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PASSENGER CAR SPARK IGNITION DATA BASE
VOLUME I EXECUTIVE SUMMARY

by

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16. Abstract

Test data was obtained from spark ignition production and preproduction engines at the engine and vehicle level. The engines were applicable for vehicles 2000 to 3000 pounds in weight. The data obtained provided trade-offs between fuel economy, power, emission constraints and emission control technology, and other relevent parameters.

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PREFACE

In support of the U.S. Department of Transportation, National Highway Traffic Safety Administration, Office of Research and Development, the U.S. Department of Transportation, Research and Special Programs Administration, Transportation Systems Center contracted with Volkswagenwerk AG, Federal Republic of Germany to develop a data base on passenger car spark ignition engines. Volkswagen production, pre-production and research spark ignition engine systems were used for the test portion of the work. Published and unpublished literature was used for the theoretical studies.

The report consists of three volumes. Volume I, the Executive Summary, presents a summary of the data obtained and a review of the important conclusions. Volume II, the main body of the report, provides a discussion of the fuel economy and emissions obtained, a description of the engine/vehicle systems tested and the results of factory driveability tests, Volume III, the appendixes, presents miscellaneous data used during the program.

The author wishes to acknowledge the guidance and assistance provided by Mr. H. H. Gould and Dr. R. R. John of the Department of Transportation - Transportation Systems Center, and Dr. K. H. Digges of the Department of Transportation - National Highway Traffic Safety Administration, Office of Passenger Vehicle Research.

Our working team consisted of the following persons:

Misses E. Logsdon, M. Sowka, H. Welke
Messrs. Dr. R. Beckmann, U. Westphäling, B. Dombrowski, H.P. Henning and the author.

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For translation work we acknowledge the assistance provided by Mr. Wilfried Becker, Germersheim, Federal Republic of Germany.

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

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

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

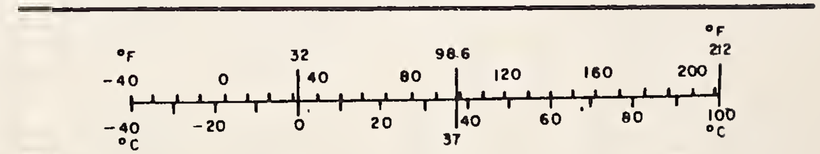

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

This Executive Summary represents Volume I of a three-volume report. The objective of the study reported herein was to obtain a data base on passenger car spark ignition engines. The power range of the engines studied was from 56 to 102 horsepower and the inertia weight ranged from 2,250 to 3,000 pounds.

In all these engine/vehicle systems, we investigated the way in which fuel economy, unregulated emissions, and consumer attributes were affected by the introduction of certain technologies which were required to meet given emission standards of HC/CO/NOx.

All engines were naturally aspirated. The engine/vehicle systems tested and analysed were:

a. A subcompact vehicle (VW Rabbit; 2,250 lbs inertia weight) equipped with a 4-cylinder 1.6 l inline engine (67 - 74 hp).

b. Same system as a. but of 3,000 lbs inertia weight.

c. A subcompact vehicle (VW Rabbit; 2,250 lbs inertia weight) equipped with a 4-cylinder 1.3 l inline engine (56 - 60 hp).

d. A compact vehicle (Audi 100; 3,000 lbs inertia weight) equipped with a 4-cylinder 1.6 l inline engine (85 hp).

e. A compact vehicle (Audi 5000; 3,000 lbs inertia weight) equipped with a 5-cylinder 2.2 l inline engine (102 hp).

Our goal was to meet the following emission levels:

1) Uncontrolled
2) 1.5/15/3.1 (gpm HC/CO/NOx)
3) 0.9/9.0/2.0 "
4) 0.41/3.4/1.0 "
5) 0.41/3.4/0.4 "

Levels 2) and 3) had to be met because, in addition to level 5), these were the only emission standards regulated at the time of contract initiation.

According to current Federal regulations, we measured fuel economy both in the Urban (UDC) and in the Highway Driving Cycle (HDC) and evolved these results into a Composite fuel economy. The unregulated emissions investigated by us were sulfate and hydrogen cyanide.

The consumer attributes considered by us were startability, driveability, acceleration performance, gradability, and percent change in engine system cost.

2. MAJOR CONCLUSIONS

The data of vehicles and engines which were evaluated are listed in Tables 2.1 through 2.3, summarizing the major results as well.

2.1 FUEL ECONOMY

Fuel economy is affected mainly by inertia weight, air drag, drivetrain, engine displacement, peak horsepower and emission standard.

For the configurations investigated, an inertia weight drop from 3,000 to 2,000 lbs improves fuel economy by 10 to 20 percent. An air drag drop of 10 percent improves fuel economy by 3 to 4 percent.

Reducing transmission ratios by 20 percent, within acceptable driveability bounds, improves fuel economy by up to 10 percent.

Reducing engine displacement by 20 percent, within acceptable consumer attributes, improves fuel economy by 5 percent.

Reducing peak horsepower by 15 percent, within acceptable performance, range, improves fuel economy by 5 percent.

Changing the emission level from uncontrolled to 1.5/15/3.1 and 0.9/9/2.0 respectively (gpm HC/CO/NOx) causes fuel economy to drop by between 0 and 12 percent.

Introducing fuel injection (K-Jetronic) and the closed-loop system required to meet the engineering goal for 0.4/3.4/1.0 leads to a fuel economy increase of 5 percent.

Meeting the research emission standard of 0.4 gpm NOx brings the fuel economy down again by 5 percent.

2.2 REGULATED EXHAUST EMISSIONS

The major emission standards which were applied were 0.41/3.4/1.0 and 0.41/3.4/0.4 gpm HC/CO/NOx.

The first task was to set engineering goals for these standards without sufficient experience from durability and field tests involving suitable engine concepts. It was found that the HC and CO standards had to be enhanced by a

TABLE 2.1 ENGINE/VEHICLE SYSTEMS

Modification Code	Inertia Weight 2250	Inertia Weight 3000	F × CD	Dyn Wheel Diameter [cm]	Transmission Ratios Gears 1.	2.	3.	4.	Axle	No of Cylinders	Displacement cu in	Compression Ratio	Emission Standard [gpm] HC	CO	NOx	Engineer. Goals [gpm] HC	CO	NOx	Carburetor	K-Jetronic	Decel Control	Spark adv diaph	Spark ret diaph	Air Syst Pump	Air Syst Self aspir	EGR-Contr On-Off	EGR-Contr Proportional	Cat System 3" Ox Cat	Cat System 6" Ox Cat	Cat System 6" 3-way	Closed Loop
01	×		0 77	55 8	3 46	1 94	1 29	0 97	3 90	4	96 9	8 0	uncontrolled			—	—	—	×			×									
02		×	"	"	"	"	"	"	"	"	"	"		"		—	—	—	×			×									
03	×		0 79	54 8	"	2 05	1 35	0 96	4 06	"	77 6	8 2		"		—	—	—	×			×									
04		×	0 78	60 0	"	1 94	1 29	0 91	4 44	"	96 9	"		"		—	—	—	×			×									
05	×		0 79	55 8	3 46	1 94	1 29	0 97	3 90	4	96 9	8 0	1 5	15	3 1	—	—	—	×			×	×		×			×			
06		×	"	"	"	"	"	"	"	"	"	"	"	"	"	—	—	—	×		×	×	×		×	×		×			
07	×		"	54 8	"	2 05	1.35	0 96	4 06	"	77 6	8 2	"	"	"	—	—	—	×			×	×		×			×			
08		×	0.78	60 0	"	1 94	1 29	0 91	4 44	"	96 9	"	"	"	"	—	—	—	×		×	×	×		×	×		×			
09	×		0.79	55 8	3 46	1.94	1 29	0.97	3 90	4	96 9	8 0	0 9	9 0	2 0	—	—	—	×		×	×	×		×	×			×		
10		×	"	"	"	"	"	"	"	"	"	"	"	"	"	—	—	—	×		×	×	×		×	×			×	—	
11	×		"	"	"	2 05	1 35	0 96	4 06	"	77 6	8 2	"	"	"	—	—	—	×		×	×	×		×	×			×		
12		×	0 78	60 0	"	1 94	1 29	0 91	4.44	"	96 9	"	"	"	"	—	—	—	×		×	×	×		×	×			×		
13	×		0 79	55 8	3 46	1.94	1 29	0 97	3.90	4	96 9	8 0	0 41	3 4	1 0	0 2	1.7	0 25		×	×	×	×	×					×	×	×
14		×	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"		×	×	×	×	×			×		×	×	×
15	×		0 71	54 8	"	2 05	1 35	0 96	4 06	"	77 6	8 2	"	"	"	"	"	"		×		×	×							×	×
16		×	0 84	60 0	3.60	2.13	1 36	0.97	4 11	5	130 8	8 0	"	"	"	"	"	"		×	×	×	×	×			×		×	×	×
17	×		0 79	55 8	3 46	1.94	1 29	0 97	3 90	4	96 9	8 0	0.41	3 4	.04	0 2	1.7	0 1		×	×	×	×	×					×	×	×
18		×	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"		×	×	×	×	×			×		×	×	×
19	×		0 71	54 8	"	2 05	1 35	0 96	4 06	"	77 6	8 2	"	"	"	"	"	"		×	×	×	×							×	×
20		×	0 84	60 0	3 60	2.13	1 36	0 97	4 11	5	130 6	8 0	"	"	"	"	"	"		×	×	×	×	×			×		×	×	×

TABLE 2.2 PERFORMANCE, FUEL ECONOMY AND EMISSIONS

Modification Code	Peak Horsepower	Max. Torque [kpxm]	UDC	HDC	Comb.	HC	CO	NOx	SO_4 [mg/mi]			HCN [mg/mi]			Noise DB [A]					
															Idle		Cruise 30 mph		Acceleration from 30 mph	
									UDC	SET	HDC	UDC	SET	HDC	ex*	in**	ex.	in	ex	in.
01	66.7	11.5	24.8	35.1	28.5	2.91	23.8	3.44	0.94	1.08	1.21	10.1	8.9	64.8	70.0	56.0	62.5	63.0	73.5	74.5
02	"	"	22.5	29.8	25.3	3.10	29.3	4.34												
03	60.4	9.4	26.9	40.9	31.8	2.44	26.5	2.02							71.0	56.0	62.0	65.5	74.0	81.5
04	84.9	12.6	21.1	31.3	24.8	3.13	27.9	3.74							71.0	49.0	60.5	61.0	72.5	73.5
05	66.7	11.5	23.9	35.1	27.9	0.59	7.26	2.18	0.62	0.55	0.45	12.5	6.2	4.4	76.0	59.0	62.5	64.0	72.0	75.5
06	67.6	11.9	21.7	30.5	25.0	0.71	9.69	2.00												
07	60.4	9.4	24.4	34.0	27.9	0.95	8.08	2.32							72.0	56.0	62.0	65.5	73.0	78.5
08	84.3	12.3	21.9	31.6	25.6	1.26	10.6	1.77							71.5	51.0	61.5	61.1	73.0	74.3
09	67.6	11.9	23.3	32.3	26.6	0.34	4.03	1.40	0.54	0.50	0.55	5.4	2.7	2.2	77.5	57.0	62.0	64.5	72.0	71.0
10	"	"	22.0	30.3	25.1	0.40	6.50	1.76												
11	55.8	9.0	24.6	35.5	28.3	0.72	6.67	1.52							71.5	55.5	61.5	65.0	72.0	78.5
12	84.3	12.3	20.9	30.8	24.4	0.62	7.63	1.74							72.0	50.5	61.5	59.5	73.5	75.0
13	73.8	11.2	25.3	33.7	28.5	0.12	0.81	0.18							69.0	54.0	61.0	63.5	72.5	78.0
14	"	"	23.5	30.6	26.2	0.16	1.24	0.18												
15	58.9	9.1	26.6	34.8	29.7	0.15	1.52	0.13							74.0	54.0	61.0	63.0	71.0	73.0
16	101.7	16.0	16.3	24.2	19.1	0.10	1.30	0.18							70.5	49.0	60.5	58.0	71.5	73.0
17	72.5	11.3	24.0	32.4	27.2	0.13	0.87	0.12	0.58	0.79	0.94	3.34	0.66	0.82						
18	74.1	10.9	20.5	29.1	23.6	0.16	1.51	0.13												
19	58.8	8.9	24.6	36.5	28.8	0.23	1.66	0.10												
20	102.6	16.0	15.5	23.0	18.2	0.06	1.28	0.15												

* exterior
** interior

TABLE 2.3 CONSUMER ATTRIBUTES

Modification Code	Startability* Low Altitude -10°C	Startability* Low Altitude +10°C	Startability* Low Altitude +30°C	Startability* High	Driveability* Low Altitude -10°C	Driveability* Low Altitude +10°C	Driveability* Low Altitude +30°C	Driveability* High	Passing Ability** (FR, Vol. 34, No.99 5-23-1969) Low-speed Distance [mi]	Passing Ability** Low-speed Time [sec]	Passing Ability** High-speed Distance [mi]	Passing Ability** High-speed Time [sec]	Gradeability [%] 1.	Gradeability [%] 2.	Gradeability [%] 3.	Gradeability [%] 4.	Weight [kg]	Width [cm]	Length [cm]	Height [cm]	Cost
01	10.0	10.0	10.0	10.0	8.13	8.65	9.33	9.37	0.071	7.8	0.217	12.2	47.5	25.8	15.8	10.8	113	60	54	70	100
02	10.0	10.0	10.0	8.0	7.82	8.81	8.85	8.24	0.073	8.2	0.248	14.3	35.4	19.0	11.5	7.9	113	60	54	70	100
03	9.0	10.0	10.0		7.92	8.79	9.06		0.071	7.8	0.232	13.2	46.0	26.3	15.9	9.7	99	67	61	63	100
04	6.0	10.0	10.0		8.31	8.57	9.34		0.073	8.2	0.223	12.6	37.8	20.1	12.8	7.3	113	60	54	70	100
05	10.0	10.0	6.5		8.13	8.65	9.30		0.071	7.8	0.217	12.2	47.5	25.8	15.8	10.8	115	60	54	70	118
06	9.0	10.0	10.0		8.65	8.78	8.38		0.073	8.2	0.248	14.4	36.7	19.8	12.1	8.1	115	60	54	70	121
07	10.0	10.0	6.0		7.92	8.79	9.06		0.071	7.8	0.232	13.2	46.0	26.3	15.9	9.7	101	67	61	63	120
08	6.0	10.0	10.0		7.59	7.85	8.21		0.072	8.0	0.226	12.8	36.7	19.4	12.6	7.4	115	60	54	70	119
09	10.0	10.0	6.5		8.73	9.11	8.30		0.070	7.65	0.223	12.5	49.2	26.8	16.5	11.1	116	60	54	70	121
10	9.0	10.0	10.0		8.65	5.78	8.38		0.073	8.2	0.248	14.4	36.7	19.8	12.1	8.1	116	60	54	70	121
11	10.0	10.0	6.0		7.43	8.23	7.17		0.072	8.1	0.242	13.8	43.9	25.3	15.6	10.0	102	67	61	63	124
12	6.0	10.0	10.0		7.59	7.85	8.21		0.072	8.0	0.226	12.8	36.7	19.4	12.6	7.4	116	60	54	70	119
13				9.0				9.03	0.071	7.9	0.217	12.0	46.3	24.9	15.1	10.1	129	54	54	70	178
14				10.0				8.83	0.073	8.3	0.242	14.0	34.2	18.4	11.2	7.5	129	54	54	70	189
15				10.0				9.56	0.072	8.1	0.236	13.5	43.6	24.9	15.3	9.7	111	55	61	63	164
16									0.071	7.8	0.204	11.2	50.1	28.5	16.7	10.8	187	50	72	83	177
17	8.0	10.0	10.0	9.0	9.31	9.67	9.69	9.31	0.070	7.8	0.217	12.0	46.6	25.1	15.1	10.1	129	54	54	70	178
18	10.0	10.0	10.0	9.0	9.43	9.52	9.49	9.51	0.073	8.2	0.242	13.8	33.6	18.0	10.9	7.3	129	54	54	70	189
19	10.0	10.0	9.0	9.0	9.51	9.51	9.32	9.40	0.073	8.1	0.236	13.4	42.4	24.3	14.9	9.5	111	55	61	63	164
20									0.070	7.8	0.204	11.2	50.4	28.7	16.8	11.0	188	50	72	83	177

* Best Value 10, Sufficient 6

** Time and Distance to Pass a Vehicle 55 ft Long Traveling 20 mph (Low-speed) or 50 mph (High-speed) factor of 0.5, whereas the NOx standard had to be lowered by a factor of 0.25.

The vehicles suitable for the '76 standards met their standards with a sufficient margin of safety.

The engineering goals (0.2/1.7/0.25 gpm HC/CO/NOx) suitable for the U.S. standards of '81 were met in each case. The research standard engineering goal of 0.1 gpm NOx was also met with a Rabbit equipped with a 1.3 liter fuel injection engine. All other vehicles came close to meeting this goal (1.6 liter Rabbit: 0.13 gpm NOx; 2.2 liter 5-cylinder Audi 5000: 0.15 gpm NOx).

2.3 STARTABILITY AND DRIVEABILITY

All engine/vehicle systems which were investigated met the current VW startability and driveability standards when tested at -10, +10, and +30°C at sea level and at +10°C at an elevation of 1,600 m. In these respects, the results obtained from the low emission concepts ('81 and research standard) were especially good because the engines involved were equipped with K-Jetronic fuel injection and closed-loop λ-sensor systems.

As a first approximation, it may be said that any improvement of startability and driveability by adjustment entails a loss of fuel economy.

2.4 PERFORMANCE

As far as passing and gradeability are concerned, there are no differences between the various engine/vehicle systems which are traceable to emission standards. Any existing differences are mainly due to the factors of inertia weight, maximum torque, peak horsepower, and drivetrain.

Engine performance increases, however, always entail UDC and HDC fuel economy losses.

2.5 NOISE

Emission standards do not influence the level of the noise emitted by a vehicle powered by a spark ignition engine.

It is, however, a general rule that the smaller engine for constant technology emits more noise, in a given vehicle, which is why the demands for low noise and good fuel economy may be said to be counterproductive.

2.6 UNREGULATED EXHAUST EMISSIONS

The unregulated exhaust emissions which were investigated were hydrogen cyanide (HCN) and sulfate (SO_4). Emissions of these substances were found to be extraordinarily low in all engine concepts (10 mg/mi). It was found that HCN emissions drop together with the regulated emissions, whereas the emissions of SO_4 show practically no reaction to variations in the emission concept.

2.7 COST

Engine concepts suitable for emission standards of '76 are 20 percent more expensive as uncontrolled engines.

The introduction of the K-Jetronic fuel injection with the closed loop system and 3-way catalyst, plus clean up catalyst for compliance with 1981 Federal Standards, results in an engine cost increase of another 60 to 70 percent.

3. APPROACH EMPLOYED IN THE STUDY

In addition to investigating, by means of computer projections and available data, the way in which a large number of peripheral factors influence fuel consumption, we structured, assembled and tested a system of engine/vehicle combinations closely related to the current VW production.

This system consisted of Rabbits powered by the 1.6 liter engine as well as by a 1.3 liter engine which is common in Europe. (The latter is not introduced in the US because the customer service organization would not accept an additional engines). The 1.6 liter Rabbit was tested at an inertia weight of 2,250 lbs, for which it is certified, and at an inertia weight of 3,000 lbs, so as to find out what the influence of inertia weight is if all other parameters are really kept constant.

Furthermore, we tested an Audi 100, powered by a 1.6 liter engine which had been brought to about 85 hp, and an Audi 5000, with its 2.2 liter 5-cylinder engine.

At first, we tested emission concepts in these vehicles which we thought would meet the given emission levels with sufficient safety margins. In this, we were immediately successful with catalyst/carburetor concepts in meeting both the '76 California Standard (0.9/9/2.0 gpm HC/CO/NOx) because these standards were already met by our production vehicles.

To meet the '81 Federal and the research standards, we employed only fuel injection engines (K-Jetronic) equipped with 3-way catalysts. Having defined the engineering goals applicable to those standards, we found that these goals could only be met by additional component synthesis.

The test matrix for all vehicles is shown in Table 3.1. It should be noted that all emission and fuel economy measurements were repeated five times and the noise measurements with the exception of the idle noise were repeated ten times without changing the engine adjustment, so that these figures can be assumed to be statistically sound. All other figures have been obtained from single tests.

Passing performance and gradeability were assessed from all pertinent engine and vehicle data by means of a computer program.

TABLE 3.1. TEST WORK (0 performed)

Modification Code	ENGINE MAPS															Fuel Economy (UDC, HDC, Comb)	Regulated Emissions (HC, CO, NOx)	SO_4	HCN	Noise	Startability		Driveability		Passing Ability	Gradeability
	α^{*} and HP	SFC $[\frac{g}{HPh}]$	FC^{+} $[\frac{kg}{h}]$	CO [%]	CO $[\frac{g}{h}]$	HC [ppm]	HC $[\frac{g}{h}]$	NO [ppm]	NO $[\frac{g}{h}]$	O_2 [%]	O_2 $[\frac{g}{h}]$	CO_2 [%]	CO_2 $[\frac{g}{h}]$	α_s^{**}	λ^{++}						Low	High	Low	High		
01	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
02	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O				O	O	O	O	O	O
03	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			O	O		O		O	O
04	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			O	O		O		O	O
05	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		O		O	O
06	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O				O		O		O	O
07	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			O	O		O		O	O
08	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			O	O		O		O	O
09	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		O		O	O
10	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O				O		O		O	O
11	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			O	O		O		O	O
12	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			O	O		O		O	O
13	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			O		O		O	O	O
14	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O					O		O	O	O
15	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			O		O		O	O	O
16	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			O					O	O
17	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		O	O	O	O	O	O
18	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O				O	O	O	O	O	O
19	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O				O	O	O	O	O	O
20	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O								O	O

* - Throttle Angle
\+ - Fuel Consumption
** - Spark Advance (DEG bTDC)

++ - $\frac{air}{fuel} \Big/ (\frac{air}{fuel})$ Stoichiometric

4. ENGINE SYSTEMS

Figures 4.1 through 4.7 show the emission control systems used to meet the engineering goals. Table 4.1 contains the legend of these figures.

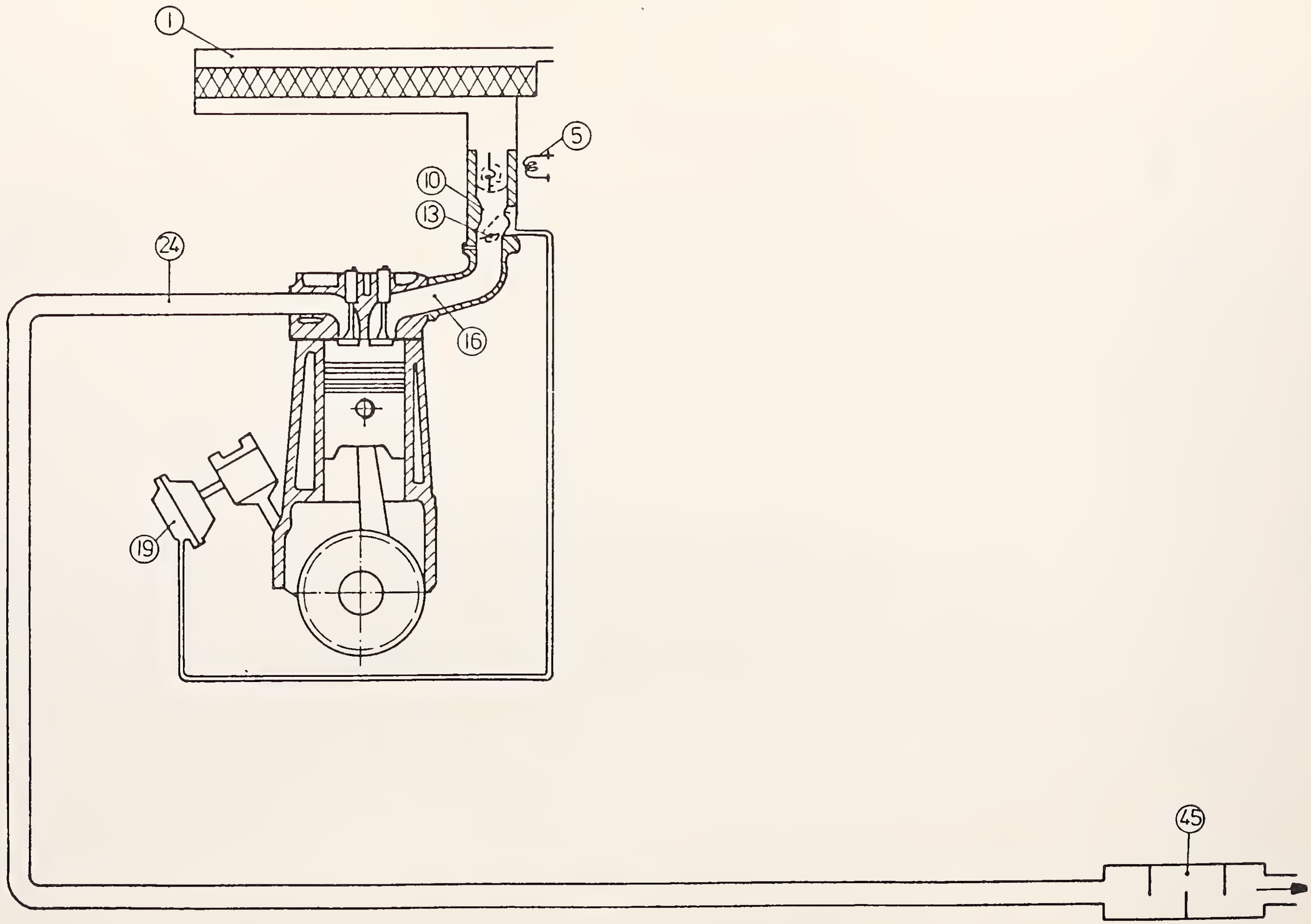

FIGURE 4.1. EMISSION CONTROL SYSTEM MODIFICATION CODES 1/2/3 AND 4 (Carburetor, Uncontrolled)

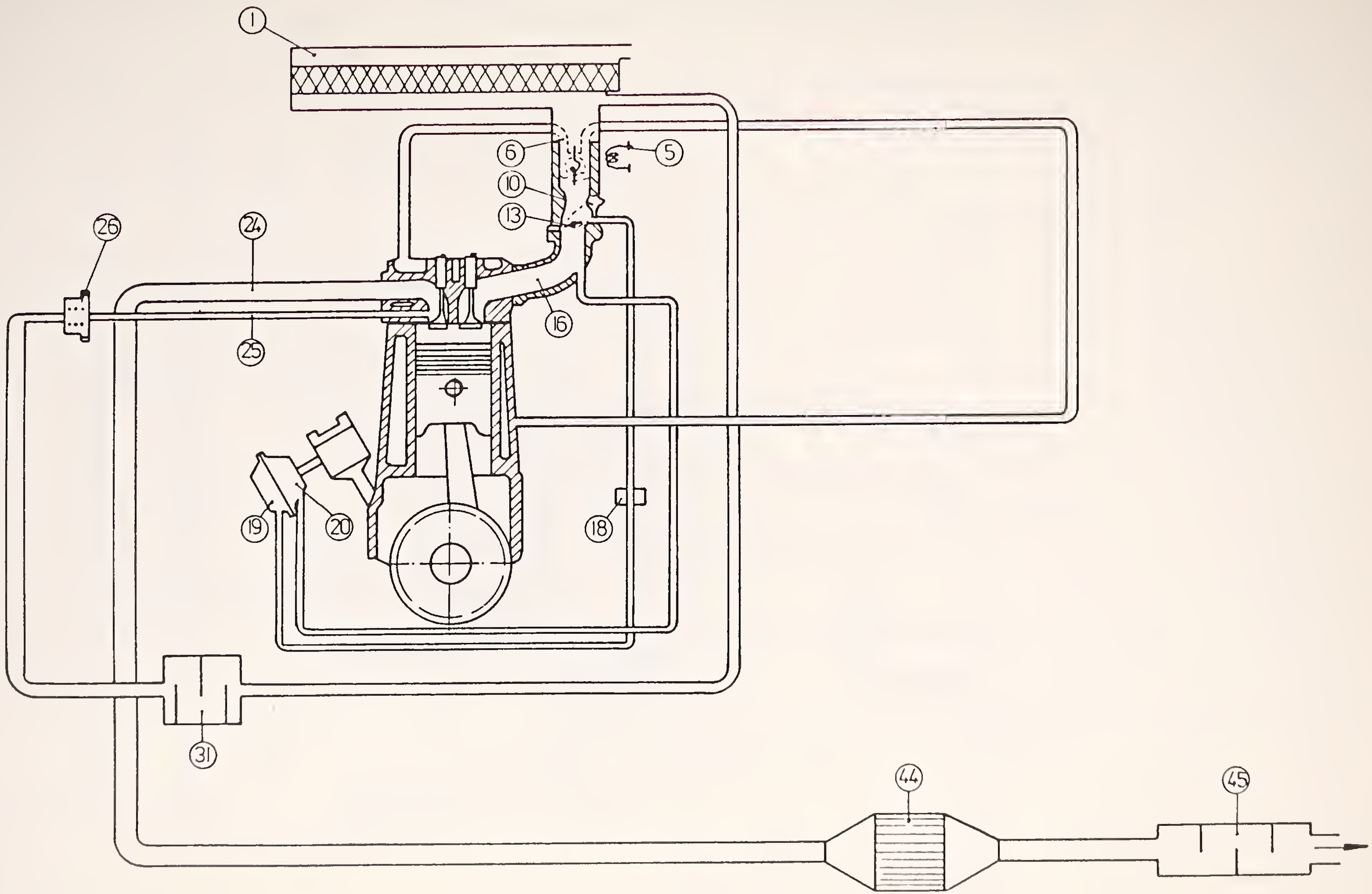

FIGURE 4.2. EMISSION CONTROL SYSTEM, MODIFICATION CODES 5 AND 7
(Carburetor, Oxcat, Self Aspirating SA, US 76)

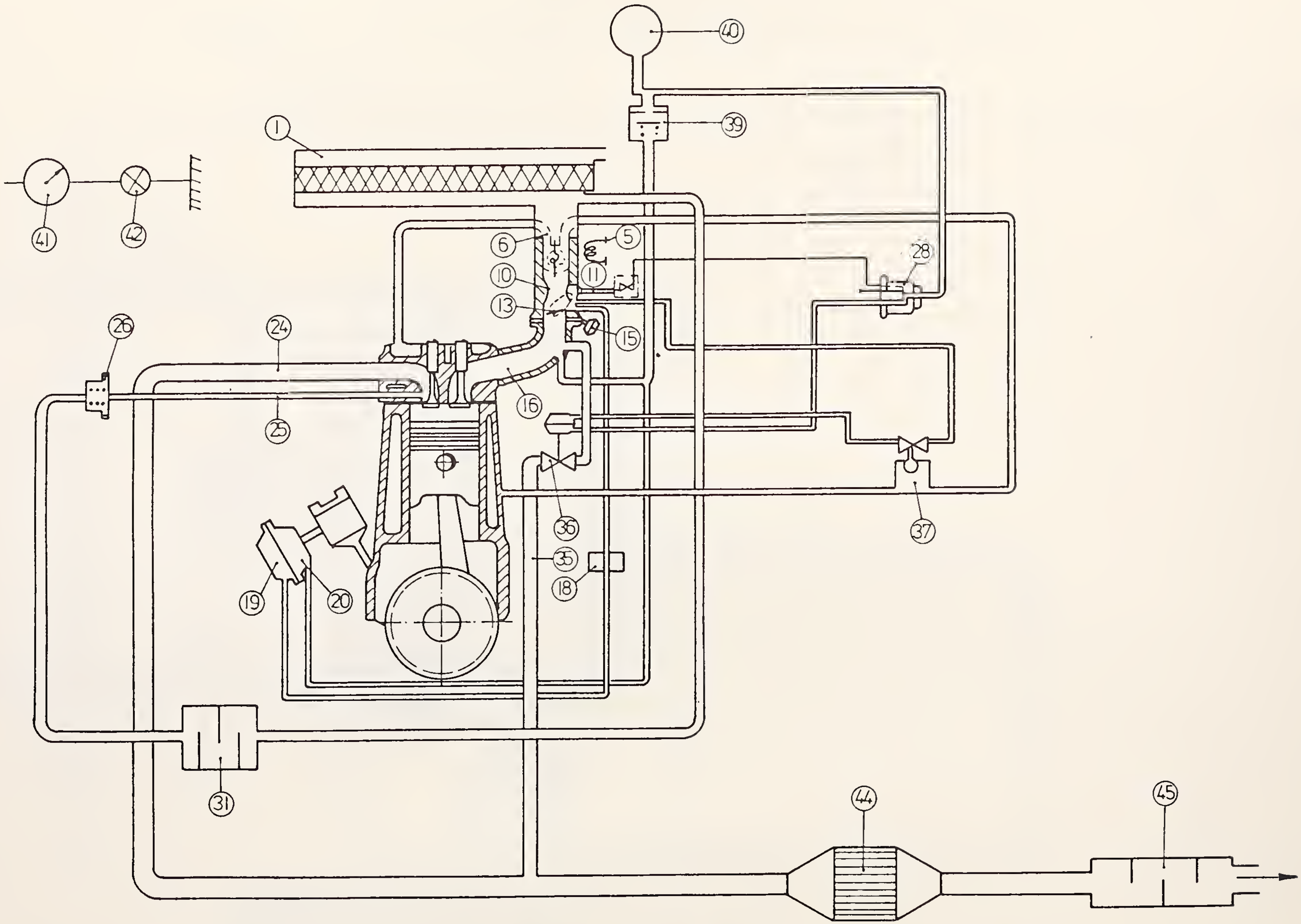

FIGURE 4.3. EMISSION CONTROL SYSTEM, MODIFICATION CODES 6 AND 8
(Carburetor, Oxcat, Self Aspirating SA, EGR, US 76)

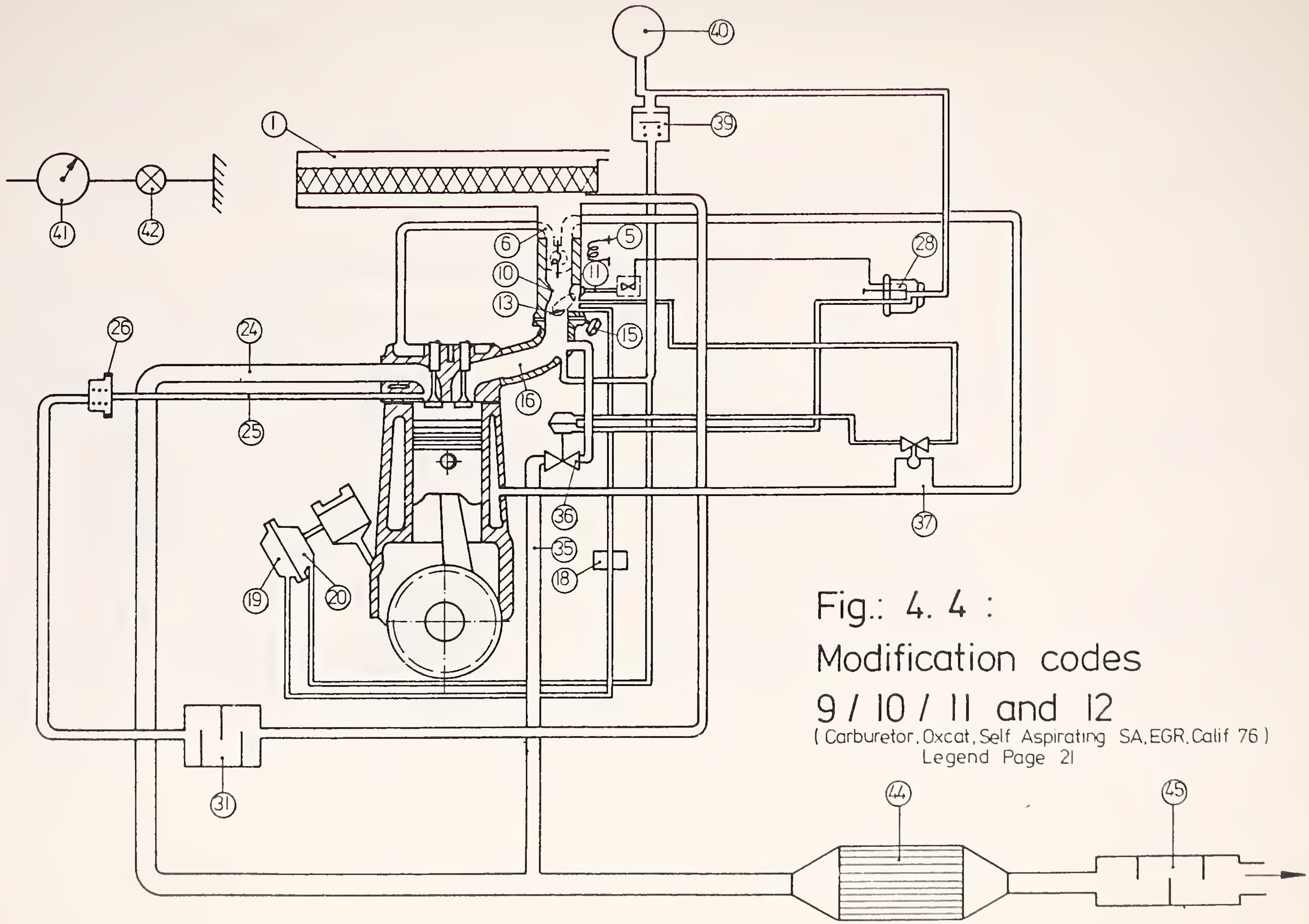

FIGURE 4.4. EMISSION CONTROL SYSTEM, MODIFICATION CODES 9/10/11 AND 12
(Carburetor, Oxcat, Self Aspirating SA, EGR, Calif 76)

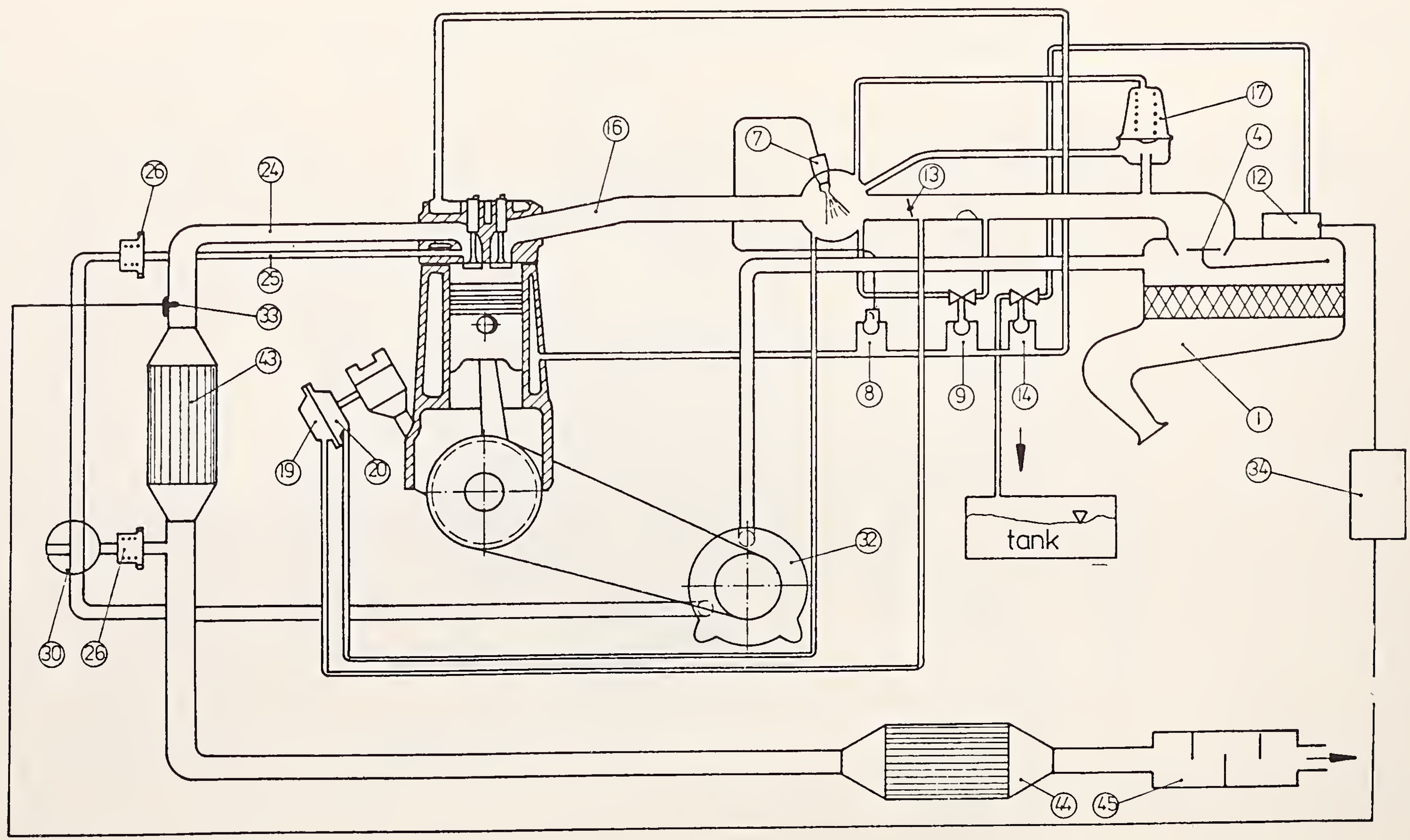

FIGURE 4.5. EMISSION CONTROL SYSTEM, MODIFICATION CODES 13 AND 17 (FI, TWC, Closed Loop, Oxcat. SA, US81 and Research)

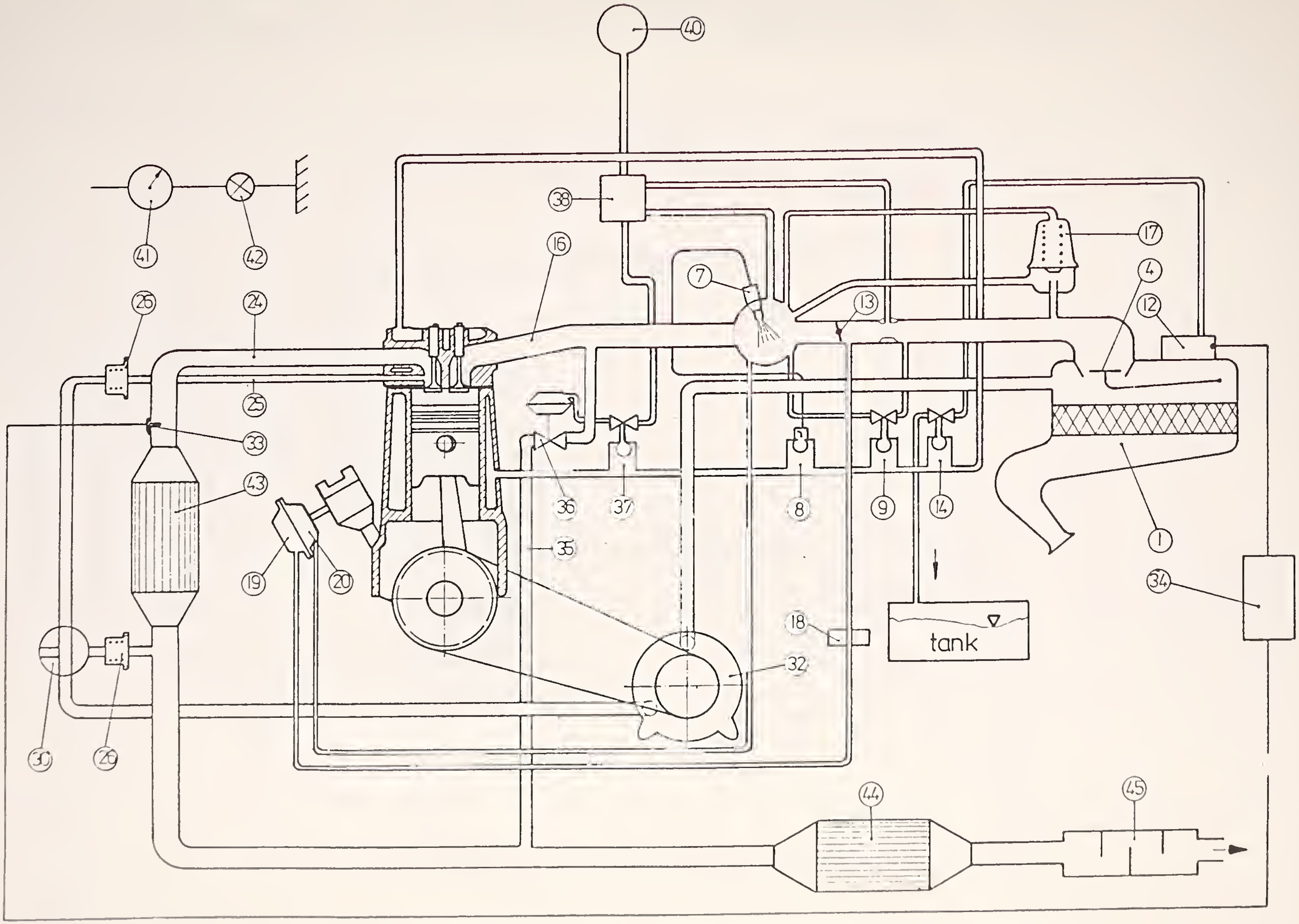

FIGURE 4.6. EMISSION CONTROL SYSTEM, MODIFICATION CODES 14/16/18 AND 20 (FI, TWC, Closed Loop, Oxcat, SA, EGR, US81 and Research)

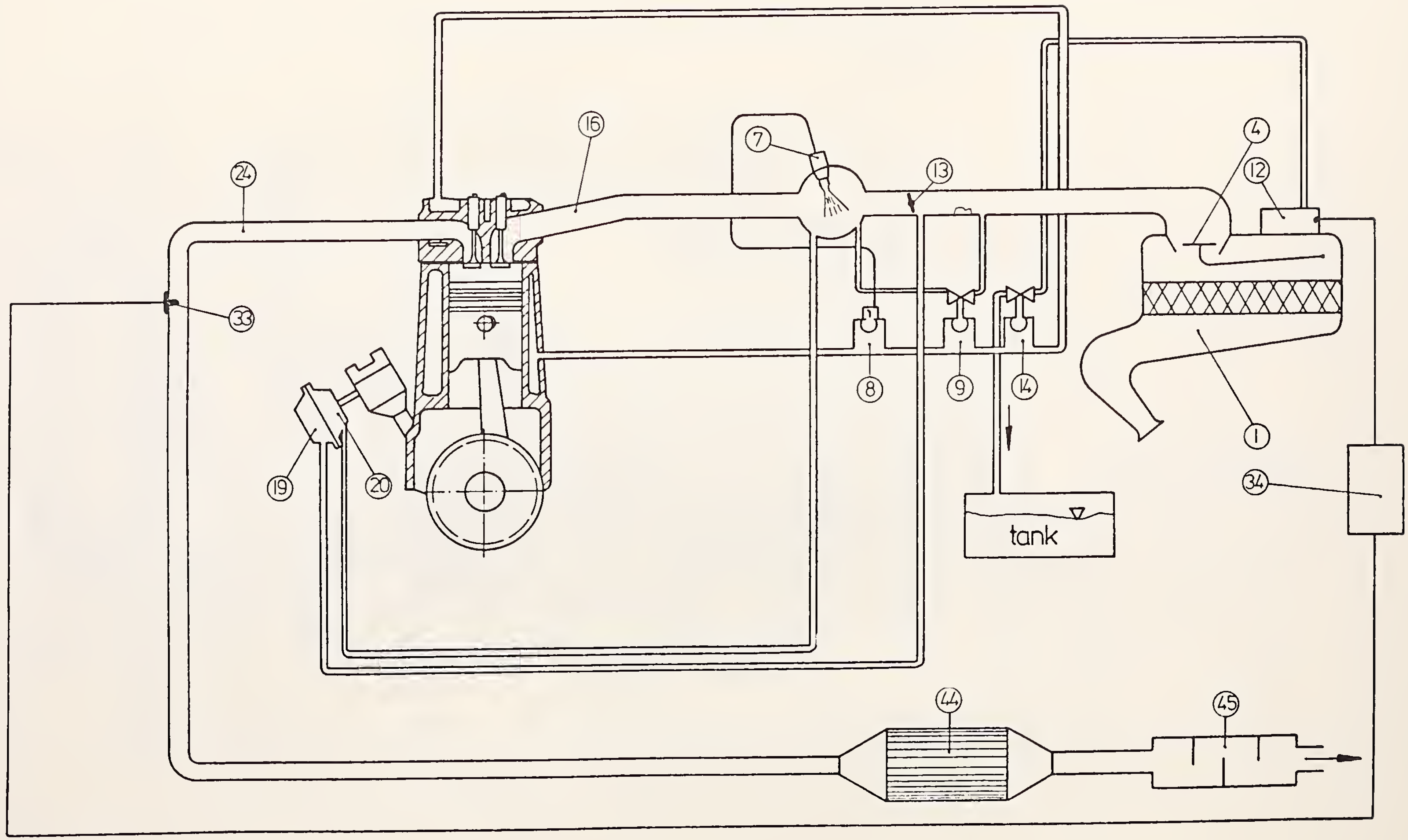

FIGURE 4.7. EMISSION CONTROL SYSTEM, MODIFICATION CODES 15 AND 19 (FI, TWC, Closed Loop, US 81 and Research)

TABLE 4.1. LEGEND TO FIGURES 4.1 THROUGH 4.7

1	Air cleaner
4	Air flow sensor
5	Electrically heated choke system
6	Water heated choke system
7	Starting solenoid
8	Temperature related time switch
9	Auxiliary air valve
10	Carburetor
11	Wide open throttle switch
12	Fuel distributor
13	Throttle
14	Warm up regulator
15	Closing damper
16	Intake manifold
17	Deceleration control valve
18	Time delay valve
19	Spark advance diaphragm box
20	Spark retard diaphragm box
24	Exhaust pipe
25	Secondary air pipe
26	Secondary air check valve
28	Dual solenoid
30	Dual valve
31	Secondary air muffler
32	Secondary air pump
33	λ - sensor
34	λ - control unit
35	EGR cooling line
36	EGR valve
37	Thermal vacuum valve
38	EGR control amplifier
39	Vacuum check valve
40	Vacuum reservoir
41	Mileage counter for EGR
42	EGR check indication lamp
43	3-way catalyst
44	Oxidation catalyst
45	Muffler

5. RESULTS

5.1 FUEL ECONOMY

Fuel economy is affected mainly by inertia weight, air drag, drivetrain, engine displacement, peak horsepower and emission standard.

The composite fuel economy of vehicles in the 2,250-to-3,000 lbs inertia weight range equipped with 4-and 5-cylinder naturally aspirated spark ignition engines varies by 78 percent from 18 to 32 mpg.

Within the range of 4-cylinder engines alone, a scatter bandwidth of 35 percent can be found.

4-cylinder 1.6 liter engines consume between 0 and 12 percent more fuel than comparable 1.3 liter 4-cylinder engines (same inertia weight and emission level).

4-cylinder 1.6 liter engines producing 85 hp use 1 percent more fuel than comparable 4-cylinder 1.6 liter engines producing, 67 hp (same inertia weight and emission level).

5.1.1 <u>Emission Level</u>

Changing the emission level from uncontrolled to 1.5/15/3.1 and 0.9/9/2.0 respectively (gpm HC/CO/NOx) causes fuel economy to drop by 0 and 12 percent for the technology indicated.

Disregarding the change from 4-cylinder to 5-cylinder engines, the introduction of the fuel injection (K-Jetronic) and the closed loop necessary to attain the 1981 Federal Emission Standards leads to an increase in fuel economy of 4 to 5 percent.

This tendency is illustrated in Figure 5.1 by the example of the 1.6-liter Rabbit engine and the inertia-weight class of 2,250 lbs. The first three bars under each Modification Code show the declining emissions, while the last bar represents the combined fuel economy. A slight drop in fuel economy is already evident at 1976 conditions as opposed to uncontrolled conditions. The 1981 Federal Standards lead back to the uncontrolled level at substantially higher initial costs. However, fuel economy again decreases at a NOx level of 0.4 gpm.

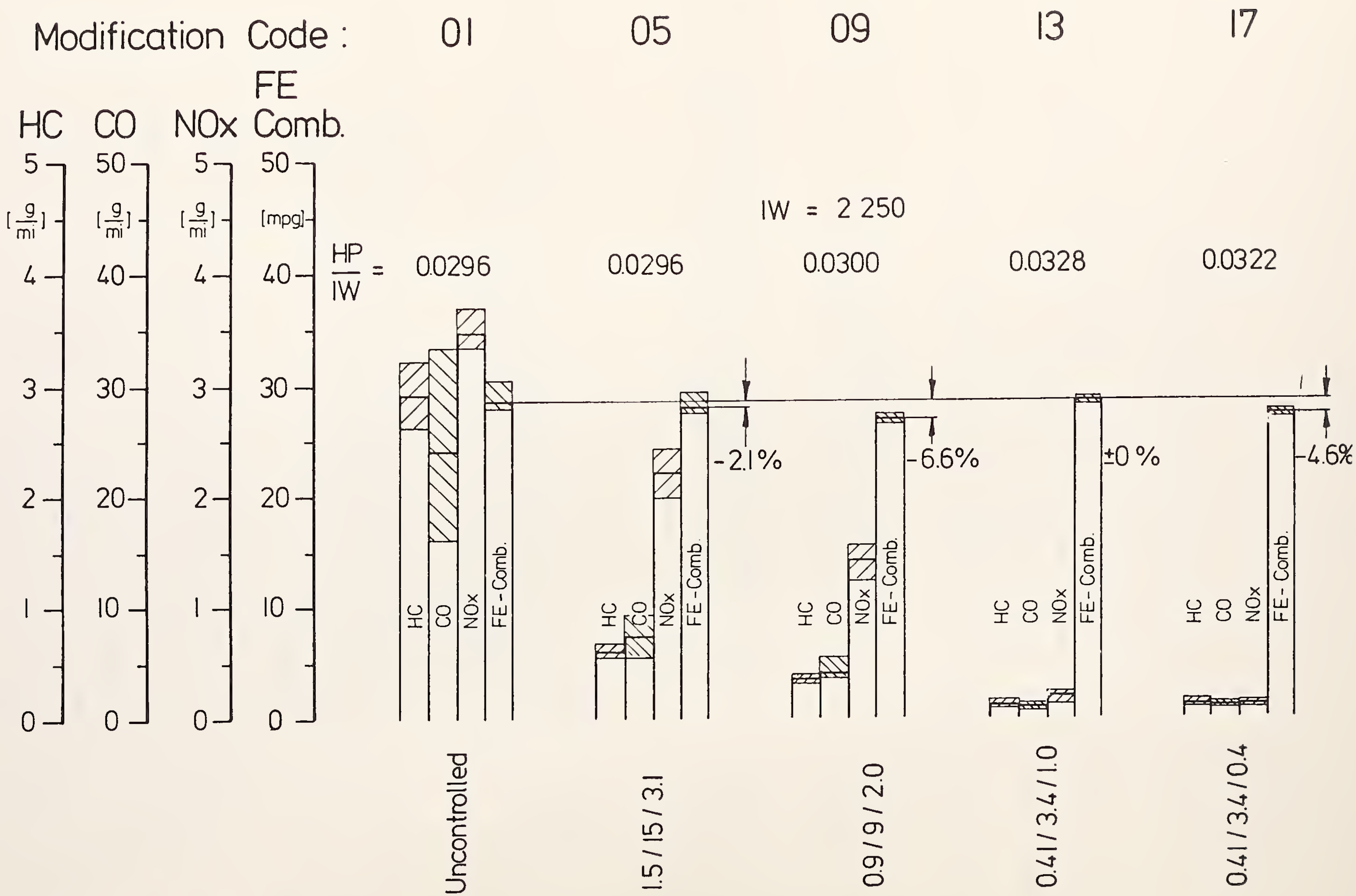

FIGURE 5.1. FUEL ECONOMY AND EMISSIONS VS EMISSION STANDARD

In other words, a comparison with present production vehicles indicates that the fleet fuel economy may be expected to improve 4 percent or 5 percent if a closed-loop system is introduced and a stoichiometric air/fuel ratio can be maintained in the field. The improvement would be lost immediately, however, as soon as the NOx emission standard is lowered to 0.4 gpm.

5.1.2 Vehicle weight

The mass of a vehicle is composed of its inertia weight and its payload. A high payload means high absolute fuel consumption. Nevertheless, for reasons of fuel economy, it would be desirable to have higher payloads. The higher the payload, the lower the percentage of fuel used for moving the inertia weight of the vehicle, or, in other words, fuel economy is much improved if six persons travel not in six passenger cars but in one.

The only weight which manufacturers of automobiles can influence is the inertia weight of a vehicle. From the aspect which is of interest here, Figure 5.2 shows the link between inertia weight and fuel economy. A closer look shows that the relationship is not linear, because the influence of a constant absolute variation of the inertia weight necessarily loses significance as the size of the inertia weight itself grows.

Based on our studies, we are in a position to state that increasing the inertia weight from 2,000 to 3,000 lbs for the vehicles tested will result in a fuel economy loss of between 8 and 11 percent, provided that all other parameters and especially engine size and type are kept constant. In the field, fuel economy losses resulting from inertia weight which increases from 2,000 to 3,000 lbs are closer to 20 rather than to 10 percent, because field tests involve bigger engines as well.

5.1.3 Performance

Figure 5.3 shows fuel economy versus horsepower-to-inertia-weight ratio. The vehicles under investigation were not equipped with special emission control systems. All figures show combined fuel economy results.

Of those factors which do have influence, inertia weight is foremost. We can see that any change in inertia weight influences fuel economy. This can also be said of peak horsepower as a factor, because if it is high,

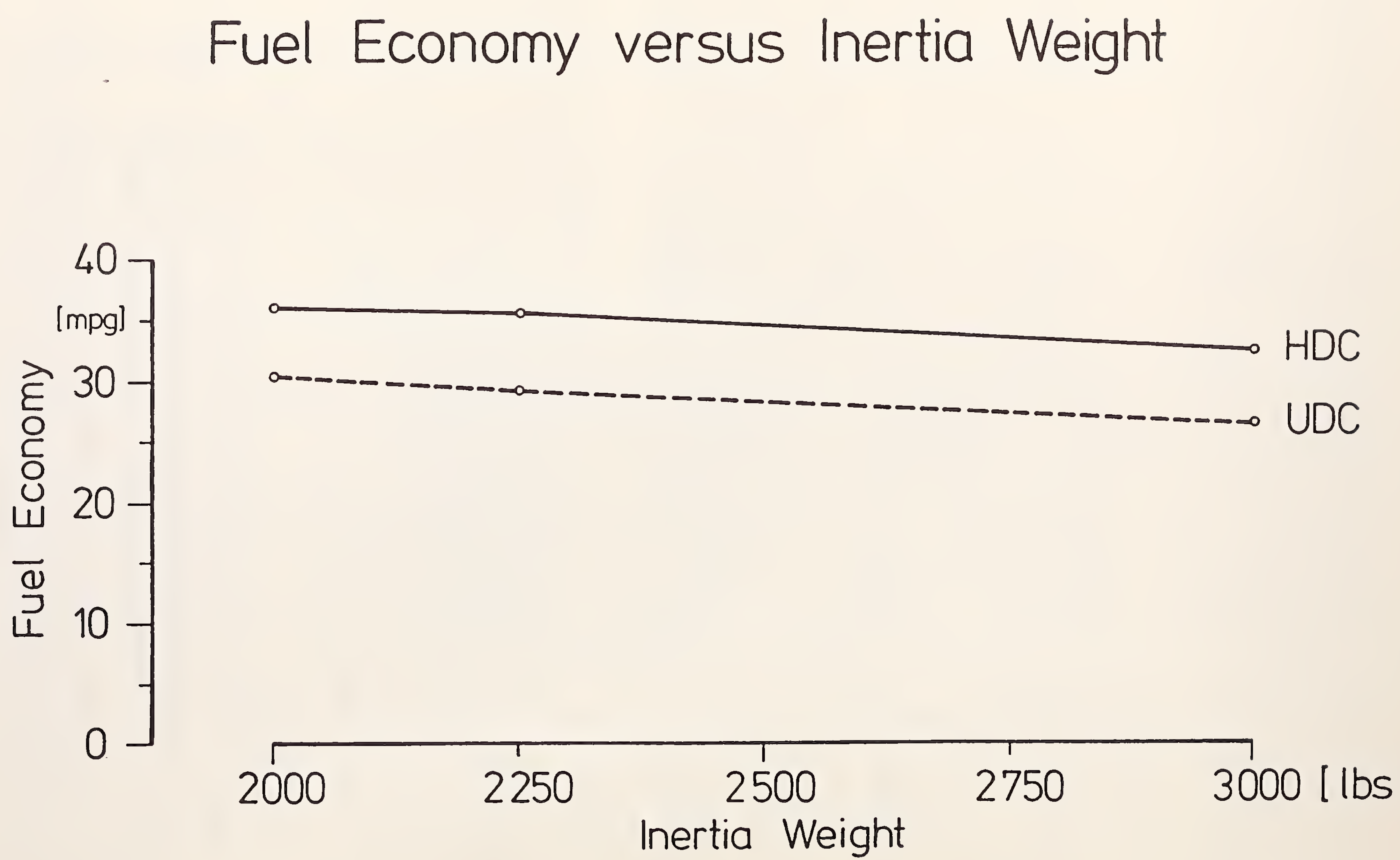

FIGURE 5.2. FUEL ECONOMY VS INERTIA WEIGHT

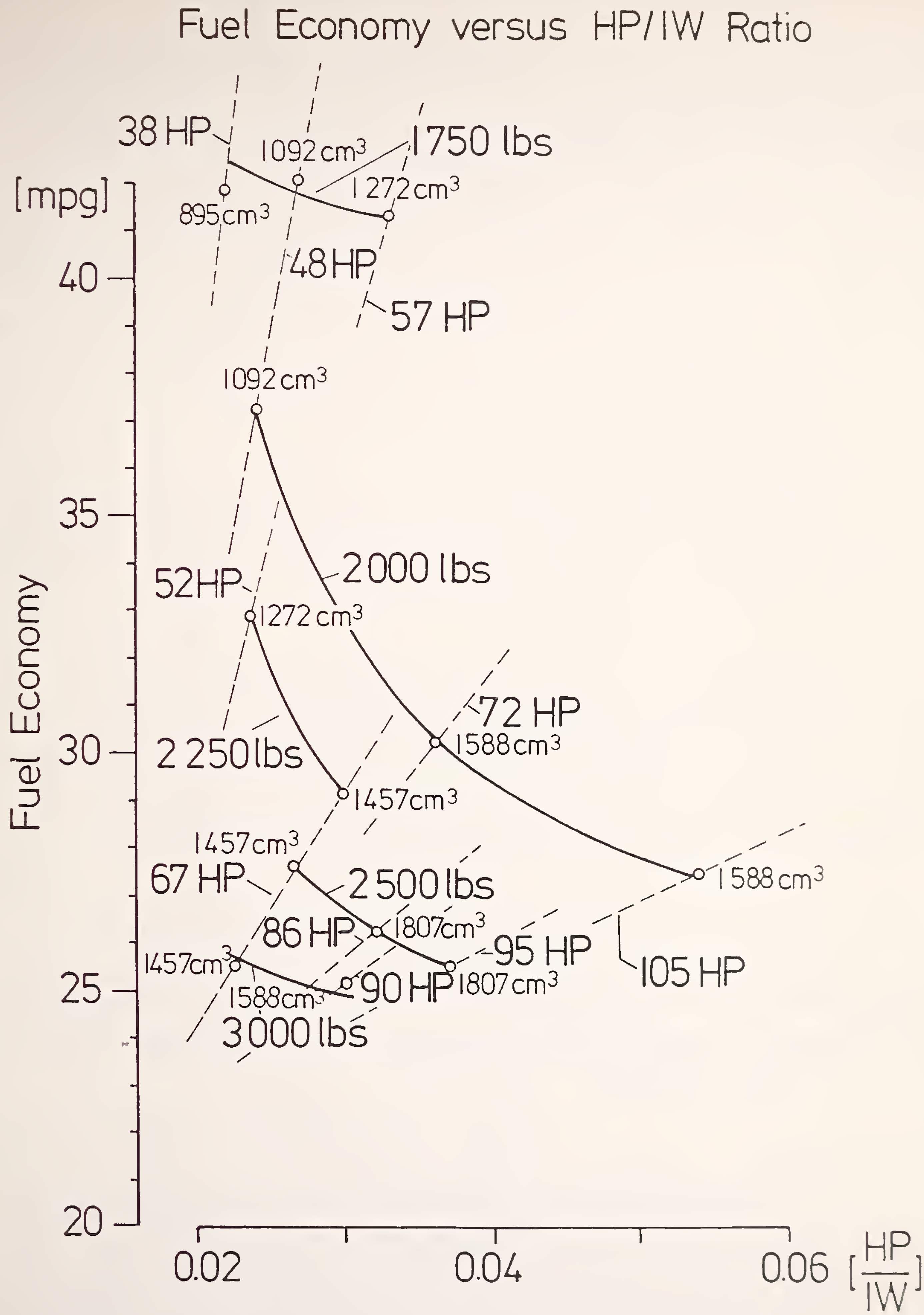

FIGURE 5.3. FUEL ECONOMY VS HP/IW RATIO

fuel economy is low, whereas a low peak horsepower means good fuel economy.

The reason why engines of relatively low performance consume less fuel is that when they are tested moving a certain inertia weight through the fuel economy cycles, less powerful engines can be run closer to their points of minimum fuel consumption. Furthermore, less powerful engines are smaller as a rule, which makes for relatively low friction and pumping losses. On the other hand, low-performance engines need relatively high speeds to produce a given power output, but this is a factor which is more than compensated by the other influences named above.

5.1.4 Drivetrain

The results of a number of spot checks, together with a number of data already available, enabled us to assess the extent to which transmission and drivetrain influence fuel economy. We found that fuel economy can be improved by a maximum of 10 percent by changing the transmission ratios in a suitable manner.

The general tendency is for the fuel economy of a vehicle running at a given velocity to improve as the engine speed required to produce this velocity is reduced. However, improvements in this direction are limited by the vehicle having to retain a certain acceleration performance, which also decreases with the engine speed related to a given vehicle velocity.

The extent to which automatic transmissions influence fuel economy depends largely on the kind of cycle used in the test. In the Urban Driving Cycle, manual transmissions hardly produce any improvement whatever, whereas in the Highway Driving Cycle their introduction results in fuel economy improvements ranging between 10 and 15 percent. Accordingly, the Composite fuel economy is improved by around 6 percent.

5.1.5 Air Drag

The air drag of a vehicle is a factor which comprises both the cross-sectional area of the vehicle and its aerodynamic air drag coefficient. The cross-sectional area of a vehicle is directly related to its roominess, which is why it can be changed only within very narrow limits. On the other hand, the air drag coefficient allows manufacturers to exercise considerable discretion in design. The air drag coefficients of contemporary European vehicles range from 0.37 to 0.52, the average being 0.46.

Studies made by VW showed that reducing the air drag coefficient from 0.5 to 0.3 will improve the UDC fuel economy by 6 percent, the HDC fuel economy by 22 percent, and the Composite fuel economy by 11 percent. It is obvious, therefore, that the influence of the air drag coefficient on fuel economy is considerable.

As a rule, however, changes of so drastic a nature cannot be made for reasons of styling. Consequently, VW has developed a trade-off method to optimize the air drag coefficient by which certain critical zones in the body of a vehicle are improved aerodynamically one after the other without changing the overall styling concept. In this way, the air drag of contemporary vehicles can be reduced by as much as 10 to 15 percent, which would mean an improvement in their Combined fuel economy of between 3.5 and 5 percent.

5.1.6 Auxiliaries

All energy-consuming auxiliaries in a vehicle are either indispensable for the operation of the engine, or help to enhance the safety and comfort of the vehicle, or both, like, for instance, the alternator.

In the engine/vehicle systems investigated by us, we found that during fuel economy testing, the auxiliaries would consume power at the following rates:

Oil pump	: 1 hp approx.
Water pump	: 0.5 hp approx.
Fan	: 0.1 hp approx. (average with thermostatic control)
Alternator	: Approximately 140 percent of the maximum power consumption of all consumer units.
Secondary air pump	: 0.5 hp approx.
Power steering pump	: 0.5 hp approx.
Heating blower	: 0.1 hp approx. (average)
Heater	: 0 - 0.5 l/h of fuel (average)
Air conditioner	: 1 hp approx.

Technical improvements in most of these auxiliaries will result in a certain amount of energy being saved; unfortunately, this would entail increases in the sticker prices.

That the alternator consumes so much energy is due to its comparatively low efficiency. Given the currents and speeds normally prevalent in fuel economy driving cycles, its efficiency is equivalent to 0.5 approx.

The heater itself does not consume any energy, provided it uses waste heat from the engine, which is the rule. If this waste heat should not suffice for the purpose, which is the case in extremely cold zones, additional heaters will be used which burn fuel directly.

5.2 EMISSIONS

5.2.1 Engineering Goals

The results of emission tests performed on research prototypes, on EPA certification test vehicles, and on vehicles spot-checked by EPA in the field may deviate widely. Therefore, we were faced with the task of setting engineering goals for the emission standards of 0.41/3.4/1.0 and 0.41/3.4/0.4 gpm HC/CO/NOx. We had to develop concepts which would meet these engineering goals in the development stage assuming that they would later meet their standards at any time, no matter when and where they would be tested.

Provided that certain conditions are met, which would mainly concern engineering, measuring and testing, production, maintenance, and EPA, we found that the HC and CO emissions would have to be at least half as low as the standard, and that the NOx emissions in the development stage should not be higher than 25 percent of the applicable standard, so as to ensure that the standards would be met at all times. Thus, our engineering goals were 0.2/1.7/0.25 and 0.2/1.7/0.1 respectively.

The following factors essentially cause scatter in emission tests:

- Driver
- Dynamometer
- Sampling equipment
- Engine
- Drivetrain
- Production tolerances.

In all field tests, the maintenance condition of the vehicles must be taken into consideration as well. In addition, we have to take into account that the dynamometers, equipment and drivers used for development testing and for Field Compliance Testing in all probability will not be the same.

Empirical data on the effects of total vehicle mileage are available from vehicle types already in the field. In addition, EPA Durability Test results are also available. There are significant differences between these two sets of data because of the different vehicle loads and different aging conditions in customer use.

But, there are no empirical data on field and EPA Durability for vehicles in the research stage, i.e., Modification Codes 13 - 20.

Taking all this into consideration, it is difficult to arrive at any projection regarding the field behaviour of an engine/vehicle system still in the research stage.

For this reason, we set demands for low emission engineering goals. They were tough, but there is a chance that they may be reached after a sufficiently extended period of development, provided everyone concerned is prepared to collaborate. The first objective is to ensure that there is no deterioration in the engine and all other parts which control emissions, disregarding for the time being the oxygen sensor and the 3-way catalyst. In other words, the deterioration factor of the engine must not exceed 1. As far as the emissions of HC and CO are concerned, the efficiency of the oxygen sensor and 3-way catalyst must also remain constant over 50,000 miles in the field. At the moment, it seems absolutely unrealistic to postulate that the NOx efficiency of oxygen sensors and 3-way catalysts should be equally constant. For this reason, we are allowing a deterioration factor of 2 in NOx emissions.

Assuming that the emissions of a vehicle in the development stage have been successfully reduced to less than half the permissible standards, there is another requirement which has to be met; namely, that the performance of all engine parts on which emissions depend, as well as the performance of the emission test procedure and the standards of mass production are so reliably uniform that the emissions of any vehicle will remain below the standards, no matter when or where it is tested.

Thus, we established our engineering goals from the emission standards by dividing the HC and CO limits by 2, and by dividing the NO_x limit by 4.

5.2.2 Regulated Exhaust Emissions

We had to meet the following standards:

1)	Uncontrolled (reference only)		
2)	1.5/15/3.1	gpm HC/CO/NOx	(U.S. Federal 1976)
3)	0.9/9/2.0	"	(California 1976)
4)	0.41/3.4/1.0	"	(U.S. Federal 1981)
5)	0.41/3.4/0.4	"	(Research)

In addition to 0.41/3.4/0.4, levels 1.5/15/3.1 and 0.9/9/2.0 were the only regulated exhaust emission standards at the time of contract initiation.

We were able to meet the current standards with the necessary margin of safety by applying conventional concepts, such as carburetors and catalysts as well as on-off EGR in some cases. Current standards are relatively close to current production conditions, which is why the repsective engineering goals, relatively speaking, are not as strict as those of the advanced standards, although, in absolute figures, they can be much stricter because the standards themselves are much higher. Thus, for example, the engineering goal related to the '81 CO emission standard is 1.7 gpm. Although this is equivalent to half the standard, it is only 1.7 gpm below the standard. If, by way of comparison, you look at the results related to the '76 Federal standard, you will find that all of them are much farther below that standard than 1.7 gpm.

In the course of the work required to meet the engineering goals of the advanced standards we found that:

- the standards of '81 require the use of closed loops in each case;
- in addition to this, in the 3,000 lbs inertia weight class, proportional EGR is required in each case to meet the standards of '81, whereas there is no demand for EGR in the IW class of 2,250 lbs;
- with the sole exception of the 1.3 liter engine, all other engines have to have clean-up catalysts with secondary air injection to meet the '81 standards;
- the 1.3 liter engine is capable of meeting the research standard engineering goal of 0.1 gpm NOx as well, without clean-up catalyst, secondary air injection, and EGR.

The HC and CO emissions of our concepts always kept below the engineering goals of the advanced standards. In all cases, we met the engineering goal of 0.25 gpm NOx, which is related to the '81 standard, but we were not equally successful as regards the goal of 0.1 gpm, which belongs to the research standard of 0.4 gpm NOx. The 1.3 liter engine did just about meet this goal, because in this engine, pumping and friction losses are at a minimum. The 1.6 liter engine was quite problematic already (0.12 - 0.13 gpm NOx), and it was even more difficult to get somewhere with the 5-cylinder engine (0.15 gpm NOx).

As far as the vehicle system is concerned, the only important factor influencing emissions in a significant way is that of inertia weight. This can be demonstrated by comparing Modifications 01 and 02, 05 and 06, 09 and 10, 13 and 14, as well as 17 and 18. The transition from 2,250 to 3,000 lbs inertia weight entails emission increases which, in the case of hydrocarbons, amounts to an average of 20 percent, in the case of carbon monoxide to 50 percent, and in the case of nitrogen oxides to 26 percent, which may drop to 0 percent if EGR is used only in the heavier vehicle of the two.

5.2.3 Unregulated Exhaust Emissions

By means of spot checks in which only the 1.6 liter Rabbit engine was involved, we tried to establish the extent to which the unregulated emissions of HCN and SO_4 are influenced by emission control concepts.

In agreement with the results of studies performed earlier, we found that the emissions of HCN drop together with those of HC and CO, although the drop at the introduction of catalysts is not quite as steep as that of HC and CO.

Sulfate emissions trends are not so clearly identifiable. That the emission of sulfate shows a tendency to grow as the temperature of the 3-way catalyst increases is reflected by the fact that the sulfate emissions of Modification Code 17, which is equipped with a 3-way catalyst, show a tendency to rise from UDC via SET (Sulfate Emission Test) to HDC, i.e., parallel to an increase in engine power output and, therefore, to an increase in the average temperature of the catalyst.

Whatever the tendencies displayed by the various emission control concepts may be, it may safely be stated that the emissions of HCN and SO_4 are extraordinarily low even in the uncontrolled vehicle, being in the range of 0.01 gpm and far below.

5.2.4 Noise

Our studies of the noise emitted by the various vehicles enable us to make three statements:

- Introducing more stringent exhaust emission regulations does not necessarily ential an increase in the emission of noise, although the total number of noise-generating devices is increased. This may be due to the introduction of silencing devices as well, such as catalysts.
- The higher the engine displacement, the lower the noise emission will be, because bigger engines run at lower speeds.
- The higher the inertia weight of a vehicle, the lower the noise emission will be, because heavier vehicles can be soundproofed more effectively.

The amount of data available now only enables us to make these qualitative statements. It is not sufficient for any quantitative conclusions.

5.3 CONSUMER ACCEPTABILITY FACTORY TESTS

5.3.1 Startability and Driveability

All startability and driveability tests began with cold start at an overall vehicle temperature of either -10°, +10°, or +30°C. Tests were conducted both at sea level and at an elevation of 1,600 m.

Figure 5.4 shows the ratings of start-up performance, indicating that the best startability is obtained from K-Jetronic engines.

Following the cold start, the vehicles were run through a VW driveability cycle. This cycle consists of a brief idle phase preceding a number of different acceleration phases. The vehicle acceleration is recorded. At the end of the test, the driver evaluates each phase. All phases are then combined to engine temperature ranges, i.e., start-up phase, cold idle, acceleration phases under start-up conditions, first warm-up, second warm-up and hot-engine driveability. The results obtained at the various temperature levels are accumulated and weighted. The resulting subtotals are added up to a grand total representing the driveability of the vehicle.

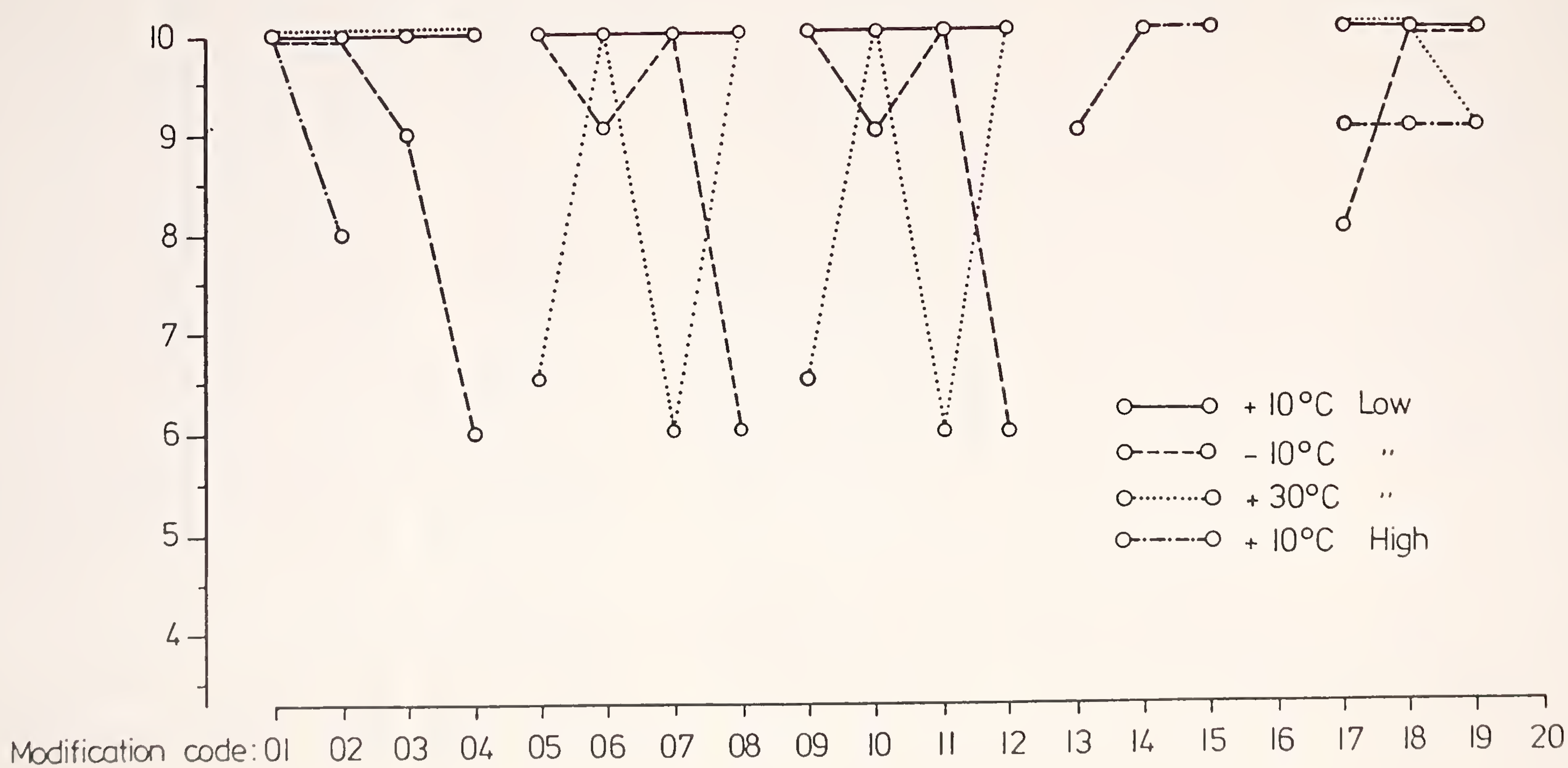

FIGURE 5.4. STARTABILITY

Figure 5.5 shows the cumulative driveability of the various Modification Codes and indicates that vehicles with fuel injection have better driveability ratings than vehicles with carburetors. However, it should not be concluded that lower emission levels are associated with better driveability. The improved driveability in the subject case is a result of the combination of fuel injection (K-Jetronic) and closed-loop system for compliance with stringent emission standards.

5.3.2 Performance

For all engine modifications concerned in this study, engine maps were drawn up from dynamometer tests. The data contained in these maps were used in conjunction with data concerning the drivetrains and vehicles to compute the passing performance and gradeability of all engine/vehicle systems. The results of these computations are listed in Table 2.3.

There are significant findings regarding the influence of inertia weight, air drag, transmission ratio, and maximum engine torque over engine speed, but it is impossible to discern any influence of the emission levels, not even an indirect one, because the factors just named are independent of the emission level. In other words, it can be seen that low-emission K-Jetronic engines are quite able to keep up with other engines.

5.3.3 Cost

All low-emission concepts, and in particular those with a NOx level of 1.0 gpm, are a positive engineering contribution. However, the financial aspects were to be taken into account, too. We made an analysis of this problem on the basis of sticker prices.

We expressed the cost of all emission control concepts in terms relative to the cost of comparable uncontrolled engines, with the sticker price of the uncontrolled engine being 100, i.e., we computed the percentage by which the sticker prices of the controlled concepts exceeded those of the uncontrolled engines. The following concepts are comparable in that respect:

a) 01; 05; 09; 13 and 17,
b) 02; 06; 10; 14 and 18,
c) 03; 07; 11; 15 and 19,
d) 04; 08; 12; 16 and 20 (see Table 2.3).

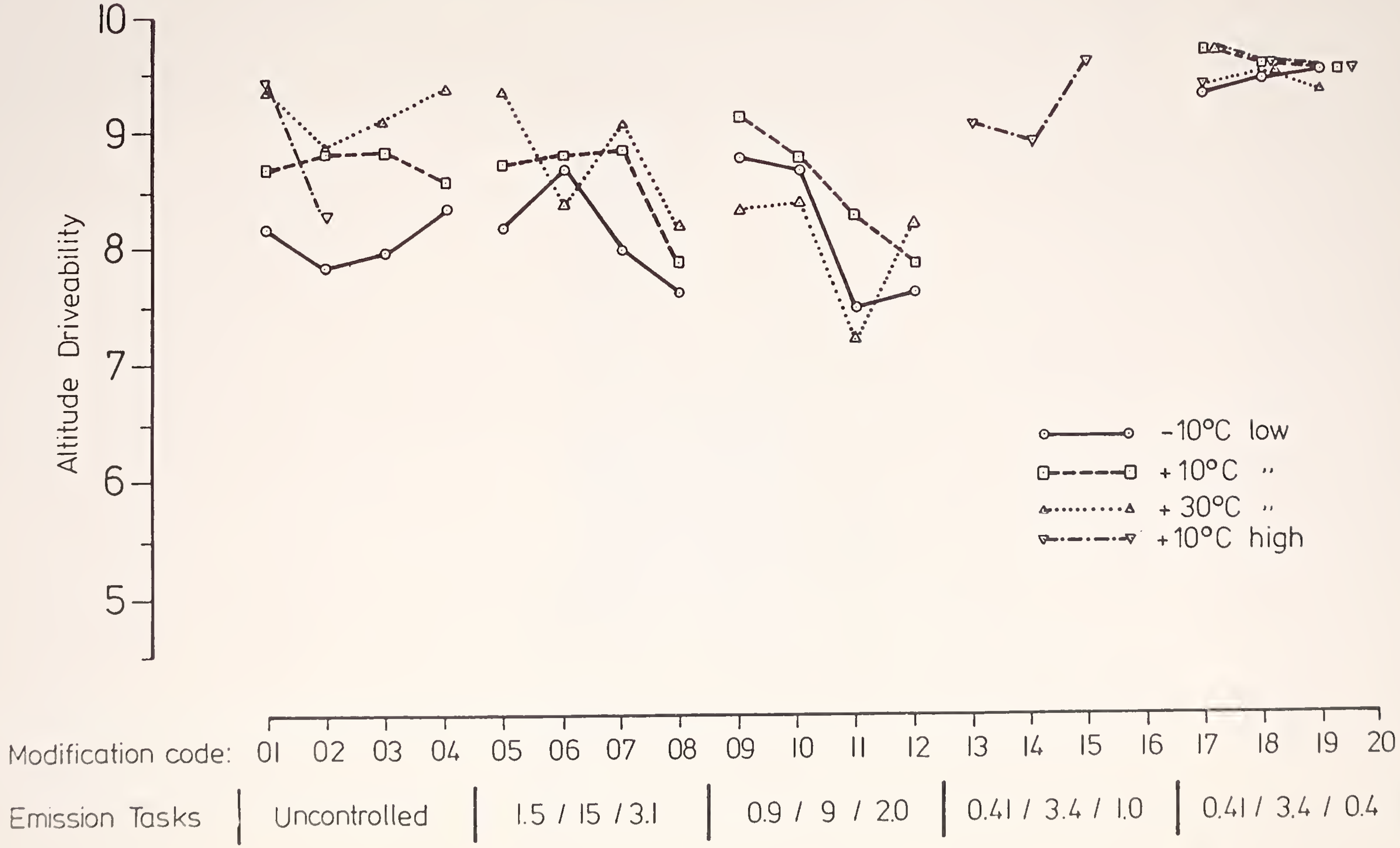

FIGURE 5.5. CUMULATIVE DRIVEABILITY

Comparison a) shows that the introduction of the emission control concept entails a price increase of approximately 20 percent. Another 60 percent is added when the system is introduced to comply with the low emission levels.

This particular step has even more pronounced effects on b). The transition from the present emission levels to those of the future will entail a 70 percent cost increase, largely caused by sophisticated EGR systems and secondary air pumps.

In relative terms, the cost of the small engine will increase somewhat more steeply, c), within the range of present emission standards because of its lower original price, while the cost of complying with the emission standards remains about the same as with a larger engine. The cost of complying with the strict emission standards of the future, however, is lower in absolute and relative terms for this particular engine.

As far as the larger engine is concerned, d), it should be born in mind mind that the transition from Modification Codes 4, 8, and 12 to Modification Codes 16 and 20 involves switching from a 4-cylinder to a 5-cylinder engine. Adding the additional cost to an already high base price, however, results in a comparatively low relative cost increase.

The introduction of the K-Jetronic fuel injection and 3-way catalyst plus clean up catalyst required for compliance with the 1981 Federal Standards results in an engine cost increase of 60 - 70 percent compared to engines meeting the present emission levels.

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