pressurized air that inducts and burns more fuel, producing higher combustion pressure. Improvements in an engine's specific output are related to the amount of charge that passes through the engine. There are basically two ways to precompress the charge before its induction into the engine. The first employs belt or gear driven blowers which use direct engine drive of a centrifugal compressor. These mechanical blowers have little application on modern passenger cars either in racing or in normal use because they absorb useful crankshaft power, hence adversely affecting an engine's economy. A blower drive takes away one-third to one-half of the power gained by the use of a supercharger. Moreover, it is difficult to turn on and off, and consequently absorbs power when no boost is required.[1]

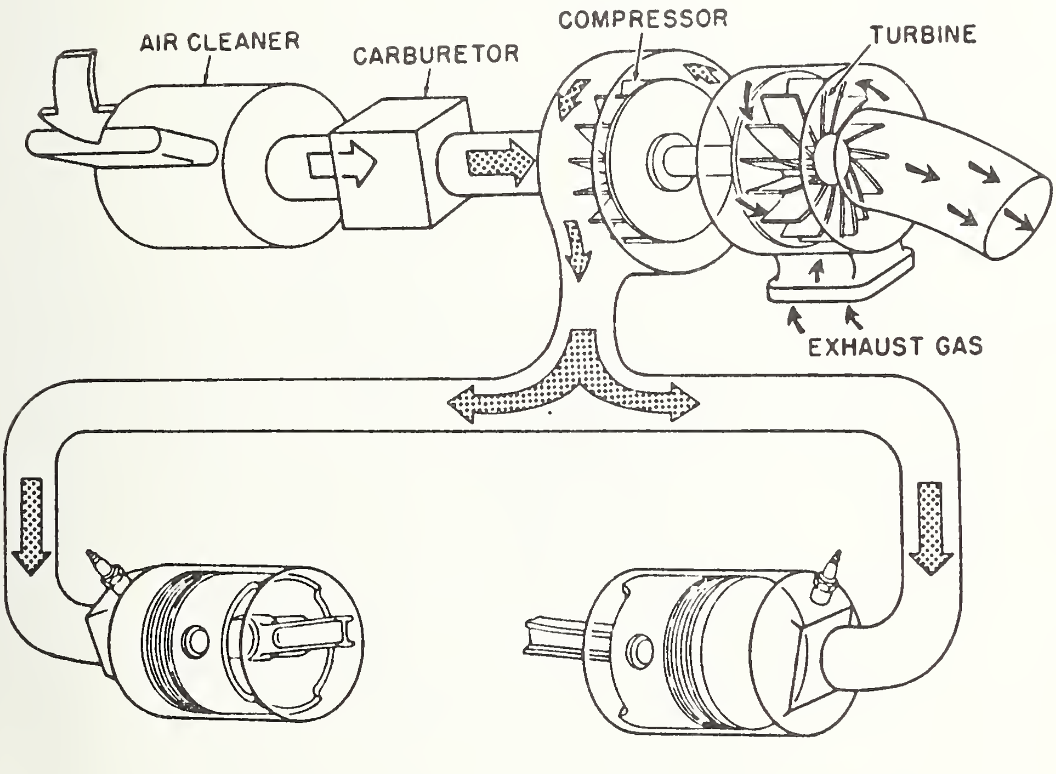
2. TURBOCHARGER -- DESCRIPTION AND OPERATION

The turbocharger is an entirely different proposition. It is an exhaust powered turbine that drives a compressor. It has an advantage over mechanical blowers in that it utilizes energy in the engine's exhaust fan that would otherwise be wasted. Its disadvantages are poor boost capacity at low engine speeds and a potential to lag in response to power needs.[2]

The turbocharger takes up a small amount of room and weighs little. On the average, a unit weighs 14 lbs. and is about the size of a foot square breadbox.[3] The unit itself consists of two parts, a compressor and a turbine (See Fig.1). The turbine wheel and compressor wheel are mounted axially on a common shaft. The compressor is comprised of three components: the wheel, diffuser, and housing with its inlet and discharge connections. The turbine consists of a housing, nozzle, and wheel.[4]

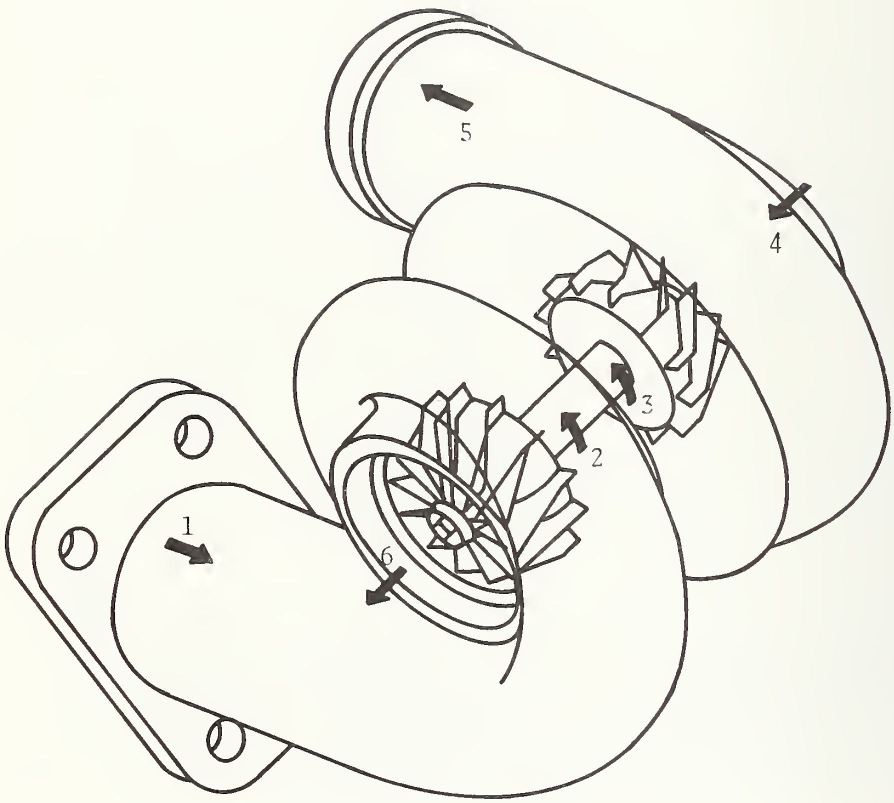
A turbocharger uses the energy of the exhaust gases to drive the turbine. As shown in Figure 2, exhaust gas from the engine enters the turbine housing (1) and expands to the atmosphere through the turbine's wheel, where part of its energy is converted into

Figure 1. Schematic of Turbocharging System



Source: <u>Assessment of the Effects of Short-Term Drive Train Options on the Automobile and Related Industries</u>, Vol. II, prepared by the Aerospace Corporation, El Segundo , California, December 1976, Chapter 2, pp. 2-96.

Figure 2. Operation of Turbocharger



SOURCE: <u>Wallace Murray Annual Report, 1972, p. 8.</u>

mechanical work. The turbine is connected by a shaft (2) to a compressor wheel (3), made of a lightweight high strength aluminum alloy, running at the same rotational speed on the turbine. Air is drawn into the center of the wheel where centrifugal action forces it outward between the diffuser surfaces (4). Now compressed, air is discharged out of the housing and toward the engine's specially cast intake manifold.

Because it is impossible to compress air without heating it, most turbocharger installations have intercoolers as part of the intake manifold. Improved cooling is necessary because of the increased charge densities accompanying turbocharging increase the thermal load on the cylinder. The higher heat release from turbocharging, as well as the higher heat transfer, serves to increase the temperature of the combustion chamber components. For this reason, the turbocharger uses a system of piston cooling or sodium filled valves for improved cooling of the components. In addition, water and/or alcohol injection is needed to cool the fuel mixture during sustained higher rpm.[5]

3. TURBOCHARGER HISTORY AND EVOLUTION -- PRE 1950

A Swiss engineer, Alfred J. Buechi, of Winterthur, invented the turbocharger, the basic patent dating from 1905. He designed it principally as a means of getting higher specific output from large diesel engines.[6] At the same time as Buechi's experiments in Switzerland, a French scientist, August Rateau, was experimenting in Paris with gas turbines as well as turbochargers for aircraft engines. In 1918, Dr. Sanford Moss of General Electric demonstrated the first successful aircraft application of the turbocharger on a Packard-built, Liberty-powered fighter plane. From 1936, General Electric turbochargers were common on high-altitude U.S. military aircraft and almost universal on World War II fighter planes.[7]

By 1926, Buechi had investigated thoroughly the theoretical advantages of a well-matched turbocharger-engine combination. That year he perfected a turbocharger for diesel locomotives and started production. In 1938, he installed a turbocharger on a 4-cylinder Saurer - the first successful motor truck application. By 1939, turbocharged diesel engines were common to railroad locomotives, ships, and a variety of stationary and industrial applications. Saurer in Switzerland began production of diesel trucks with Buechi turbochargers as early as 1949. Soon after, other companies, in particular Eberspaecher in Germany and AiResearch in America, entered the market, concentrating on diesel application. Volvo, which started production of diesel engines in 1946, introduced turbocharging in 1954, mainly on engines for heavier trucks with total weights above 26,000 lbs.[8] Volvo did make some turbocharger engines for buses, tractors, and industrial and marine applications.

3.1 Turbochargers and Diesel Engines -- Post 1950

Mass-produced turbochargers have been primarily a post-World War II industry directed toward high-speed diesel engines. In the fifties, the turbocharger industry existed as a service industry to engine manufacturers. Small turbochargers first became available in the U.S. for experimental use in the late forties and early fifties.[9] At that time, several U.S. diesel engine builders undertook extensive development programs in order to apply turbochargers to compact, high-speed diesel engines in high-volume production. Until the early fifties, the turbocharger had found its greatest application for large, low-speed, stationary marine diesel engines in low-volume production.[10]

3.2 Development of the Commercial Turbocharger

The first design prototypes for diesel engines were large, bulky machines with cumbersome rotating assemblies containing a number of parts. Moreover, they were low in component efficiency.[11] Despite these problems, engineers felt that a high-speed, compact, and low-cost turbocharger offered very substantial and economical increases in specific output for small diesel engines, possibly doubling the output of a naturally-aspirated engine. A turbocharger installation offered particular advantages over naturally-aspirated engines in high-altitude operation as well.[12] Also, the turbocharger appeared to provide better control of the high temperatures associated with a diesel powerplant, in effect giving improved engine cooling without extensive redesign of vital components.[13]

Several U.S. manufacturers, in particular Schwitzer, undertook the development of commercial turbochargers for high-speed diesels in the early fifties. Wolfgang Lang, Senior Development Engineer for AiResearch, outlined the basic objectives behind these development programs. The new turbocharger, he said,

> had to be extremely simple, rugged for road service, easy to install with a minimum of plumbing, impervious to weather, lightweight, fast in response, and inexpensive relative to the low-cost per horsepower of the heavy duty diesel engine.[14]

The manufacturers wanted a reduction in the turbocharger's size and weight in order to facilitate the mounting of the unit on a variety of engines with space restrictions. Another consideration was the simplification of the design to reduce costs and to make the unit easier to service.[15]

The application of the turbocharger to high-speed diesels necessitated changes in the unit's design. Manufacturers developed sleeve bearings suitable for extremely high rotating speeds. Moreover, using wheel designs suitable for mass production from precision castings, they developed centripetal, radial in-flow turbines, which had advantages in terms of design simplicity and cost. In addition, manufacturers developed compressors of different flow ranges and characteristics.[16]

Most important, the development work in the early fifties led to a standardization of parts. Component rationalization allowed the manufacturer to use the same frame size and same parts for a multitude of engines with different displacements and speed ratings. Hence, the manufacturer could limit the number of turbocharger models while allowing the user to upgrade his engine or to match the turbocharger to different applications and speed ratings without changing the installation on the diesel engine.

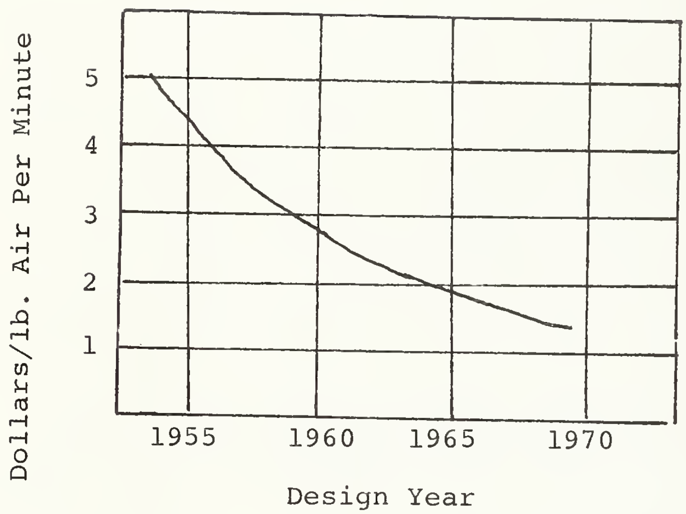
Most of these developments and, in particular, design improvements and component standardization were possible because of the increased knowledge the industry had gained in wheel design, stress distribution, materials and casting techniques.[17] Improvements in design and materials, as well as the standardization of parts led to steady reductions in cost. Figure 3 shows turbocharger selling price from the early fifties through the late sixties. Price is calculated on the basis of dollars per pound of air delivered per minute by the turbocharger. Engine power is directly related to the air delivered. This reduction from $4 to $2 per pound of air represents a reduction to one-half the cost per horsepower chargeable to the turbocharger.[18]

These development programs were very successful. Not only had the suppliers achieved their prime objective of increasing the power and efficiency of small diesel engines, but they had carried out extremely important development work on the turbocharger for later applications. Their programs served to establish the fact that turbocharging small, high-speed diesel engines was possible, thus providing the incentive to both engine and turbocharger manufacturers to pursue further research and development efforts.[19]

3.3 Commercial Success of the Turbocharged Diesel

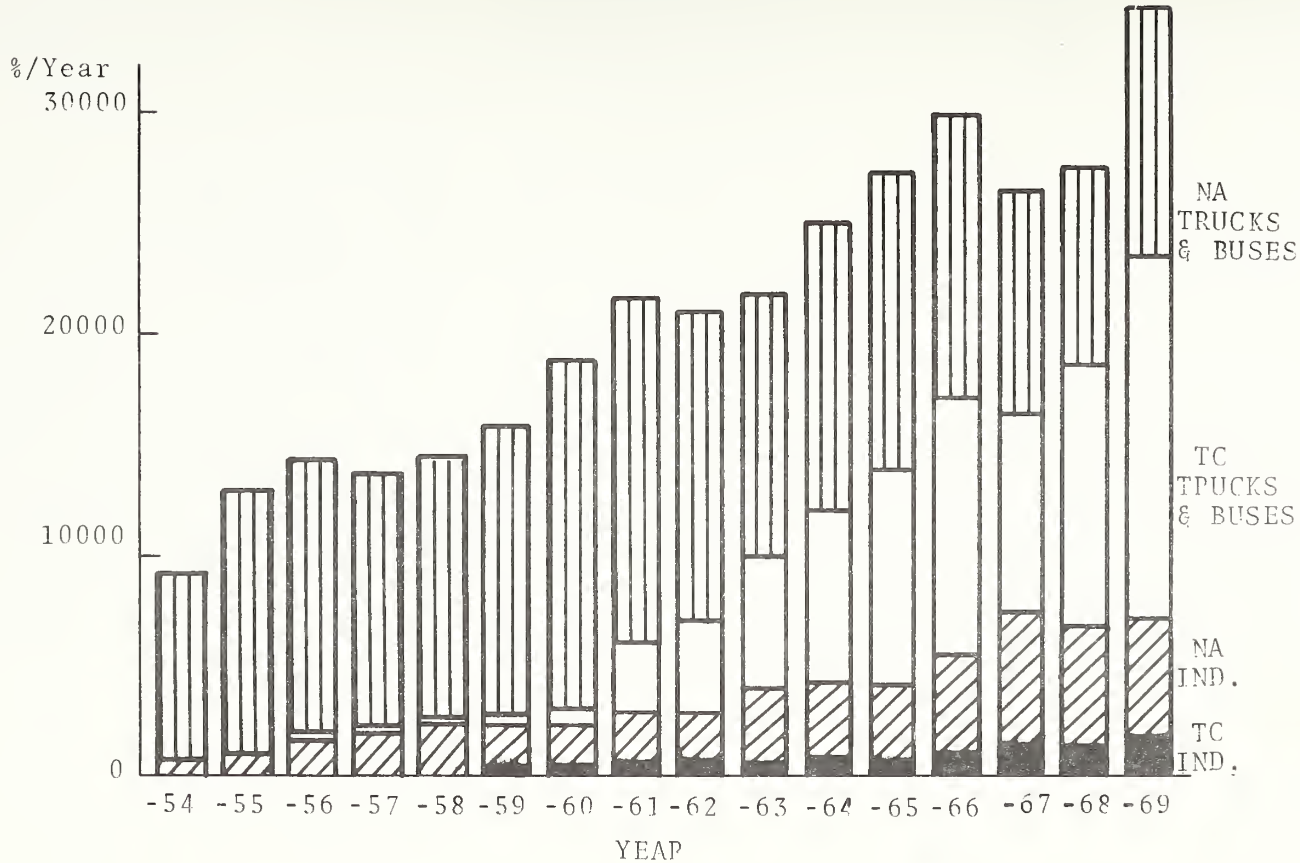
Since the production of turbocharger diesel engines in the early fifties, there has been a strong interest both in the U.S. and overseas. By 1955, all leading diesel truck manufacturers were testing or using turbocharger diesels in production.[20] Figure 4 shows production figures in Scandinavia for different diesel engine types and the increasing proportion of turbocharger engines on trucks, buses, as well as in industrial applications, from 1954 through 1969. More than 60 percent of the trucks and buses sold on the Scandinavian market in 1968 were equipped with turbochargers.[21]

Figure 3. Turbocharger Cost versus Air Delivery



Source: Glen Holzhausen, "Turbocharging Today and Tomorrow," SAE technical paper, No. 660172, 1966, p. 2.

Figure 4. Scandinavia's Total Diesel Engine Production Broken Down into Turbocharged and Naturally Aspirated Engines



Source: Bertil Haggh and Ernst Holmer, "Experience and Developments of Turbocharged Diesel Engines in Scandinavia," SAE technical paper, No. 690746, 1969, p.4.

In the U.S., diesel engines, such as those on heavy-duty trucks, were the principle users. Fifty percent of all such engines in use in 1972 were turbocharged.[22] According to industry forecasts all new heavy-duty diesel engines would carry turbochargers by 1975.[23] Aside from trucks, off-highway vehicles, such as construction, earth-moving, agricultural and marine, constituted another growing market.[24]

It is not difficult to see the reasons behind the diesel engine industry's adoption of the turbocharger. The average unit delivered 45 to 60 thousand cubic feet of air per hour into the diesel engine of a truck or off-highway vehicle, increasing the horsepower by as much as 100 percent. In addition to increasing specific output, it simultaneously increased fuel efficiency and reduced exhaust emissions and noise.[25] Such were Lang's conclusions after his test of two diesel engines of the same displacement, one turbocharged and the other naturally-aspirated. He noted the turbocharged engine's appreciable gain in bmep and bsfc and commented on its fuel economy:

> While the naturally aspirated engine operates at more or less constant air/fuel ratio along a full power curve and smoke limit, the air/fuel ratio increases with engine speed on the turbocharged engine due to the increase in turbine speed, compressor discharge pressure, intake manifold density, and air-flow as a function of turbine inlet pressure and turbocharger overall efficiency.[26]

<u>1958-1966</u>

In general, significant cost, weight and size reductions were achieved during the period between 1958 and 1966. These occurred simultaneously with improvements in quality, reliability, and performance.[27] AiResearch and Schwitzer Division of Wallace-Murray Corporation began experimenting with turbochargers for automotive gasoline engines in 1958.[28] By this time it was evident that the turbocharged diesel engine, when compared to a naturally-aspirated engine with similar power output, held substantial advantages. Not only had it shown important acceleration gains, but there was evidence that it led to lower emissions and improved fuel economy. Turbocharger manufacturers expected comparable benefits by applying the turbocharger to spark-ignition automotive engines.

The potential market for turbochargers looked strong in the early sixties. It was restricted to heavy-duty diesel engines, its biggest sales being in the truck field. Sales were limited to 4-cycle diesel engines, but it was believed that the 2-cycle diesel had design characteristics which offered promise of increased turbocharger application. Authoritative estimates were that 10 per cent of total commercial diesel trucks in the U.S. were turbocharged. This excluded military orders which were beginning to be substantial. There was also a trend toward turbocharging in the earth-moving equipment and big crawler tractor field. By the early sixties, for example, International Harvester was turbocharging all of its diesel equipment. In the wheel-type farm tractor field, Allis-Chalmers introduced a Thompson turbocharger in its D-19 75 hp series in December 7, 1971. The turbocharger provided a 50 percent boost in horsepower and was trouble free. Allis-Chalmers reported that its sales were high for this particular series.[29]

While turbochargers had been common since the early fifties in the diesel and aviation fields, application to the automotive field was slow in coming. Oldsmobile was the first major company in the U.S. or abroad with a turbocharged production model. In 1962, it offered a performance model F-85 Jetfire in which the turbocharger was fitted to a 215 cu.-in. aluminum power plant -- the same engine that Buick used in its 1961 model F-85. Chevrolet, that same year, turbocharged its 150 hp. engine for the six-cylinder, air-cooled Corvair Spyder. Neither model sold very well or stayed in production long. The turbocharged Corvair sold only 60,000 cars and was dropped after three years of production. Oldsmobile produced about 3,765 Jetfires in 1962, but dropped the turbocharged version of the F-85 the following year.[30]

One possible interpretation of Chevrolet's use of the turbocharger in Corvairs was that it allowed Chevrolet to compete with Ford's newly introduced "sporty" Mustang. Added performance was being stressed in advertising campaigns, and the turbocharged Corvair filled in the gap until Chevrolet came out with the Camaro model the following year. It is clear that Oldsmobile also perceived the turbocharger as a temporary performance option, as Oldsmobile dropped the turbocharger after it increased the F-85's engine displacement, thus gaining the desired performance with size, and not supercharging.[31]

Ford, in 1963, built a few experimental turbocharged 390 cu.-in. engines, but did not pursue development work. With John DeLorean as Chief Engineer, Pontiac experimentally installed turbochargers on its Tempests and Catalinas.[32] And Chrysler worked on a turbocharged 413 V-8 in the mid-sixties, but gave it up because of severe problems with cold starting.[33]

It is not difficult to explain the auto industry's refusal to consider seriously turbocharging during this period. Lawrence White has described the trend at the time toward larger size automobiles and Detroit's competition based on horsepower. White says,

> Between 1949 and 1959, low, medium, and high price makes grew in all relevant dimensions. After 1959 the high and medium price makes tended to remain the same size or shrink slightly, while the low priced makes continued to grow.[34]

Detroit tended to introduce bigger engines with more horsepower.[35] Advertised engine power had become an important area of competition with power connected in the consumer's mind with engine size. Moreover, the long-run trend has been to larger, more luxurious cars with more power and luxury options. The industry believed that consumers wanted larger, heavier, and higher priced cars. In this context, the turbocharger did not seem to have a market. The turbocharger's advantage - good performance - was a quality which the consumer presumably was willing to buy in a larger car with a bigger engine.

3.4 Competitive Engines

It has been pointed out that racing serves as a critical proving ground for automotive innovations that become standard equipment on passenger cars. Torsion bar suspension, synchromesh gears, high-performance tires are some examples of this. Such seems to be the case with turbochargers, as well. Turbochargers, during this period, were very important in competitive racing. Schwitzer Division of Wallace-Murray had built the turbocharger for the Cummins Diesel that held pole position at the 1952 Indianapolis 500. The race car employed a small, high-speed turbocharged diesel engine, designed and manufactured by the Elliot Co. It was one of the first public appearances of a turbocharged diesel engine in competitive racing. Compared with the highly-developed, spark-ignition engine cars, this turbocharged racing engine had obvious disadvantages in size and weight. Nonetheless, the turbocharged diesel-powered car broke the track record in qualifying speed.[36]

Since 1952, the turbocharged competition engine has dominated the Indianapolis 500 mile race, as well as other competitive events.[37] In 1967, for example, Alex von Falkenhauser, Chief Engineer of Engine Development for BMW, turbocharged a 2002 engine for Group 5 racing with outstanding results, using a Kuehnle, Kopp, and Kausch (KKK) unit built under Schwitzer license.[38] The success of the turbocharged diesel engine in racing applications was important to the overall development and adoption of turbocharger technology. It served to establish that good acceleration characteristics and power output could be obtained from a turbocharged engine by paying proper attention to design characteristics and by properly matching the performance characteristics of the turbocharger to those of the engine.[39]

3.5 The Suppliers and Manufacturers -- 1967-74

The market for mass-produced turbochargers was restricted to heavy-duty, diesel-powered vehicles in the late sixties. There were three major U.S. manufacturers of turbochargers which supplied the units to diesel engine and truck markets - Schwitzer Division of the Wallace Murray Corporation, AiResearch Industrial Division of Garret Corporation, and Rajay Industries of Texstar Corporation. While their major market was trucks, off-highway equipment, and stationary applications of turbochargers, each manufacturer, during this point, saw the turbocharger's potential application on passenger cars and, in particular, small cars wanting in power output. They developed a consistent aftermarket strategy of not selling directly to the public, but rather introducing special kits for particular cars through performance distributors.

Wallace Murray Corporation, a manufacturer of building products, cutting tools, power components, and custom metals, bought Schwitzer in 1965. Schwitzer was a well-known manufacturer and designer of components for internal combustion engines with manufacturing facilities in Indiana, Missouri, Canada, and Brazil. Its products included turbochargers for truck, industrial, and marine engines, cooling fans, air pumps, air motors, torsional vibration dampers, water pumps, superchargers, and fan drives. Schwitzer exported its products to Europe, South America, and Japan and held numerous licensing agreements with foreign countries.[40]

In 1966, Schwitzer began developing a small, less-costly turbocharger for consumer power equipment.[41] A modified version of this turbocharger, mounted on a Ford engine, increased horsepower by over 40 percent, and helped to win in 1962 six USAC championships, including the Indianapolis 500.[42] In 1969, Schwitzer investigated the possible application of this turbocharger for passenger autos.[43] In 1971, it tested the effects of a turbocharger on engine emission control. Schwitzer engineers carried out these tests on both VW and Vega engines, naturally-aspirated and turbocharged. The tests indicated that the addition of a turbocharger to the standard engine reduced HC emissions by 14 percent, CO by 13 percent, and NO_x by 8 percent.[44] On the basis of the tests, Schwitzer proposed the turbocharger as early as 1971 as a possible solution to the growing problem of automotive exhaust pollution.

However, the immediate market that Schwitzer hoped to enter with its turbochargers was performance cars. During 1970, Schwitzer completed a survey designed to find the best point of entry into this large and potentially receptive market. The survey's results suggested one specific automobile - the Volkswagen. The VW's need for increased power output at high speeds was obvious. And the market was large - there were 4 million VWs on U.S. highways. Schwitzer calculated that turbocharging only one-half of one percent of them represented a market of $8 million per year.[45] The best channel of distribution, Schwitzer decided, was performance dealers. There were 1,600 distributor outlets in

Florida, Arizona, and Texas - the first test area that Schwitzer selected. California, another potential market area, had another 2,000.

Schwitzer's product was a bolt-on turbocharger kit which could be installed quickly and easily on standard VW 1500 and 1600 engines, as well as VW-powered dune buggies. A minimum of extra plumbing was needed to install the turbocharger. Schwitzer estimated the total installation time to be 8 hours. The turbocharger, the company claimed, provided the VW with a 100 percent boost in horsepower, 70 percent increase in torque, and a cleaner exhaust. Schwitzer shipped the first units of the kit to distributors in November 1971.[46] The kit was so successful that, by 1972, Schwitzer was working on plans that envisioned the inclusion of a turbocharger as a performance option on original equipment on future models of production cars.[47]

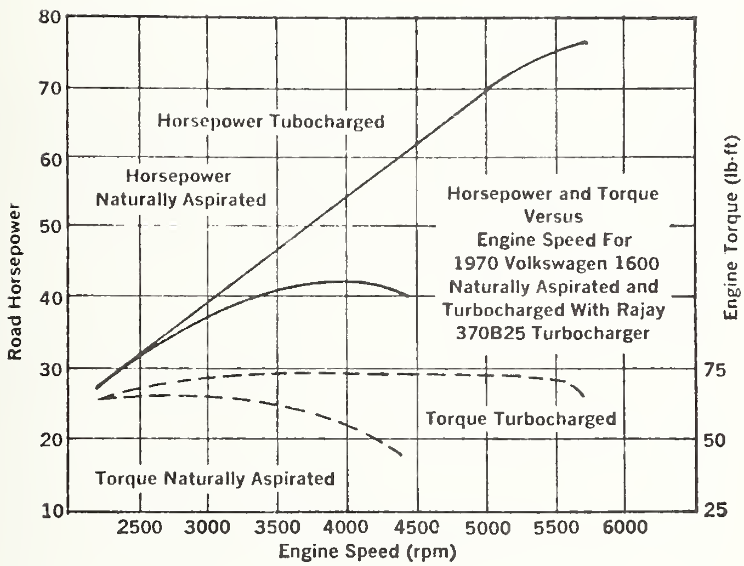
Garret Corporation, which is active in commercial and military aircraft, ground transportation, and industrial supply fields, owns AiResearch Industrial Division. AiResearch produced turbochargers for off-highway trucks, diesel trucks, and aircraft engines. AiResearch started from a background of designing, developing and producing turbochargers for medium horsepower diesel engines. As early as 1958 and 1959, it started to apply its experience in developing passenger car turbocharged concepts.[48,49]

Rajay Industries, a subsidiary of Texstar Corporation, has been designing and manufacturing turbocharger installations for light aircraft since 1962. All of Rajay's early installations employed TRW turbochargers similar to those used by TRW on automotive and marine applications. TRW's Valve Division had entered turbocharger production in 1961, attracted first by the heavy-duty diesel market and later by GM's acceptance in the early sixties of the turbocharger as a performance option. Rajay, in 1969, purchased TRW's complete turbocharger business, including all tooling and manufacturing equipment. It made this purchase with the intention of producing a line of turbocharger kits for passenger cars. At the time, Rajay saw turbochargers as a means of increasing power at relatively low cost without resorting to expensive welding or disassembly of the engine. The company chose the 1970 VW 1600 engine for its first turbocharger installations. It chose the VW for two reasons: the VW was a car model badly in need of power and VW owners seemed particularly prone to purchase non-stock equipment. Rajay claimed the turbocharger increased VW power 100 percent without loss of low-end performance.[49] (See Figure 5)

By 1974, these three major turbocharger manufacturers had a variety of kits available to distributors. (See Figure 6) Applications included passenger and competition cars, consumer trucks, and recreational vehicles. More kits for different models were being developed. Approximate cost to the consumer was very high for these units. Average price for a Vega or VW Beetle kit was upwards of $540. Schwitzer, for example, sold a turbocharger kit for the VW Beetle for $796. Prices included the necessary hardware to install the turbocharger, but did not include installation costs.[50]

California's state regulation erected an interesting barrier to turbocharger development during this time. California was potentially the biggest market for aftermarket turbochargers. But

Figure 5. Turbocharged 1970 VW 1600 Engine versus Naturally Aspirated Engine



Source: "Turbocharge!!!," <u>Hot Rod Magazine</u>, October 1970, p. 59.

Figure 6. Turbocharged Kits Available (1974)

Manufacturer	Application		Model	Approx. Cost to Consumer*	Dealers/ Installers
AiResearch	auto, truck & RV engines		Chevrolet 265-400 V-8	$700	
			Pinto 2000 cc (Competition)	$641	
			Colt 1600 cc	$641	
		In Development as of 1974	Ford 332-351 V-8s		
		In Development as of 1974	Chrysler 273-360 V-8		
		In Development as of 1974	Pinto (Street version)		
			Chevrolet 350 V-8	$600	
			Ford 360-390 V-8	$600	
			Dodge 360-400 V-8	$600	
			Pinto 2000	$550	
			Capri V-6	$550	
			Toyota RC-18	$550	
Schwitzer	automotive and RV engines		Vega	$796	200
			VW Beetle	$796	
			Late model Mercedes-Benz	$585	
			Peugeot diesel passenger cars, 200-D, 220-D, 504-D	$500	
Rajay	automotive and RV engines		Datsun 240-Z	$625	
			Porsche 914	$595	
			Datsun 1600-1800 cc	$525	
			Volkswagen models	$540	
			Mustang II 2.8-litre	$625	
			Capri V-6 2.6-litre	$625	

Source: Popular Mechanics, December 1975, p. 74.

*Prices include the necessary hardware to install turbocharger. They do not include installation.

the state prohibited turbochargers pending certification by its Air Resource Board. The test - a durability test of at least 30,000 miles - was complicated and costly, too great an undertaking for the small turbocharger manufacturers.[51]

4. THE DEVELOPMENT OF TURBOCHARGED PASSENGER CARS -- 1968-1975

Because there was considerable experience in manufacturing turbochargers for diesel engines, there was reason to believe that the technical problems in applying this concept to passenger car gasoline engines were of medium to medium-to-low risk.[52] On the one hand, possible problems included manufacturability, inertia lag, engine reliability and durability, noise, maintenance, weight and size, and engine knock. On the other, the turbocharger offered substantial promise in the areas of performance and fuel economy. The turbocharger industry felt that, on the balance, the cost of turbocharging an engine, including the fuel economy benefits gained by using a smaller engine and the performance increases, was worth their efforts.

4.1 Cost to Producers

The turbocharger as of the early seventies was an expensive piece of equipment. AiResearch stated that the most critical factor in the manufacture of the turbocharger was high-quality castings.[53] The turbine rotor, casing and duct system must be capable of withstanding high temperatures (700° to 1000°C) without distortion or structural defects occurring. Studies pointed out that, aside from the unit itself, turbocharging entailed additional costs because of its attendant equipment. A turbocharged engine might need more durable engine parts - heads, valves, pistons, bearings, rods and rings. Another item might be a heavy-duty automatic transmission, since a turbocharged engine experienced heavy loading at shift points.[54] A.D. Little concluded that more expensive exhaust valves could be necessary on turbocharged engines. In addition, if the carburetor were downstream of the turbocharger, it would be more expensive because it would be operating at much higher pressure. While the report provided no actual cost figures, it pointed out that these costs could be offset by a smaller engine, lighter chassis, and possible elimination of EGR.[55] Wildhorn concluded that a supercharged engine would be 10 percent higher cost per pound, but 20 percent less cost per horsepower, than a naturally-aspirated engine.[56] In the study conducted by the Aerospace Corp., automobile manufacturers refused to supply cost data. Chrysler, however, stated it considered turbochargers to be too expensive.[57]

In the Aerospace Corp. study, both Rajay and AiResearch provided figures for capital costs and OEM costs, which are shown in Table 1. The disparity in each manufacturer's estimated capital costs derived from AiResearch's feeling that a new unit would have to be developed for passenger cars, whereas Rajay based its estimates on producing an existing diesel unit design.[58]

4.2 Implementation

Were Detroit to adopt the turbocharger, Coons pointed out that, as of 1974, suppliers did not produce an adequate amount of turbochargers to meet a demand of 1 million units.[59] AiResearch provided the following product development schedule for the

Table 1. Capital & OEM Costs

Manufacturers	Production Level		
	10,000	100,000	1,000,000
Capital			
AiResearch			$40 Million
Rajay		$500,000	$ 1 Million
OEM			
AiResearch	$100	$70	$60
Rajay	$75-80	$75-80	$75-80

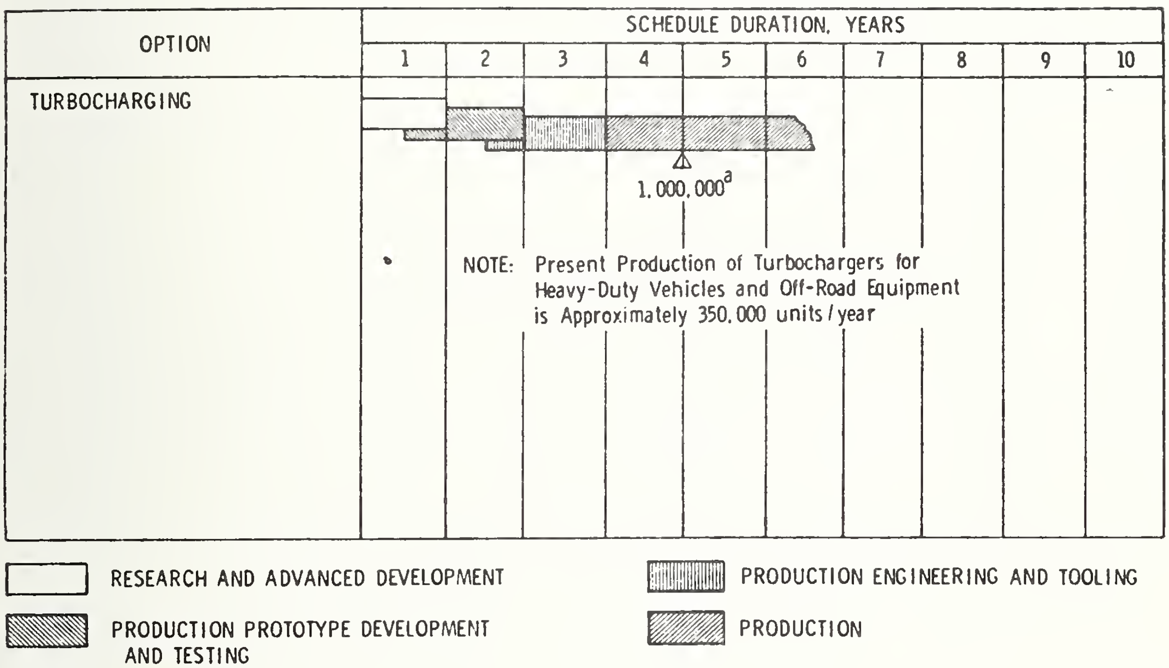
Source: Assessment of the Effects of Short-Term Drive Train Options on the Automobile and Related Industries, Vol. II, prepared by the Aerospace Corporation, El Segundo, California, December 1976, Chapter 2, pp. 2-114.

Aerospace Corporation Study. (See Figure 7) AiResearch estimated that at least one year of research and development time with another year for production prototype development and testing would be needed to come up with an acceptable turbocharger for mass-produced spark-ignition engine. As of 1976, AiResearch had the capacity to produce 300,000 units at its two facilities. It could provide an additional 10,000 to 100,000 units with no expansion or production problems. Were demand to escalate to 1,000,000 units, AiResearch predicted a total of three years before production could begin, since a new facility would be necessary and foundry capacity would have to be increased.[60]

Rajay Industries, the second major turbocharger manufacturer, was producing 20,000 to 30,000 units as of 1976, with a maximum capacity for 40,000 units. It indicated that it could handle an additional 10,000 units with no expansion. For levels of 100,000 or more units, it required new facilities, with 9 to 12 months before this facility could go into production. Rajay claimed that the shorter lead time resulted from the fact that the grinding equipment required does not take nearly as long to procure as some other types of tooling and machinery.[61]

Professor Cole of the University of Michigan Automotive Laboratory observed that significant production of turbochargers could not be implemented until 1980. Furthermore, he believed that automakers would procure them from outside suppliers rather than trying to produce them in-house.[62]

Figure 7. Product Development Schedule



Source: Assessment of the Effects of Short-Term Drive Train Options on the Automobile and Related Industries, Vol. II, prepared by the Aerospace Corporation, El Segundo, California, December 1976, Chapter 2, pp. 2-113.

4.3 Cost Considerations -- Consumer Price

Retail cost to the consumer was high. In the mid-seventies, turbocharging kits available on the aftermarket ranged in price from $600 to $1300 (custom-ordered Pantera unit). (See Figure 6) The retail price for a Rajay turbocharger for an Opel Kadet was $323, with the cost of fabricating the manifolds and brackets adding at least another $300.[63] Thus, the total price of this turbocharger unit, without installation, was $623. This was more than double the manufacturer's cost for an entire engine in standard form.[64]

However, this cost is very different from what could be expected if a turbocharger model for a passenger car were mass-produced and installed at the factory. Estimates on a mass-produced retail price vary. Hurter's study determined projected cost in the range of $150 to $250 for the initial added cost of the turbocharged system over a 1977 car.[65] A.D. Little estimated the added cost to be $150 to $250 for its turbocharged engine.[66] Wildhorn, whose analysis included the cost benefits of using a smaller, lighter engine with supercharging, estimated that a supercharged, full-size car would cost 6 percent less, and a sub-compact would cost 8 percent less than a conventional vehicle. In each case, Wildhorn projected the annual cost to be 10 percent less when fuel economy savings and maintenance costs were evaluated.[67] Coon determined that the incremental cost factors on a turbocharged 250 CID were: a smaller engine; addition of the turbocharger; addition of a inter-alcohol cooling system; and higher loading on the engine. In this study, Coon concluded that the reduction in material cost due to the decrease in engine displacement is probably nullified by the necessity for higher quality exhaust valves and added structural strength to permit operation at generally higher bmep and consequently higher temperatures. Coon estimated that the incremental cost increase of 250 CID turbocharged engines over the 350 CID naturally-aspirated engine was $75 to $150. If, however, instead of a water-cooled injection system, one employed an aftercooler and blower system (as Coons did on a 280 CID turbocharger engine), these items would significantly increase the cost of a 250 turbo-charged engine anywhere from $150. to $250.[68]

On the basis of OEM costs displayed in Table 1 for 1,000,000 units, the added cost to the consumer for a turbocharged car would be about $120. This price includes a mark-up of 50 percent for the automaker plus dealer mark-up. Another $30 needs to be added to this figure to take into account changes made in ducting valves, and fittings.[69] It is interesting to note that AiResearch, who supplied GM with the turbochargers for its '63 Oldsmobile Jetfire, claimed that this supercharged version cost the consumer only about $100 extra.[70]

One argument was that the turbocharger's better fuel economy would quickly pay the added cost. Based on simple pay-back calculation which takes the improvement in fuel economy on a turbocharged engine to be 15 percent, the car's annual mileage to be 12,000, and the vehicle's economy to be 18 mpg, a turbocharged engine's total fuel savings would be 87 gallons/year. If the price of gas were 60¢/gallon, a turbocharger costing $150 would pay for itself in slightly less than three years.[71] In any case, the cost situation for turbocharged passenger cars did not appear to parallel that of the truck industry where the cost of fuel was a much more significant factor and the use of a turbocharger, representing a 20 percent addition to the cost of a big diesel, constituted a more favorable cost/benefit ratio.[72]

4.4 Inertia Lag

One possible problem with a turbocharged engine was its delay in response to the driver's need for quick acceleration. Turbocharged engines did not necessarily respond quickly enough during sudden changes in load. This problem had to do with the existence of a separate system of rotating masses, and a longer, more tortuous gas flow path. During acceleration, the system needed more time for increased throttle opening to produce a greater gas volume to accelerate the turbine.[73] However, by 1976, it seemed that designers and producers had largely overcome this problem of inertia lag. One solution was to minimize the delay by bypassing the compressor flow until the turbine came up to speed.[74] This was Porsche's design innovation in 1975. In its turbocharged Carrera, throttle lag was hardly noticeable because Porsche had built a valve in the inlet manifold that opened to bypass the turbocharger when its revs were low and the driver demanded power. Thus, the turbocharger did not act as a restriction in the inlet stream.[75] In general, engineers felt that the turbocharger's lag in initial response was not likely to be much of a problem.[76]

Most studies also commented on the issues of engine reliability and durability, noise, and maintenance. The Aerospace Corporation study concluded that for everyday passenger vehicles, it seemed possible to employ turbocharging without significant sacrifices in engine reliability or durability.[77] Coon, in his report, pointed out that turbocharging will have a detrimental effect on engine reliability due not only to the turbocharging unit itself, but to the necessary additional devices like the aftercooler, blower, and knock-suppressant systems.[78] As to the durability of a turbocharged engine, it has been pointed out that an engine equipped with a turbocharger might require improved engine parts, in particular heads, valves, pistons, bearings, rods and rings. The unit itself, Schwitzer maintained, usually outlived the vehicle on which it was mounted.[79]

With regard to noise, reports were contradictory. Some claimed that the turbocharger tended to act as an exhaust noise silencer with the turbine whine being almost inaudible. The Aerospace Study, for instance, mentioned that a turbocharged diesel in the 1970 Clean Air Car Race passed all of the standard vehicle noise tests without the use of a muffler.[80] Coon, however, asserted that the overall noise levels of the turbocharger engine will be higher, but not significantly so.[81]

Maintenance would not present any large problems. The complexities of a turbocharger were not considered to be beyond the ability of the average auto mechanic.[82] The unit required certain special, but not overly problemsome considerations. It was necessary to keep the exhaust system free of foreign objects; it required frequent cleaning of the turbocharger's housing unit if highly leaded gas were used; and the unit needed frequent lube changes.[83] The knock-suppression systems like water/alcohol injection added another service consideration. A case in point was the Oldsmobile Jetfire F-85 which used a water/alcohol system in the early sixties. Owners tended to forget to keep the water bottle on the firewall filled and, consequently, were upset when engine problems developed.[84]

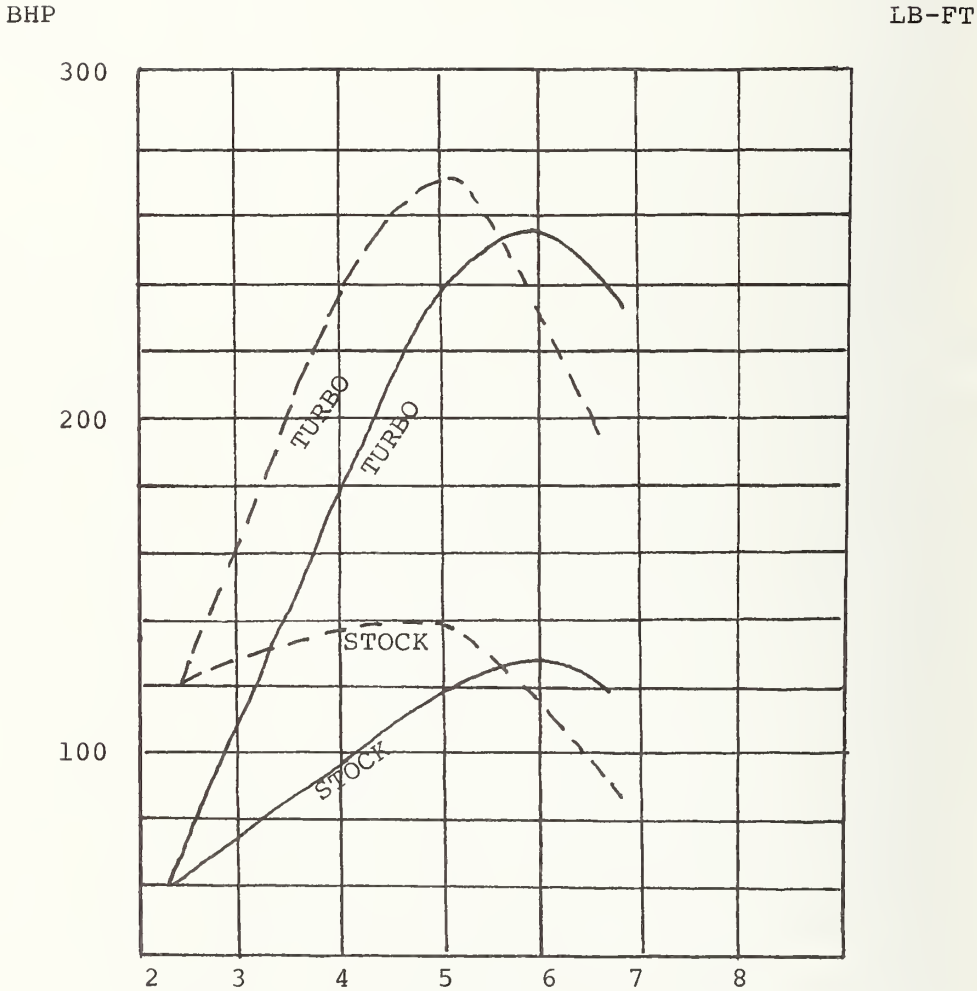
Most studies indicated that the turbocharger's weight and size presented no problems. The average turbocharger unit weighed only 14 lbs. and was no bigger than a foot square breadbox.[85] In fact, its use on smaller lighter engines led to substantial savings in the vehicle's overall weight. A lighter engine led subsequently to lighter chassis components. One estimate figured that a 1.0 lb. savings in engine weight could save from .33 to 1.0 lb. in the chassis.[86]

Saab estimated that a 6-cylinder engine of power output similar to a 4-cylinder, 2-liter turbocharged engine would weigh 95 lbs. more and would be 20 to 30 percent higher in fuel consumption.[87] The 1974 Rand Study concluded that a turbocharged engine would result in 26 percent less weight and 10 percent less volume compared to a naturally-aspirated engine of similar output.[88] Coon, et al., concluded that a turbocharged engine could lead to a 10 to 25 percent decrease in weight, depending on the method of anti-knock suppression.[89] Finally, Coon, in 1974, made the following estimates of two test turbocharged engines relative to a naturally-aspirated 350-CID engine, based on considerations of engine displacement, turbocharger weight, and noise alternative materials. The 250-CID turbocharged engine weighed only 75 percent as much as the conventional 350-CID engine, with the same box volume. The 280-CID turbocharged engine, equipped with an aftercooler, weighed 90 percent as much as the conventional 350-CID engine, but was 10 percent larger in engine box volume.[90]

One problem associated with turbocharging passenger car engines was that the higher air inlet temperatures due to the pressure boost increased the knock tendency of the engine. However, there were a variety of solutions to this problem: spark retardation; use of water injections to provide internal cooling; lowering the engine's compression ratio; the use of fuel with higher octane number; and, adoption of an aftercooling device - a heat exchanger with a coolant, for example -- to cool the air between the compressor outlet and combustion chamber.[91] Most engineers felt at the time that the horsepower output of a larger naturally-aspirated engine could be obtained in a smaller, lighter, turbocharger engine, without engine knock, by adopting one of these available methods for suppression.[92]

It was clear from the work that had been done in conjunction with the diesel engine that a turbocharger-engine combination presented, in an economical way, the possibility of doubling the output of an internal combustion engine.[93] Figure 8 shows the typical power curve comparing a turbocharged with a stock engine. The torque (dotted line) and brake horsepower (solid line) increase substantially. In 1971, Thomson reported on the performance characteristics of a VW retrofitted with a turbocharger kit. The changes in road performance compared with the stock vehicles were dramatic. The turbocharger reduced the 50 to 80 mph passing time from 30 to 20 seconds without any changes in fuel economy.[94] Coon tested two turbocharged engines, a 250-CID and a 280-CID, with good results, achieving the same maximum power output as a 350-CID naturally-aspirated engine. Thus, vehicle top speed was the same for all three engines.[95] As early as 1966, Lang documented the dramatic

Figure 8. Power Curve - Torque (Dotted Line) and Brake Horsepower (Solid Line) For Turbocharged and Stock Engine



Source: Jan P. Norbye, "Turbocharging," Road & Track, August 1976, p. 87.

increase in the turbocharged engine's bmep and bsfc. (See Figure 6.) Lang's tests went so well, in fact, that he asserted:

> The turbocharger has proven its capability to increase the specific output of the reciprocating engine in an economic way so that it is safe to predict that in the future the majority of internal combustion engines will be designed for turbocharging.[96]

4.5 Fuel Economy

The widespread use of the turbocharger in the diesel engine for two decades had brought this device to a high degree of reliability, optimum design, and good material selection. There were problems associated with attaching a turbocharger to a spark-ignition, gas-powered passenger vehicle - for example the turbocharged engine's response to changes in load and the threat of detonation, but solutions seemed possible. Moreover, a variety of studies pointed out the advantages to turbocharged automobile engines. They suggested that turbocharging, in addition to increasing an engine's power output, could be effectively used to maintain exhaust emission levels while improving fuel economy.

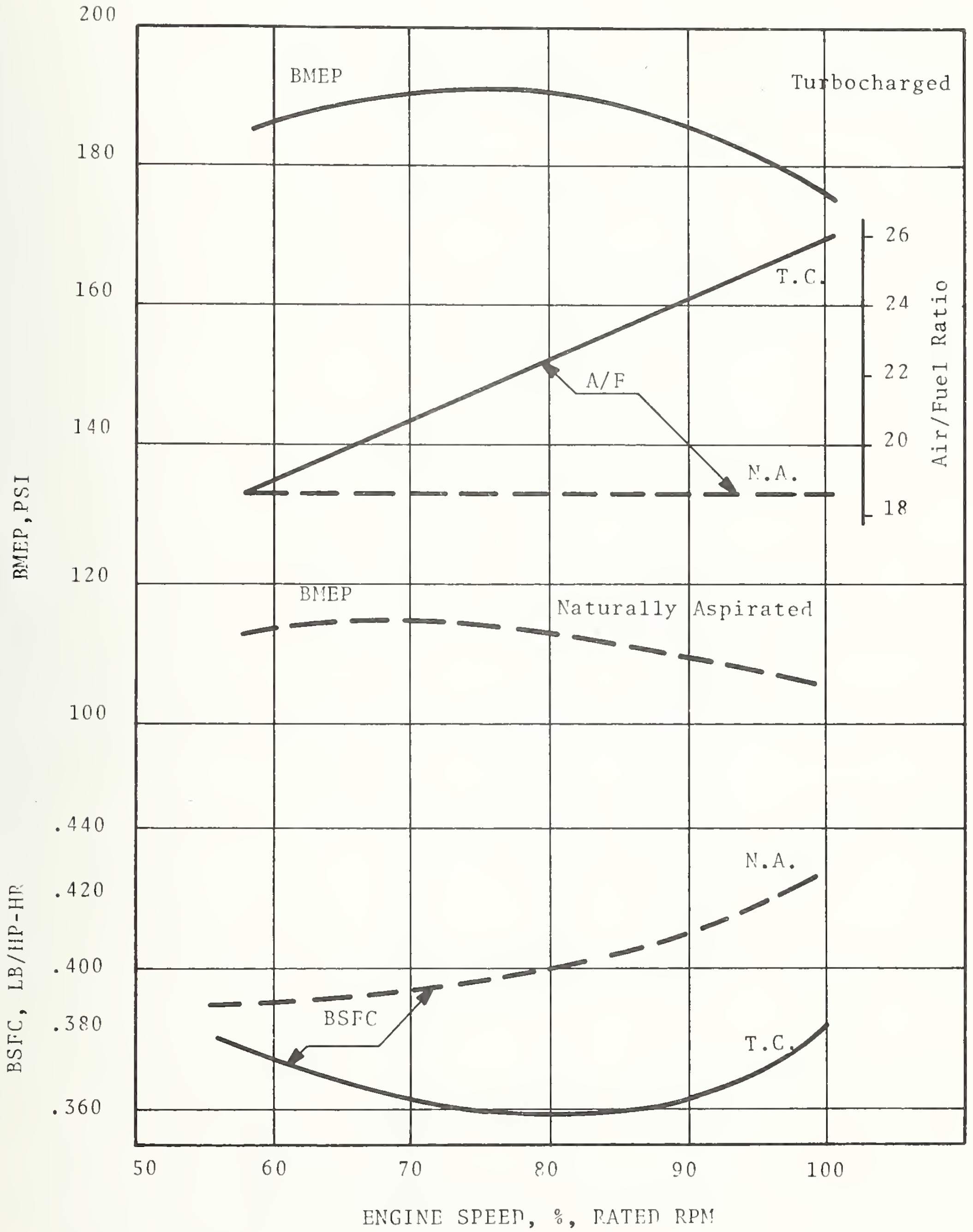
Numerous studies emerged in the late sixties and early seventies suggesting that turbochargers increased horsepower and torque without raising fuel consumption and, in some cases, with appreciable gains in fuel economy. As early as 1966, Lang claimed:

> The turbocharged engine by operating at intake and discharge conditions several times higher than atmospheric pressures is capable of increasing its specific output to several times that of its naturally-aspirated version at better fuel economy.[97]

Figure 9 from Lang's study shows the performance of the same displacement engine, naturally-aspirated and turbocharged. The gain in bmep and bsfc is obvious. Lang claimed that because of the increase in turbine speed, compressor discharge pressure, intake manifold density and air-flow, the naturally-aspirated engine operated at a more or less constant air/fuel ratio along a fuel power curve and smoke limit, while the air/fuel ratio increased with engine speed on the turbocharged engine.[98]

Other studies suggested that, when compared to an unsupercharged engine with the same power output and performance levels, the turbocharged engine showed good potential for fuel economy gains. In 1973, Schweikert and Johnson conducted steady-state engine dynamometer tests on a turbocharged engine and a large displacement, naturally-aspirated engine of equal power output. Their test data showed fuel economy improvements of 17 to 25 percent.[99] Hurter, in a similar test, concluded that a turbocharger gained 8 percent in fuel economy over the FCD for a full-sized car and 9 percent for a subcompact.[100] AiResearch's steady-state tests showed a savings in fuel of 18 percent at 50 mph, and 23 per cent at 30 mph.[101] And Coon's study, conducted in 1973, concluded that the improvement in fuel economy obtainable in a fully developed, production automobile with a turbocharged engine could be as high as 5 to 10 percent.[102] Finally, Car and Driver magazine fitted a turbocharger to an ex-showroom stock 1972 Opel and achieved fuel economy gains of better than 14 percent over the standard engine in the EPA driving cycle.[103]

Figure 9. Engine Speed versus BSFC and BMEP



Source: Wolfgang Lang, "What Can the Turbocharger Do for the Engine," SAE paper, March 4, 1966, presented at Education Lecture Series, p. 84.

4.6 Emissions

The effect of turbocharging on emission levels was unclear. The turbocharged engine shared important factors and features with conventional naturally-aspirated engines. The fuel/air ratio was basically the same. Combustion chamber design and spark advance, as well as the exhaust and valving system, were the same. Theoretically, at low engine speeds, when the turbocharger had little effect, emission levels should remain the same. At higher speeds, the system routed exhaust gases through the turbocharger system, allowing them more time to burn before getting into the fuel pipe. The increased back pressure translated into higher temperature and higher pressure in the gases discharged from the combustion chamber. This contributed to more complete combustion inside the cylinder, and could lead to continued combustion in the exhaust port area. The increased combustion temperature would help keep down HC and CO emissions, though the increased peak temperature in the combustion chamber would be expected to raise NO_x levels to some extent.

Test reports from independent sources at the time were inconclusive and varied for different types of engines. In 1973, Schweikert and Johnson of the Michigan Technological Institute reported on a very thorough series of emissions tests made with an experimental turbocharged Chevrolet 307 cu.-in. V-8. They chose an AiResearch model TE-0670 turbocharger and added a set of Du Pont type V Thermal reactors. The test program included comparisons of running with and without EGR. (See Table 2.) Schweikert and Johnson found that in the turbocharged V-8, HC and CO emissions were

Table 2. Calculated Road Load Vehicular Emissions and Fuel Consumption

	Without EGR					With EGR			
	Bmep (psi)	HC (g/mile)	CO (g/mile)	NO_2 (g/mile)	(mpg)	HC (g/mile)	CO (g/mile)	NO_2 (g/mile)	(mpg)
30 mph road load									
307 turbocharged	29.2	0.06	2.12	0.79	15.9	0.09	1.09	0.54	11.9
450 naturally aspirated	19.9	0.13	2.45	0.84	12.7	0.08	1.41	0.49	9.6
40 mph road load									
307 turbocharged	32.9	0.05	1.82	1.66	15.2	0.07	0.56	0.83	12.2
450 naturally aspirated	22.4	0.04	0.66	1.61	12.6	0.05	0.62	0.69	9.8
50 mph road load									
307 turbocharged	38.7	0.02	0.78	2.74	14.0	0.04	0.54	0.91	11.8
450 naturally aspirated	26.4	0.03	0.90	2.51	12.0	0.03	0.50	0.76	9.5
60 mph road load									
307 turbocharged	46.0	0.02	0.29	4.58	13.2	0.03	0.40	1.54	11.6
450 naturally aspirated	31.4	0.02	0.50	4.21	11.3	0.02	0.44	1.21	9.8

Source: J.F. Schweikert and J.H. Johnson, "A Turbocharged Spark-Ignition Engine with Low Exhaust Emissions and Spark Improved Fuel Economy," SAE Technical paper 730633, 1973, p. 99.

higher than in the baseline 307 V-8, and NO_2 emissions were lower when running without EGR. With EGR, NO_2 output increased with no appreciable benefits for HC and CO control. In addition to the baseline Chevy 307 V-8, they tested a 454 cu-in. V-8 which matched the turbocharger's peak power output. Their tests led to the following observations: (1) turbocharging without EGR made no practical difference in emission levels; and (2) with EGR's turbocharging led to an increase in HC, no change in CO, and about 20 percent higher NO_2 emissions.[104]

Other reports on emission tests showed that a turbocharged engine should have good potential for maintaining emission levels. Coon, who arrived at similar conclusions as Schweikert & Johnson observed:

> It would not be expected that turbocharging would have any major effects upon engine exhaust emissions, when two engines of equal maximum output are considered - one turbocharged and one naturally-aspirated.[105]

And the Aerospace Corporation Study, noted that while some increase in NO_2 might be expected, "No significantly adverse effects on emissions are anticipated, or indicated based on the data available."[106]

These studies were important at the time to demonstrate to Detroit that turbocharger technology fit within the parameters of pollution control. However, it is to be noted that the studies were not necessarily valid for different engine types, such as power units of smaller cylinder size, with fuel injection, and capable of tolerating higher turbocharged boost pressure. The major conclusion to be drawn from these data was that turbocharged engines required the same emissions controls - EGR or oxidation reactors like the thermal or catalytic - as a naturally-aspirated engine to meet the same emission standards.

5. INDUSTRY ATTITUDE AND ORIENTATION -- 1966-1976

From the middle sixties through the early seventies, Detroit's automakers tended to ignore turbocharging for use on mass-production automobiles. Such rejection must be seen in the context of the times. Federal regulation had focused on two major issues with regard to automobiles: the problems of emissions pollution and safety. Automobiles were a major source of environmental pollution. A 1966 survey in the U.S. estimated that out of a total of 142 million tons of pollutants, 86 million tons were attributable to automobiles.[107] In certain U.S. localities such as Los Angeles, automotive emissions were responsible for up to 90 percent of urban atmospheric contamination.[108]

With pollution problems reaching crisis proportions in the mid-sixties, state and national legislatures adopted a series of measures aimed at curbing exhaust emissions and at stimulating auto industry efforts to find improved ways of controlling motor vehicle exhaust pollution. The auto industry's response was to concentrate R&D on meeting these immediate standards with add-on devices like thermal and catalytic reactors and to focus long-term development on alternative power plants like the Wankel, Sterling, steam, electric and statified charge engines. In such a context, the turbocharger offered no immediate, easily perceived advantage. The industry's attitude toward the turbocharger, formed during the early sixties, was that it was strictly a performance device for which consumers were unwilling to pay a premium. Fuel economy was not an issue yet, with gas prices remaining fairly low.

Michael May, the Swiss engineer who worked with Ford of Germany, suggested one other reason for Detroit's rejection of turbocharged passenger cars in the late sixties and early seventies. He believed that GM had learned the wrong lesson from a poor technical design. Based on GM's experience with turbocharging in the early sixties, the industry thought certain problems were inherent in turbocharging and not simply the result of the poor turbocharger-engine matches made earlier in the decade. May, however, claimed that GM "must have spent more on turbocharging than on any single auto system in history." But, he said, GM made a mistake in its Corvairs and F-85s when it installed long intake tracts that led to both cold- and hot-starting problems. Moreover, GM was wrong to operate the turbocharger from 2000 rpm upwards. Such a high end produced a hole in the torque curve high in the rev range, overloading the bearings and crankshaft. Finally, May stated that GM erred in controlling turbocharging variables by regulation units on both hot and cold sides of the engine.[109]

Other possible reasons for Detroit's rejection of turbocharging during this period include the industry's feeling that consumer acceptance would be adversely affected by the increased acquisition cost, engine noise, possible acceleration deficiencies and more difficult maintenance. Despite the growing evidence that these problems were not insurmountable, Detroit's automakers expected consumer acceptance to be more difficult to obtain with turbocharged engines. Finally, the Big Three may have neglected turbocharging technology and misperceived its possible advantages because the major development work was occurring in the diesel engine field, outside the industry by small suppliers.

As late as 1976, the major automobile manufacturers did not appear interested in turbocharging and, indeed, were highly critical towards it. The study by Aerospace Corp. reported on the basis of industry interviews that GM:

> was not enthusiastic, faulted the turbocharger for its poor response, and stated that its experience showed little or no benefits were to be gained by going to supercharging.[110]

It is to be noted that, at this same time, GM's Buick Division was quite hopeful about the possibilities of turbocharging its 231 CID V-6 engine, though Buick acknowledged no further commitment to the development of the technology beyond its use in Buick's Indy Pace car.[111] The Aerospace Corp. report similarly found that Chrysler:

> saw no fuel economy advantages, did not feel that the consumer is sufficiently interested in performance to pay the price of the supercharger, and did not think the supercharger would even go into production on a spark-ignition engine.[112]

AMC "did not consider turbocharging worthwhile."[113] None of these automakers, including Ford, mentioned any interest or research in turbochargers in their annual reports.

Turbocharged passenger cars did appear now and then in the early seventies. In 1970, Ford of Germany combined with Michael May to modify an Eberspaecher turbocharger for gasoline engines and to build a kit for the Ford Capri. The kits sold through selected Ford dealers in Europe and cost $800. May believed that this price could be reduced to $200 with larger production runs. The turbocharger resulted in a tremendous increase in performance: it lifted Ford's 108 hp, 140 cu.-in. V-6 to 180 hp. May claimed that this turbocharged engine had greater tractability and parity with the standard Capri engine in regard to fuel consumption. Ford Motor Co. in the United States was reported to be officially against May's project.[114] Later, Opel engaged May to develop an experimental series of turbocharged Manta cars raising power output from 90 to 140 hp.[115].

The most spectacular and expensive turbocharger application was made by Porsche in a limited series production of the Turbo Carrera. Dr. Ing. Ernst Fahrmann, Porsche's technical director, pushed for the Carrera's turbocharger development. He built a 3-litre (182 cu.-in.) fuel injected engine, teaming it with a KKK exhaust driven turbocharger. The car got 24 mpg on the highway and 14 mpg in the city. It sold for $25,850. Only 500 were built for the U.S. market. As of 1976, the turbo Carrera was the only turbocharger car sold in the U.S.[116]

Despite these exceptions, the fact was that as of the summer of 1976 no mass-produced car came turbocharged in standard form in the U.S. or abroad and no major automaker seemed to be seriously considering turbocharging. This situation changed drastically in the fall. In November, Saab announced that it would be the first company to offer a line production version of turbochargers in its 99E series which would go on sale in the U.S. in 1979, probably as a not-too-expensive EMS option.[117] At the same time, GM's Buick Division became more open about its work with the turbocharged Indy pace car project and GM's other divisions admitted that they were "looking into" turbocharging.[118] By 1978, VW had announced that it would turbocharge its '78-model Rabbit diesel. That same year Ford announced its intentions of turbocharging its 4-cylinder Mustang. Mercedes Benz revealed that it would introduce into the American market in 1979 a turbocharged version of its 5- cylinder diesel.[119]

Various related factors contributed to the industry's new interest in turbocharging. After the 1973 oil embargo, attention had focused on questions of fuel economy. President Ford, in an anti-inflation speech to Congress in October 1974 called for an overall 40 percent improvement in fuel economy for passenger cars within four years. GM and Ford responded by announcing plans to reduce the size of their cars by 1977-78. In July 1975, the Senate passed the Energy Conservation Act, part of which directed the Secretary of Transportation to set fuel economy standards of 100 percent improvement by 1985. On December 22, 1975, the President signed the Energy Policy and Conservation Act of 1975. The provisions that concerned automotive fuel economy required that the average mileage for passenger cars in any model year after 1977 be no less than:

18 miles per gallon in 1978

19 miles per gallon in 1979

20 miles per gallon in 1980

27.5 miles per gallon in 1985 and subsequent years.

In September 1976, the Interagency Task Force on Motor Vehicle Goals Beyond 1980 issued a report known as the "300 Day" Study. This report concluded that fuel economies in the range of 27.0 to 27.5 miles per gallon, as scheduled for 1985, could be achieved for a full line of automobiles under the current safety and emission standards. To achieve this goal, however, the study pointed out the necessity of building a fleet of downsized, lighter passenger cars with smaller engines.

The major reason for the auto industry's interest in turbocharging appeared to be its new perception of what role the turbocharger could play in this context. In order to meet the mandated corporate fuel economy standards, automakers planned to reduce the size of their cars. This downsizing entailed a reduction of engine horsepower and the need for improved engine specific weight, volume and performance. The more compact, light, and high rpm four- and six-cylinder gasoline engines lacked high acceleration levels and were limited in maximum speed. Automakers began to see the turbochargers as part of a larger strategy to provide smaller engines with improved fuel economy and emissions, as well as performance equal in comparison to large naturally-aspirated engines. With turbocharging, there need not be a trade-off between performance and economy.

Market strategies had changed as well. In the early sixties, competition had been based on size and performance. By the middle seventies, the industry competed more on fuel efficiency. While it was true that market demands were moving toward smaller, more fuel efficient cars, the industry maintained that only by building a full range of cars that served varying consumer needs would it make any real and lasting contribution to increased overall fuel economy.[120] Moreover, there was a trend toward smaller but high priced cars like GM's Cadillac Seville. The auto industry began to see the turbocharger as a device which would not only add performance but allow a reduction in the kinds of engines manufactured.

Thus, the industry which had decided against large displacement, slower-running, high-geared and low-stress types of power units and in favor of lightweight, small-size, high-rpm engines, saw turbochargers as one way to provide a sufficient power boost for acceleration and high vehicle speeds. In other words, the turbocharger offered Detroit the possibility of replacing medium-sized V-8's on passenger car intermediate sedans and station wagons with turbocharged four- and six-cylinders. The cars would be appreciably lighter with improved fuel consumption and a reserve of power for handling heavy loads.

J.D. Collins, executive director of Ford's powertrain research, reflected the industry's new perception of the possibilities for turbocharging in his statement on April 1978:

> As the car industry switches to smaller engines with better fuel economy in the 1980's, there'll be more and more applications for turbos in order to make up the performance loss. It's the best of both worlds.[121]

Turbochargers were also one way for Ford to compete in performance and economy with GM, whose huge resources permitted it to offer a large array of engines. In fact, because of GM's resources and current strategy of introducing more diesels into its automobiles, as well as a large number of engine types, the turbocharger probably would continue to be a consumer option, such as on the 1978-model year Buick. As of spring 1978, Buick had stepped up production of its turbocharged V-6 engines from 10 to 22 an hour. It had plans for increasing this to 27 units/hr. shortly.[122] GM announced that the turbocharged V-6 in the Regal and LeSabre sports coupe would be a $1000 option offered in the fall 1978, and that later it would expand the use of the turbocharged 231 cu.-in. V-6 to the Century coupe and sedan, as well as the 1979-model Riviera.[123] The unit employs an electronic control device that monitors the detonation level and retards the spark during boost to avoid knock. This device allows Buick to use a normal compression ratio and permits spark timing to be calibrated for maximum fuel economy under normal operating conditions.[124] Buick dealers said that, as of June 1978, the turbocharged V-6 had sold very well, but that dealers were having trouble getting them from the factory. The price of the optional turbocharger unit had decreased to $300.[125]

Saab's development of the turbocharged 99 EMS was dictated by a set of objectives similar to the U.S. automakers: the search for better economy while maintaining acceptable performance. Turbocharging allowed Saab to fall back on a smaller-displacement engine and to reject six-cylinder and even V-8 versions of their 99 power plant. Interestingly, unlike other automakers, Saab decided to maximize low-end power with its AiResearch turbocharger unit, concentrating entirely on the lower range from 1500 rpm to a maximum of nine pounds of boost at 3500 rpm. The turbocharger engine carries Bosch's three-component catalyst.[126]

Motor Trend magazine tested Saab's new turbocharged 99 EMS against a normally-aspirated 99 powerplant. It found substantial increases in maximum power and torque outputs and a 19 percent decrease in fuel economy. Ride and handling were unchanged.[127] Saab's own test data indicated a 45 percent boost in maximum torque without any appreciable increase in engine weight or fuel consumption, and with no change in exhaust pollutants.[128]

The Saab Turbo, equipped with a Garret turbocharger, costs $9,998. It was not readily available in the U.S. in 1978. Saab's advertising campaign heavily emphasized performance.[129] During the year, Saab was forced to adopt chain drive to carry the power flow from the flywheel to the transmission because the standard three-gear set could not handle the torque load of the turbocharged engine.[130] Saab had to recall about 400 of its 1978-model turbocharged cars in the U.S. because of problems with the clearance between the air flash fuel mixing regulator and the throttle housing which is attached to the intake manifold.[131]

Mercedes-Benz decided to introduce into the American market in the summer of 1979 a turbocharged version of its 5-cylinder diesel, the 300-SD. It had been developing the turbocharger-engine unit over a number of years in its C-111-3 race engine. Its intentions seemed to be to help the sluggish diesel attain performance equal to other types of engines without disastrous effects on diesel fuel efficiency. In fact, Mercedes-Benz's marketing campaign emphasized the race engine's fantastic power and substantive fuel economy.[132] In the passenger car, Mercedes-Benz hoped the turbocharger would boost the power of the 3-litre engine up an equivalent of a 4.5 litre engine -- a 50 percent hike -and horsepower from 80 to 115.[133]

VW intends to put a turbocharger on its Rabbit diesel in the hopes of getting not only better acceleration than the standard diesel, but better fuel economy. As of spring 1978, the turbocharged Rabbit was not available for consumers, and VW would not speculate on when it would be introduced.[134] VW also is preparing a turbocharged Scirocco with performance levels that compete with the BMW sixes and the Capri V-6.[135]

Alfa Romeo will launch a turbocharged-diesel car in 1979. It intends to equip its Alfetta sedan with a VW engine and a Kuehnle Kopp and Kausch (KKK) turbocharger. Alfa Romeo chose the KKK turbocharger mainly because of KKK's ability to assure adequate supplies in large numbers at short notice.[136] Aix Industries expects to introduce a Sebring turbocharged sports car by 1980. The car, priced at $14,900, will be powered by a modified 1.5-litre Volkswagen Scirocco overhead-cam four-cylinder engine. In EPA tests, the car got 42 mpg on the highway and 27 mpg in the city.[137] Finally, Ford has planned a turbocharged version of its 1979-model year Mercury Capri. It expects the turbocharged four-cylinder 140-CID engine will deliver about 45 percent more horsepower than the base engine.[138]

Volvo is doing some preliminary development work on a production model turbocharged engine for 1981. Volvo's Manager of Product Development, Don Taylor, said that there was a good deal more work to be done before a specific timetable for production could be worked out. Specifically, he mentioned that modifications to the in-flow characteristics remained to be worked out as well as changes to the control system. Volvo is testing a form of anti-detonation similar to what Buick uses in its turbocharged V-6 engine.

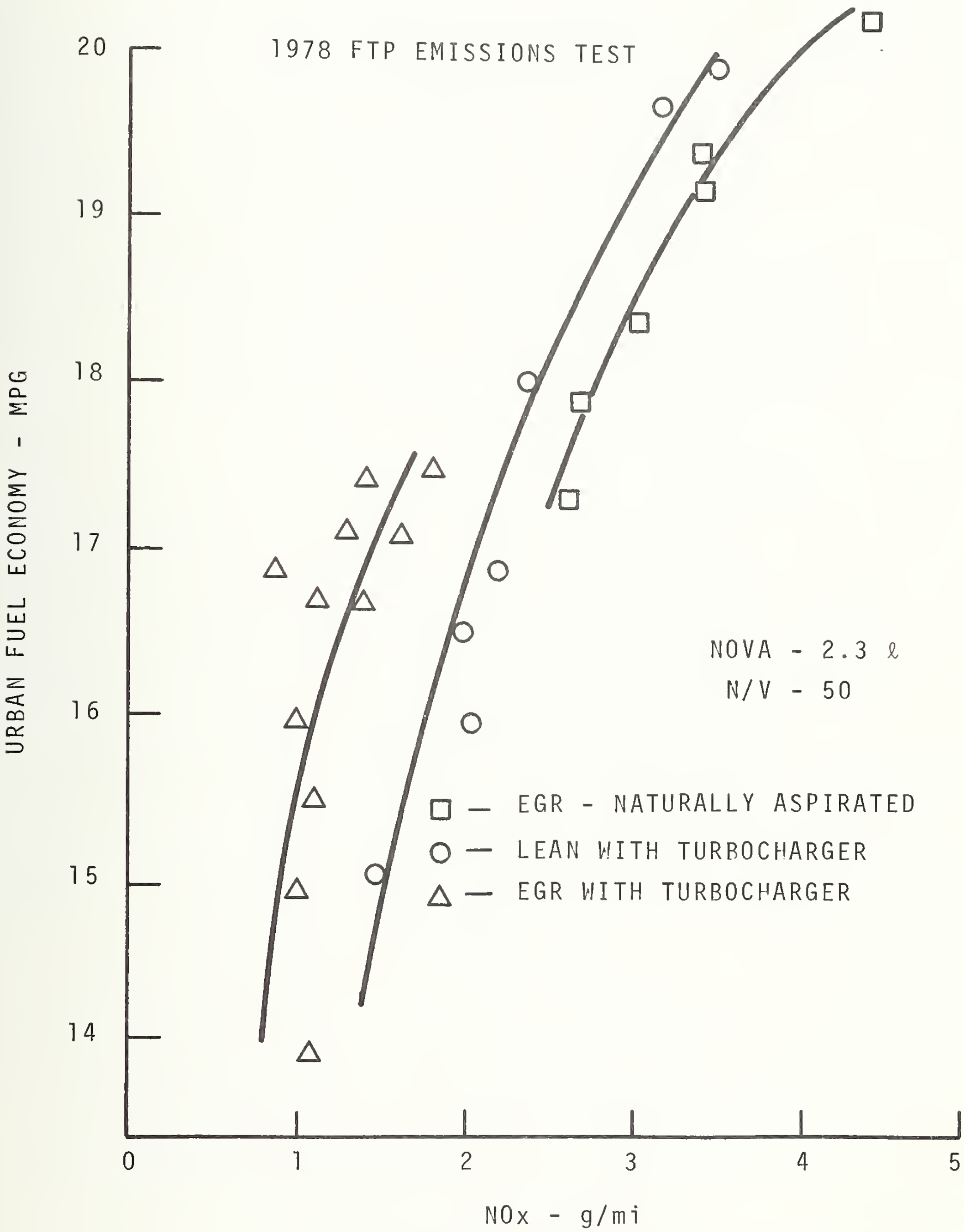
AiResearch, as of 1978, was equipping four of the five turbocharged production cars on the market.[139] It has begun expanding rapidly to meet the growing demand for turbocharged units, starting construction on a $4 million, 100,000 square-feet steel foundry. Production will begin in January 1979 and quadruple the firm's steel casting capacity. AiResearch is also expanding facilities for casting aluminum and iron and its foundry for production of aluminum impellers. The company's 1980 output should be about 1 million units - double AiResearch's current output.[142] Chrysler has announced that it intends to manufacture its own turbochargers.

The primary objective of most of the automobile manufacturers is to introduce smaller turbocharged engines with improved fuel economy and equal performance in comparison to currently used larger displacement, naturally-aspirated engines. The immediate technical problem automakers face in turbocharging their cars is the proper matching of the turbocharger to a particular engine. For each engine, there is a speed range in which occurs optimum turbocharger performance. Engineers must match the ratio of the turbocharger's turbine inlet area (A) to its radius (R) and to the center of the inlet, for the given engine. Increasing the (A)/(R) ratio increases the engine speed for a given boost pressure.[143]

Automakers face two other problems when turbocharging an undersized engine: engine knock and NO_x control. As mentioned previously, most engineers feel that the problem of engine knock is not serious or insurmountable. In fact, manufacturers have found they can control engine knock, without sacrifice in performance and fuel economy, by carefully selecting compression ratio, boost pressure ratio, and spark advance.[144]

Control of NO_x, however, appears to be more problemsome. Depending on the method of pollution control, there seems to be a trade-off between control of the regulated pollutants HC, NO_x and CO and fuel economy. For example, GM replaced a 250 cu.-in. (4.1 L) L6 engine in a Chevrolet Nova with a turbocharged 140 cu.-in. (2.3 L) L4 engine. It investigated both lean construction and EGR, and evaluated three systems: EGR to a naturally-aspirated engine; lean carburetion with a turbocharger; and EGR with a turbocharger. Figure 10 represents

Figure 10. Urban Fuel Economy versus NO_x Emissions



Source: <u>1977 Annual Report of General Motors on Advanced Emission Control System Development Programs</u>, submitted to EPA January 16, 1978, Vol. II, V.H.2.

the results of GM's test, showing the trade-off between NO_x and fuel economy. GM found that, by adding EGR to the naturally-aspirated version to reduce the NO_x level, driveability rapidly deteriorated as a result of power loss. Although the turbocharged engine with EGR control showed the most favorable NO_x and fuel economy trade-off, the levels of HC were high - in the range of 1.5 to 3.0 g/mile. In lean control, HC levels were only 0.8 to 1.5.[145] Saab appears to have mitigated the NO_x - fuel economy trade-off by using Bosch's three-component catalyst.

6. <u>FUTURE PROSPECTS</u>

Andrew F. Burke, in his paper, "The Moving Baseline of Conventional Engine-Powered Passenger Cars (1975-1985)," notes two recent trends, among others, in design and conventional engine development. The first has to do with the industry's use of lower power-to-weight ratio resulting in reduced load performance. The second is the development of more compact, lighter, higher rpm four- and six-cylinder gasoline engines (in-line and V configurations.)[146] He concludes that, given these trends in design and engine development, by 1985 the size and weight of new vehicles in the four passenger car classes - small, compact, mid-size, and full-size - will be reduced considerably from most of the cars today. This general downsizing of passenger cars will be done in order to meet the mandated corporate fuel economy standards. Smaller displacement engines, says Burke, will result in reduced horse power and the need for improved engine specific weight, volume, and performance. This observation leads him to conclude that:

> It seems likely that the advanced gasoline engine system will be augmented using either a turbocharger or supercharger so that smaller displacement engines can be used while maintaining the desired acceleration and passing performance.[147]

The following data are taken from Burke's paper. Tables 3 and 4 project the moving fuel economy baseline in vehicles equipped with either internal combustion or diesel engines. Note the adoption in 1980 of low-displacement turbocharged engines resulting in appreciable fuel economy gains.

Perhaps one indication of the turbocharger's future use is demonstrated by the experimental Large Research Safety Vehicle (LRSV) built by Minicars, Inc. under a research contract with the National Highway Traffic Safety Administration. Minicars, headed by two former GM engineers, redesigned, converted, and downsized a six-passenger Chevrolet Impala in order to achieve a variety of goals: high performance, low emissions, good fuel economy, improved power-weight ratio, and improved occupant crash protection.

Table 3. Moving Fuel Economy Baseline in Vehicles Equipped with I.C. Gasoline Engines

Year	Small-Size IW = 2000 lb M4 Trm(1) Eng. Type	mpg	Mid-Size IW = 3000 lb M4 Trm Eng. Type	mpg	Full-Size IW = 4000 lb M4 Trm Eng. Type	mpg
1973	L4, 55 HP		L6, 105 HP		V8, 150 HP	
City		26		17.5		12.4
Highway		--		--		--
Composite		--		--		--
1975(2)	L4, 55 HP		L6, 105 HP		V8, 150 HP	
City		29		21		13.5
Highway		38		27		18.0
Composite		32.5		23.3		15.2
1978(3)	L4, 55 HP		L6, 105 HP		V8, 150 HP	
City		40		23.3		15.0
Highway		50		31.5		21.5
Composite		44		26.4		17.4
1985(4)	L4, TC, 50 HP		L4, TC 90 HP		V6, TC 125 HP	
City		46		28.5		18
Highway		57.5		38.5		26
Composite		50.5		32.3		20.9
NO_x, g/mi	0.4		0.6		0.8	

(1) All vehicles equipped with transmissions having overall torque ratios and efficiencies equivalent to M4 transmission.
(2) Vehicles utilize an oxidation catalyst and EGR for emission control and meet Federal 1975 Standards.
(3) Vehicles utilize a carbureted fuel system and a three-way catalyst, O_2 sensor with feedback control, and EGR to meet the California 1978 standards.
(4) Vehicles utilize a fuel-injection-type fuel system with electronic control, turbo- or supercharger boost, and a three-way catalyst and meet the Federal 1985 Standards except as noted for NO_x.

Source: Andrew F. Burke, "The Moving Baseline of Conventional Engine-Powered Passenger Cars (1975-1985)," SAE Technical paper 780347,

Table 4. The Moving Fuel Economy Baseline in Vehicles Equipped with Diesel Engine

	Small-Size IW = 2000 lb M4 Trm(1)		Mid-Size IW = 3000 lb M4 Trm		Full-Size IW = 4000 lb M4 Trm	
Year	Eng. Type	mpg	Eng. Type	mpg	Eng. Type	mpg
1978(2)	L4, 50 HP		L5, 80 HP		L6, 100 HP	
City		45		30		22
Highway		55		40		32.5
Composite		49		33.8		25.7
1985(3)	L4, TC 50 HP		L5, TC 90 HP		V6, TC 125 HP	
City		52		34.5		25.3
Highway		66		48		39
Composite		57.5		39.5		30
NO_x, g/mi	0.4		0.6		0.8	

(1) All vehicles equipped with transmissions having overall torque ratios and efficiencies equivalent to M4 transmission.
(2) Vehicles utilize no exhaust treatment and meet Federal 1978 Standards.
(3) Vehicles utilize turbocharged engines with EGR and electronic control to control smoke, odor, and NO_x emissions and meet the Federal 1985 Standards except as noted for NO_x.

Source: Andrew F. Burke, "The Moving Baseline of Conventional Engine-Powered Passenger Cars (1975-1985)," SAE Technical paper 780347, 1978, p. 20.

Minicars hoped to achieve high performance and to meet the EPA's 1980 research emission goal of .41 gpm HC, 3.4 gpm CO and .4 to 1.0 gpm NO_x with a Volvo turbocharged engine. Minicars chose Volvo's B-21, 2.1-litre overhead-cam engine because of its reputation for strength, durability, low emissions, fuel economy, and performance potential. Working under subcontract from Minicars, the Product Planning Group of Volvo of America, in conjunction with engineers from its parent company, AB Volvo of Sweden, undertook the development of the LRSV's engine in 1977. Bjorn Ahlstrom, President of Volvo of America, said that his company agreed to cooperate with Minicars' project in order to assess, among other things, the feasibility of turbocharging for increased performance and fuel economy.[148]

Volvo's experimental engine employs manifold fuel injection (Bosch L.I) with oxygen sensing, feed-back loop controlled mixture correction and a three-way catalyst. The turbocharging unit, which uses boost pressure controls and other detonation limiting devices, should increase horsepower almost 40 percent - from 101 to 140 hp. - and allow the car to accelerate from 0 to 60 in under 13.5 seconds. This more than matches the performance provided by the V-8 used in the standard Chevrolet Impala. Volvo's fuel economy goal is the legislated 27.5 mpg required by 1985.

In April 1978, Brock Adams, then the Secretary of Transportation, unveiled the experimental car. Despite very favorable media response, the LRSV quickly came under criticism. Representatives of the auto industry pointed out that the car lacked adequate road testing to validate its claims. It was noted that, while LRSV meets the emissions requirement, it falls short on fuel economy, achieving only as much economy as Volvo's 240 model series. These cars are rated at 20 mpg according to EPA estimates. Critics also questioned the LRSV's performance claims.

7. SUMMARY

Advantages

The use of a turbocharger on a reduced displacement automobile engine offers the possibility of achieving the twin goals of improved fuel economy and increased power and performance.

Role of Suppliers/Advocates

Suppliers played an important advocacy role in the development of turbochargers: first, in the early fifties, for use with high-speed, compact, light diesel engines; and later, for use with competitive and automotive engines.

Adoption of Technology

The diesel engine industry was the first to adopt commercial turbochargers. Diesel engines for trucks was a natural point of entry for mass-produced turbochargers because of the truck industry's need for increased fuel efficiency and horsepower.

Gestation Period

Prior to World War II, turbochargers were used in the aviation, marine, and heavy-duty diesel engine fields. These early units were large, bulky machines with cumbersome rotating assemblies containing a number of parts. In the early fifties, suppliers undertook the development of commercial turbochargers for compact, light, high-speed diesel engines. In the period between 1954-1966, suppliers achieved significant cost, weight, and size reductions. These advances occurred simultaneously with improvements in quality, reliability, and performance. Design changes made the turbocharger more durable, easy to install, impervious to weather and fast in response to engine needs. Because there was considerable experience in the use and manufacturing of turbochargers for diesel engines, the development work for application to passenger cars in the mid-seventies was not considerable.

Role of Competitive Racing

Competitive racing was a critical proving ground for turbocharger technology. The success of the turbocharged diesel engine in racing applications was important to the overall development and adoption of turbocharger technology. It served to establish that good acceleration characteristics and power output could be obtained from a turbocharged engine by paying proper attention to design characteristics and by properly matching the turbocharger's performance characteristics to those of the engine.

Role of Regulation

California's state regulations presented a barrier to turbocharger development in the seventies. California, potentially the biggest market for aftermarket turbochargers, prohibited the use of turbochargers pending certification by its Air Resource Board. The test -- a durability test of at least 30,000 miles -- was complicated and costly, too great an undertaking for small manufacturers of turbochargers.

Regulation played a large role in Detroit's adoption of turbochargers in the late seventies. The mandatory fuel economy standards required by the Energy Policy and Conservation Act of 1975 led to the downsizing of passenger cars and the development and introduction of compact, lighter, and higher rpm four- and six-cylinder gasoline engines. Automakers saw the turbocharger as part of a larger strategy to provide small engines with improved fuel economy and performance.

Barriers to Adoption

Barriers to adoption of turbochargers for passenger cars in the sixties included poor technical design, the fear that consumer acceptance would be adversely affected by the increased acquisition cost, engine noise, acceleration deficiencies, and more difficult maintainability. Moreover, market conditions were adverse to turbochargers. Competition was based on size and horsepower; the industry believed that the consumer wanted larger, heavier, and higher-priced cars with bigger engines. In this context, the turbocharger lacked a market.

Barriers to adoption in the late sixties and early seventies included manufacturability, inertia lag, engine reliability, noise, maintanance, engine knock, and high cost. Most engineers, however, felt that these problems were neither serious nor insurmountable.

Current Status

As of 1976, automakers were introducing turbochargers for downsized passenger cars with compact, lighter and higher rpm four- and six-cylinder engines.

Future Outlook

Because the turbocharger has proven its capability to increase the specific output of the conventional engine in an economical way, it is safe to predict that in the future, turbochargers will find increased applications in production line passenger cars. Manufacturers have announced plans to step up turbocharger use.

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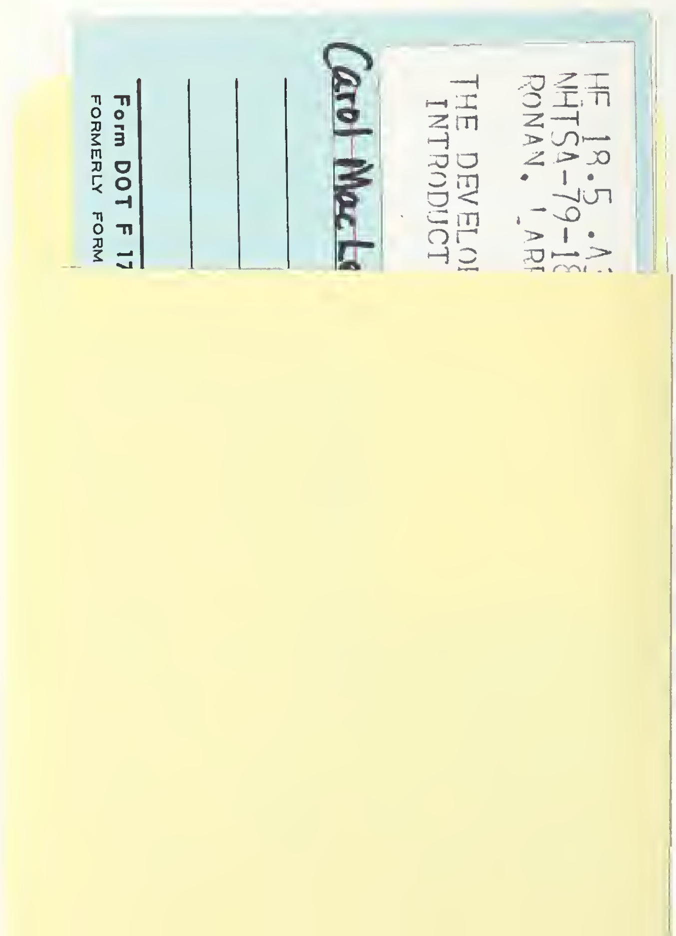

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