STUDY ON POTENTIAL TO IMPROVE FUEL ECONOMY OF PASSENGER MOTOR VEHICLES

WORKING PAPERS

Prepared for:

DEPARTMENT OF TRANSPORT AND COMMUNICATIONS

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STUDY ON POTENTIAL TO IMPROVE FUEL ECONOMY OF PASSENGER MOTOR VEHICLES

PART 2 -WORKING PAPERS 1 to 7

WORKING PAPER NO. 1

AVAILABLE OPTIONS FOR FUEL EFFICIENT TECHNOLOGY

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TABLE OF CONTENTS

LIST OF TABLES

CONTEXT

Within the context of developing a comprehensive policy response to the Government's planning target to reduce greenhouse gas emission, the Department of Transport and Communications acting in concert with a number of other government agencies commissioned Nelson English, Loxton and Andrews Pty. Ltd. (NELA) to assess the potential to reduce fuel consumption by new passenger cars sold in Australia.

Interim information is being presented to the Steering Committee by way of a series of seven Working Papers as follows:

Working Paper No.	Title
1	**AVAILABLE OPTIONS FOR FUEL EFFICIENT TECHNOLOGY**
2	Documentation of Technologies Available to Improve Vehicle Fuel Economy
3	Production and Marketing Factors Affecting the Introduction of Fuel Efficient Technology
4	Population, Passenger Car Stocks and Fuel Consumption Performance
5	Report on International Conference on Tomorrow's Clean and Fuel-Efficient Automobile, Berlin, 25-28 March, 1991
6	Review of Policy Instruments Available to Governments
7	Definitions, Process and Procedures

1. INTRODUCTION

1.1 BACKGROUND

The Brief requires, inter alia, that the Study discuss available technologies and the economic and technical feasibility of introducing them within the time frames set down for the Study.

These matters are discussed in Working Papers 1 through 3.

1.2 OBJECTIVES

The objective of this Working Paper 1 is to list and describe possible technologies for improving the fuel efficiency of new passenger cars sold in Australia, which are powered by petrol or diesel fuelled internal combustion engines. These technologies are referred to throughout this Study as the "technical options".

If read in conjunction with WPs 2 and 5, this paper provides an overview of the directions being taken in automotive design practice towards delivering fuel economy through technical improvement of such vehicles.

Specifically, this paper outlines the technical options considered feasible for introduction into passenger cars sold in Australia during the period to 2005, and the mix of technologies which are likely to be introduced.

The document also envisages changes to the ADRs as they affect occupant safety and noxious emissions standards, and their implications for fuel consumption.

Anticipated changes to fuel consumption as a result of a Product Plan Scenario and a Maximum Technology Scenario are discussed and quantified as far as possible.

1.3 APPROACH

For the purpose of this Study, there are two relevant perspectives for fuel economy:

- a manufacturing perspective which addresses the technical options which might be brought to bear on fuel economy during the planning period;
- a policy perspective which address the product features likely to emerge in response to consumer demands and particularly in response to anticipated government intervention on safety and emissions controls.

This WP addresses the former; the latter are discussed in WP3, WP6 and in the main report.

There are three relevant markets:
(a) vehicles manufactured and sold in Australia;
(b) vehicles imported for sale in Australia;
(c) vehicles not now sold in Australia but which might be under different market conditions or policies.

Items (a) and (b) are fairly readily defined by available statistics. Assistance was obtained from Agencies in this regard.

Within (c), there is a range of production, prototype and concept vehicles mentioned in the literature and the trade press which have fuel consumption characteristics much lower than vehicles currently sold in Australia. These provided a source of information for identification of feasible technical options for the period to 2005.

The feasible technical options were analysed according to the laws of physics as described in WP2, and an estimate of fuel consumption for each vehicle class was obtained. These estimates were then applied to the known product mix at the base year(s) to provide a background to conclusions about the action necessary to deliver fuel economy to new vehicles sold in Australia in the period to 2005.

2. VEHICLES NOW SOLD IN AUSTRALIA

According to the AIA, there were 410,473 vehicles sold in Australia in 1988 including about 4800 commercial derivatives used as passenger vehicles. Table 2.1 provides the breakdown of sales of passenger vehicles in 1988.

TABLE 2.1: ESTIMATED PERCENTAGE SALES OF PMVs BY MAKE - AUSTRALIA, 1988

	SALES 1988			
Make of Vehicle	Percentage of Total	Locally Produced	Imported	Total
Estimated Percentage of each Australian Resident Manufacturer (ARM): (1)				
Ford	27.5	31.6	42.7	
Holden	21.6	24.8	18.2	
Toyota	14.9	17.1	23.7	
Mitsubishi	12.7	14.6	8.7	
Nissan (incl. Datsun)	10.3	11.8	6.7	
ARM Total (2)	86.9	330,416	26,372	356788
Estimated percentage of Major Imported Makes (MIM):				
Honda	3.3		25.6	
Mazda	2.7		20.3	
Hyundai	1.3		10.0	
Volvo	0.9		7.2	
Mercedes Benz	0.8		6.2	
Subaru	0.8		5.8	
Diahatsu	0.7		5.5	
B.M.W.	0.7		5.2	
SAAB	0.5		3.7	
Jaguar/Daiml.	0.3		2.0	
Alfa Romeo	0.2		1.8	
Rover	0.2		1.6	
Other	0.7		5.2	
M.I.M. Total: (3)	13.1		53,685	53,685
Total	100	330,416	80,057	410473

SOURCES: ABS No.9309.0, p9.; AIA 1988; and

PAXUS Australia Pty Ltd, Bulletin - New Motor Vehicle Registrations, 1988.

Notes:

(1) Local manufacturers of cars and station wagons are vehicle manufacturers with manufacturing facilities located in Australia.

(2) Includes derivatives of PMVs produced locally (eg. Panel Vans), which are less than one percent of the total produced.

(3) All vehicles are petrol powered except for Mercedes Benz 190d and 333d and the Peugot 505, which are diesel powered.

These were classified as locally produced or imported.

2.1 VEHICLES MANUFACTURED IN AUSTRALIA

There is no vehicle which is 100 percent local manufacture, the maximum being about 80-85 percent. Of the total 410,473 vehicles sold in 1988, 330,416 or just over 80 percent were manufactured locally.

The Study defined local manufacture as all those vehicles which are imported in "completely knocked down" (CDK) form, a typical example of which is the Ford Laser. This definition represents about 50 percent local content for the assembly function.

Table 2.2 summarises the proportions of locally produced and sold passenger cars in 1988, by make, model, class and body type. The Table includes vehicles made under the Car Plan.

Of the five Plan Producers, GMH and Ford produce the large classes (Holden and Falcon) while Mitsubishi, Nissan and Toyota all manufacture cars of medium-large class, only slightly smaller consistent with their Japanese antecedents.

These vehicles dominate the market, representing 60 percent of all vehicles sold in 1988.

2.1.1 Model Production and Cross Badging

Rationalisation of the PMV industry is a key strategy of the Car Plan. Central to the rationalisation process is a reduction in the number of locally manufactured models. At the outset of the Plan in 1985, thirteen models were being produced in Australia. Nine models remained in local production at the end of 1988, following the removal of the Holden Camira during the year. By the end of 1989, eight was the count following the phasing out of the Mitsubishi Colt.

Of the eight models which were in production, four of these models were the subject of model sharing arrangements entered into during the year, namely: Corolla/Nova; Camry/Apollo; Commodore/Lexcen; (all involving Holden and Toyota), and Pintara/Corsair (involving Ford and Nissan).

There are no Mini class vehicles produced in Australia. Ford was the only local producer of luxury class vehicles (Fairlane and Ltd) in 1988.

2.2 VEHICLES IMPORTED FOR SALE IN AUSTRALIA

Many vehicles are 100 percent imports, particularly in the small and luxury classifications. In 1988, there were 80,057 passenger cars imported to Australia, of which 26,372 or almost 33 percent were imported by the major resident manufacturers (Table 2.1).

The proportions of imported makes is summarised in Table 2.1.

TABLE 2.2: ESTIMATED PROPORTION OF SALES OF LOCALLY PRODUCED VEHICLES BY MAKE, MODEL CLASS AND BODY TYPE, AUSTRALIA, 1988

Make	Model	Class	Cars	Stat'n Wagons	Total Passenger Motor Vehicle	Percent Per Producer
			Percentage of Total Production			
Ford	Laser	Small	8.1	0.5	8.6	
	Falcon/Fairmont	Up.Medium	16.1	5.2	21.3	
	Fairlane	Luxury	1.4	0.0	1.4	
	Ltd.	Up.Luxury	0.3	0.0	0.3	
Sub total						31.6
Holden	Astra	Small	2.6	0.0	2.6	
	Camira	Medium	3.0	1.6	4.5	
	Commodore 6	Up.Medium	14.1	2.8	16.9	
	Commodore 8	Up.Medium	0.7	0.1	0.8	
Sub total						24.8
Toyota	Corolla/Tercen	Medium	7.2	0.1	7.2	
	Corolla 4x4	Medium	0.0	0.4	0.4	
	Camry/Corona	Medium	7.1	2.2	9.3	
	Camry 6	Medium	0.3	0.0	0.3	
Sub total						17.1
Nissan	Pulsar/Prairie	Small	4.9	0.0	4.9	
	Pintara	Medium	2.4	1.2	3.6	
	Skyline	Up.Medium	2.7	0.6	3.3	
Sub total						11.8
Mitsubishi	Colt	Small	2.2	0.0	2.2	
	Magna	Medium	8.8	3.6	12.4	
Sub total						14.6
Total					330416(1)	100

Source: AIA 1988; PAXUS Australia Pty Ltd, Bulletin - New Motor Vehicle Registrations, 1988.

Note: (1) This total includes all PMV derivatives (about 1 percent of total).

2.3 VEHICLES EXPORTED FOR SALE OVERSEAS

Local manufacturers exported 1,921 cars in 1988 to make up their total sales of 358,709 vehicles. The number of vehicles exported was the lowest recorded since the commencement of the Plan and represented a decline of 81 percent over 1987 (AIA:1988). The drop in export sales was due mainly to the decrease in demand for Australian automotive products in the New Zealand market, the major overseas buyer of Australian PMVs and components.

2.4 VEHICLE CLASSES SOLD IN AUSTRALIA

The classification system for passenger cars used by the Study is discussed in WP7. Appendix A provides a listing of all vehicles sold in Australia by vehicle class, and includes volumes sold in 1988 and 1990.

The breakdown of new vehicle sales by vehicle class and production status for 1988 is summarised in Tables 2.3(a) and (b).

TABLE 2.3(A): ESTIMATED PROPORTION OF PMVs BY CLASS AND STATUS PRODUCTION, 1988

	Percentage by type of Production				
	Product Plan Manufacturers				
	Locally Produced	Imported	Total	Other Imported	All PMV
Total Mini	0.0	18.2	1.3	19.9	3.74
Total Small	26.0	3.3	24.4	14.0	23.01
Total Medium	30.1	47.4	31.3	18.9	29.64
Total Upper Medium	42.3	0.0	39.3	0.0	34.14
Total Sports	0.0	20.4	1.4	10.5	2.63
Total Luxury	1.4	8.9	2.0	7.7	2.72
Total Upper Luxury	0.3	1.7	0.4	29.0	4.14
Total Percentages	100	100	100	100	100.00

Source: AIA 1988; PAXUS Australia Pty Ltd, Bulletin - New Motor Vehicle Registrations, 1988.

Table 2.3 shows that over 81 percent of all vehicles locally produced in Australia are medium and large class vehicles.

All vehicles locally produced are powered by petrol engines.

TABLE 2.3(B): ESTIMATED PROPORTION OF PMVs BY CLASS AND STATUS OF PRODUCTION, 1988

	Percentage of Total Sales				
	Product Plan Manufacturers				
	Locally Produced	Imported	Total	Other Imported	All PMV
Total Mini	0.0	1.1	1.1	2.6	3.7
Total Small	21.0	0.2	21.2	1.8	23.0
Total Medium	24.3	2.9	27.1	2.5	29.6
Total Upper Medium	34.1	0.0	34.1	.0	34.1
Total Sports	0.0	1.2	1.2	1.4	2.6
Total Luxury	1.2	0.5	1.7	1.0	2.7
Total Upper Luxury	0.2	0.1	0.3	3.8	4.1
Total Percentages	80.7	6.1	86.8	13.2	100.0

Source: AIA 1988; PAXUS Australia Pty Ltd, Bulletin - New Motor Vehicle Registrations, 1988.

3. VEHICLES NOT NOW SOLD IN AUSTRALIA

There are a large number of makes and models sold overseas which do not appear in the Australian market. These range from vehicles from European bloc countries which are not available outside those countries to "world cars" which, albeit very similar to cars sold in Australia, are sold in other countries under different names to the name used in Australia.

These vehicles are of interest to this Study, because of the possibility for inter-country comparisons of fuel economy discussed under WP4, and the potential for import of other passenger car types if Government intervention in Australia results in further distortion of the automobile market (present distortions are discussed under WP4).

It was noted that high fuel economy models such as the Geo Metro XFi and Honda CRX-HF are not available in Australia, possibly due to limited demand - after all, WP3 suggests that fuel economy is not greatly valued either by purchasers of new motor vehicles or by manufacturers.

The commentary below does not purport to address all types of vehicles which might be available in all countries. However, it also summarises what is known about prototypes and concept cars which might be developed to market condition by 2005.

3.1 VEHICLES APPEARING IN OVERSEAS MARKETS

Working Paper 4 identifies a range of vehicles sold in Australia which have close equivalents in overseas markets. The purpose there is to compare fuel consumption of vehicles sold in Australia with that for equivalent vehicles from overseas markets.

3.2 PROTOTYPE AND CONCEPT VEHICLES

There are at least eight manufacturers in the world who have built and/or tested prototype models using petrol or diesel engines.

Table 3.1 lists a number of prototype vehicles discussed by IEA (1991), which incorporate many of the technological improvements being considered by this Study.

The most advanced is the Toyota AXV which has a fuel consumption of 2.4 l/100km. on the assumed test basis.

Although it is clear that the technology exists to produce vehicles with far lower fuel consumption than existing vehicles, there are some points to be made about their acceptability in the market place.

TABLE 3.1: KNOWN PROTOTYPE AND CONCEPT VEHICLES AVAILABLE OVERSEAS

COMPANY	GENERAL MOTORS	BRITISH LEYLAND	VOLKSWAGEN	VOLKSWAGEN	VOLVO	RENAULT	RENAULT	PEUGEOT	PEUGEOT	FORD	TOYOTA
MODEL	TPC (gasoline)	ECV-3 (gasoline)	AUTO 2000 (diesel)	VW-E80 (diesel)	LCP 2000 (diesel)	EVE+ (diesel)	VESTA2 (gasoline)	VERA+ (diesel)	ECO 2000 (gasoline)	- (diesel)	AXV (diesel)
Number of Passengers	2	4-5	4-5	4	2-4	4-5	2-4	4-5	4	4-5	4-5
Aerodynamic Drag Co-efficient	.31	.24-.25	.25	.35	.25-.28	.225	.186	.22	.21	.40	.26
Curb Weight (kg)	472	662	778	698	705	853	475	780	458	850	649
Maximum Power (hp)	38	72	53	51	52,88	50	27	50	28	40	56
Fuel Economy (L/100km)	3.9 city	5.9 city	3.8 city	3.2 city	3.8 city	3.4 city	3.0 city	4.2 city	3.5 city	4.1 city	2.6 city
Innovative Features	Aluminium body and engine.	High use of aluminium and plastics.	DI with plastic and aluminium parts, fly-wheel stop-start.	Modified DI 3-cyl. Polo, fly-wheel stop-start supercharger.	High magnesium use; 2 DI engines developed, 1 heat insulated.	Supercharged DI with stop-start.	High use of light material.	DI engine high use of light material.	2-cylinder engine, high use of light material.	DI engine	Weight is 15% plastic, 4% aluminium, has CVT and DI engine.
Development Status	Prototype complete, no production plans.	Prototype complete.	Prototype complete.	Ongoing research, possibility of production.	Prototype complete, adaptable to production.	Prototype complete.	Programme completed.	Ongoing development.	Ongoing development.	Research	Ongoing development.

Source: Based on Johansson and Williams, 1987, Bleviss, 1988 and Delaey, 1990.

Note: CI = Direct Injection. HHwy = Highway CVT = Continuously Variable Transmission

For example, many concept cars are defined so that fuel economy is the only goal. When designing such vehicles, engineers typically do not concentrate on matters such as drivability, ride quality, and so on. In particular, there is commonly no attempt to ensure that such cars meet emission and safety standards; rather, the vehicle represents a design exercise or demonstration project whose aim is simply to evaluate the potential for technological gains in fuel economy (or some other objective).

Major constraints to their introduction are linked to economic factors and purchasers' preferences. For example, the Volvo LCP 2000 has rear seats which face backwards, in order to maximise interior space. It also uses lightweight materials including polymer alloy, glassfibre plastics, magnesium engine and transmission housings, and so on. Such advanced materials have a disadvantage in that the manufacturing techniques for mass production have not yet been established.

The question of advanced materials gives rise to the need for an holistic assessment of energy consumed by the manufacture, use and recycling of a vehicle throughout its life. Many of these advanced materials are very consuming of energy in the production phase. Typically the production energy is highest for steel parts, and the recycling credit is highest for aluminium. Introducing polymers into cars can save energy, resources and reduce environmental loads (Krummenacher:1991). This question is a research study in itself and was not addressed further in this Study, largely because the materials are unlikely to be found in production cars in Australia before 2005.

When considering claims for fuel economy from prototype cars, care should be taken to ensure that the test procedures used as the basis of the claim are consistent with those used in Australia. The question of testing is discussed in WP7, and has emerged as a significant issue for the Study. For example, the Peugeot ECO is assessed on a constant speed test (we do not have the details of this).

An OECD/IEA expert panel in 1990 noted that concept cars and prototypes were yet to give rise to the development and production of highly efficient vehicles based on those experiments. This situation has not changed substantively.

However, it is not the intention here to be too negative. The Volvo LCP 2000 is an operational prototype which has passed stringent crash and emissions testing and still achieved 3.6 l/100km. (Plastics News:1984).

Again, Brogan and Venkateswaran (1991, p.11) suggest that:

> "...the two-stroke SI engine, battery powered electric vehicles (EV)...could appear...in..5 years or less...In 5-10 years EVs with advanced batteries might appear, perhaps in some hybrid configuration. In..10 years...gas turbine powered vehicles appear possible."

3.2.1 Conclusion

On balance, it was concluded that the barriers to introduction of advanced technologies other than those discussed in WP2 should not be discounted, especially when one considers the size of the Australian market.

It was also concluded that while technology can provide benefits, it cannot be used to attain the 100 MPG (2.5 l/100 km) that some prototypes have demonstrated without additional addressing of consumer requirements.

4. AVAILABLE TECHNICAL OPTIONS

The car has been in existence for 100 years and is a mature technology; future improvements are largely evolutionary and the individual impact of most technical options on fuel economy is small.

A number of studies in recent years have examined the potential for fuel economy improvements using new technology options for new passenger vehicles. In particular, conferences at Rome (1990) and Berlin (1991) under sponsorship of the OECD and the IEA provide summary information which has provided a point of departure for this Study. Refer Bibliography and WP5.

It is to be noted however, that there are at present no technical options available for gasoline and diesel powered vehicles which will reduce CO_2 emissions (Beger:1991).

4.1 TECHNOLOGY CURRENTLY AVAILABLE

Discussions with Australian Plan Producers provided information on which to update for Australia, EEA's knowledge of manufacturers' global strategies and the status of technical development in passenger cars sold overseas.

Table 4.1 summarises the penetration into the existing fleet at 1990, of a number of technologies which are relevant to the developing outlook for fuel economy in passenger cars sold in Australia through to 2005.

The mechanical details of the technologies listed in the Table are discussed in WP2 and the literature.

4.2 TECHNICAL OPTIONS FOR FUEL ECONOMY IN AUSTRALIA

Forecasts of new car fuel economy are based on potential technological improvements to cars combined with increased consumer demand for highly efficient and clean automobiles. This is a powerful combination which could lead to important gains in fuel efficiency in Australia.

Automotive technology for piston engines is considered mature, and future technological improvements are conceptually well understood. In addition, the long lead time from technology concept to product allow a reasonable forecast of technology that can be commercialised by 2005. Finally, the growing internationalisation of the automotive industry suggests that technologies commercialised in major automotive markets such as the U.S. or Japan will be available in Australia within a year or two of their introduction anywhere else.

The EEA methodology utilises these concepts to forecast technologically based improvements to vehicles and their resultant fuel economy.

TABLE 4.1: 1990 TECHNOLOGY PENETRATION BY MARKET CLASS

	Mini	Small	Medium	Upper Medium	Sports	Luxury
Front Wheel Drive	100	100	100	0	100	13
Drag Reduction (C_D <0.34)	70	35	20	55	77	23
M-5 Transmission	80	60	30	10	75	10
A-4 Transmission	5	5	70	90	25	90
(Total Auto Transmission)	(20)	(40)	(70)	(90)	(25)	(90)
Torque Converter Lock-Up	5	20	70	90	20	90
Electronic Trans. Control	0	5	35	0	0	18
Overhead Cam Engine	100	100	100	45	100	85
Roller Cam Followers	0	6	2	55	0	4
Low Friction Pistons/Rings	0	5	50	100	10	45
4-valve/cylinder	22	62	36	0	100	34
3-valve/cylinder	0	7	19	0	0	0
Central Fuel Injection	0	12	0	25	0	0
Multipoint Fuel Injection	40	36	80	75	100	100
10W-30 Oil	0	0	0	0	0	0
Accessory Improvements	0	0	0	0	0	0

Source: Automobile manufacturer specifications.

Broadly, opportunities for improved fuel consumption can be addressed in five areas:

- o reduction of weight and aerodynamic resistance in bodywork;
- o incremental development of fuel efficiency in engines, especially through increasing use of electronic engine management systems;
- o improved efficiency in the drive train through transmission design changes (especially more gear steps), improved lubrication, tyre resistance, and so on;
- o reduced energy consumption by essential accessories, such as water pump, generator, etc.;
- o reduced weight and energy consumption by optional extras, such as air conditioning, sound systems, luxury appointments, etc.

WP2 summarises the status of technology development in overseas markets relevant to options for this Study, and WP5 summarises the EEA interpretation of the results of a Conference it attended in Berlin during the course of the Study. There is a wide body of other literature about new inventions, prototypes and practices which aim to develop fuel economy in gasoline and diesel powered passenger cars (e.g. Bleviss:1988).

Each technical option has its own technical, economic or environmental advantages or disadvantages; potential market niches and time horizon.

A summary of the new technologies being referenced in this Study is provided in Table 4.2. More detail is provided in WP2.

The reference assumes that all manufacturers will have access to and may utilise all available and applicable technologies in their vehicles by 2005. In this context, the term "available" refers to technologies that are already in production in at least one model in the world in 1991. (There is one exception, the two-stroke engine, which is discussed further below and in WP2). The term "applicable" is used to signify that some technologies are specific to a market class and cannot be applied to all classes. For example, the Continuously Variable Transmission (CVT) is torque limited and is applied only to small and mini car classes.

A possibly controversial aspect of this outlook (which applies both to the Product Plan and the Maximum Technology Scenario) is associated with the modified (Sarich) 2-stroke engine, the only technology not in production today. However, this engine has demonstrated significant fuel economy benefits while attaining U.S. 1994 standards on cars up to 3000 lb (1361 kg) test weight, i.e., small and mini cars. These demonstrations include a claim of 3.8 l/100km for an 2-stroke engine fitted to a Honda CRX HF body (AFR:24/5/91.p.23).

Plants are being established in the US to manufacture the engine for light marine and stationary applications. In addition, licensing arrangements are in place with a number of global manufacturers. Nominally therefore, modified 2-stroke engines should be available in Australia towards the end of this decade.

Even if actual engines were manufactured overseas, it may be that existing or slightly modified arrangements can be identified under the Car Plan to allow Plan Producers to "count" Sarich engines under the export credit rules.

Penetration levels in 2005 as estimated for the 2-stroke under the Product Plan and the Maximum Technology Scenario were approximated on the basis of market share of Plan Producers in the small (and in the future, the mini-car) class, as well as in the lower trim level versions of medium class, for the Maximum Technology Scenario.

TABLE 4.2: TECHNOLOGY DESCRIPTION

BODY

Drag Reduction I (C_D from 0.37 to 0.32/0.33)	Accomplished by restyling and attention to detail; several Australian models already are $C_D = 0.32/0.33$.
Drag Reduction II (C_D from 0.32 to 0.29)	Advanced body design. Requires flush fitting glass windows, improved assembly techniques to minimise gaps in the body.
Weight Reduction Material Substitution	Extensive use of plastics; Sheet Moulding Compound for hood and deck lid, Injection moulding for fenders and fascias. Aluminium in some structural parts and wheels (Engine related weight reduction accounted for separately).
Front-Wheel Drive	Conversion of rear-wheel drive cars to front-wheel drive while maintaining constant passenger and luggage room. Transverse engine allows improved packaging and reduced exterior size; weight reduction also associated with elimination of propeller shaft, differential and rear axle.

ENGINES

Low Friction Pistons/Rings	Use of better piston designs, low tension rings and improved quality control.
Roller Cam Followers	Use of roller bearing for the cam control surface instead of a sliding contact.
Advanced Friction Reduction	Low mass squeeze cast aluminium pistons, lightweight valves and titanium springs, improved control of bore and piston dimensions.
4-Valve/cylinder	Replaced 2 valve/cylinder OHC engine of equal performance. Improved thermodynamic efficiency due to compact combustion chamber, central spark plug and higher compression ratio. Reduced pumping loss due to reduced displacement and larger valve area.

TABLE 4.2: TECHNOLOGY DESCRIPTION - Continued

Variable Valve Control	Varies intake valve timing and lift to match engine RPM and load requirement. Reduces pumping loss.
Two-Stroke Engine	Advanced engine as pioneered by Orbital, with direct injection stratified charge combustion system.
Central Fuel Injection	Replaces carburettor. Improved fuel atomisation and reduced cold start fuel consumption. Eliminates use of air pump to most U.S. 1983 emission standards.
Multi Point Fuel Injection	Uses one injector per cylinder. Allows more precise fuel metering, use of deceleration fuel shutoff and tuned intake manifold with long runners to maximise torque.
TRANSMISSION	
Torque Converter Lock-up	Eliminates slippage in the hydraulic torque converter used with automatic transmissions by means of a rigid mechanical link.
Four Speed Automatic	Replaces three speed automatic with an additional overdrive gear. This reduces engine RPM at highway speeds, decreasing both friction and pumping loss.
5-Speed automatic/ 6-speed manual	Adds an extra gear. More gears allows the engine to operate closer to the best fuel economy point at any vehicle speed and load.
Continuously Variable Transmission	Logical extension of more gears to an infinite selection. Current designs are torque limited and can be used in small cars only.
Electronic Transmission Control	Integrates engine operating information with vehicle speed information to select optimum gear for best fuel economy. Also engages torque converter lockup to minimise slippage.

TABLE 4.2: TECHNOLOGY DESCRIPTION - Continued

OTHER

10W-30 Oil	Replaces current 20W-40, reduced viscosity results in lower friction loss.
Improved Tyres I/II	Evolutionary improvements to tyres. Rolling resistance reduced by improved tread/shoulder design and better rubber compounds for lower hysteresis loss.
Accessory Improvements	Evolutionary improvements to alternator, oil pump, water pump, fan drive and power steering pump.
Electric Power Steering	Replaces hydraulic power steering where considerable energy is wasted in maintaining hydraulic pressure. Large electric power demand may limit technology to small and medium cars.

Note that the reference also includes the increased use of multivalve engines. This latter reflects a broad finding is that for passenger cars, the conventional Otto cycle gasoline powered engine is continually undergoing improvements and remains a formidable competitor to advanced alternatives (Brogan and Venkateswaran:1991,p.2).

However, the technology options with the greatest impacts on fuel economy are:

- two stroke engines, which can deliver 14 percent benefit over 1990 2-valve OHC engines;
- 4-valve engines with variable valve timing, which produce about 9 percent benefit over 2-valve OHC engines;
- weight reduction, which delivers a 6.6 percent benefit over a base 1990 car.

Of course, diesel engines have advantages for fuel economy also, as discussed in WP2. However, there is an offsetting effect due to energy losses in refining, which was assessed in WP7 as about 5 percent. Diesel engines are more expensive than gasoline engines, also.

The fuel economy benefit over a 1990 base diesel engine at a given level of performance are as follows:

o	Prechamber diesel	18 to 20 percent;
o	Turbocharged prechamber diesel	28 to 30 percent;
o	Turbocharged direct injection diesel	40 to 45 percent.

Of these, the direct injection diesel may have greater difficulty with future NO_x emission standards, as well as noise and vibration control.

The global strategies of individual manufacturers typically pursue multiple options based on short and long term priorities set by governments and consumers in country markets; resources and profitability available in those markets, and the size of each country market. These fundamentals can be influenced in part between countries by government intervention which varies the attractiveness of one or other particular courses of action during product development.

Taxation on imports, purchase and use of passenger cars; emission controls set by the ADRs and manufacturing incentives provided via the Car Plan are the instruments which impose Australian variations on manufacturers' global strategies.

4.3 DEVELOPMENT OF TECHNICAL SCENARIOS

The EEA methodology relies on starting from a known baseline of vehicle technological characteristics and fuel economy based on actual vehicle specifications in year 1990.

It then utilises technological improvements from the baseline vehicle to improve fuel economy, while holding vehicle size, as defined by interior volume, and vehicle performance, as defined by the power to weight and torque-to-weight ratios, constant at baseline levels.

Of course, the Study was aware that historically, car size and performance have not been held constant but are increasing in response to consumer demand and competitive pressure. The technologically based forecasts can be readily adjusted to capture the effect of size (weight) increases as well as performance (engine output) increases. Similar adjustments are made to capture the effects of new safety standards (which increase weight) or emission standards (which decrease engine efficiency) that may be imposed in the future.

One issue unique to the Australian market has surfaced from detailed comparisons of vehicle fuel economy in the U.S. and Australia. Both countries utilise identical test procedures to measure fuel economy, but comparison of the same model cars with identical engines and transmissions revealed U.S. models to be 10 to 20 percent more efficient in a large number of cases. This issue is explored in WP4.

The EEA methodology can be applied to individual vehicle models that are defined as a specific model name/body style/engine/transmission/power output combination. However, there is a very large number of such combinations available in the Australian market and time and resource constraints did not permit an analysis at this level of detail. Instead, the car models were aggregated into "market classes" where vehicles in each class were approximately similar in consumer perceived attributes of size, price and performance.

Within a market class, vehicles can be expected to have similar potential for technological improvement, while competitive pressures would assure similar effects on retail price within a class.

The forecast is provided for two scenarios, identified as the "Product Plan" and "Maximum Technology" Scenario.

Based on the detailed technical specifications of each model, and the sales mix, a technological profile of each market class can be constructed. This information would normally include the details of the penetration of each model/engine/transmission combination, which is available in manufacturers' annual CAFC calculations.

However, these were not made available to the Study and in their absence forecasting proceeded on the basis of estimated penetration of manual vs. automatic transmissions by class, as well as the penetration of "performance engine" options, from limited published data as well as from anecdotal information obtained at meetings with the manufacturers.

4.4 PRODUCT PLAN SCENARIO

The Product Plan scenario provides the baseline for the Study. It assumes that there is no regulatory pressure on the manufacturers to improve fuel economy, but competitive pressures and the evolution of technology will cause fuel economy to increase regardless.

At the same time, the size of some vehicles and the performance of some vehicles will increase, based on available data on manufacturer product plans for the next five years.

However, the Product Plan involves no move to recalibrate test facilities, engines or transmission management systems to attain fuel consumption equivalence with similar vehicles sold overseas. This issue is discussed further in WP4.

The Product Plan scenario shows increased market penetration of those technologies which are partially in the market today; refer Table 4.1. It also envisages partial penetration of a selection of new technologies, as listed in Table 4.3 for year 2005.

For model year 1995, now only about 3 years away, there is no time to incorporate any significant changes in technology beyond what is already planned.

Increases in size and performance of vehicles are expected principally in the small and medium market classes. The new Ford Laser/Mazda 323 models are somewhat larger and offer a higher performance level than the previous models.

New models in the class are expected to continue the trend, with average engine size increasing 5 percent and weight increasing 5 percent over the next five years. Similarly in the mid-size class, Mitsubishi has already introduced a new (for 1991) Magna that is longer and wider and weighs nearly 10 percent (120 kg) more than its predecessor.

This may be an unusually large weight increase, as we expect other models to increase by 60 kg only. For example, Toyota is expected to bring out a bigger Camry later in 1991.

Engine output is expected to be in the range 85kw to 94kw by 1995 for this group of cars.

For both small and medium classes, a phase-out of carburettors and 3-speed automatics is anticipated, replaced by fuel injection and 4-speed automatics.

The upper-medium class is not expected to have any new models as both Ford and Holden have an 8-year product cycle and the Falcon and Commodore are relatively new. In the mini-car class, we expect a host of new models starting with the Daihatsu Mira and Mazda 121 in 1991. It is possible that Honda, Ford and Nissan may introduce their City, Festiva and Micra models if the market class shows growth over the next few years. Average size and horsepower are not expected to change significantly for this class.

TABLE 4.3: PENETRATION OF TECHNICAL OPTIONS INTO PRODUCT PLAN SCENARIO AT 2005

Technology	**Product Plan**
Weight Reduction	5 percent for all cars except for Holden and Commodore
Drag Reduction	$C_D = 0.30 \sim 0.31$
2-stroke engines	In 20% of mini and small classes
4-valve engines	In all other vehicles except V-8, some mini
CVT (replacing automatic transmission)	In 10% of mini, small and 20 percent of medium
5-speed auto transmission	In 50% of upper medium and luxury
Variable valve timing	In 50% of 4-valve engine rated over 75 kw
Advanced engine friction reduction	In all engines
Electric Power Steering	Replaces 50 percent of power steering in mini and small cars
Improved Tires	In all cars

Typically, lead time considerations require the manufacturers to set product specification for models according to a five year rolling programme; i.e. at 1991/92 specifications will be set through 1996/1997.

Some of these specifications involve increasing the size of new models relative to a current model that will be replaced, as well as increasing the performance of some vehicles. Manufacturer product plans to 1996/97 can be tracked through articles in the automotive trade press.

Beyond 1997, EEA has assessed likely product plans based on the available technologies being "cost effective" to the consumer. In this context, cost effectiveness was based on the value of fuel saved relative to the increased price of the car due to technology adoption. EEA also assumed that the current rate of increased demand for size and performance cannot continue indefinitely and will plateau in 1996/97. (This assumption may not hold true if fuel prices are low and consumers become more affluent). Prospects for policy action to assure the performance assumption are discussed in WP 3.

No specific scenario was incorporated for 2000, but an intermediate forecast point representing the complete penetration of all technologies listed in Table 4.2 was utilised. The exact timing of this is not of issue as most of the penetration will take place by 1998 and the last few percent by 2005. Rather, the analysis focused on 2005 using the intermediate forecast point as the starting point for a number of technologies to be utilised in the 1998-2005 time frame.

4.5 MAXIMUM TECHNOLOGY SCENARIO

The "Maximum Technology Scenario" envisages a quantum improvement on Product Plan fuel economy being achieved by Australian manufacturers and importers, due to deep application of the known technologies described in Section 4.2.

All of the technologies described therein will probably be widely available world-wide so that Australian manufacturers should have no specific problem in accessing the technologies required.

Although the Maximum Technology Scenario references the same technologies as the Product Plan Scenario, it differs in several important ways:

- it assumes that manufacturers calibrate their cars to be as fuel efficient as their U.S. counterparts at equal weight and performance levels (i.e. no reduction of axle ratios or engine size from expected 1995 levels is assumed);
- there is an increased level of weight and drag reduction;
- it involves near complete use of either 2-stroke engines in mini and small cars or a 4-valve engine with variable valve timing in the other classes;
- similar differences for advanced transmissions.

The vision for the Maximum Technology Scenario at 2005 is provided at Table 4.4.

It is emphasised that the maximum technology scenario

- requires all manufacturers to redesign all products to the highest level of fuel efficiency;

- incorporates technologies such as advanced weight reduction and variable valve timing in all cars regardless of cost effectiveness to the consumers;
- does not consider the financial ability of local Australian industry to undertake the extensive product changes required.

As a result, we would caution that the scenario outlook must be understood in the appropriate context.

However, the Maximum Technology Scenario retains lead time limitations. As discussed in Section 4.2, manufacturers' production specifications have been formulated to 1996/1997 and therefore there is no technological difference between the Product Plan and Maximum Technology scenarios for 1995. The two scenarios diverge technologically in 2000 and 2005.

TABLE 4.4: PENETRATION OF TECHNICAL OPTIONS INTO MAXIMUM TECHNOLOGY SCENARIO AT 2005

Technology	Maximum Technology Scenario
Weight Reduction	10 percent for all cars; 5 percent for Holden Commodore
Drag Reduction	C_D = 0-.28 - 0.29
2-stroke engines	In 80% of mini and small and 40% of medium
4-valve engines	In all other vehicles
CVT (replacing automatic transmission)	In all mini, small and 30 percent of medium
5-speed auto transmission	In all upper medium, luxury and 40 percent of medium
Variable valve timing	In all 4-valve engines rated over 75 kw
Advanced engine friction reduction	In all engines
Electric Power Steering	Replaces all power steering in mini and small cars.
Improved Tires	In all cars

4.6 IMPACT OF ANTICIPATED SAFETY AND EMISSIONS CONTROLS

The Product Plan and Maximum Technology Scenarios considered above do not include the effect of new safety or emission regulations that may be imposed in Australia over the next 15 years.

Emissions controls imposed by ADR 37 are understood to have resulted in higher fuel consumption, while any safety measures which require greater weight (safety equipment) or friction (tyres) have similar consequences.

It was therefore decided to base a forecast for the purposes of the Study on the basis of:

- the current policy in the FORS to harmonise Australia's compliance requirements with overseas standards;
- recent studies completed by the FORS in the area of occupant protection;
- past experience of Australia's practice of adopting overseas (particularly US) standards a number of years after they are promulgated in the host country.

Emissions

In Australia, the present ADR 37 conforms to the US 1976 standard. Currently, cars sold in Australia meet the existing standards by a wide margin and this is likely to continue into the 1990s. It is understood that the automotive industry intends to voluntarily upgrade the emissions performance of passenger motor vehicles to conform to the 1980 US Standard.

Now some would argue that Australia could if desired, adopt standards lower than some others because our cities do not suffer the same climatic conditions that apply in (say) Los Angeles, where air pollution is of great concern. Only occasionally does air pollutant concentrations in Sydney or Melbourne reach levels which exceed WHO standards.

There is convincing evidence that cars equipped with a 3-way catalyst are less fuel efficient that the equivalent non-catalyst version(s), by an average of up to perhaps 4 percent (Hickman and Waters:1991,p.7). Similarly, emissions controls over diesel engines brings with it fuel consumption penalties.

For petrol engines, the position is exacerbated by lack of maintenance, because the successful operation of a 3-way catalyst depends on the composition of exhaust gases: if the exhaust contains excess oxygen, the catalyst will not promote the reduction of NO_x; and if it contains too much, it will not oxidise the CO and HC components.

In an onroad situation, the catalytic converter can and does get fouled, and subsequently the car may be less fuel efficient than if the converter had never been fitted in the first place.
Thus there is are potential economies for Australia not to press unnecessarily for more stringent emissions standards, because lower NO_x emissions standards provides a window for improved fuel economy, and perhaps lower CO_2 emissions, that is not available in countries with less forgiving climates.

However, the political climate is for continual increases to stringency of emission standards, and hence steadily increases to fuel consumption penalties.

For example, recent revisions to the Clean Air Act in the U.S.

has now resulted in new regulatory initiatives for 1994. The standards that will be imposed in 1994 are 0.25 HC/3.4CO/0.4 NOx g/mile as opposed to the 1983 levels of 0.41/3.4/1.0. The 1994 standards for the U.S. 49-states are already being phased-in California, and a detailed comparison of California vs. Federal cars suggests a small (1 percent or less) change in fuel economy due to these standards.

California is believed to be contemplating very stringent emissions standards, with zero being contemplated (i.e. electric cars). However, the California situation would appear to be a special case from the point of view of this Study.

It is also necessary to recognise the high correlation between fuel consumption and CO_2 emissions. CAFE standards such as in the US, or weight based emissions standards such as in Japan, both contribute to improved fuel economy and reduced greenhouse emissions. The question is - what are the overall social costs of these desirable outcomes.

At present, there is considerable debate in the US about mandatory fuel consumption standards for the late 1990s, and the outcome is still uncertain. The debate about CAFE standards is discussed in WP6.

From a viewpoint of fuel consumption under acceptable emissions criteria, the two biggest technology opportunities are with the diesel and the two-stroke, as these have difficulty with future (but not current) US emission standards.

However, any debate about this issue in Australia may be irrelevant. Because of the propensity for manufacturers to design their cars for overseas standards, Australia gets the higher control mechanisms anyway.

Accordingly, the Study recognised that detailed analysis by the U.S. EPA has shown that the three-way catalyst/closed-loop fuel control system can meet the US 1994 standards with no fuel economy penalty. In fact, many Australian cars already employ this system (although catalyst loading of precious metals may be lower in Australia than the U.S.) and certify at emission levels that are almost equivalent to U.S. 1983 standards.

As discussed in WP3, the cost in fuel consumption terms of adopting US 1994 standards is small.

Occupant Safety

The Federal Office of Road Safety commissioned a major review of internal occupant protection by the Monash University Accident Research Centre in 1989. The first stage of this work relating to frontal crashes has been released. Further work has been commissioned to look at side impacts and rollovers which should be finalised by the end of 1992.

The current review of passenger vehicle occupant protection by the Standing Committee on Transport (SCOT) Working Party will examine recommendations in the Monash report to improve occupant safety. Some of these include: better restraint geometry, pretensioners, webbing clamps, more forgiving steering assemblies, improved padding, better protection for lower limbs and inflatable devices.

A barrier crash program and cost benefit study are being conducted to establish the most effective means of achieving these improvements.

However, all these items involve a weight penalty to some degree. Any move to changes in side impact and rollover protection will add further weight, estimated at between 30 and 40Kg if all measures are implemented.

Conclusion

In the past, it has been shown that a tradeoff exists between fuel economy of motor vehicles and regulation of motor vehicle manufacture and use in the interests of safety and environmental protection, especially emissions controls.

On the basis of the above and discussion with the Project Manager, it was decided that the Product Plan and Maximum Technology Scenarios would both include by 2005 emissions controls and occupant safety gear equivalent to US 1994 standards.

The Study adopted these for target years 2000 and 2005.

If Australia adopts all of the US 1994 requirements, weight could increase by at least 30 to 40 kg. This will result in a fuel economy penalty of 2 percent.

The microscopic detail of changes made by the States to local speed limits, delays induced by traffic control devices, random breath testing and so on will not be addressed.

5. PROJECTIONS FOR FUEL ECONOMY TO 2005

This Section provides an estimate of the outlook for NAFC to 2005 under the Product Plan and the Maximum Technology Scenario, including estimates of fuel consumption by target year and class of vehicle.

The forecasts of fuel economy by market class are dependent on the estimates utilised for the fuel economy potential of each technology, the potential for synergy between technologies and constraints on additivity of economy between different technologies in the same vehicle. These data are at the heart of the forecast, and WP2 provides further detail about the technologies, their benefits and synergies.

The forecasts of NAFC by target year are dependent on estimates by target year and class as above, plus the assumed product mix in each target year.

In this Section, the NAFC estimates are focussed firstly on the product mix at 1988, which is the base year for estimates of vehicle registration and transport task throughout the Study; and secondly on the product mix for 1990, which is the point of departure for vehicle specification, estimates of technological development and predictions of fuel consumption by target year and class.

Table 5.1 summarises the downsizing which has occurred between 1988 and 1990.

TABLE 5.1: VEHICLE MIX BY CLASS FOR 1988 AND 1990

	Percent of Total	
	1988	1990
Mini	3.7	6.2
Small	23.0	27.2
Medium	29.6	25.9
Upper Medium	34.1	30.3
Sports	2.6	3.5
Luxury	2.7	3.6
Upper Luxury	4.1	3.4
Total	100	100

5.1 NAFC REDUCTIONS UNDER THE PRODUCT PLAN

The Product Plan envisages fuel consumption by vehicle class and target year as shown in Table 5.2. It should be noted that the class specific fuel consumption estimates are based on forecasting technical development from a 1990 technology base.

TABLE 5.2: ADOPTED FUEL CONSUMPTION (1/100km) BY TARGET YEAR AND VEHICLE CLASS - PRODUCT PLAN 1995-2005

Class	1990	1995	2000	2005
Mini	6.40	6.26	5.84	5.42
Small	7.70	7.41	6.89	6.39
Medium	9.00	8.88	8.30	7.72
Upper-medium	10.60	10.45	9.70	9.14
Sports	8.20	7.97	7.54	7.11
Luxury	10.20	9.73	9.07	8.40
Upper Luxury*	10.90	10.50	9.78	9.06

Note: Table does not include effect of new emission/safety standards that may be imposed beyond 1995.

* Not calculated but assumed to follow same trend as for luxury class.

The sales mix at 1988 (Table 5.1) was applied to the results of Table 5.2, in an attempt to match the FCAI NAFC figure of 9.16 1/100km for 1988.

As shown by Table 5.3, a result of 9.21 in 1988 and 7.87 at 2005 was obtained, assuming no change to the mix of vehicles. It was considered that the correspondence was sufficiently close to be used as a base for forecasting NAFC into future years under different product mixes.

TABLE 5.3: NAFC CALCULATIONS FOR THE PRODUCT PLAN AND MAXIMUM TECHNOLOGY SCENARIO FOR 1988 AND 1990 MIX OF VEHICLES

(litres/100 kms)

Mix of Vehicle Classes	Year	Product Plan	Maximum Technology	Applying Emissions Standards	
				Product Plan	Maximum Technology
1988 Mix	1988	9.21	9.21		
	1990	9.24	9.24		
	1995	9.05	8.17		
	2000	8.42	7.27	8.67	7.48
	2005	7.87	6.37	8.10	6.56
1990 Mix	1988	9.21	9.21		
	1990	9.05	9.05		
	1995	8.85	8.01		
	2000	8.24	7.13	8.48	7.34
	2005	7.69	6.25	7.92	6.43

The figure of 7.87 l/100km corresponds with the FCAI forecast of 8.0 l/100km at 2005. The lower fuel consumption for years 1988 and 2005 obtained by the Study can be explained in part by the fact that the Study forecast is on a 1990 technology base whereas the FCAI forecast is from a 1988 technology base.

A point made by the FCAI was that future NAFC could reduce if the mix of vehicle classes showed a downsizing of the fleet over the period to 2005. As shown by Table 5.1, there was a downsizing of the new vehicles purchased since 1988. The small and mini classes increased their market share by 4.2 and 2.5 percent respectively.

Table 5.3 also estimates NAFC assuming a 1990 product mix. 1990 NAFC is estimated at 9.05 l/100km, and the predicted 2005 figure is 7.69 l/100km by 2005, assuming the 1990 mix continues through the planning period. The FCAI figure for 1990 was not published at the time of writing this WP.

Comparisons as detailed in Tables 5.1 and 5.3 suggest that a downsizing which increases mini and small class share by only 3 to 4 percent can produce a drop in national fuel consumption of the order of 0.2 l/100km or 2.0 percent on 1988 levels.

5.2 NAFC REDUCTIONS UNDER THE MAXIMUM TECHNOLOGY SCENARIO

The Maximum Technology Scenario envisages fuel consumption by target year and vehicle class as shown in Table 5.4.

TABLE 5.4: ADOPTED FUEL CONSUMPTION (l/100km) BY TARGET YEAR AND VEHICLE CLASS - MAXIMUM TECHNOLOGY SCENARIO 1995-2005

Class	1990	1995	2000	2005
Mini	6.40	5.79	5.13	4.47
Small	7.70	6.80	6.03	5.26
Medium	9.00	8.07	7.21	6.35
Upper-Medium	10.60	9.15	8.15	7.14
Sports	8.20	7.97	7.14	6.37
Luxury	10.20	9.18	8.12	7.06
Upper Luxury*	10.90	9.91	8.77	7.63

Note: Table does not include the effect of new safety/emission standards that may be imposed beyond 1995.
* Not calculated but assumed to follow the same trend as for luxury class.

Referring again to Table 5.3, the NAFC under the Maximum Technology Scenario varies depending on whether 1988 or 1990 product mix is assumed. If the 1988 mix is used, and estimated year 2005 NAFC of 6.37 l/100km is obtained, while the 1990 mix produces an estimated 6.25 l/100km at 2005.

Because 1988 is the baseline for the Study, the discussion henceforth will concentrate on that product mix. However, it should be remembered that the change in product mix up to and beyond 1990 has already produced an approximate 2 percent reduction below the forecasts based on 1988.

At 1995, the estimated NAFC under the Maximum Technology Scenario is 8.17 l/100km, which is 9.3 percent less than the estimated figure under the Product Plan or an estimated 11.6 percent reduction from 1990.

The 9.1 percent difference between the two scenarios at 1995 is wholly attributable to calibration improvements so that Australian vehicles match the U.S. vehicles' fuel economy equivalent.

By 2005, NAFC is reduced to 6.37 l/100 km, a 31 percent decrease from 1990 levels. After the 9 percent improvement due to calibration abovementioned, the remaining 22 percent improvement is understood to be consistent with the expectation of Watson (1991) who has examined specific Australian car models and their scope for improvement.

5.3 NAFC PENALTY FOR ADDITIONAL SAFETY AND EMISSION CONTROLS AT 2000 AND 2005

Based on the estimates of fuel consumption penalty due to additional weight described in Section 4.5, the following fuel consumption penalties for safety and emission controls to US 1994 standards were adopted:

	Percent
Air bags	0.7
Side intrusion/rollover	1.4
1983 US emission standards	0.0
1994 US emission standards	0.8

	2.9

Calculation of NAFC for product plan scenario with emission controls appears in Table 5.3. The adopted fuel consumption for 2000 and 2005 were multiplied by 1.029 to account for safety and emission standards equivalent to US 1994/5 levels. The emission controls increase the NAFC by about 3 percent for all scenarios.

5.3.1 Conclusion

Adjustment of the NAFC projections shown in Table 5.3 to account for US 1994 safety and emissions standards would cause year 2005 fuel consumption to increase from 7.87 to 8.10 l/100km under the Product Plan Scenario, and from 6.37 to 6.56 l/100 km under the

Maximum Technology Scenario (applying 1988 mix).

Assuming that the current downsizing of the fleet persists through to 2005, an NAFC of about 6.5 l/100 km may be the lowest attainable if new emissions and safety legislation are imposed.

6. ACHIEVING NAFC TARGETS THROUGH TECHNOLOGY AND PRODUCT MIX

The Brief requires that an estimate be made of the action required to reduce NAFC to targets of 8, 7, 6, and 5 l/100km at 2005.

As discussed above, it seems clear that technology will provide a path to reduce NAFC to 6.5 l/100km in that year. There are two further options:

- policy action to downsize the fleet;
- placing a cap on acceleration performance and taking part of the existing power of larger and more powerful vehicles in additional fuel economy.

6.1 DOWNSIZING TO ACHIEVE FUEL ECONOMY

During meetings with manufacturers, it was suggested that increasing minicar market share was likely, given their low prices and the entry of a large number of new models. It was estimated that mini car market share could rise to 10 percent or higher, a near doubling of the 6 percent figure applicable to 1990.

At 10 percent market share, NAFC would decrease from 6.25 L/100 km to 6.17 L/100km, assuming that all other classes lost market share proportionally.

Thus to reach a target of 6.0 l/100km, additional pressure will be necessary to encourage/enforce downsizing.

6.1.1 Required Product Mix in the Presence/Absence of Additional Safety and Emission Controls

Table 6.1 identifies a mix of classes chosen arbitrarily to illustrate the extent of downsizing necessary to achieve 6.00 l/100km at 2005, both with and without US 1994 safety and emissions controls.

In choosing the arbitrary mix, it was considered impractical to assume that all luxury vehicles will be eliminated from the fleet, and this guesstimate assumed that a reduction of up to 50 percent penetration in upper luxury and luxury classes would be the maximum achievable.

Once that assumption was made, vehicles were simply moved out of classes to the class above progressively until a NAFC estimate of 6.0 l/100km was obtained.

The Table shows that there is a significant shift of all classes required to achieve 6.0 l/100km, with the mini class share increasing in the order of three times. Refer Section 6.3 for an explanation of the acceleration cap.

TABLE 6.1: EFFECT OF EMISSION AND ACCELERATION STANDARDS ON NAFC BY VEHICLE CLASS FOR MAXIMUM TECHNOLOGY SCENARIO AT 2005

	2005 (1)					
	No Emissions Standards		Emissions Standards			
					Acceleration Cap	
	Percent of Vehicle Class	Litres /100 kms	Percent of Vehicle Class	Litres /100 kms	Percent of Vehicle Class	Litres /100 kms
mini	15.1	4.47	21.1	4.60	20.5	4.60
small	26.8	5.26	26.5	5.41	26.5	5.41
medium	27.3	6.35	28.3	6.53	28.2	6.53
up medium	21.4	7.14	15.5	7.35	16.1	7.27
sports	3.5	6.37	3.5	6.55	3.5	6.49
luxury	3.5	7.06	3.5	7.26	3.5	7.19
upper luxury	2.3	7.63	1.5	7.85	1.6	7.77
Weighted Average	6.00			6.00		6.00

Note: (1) 2005 figure multiplied by 1.029 to account for safety and emission standards equivalent to US 1994/5 levels.

6.2 INTRODUCTION OF DIESEL ENGINES

As discussed in WP2 and Section 4.2, diesel engines can provide enhanced fuel consumption at a penalty of about 5 percent refining loss.

At present, the Australian fleet contains only less than one percent of diesel powered passenger cars, compared with up to 15 percent in some countries of Europe.

To test the effectiveness of encouraging the introduction of diesel engines into the Maximum Technology Scenario (from a fuel economy point of view), an estimate of the class specific fuel consumption was prepared. The estimate assumed an 80 percent penetration of turbocharged prechamber diesel engines into all classes, except sports where this would be inapplicable.

The results summarised in Table 6.2 take into account the fuel consumption both before and after the refinery penalty.

TABLE 6.2: ESTIMATED CLASS SPECIFIC FUEL CONSUMPTION (l/100km) 80 PERCENT DIESEL PENETRATION - MAXIMUM TECHNOLOGY SCENARIO, 2005

Vehicle Class	Refinery Penalty(1)	
	Without	With
Mini	4.02	4.22
Small	4.73	4.97
Medium	5.59	5.87
Upper medium	6.15	6.46
Luxury	6.07	6.37
Upper luxury	6.58	6.91

Note: 1. Factor of 1.05 used to account for refinery penalty.

Comparison between these results (with refinery penalty) and those for 100 percent gasoline engines provided in Table 5.4 under the Maximum Technology Scenario shows that an 80 percent substitution by diesel engines would produce 5.6 percent reduction for mini class vehicles and 9.8 percent reduction for luxury vehicles. A linear interpolation between 0 percent substitution and 80 percent substitution is valid.

For a 15 percent penetration, the saving is only of the order of 1.1 to 1.8 percent, which is considered insignificant.
1
Accordingly, it was concluded that substitution of diesel engines for gasoline engines at any realistic level was not likely to make any significant difference to fuel economy, if the refinery penalty is taken into account.

6.3 PLACE A CAP ON ACCELERATION PERFORMANCE

WP3 considers the nature and type of action necessary to place a cap on acceleration performance. Broadly, it was concluded that a period of 10 seconds was the necessary minimum for cars to accelerate from 0 to 100kph.

It is possible to reduce NAFC by discouraging the acquisition and use of cars with better acceleration performance (i.e. lower period).

The "maximum technology" scenario holds performance near constant at 1990 levels. However, it should be noted that several Australian car classes offer very high levels of performance in "family" cars relative to the U.S., and relative even to 1988 Australian levels.

In particular, the upper-medium category offers two products, the Ford Falcon/Fairmont and the Holden Commodore/Berlina, that offer 0-100 km/hr acceleration times under 8 seconds. Most cars in the small and medium car classes typically have acceleration times of 10 to 11 seconds with a manual transmission, about 0.5 to 0.8 seconds more with an automatic transmission. Automanufacturers have suggested that Australian cars need higher performance level because of the extensive popularity of trailer towing in

Australia.

Typically, a 10 percent increase in power-to-weight ratio results in a 2.5 percent increase in fuel consumption. It appears possible to decrease power-to-weight ratio by 10 percent in all classes except the mini-car class, and an additional 10 percent is possible in the upper-medium and luxury class (for a total of 20 percent). This would place all cars in the acceleration performance range of 10 to 12 seconds for 0-100 km/hr.

A simple calculation shows that this leads to a net 3 percent reduction in NAFC, possibly at some expense to consumer satisfaction.

However, it does represent one way to reduce NAFC to (nearly) 6.0 l/100km (refer Table 6.1) without introducing arbitrary downsizing.

6.4 CONCLUSION

For gasoline powered vehicles, downsizing the fleet is about the only way to reduce NAFC, after all technology factors have been implemented. As shown elsewhere, this will not happen under the Maximum Technology Scenario, by the action of market forces alone.

Substitution of gasoline engines by diesel engines at any realistic penetration (taken to be 15 percent) would produce insignificant gains in fuel economy (less than 2 percent). Placing a cap on acceleration performance offers a potential gain of about 3 percent, while introducing US 1994 emission/safety standards will induce a penalty of about 3 percent.

However, if all technical, substitution and performance possibilities were addressed in pursuit of fuel economy, and emission/safety standards held at the 1983 levels, it may be possible to reach 6.0 l/100km without resort to downsizing.

APPENDIX A

VEHICLE CLASSES BY MAKE, MODEL AND TYPE OF BODY, FOR PMVs SOLD IN 1988 AND 1990.(1) - 1 of 4

Make	Model	Total PMVs 1988	Total PMVs 1990
MINI:			
Diahatsu	Charade	2906	8304
Suzuki	Swift	524	3062
Hyundai	Excel	5327	5788
Holden	Barina	4481	7906
Mazda	121	1845	1785
Lada	1300		896
Fiori			53
Mira			119
FSM	Niki		534
Lada	Cevaro		73
TOTAL MINI		15083	28520
SMALL:			
Holden	Astra	8595	111
Holden	Nova		6378
Holden	Applause		3130
Mitsubishi	Lancer	761	7437
Mitsubishi	Colt	7186	3517
Honda	Civic	4491	5074
Toyota	Corolla/Tercen	23586	30350
Toyota	Corolla 4x4	1170	
Holden	Gemini	52	
Lada	Samara	490	
Ford	Laser	28031	33226
Mazda	323	2482	5953
Nissan	Pulsar/Prairie	16039	27577
Subaru	Leone		3054
Other		2	
TOTAL SMALL		92885	125807

VEHICLE CLASSES BY MAKE, MODEL AND TYPE OF BODY, FOR PMVs SOLD IN 1988 AND 1990.(1) - 2 of 4

		Total PMVs	
Make	Model	1988	1990
MEDIUM:			
Alfa Romeo	33/Sprint	479	
Holden	Apollo/Camira	14702	8760
Toyota	Camry/Corona	30273	31621
Toyota	Camry 6	830	1257
Mitsubishi	Cordia/Nimbus	638	647
Mitsubishi	Cordia Turbo	124	
Mitsubishi	Galant		2301
Fiat	Regata	132	
Ford	Telstar	10679	4563
Ford	Corsair		7632
Mitsubishi	Magna	40518	31808
Mazda	626	3941	7895
Nissan	Pintara	11615	13688
Mitsubishi	Sigma	215	
Honda	Accord	2408	3036
Hyundai	Sonata		1089
Hyundai	Sonata		368
Subaru	Liberty	3090	5221
Other			6
TOTAL MEDIUM		119644	119892
UPPER MEDIUM:			
Holden	Commodore 6	55083	56544
Holden	Commodore 8	2565	7950
Ford	Falcon/Fair't 6	69382	58954
Ford	Falcon/Fair't 8		13
Nissan	Skyline	10778	7701
Toyota	Lexcen		8736
Other		8	2
UPPER MEDIUM		137816	139900
SPORTS CAR:			
Honda	Prelude	3515	1724
Honda	Integra\CRX	1787	2470
Ford	Capri		4413
Toyota	Celica	3097	4872
Toyota	MR2	399	346
Nissan	Gazelle/Exa	1523	844
Mazda	RX7	278	
Mazda	MX5		1446
TOTAL SPORTS CAR:		10599	16115

VEHICLE CLASSES BY MAKE, MODEL AND TYPE OF BODY, FOR PMVs SOLD IN 1988 AND 1990.(1) - 3 of 4

		Total PMVs	
Make	**Model**	**1988**	**1990**
LUXURY:			
Audi	80	25	275
Alfa Romeo	33TI	176	183
Citroen	Bx	104	154
VW	Golf		96
Toyota	Cressida	2176	3498
Ford	Fairlane	4698	5774
Holden	Statesman		2773
Mazda	929	29	
Nissan	Maxima		1546
Peugeot	205	241	70
Peugeot	405		525
Peugeot	SLI/GTI	120	
Rover	416	646	54
Saab	900	857	415
Volvo	240	1874	1048
Volvo	360	19	
Other		18	4
TOTAL LUXURY		10983	16415
UPPPER LUXURY:			
Nissan	300C/300ZX	150	642
Alfa	75/90GTV	305	170
Alfa	164		161
Audi	80SD	145	
Audi	100/200T	139	
Audi	V 8		547
BMW	318i/320i	979	2452
BMW	325E/325i	414	165
BMW	5 series	878	1070
BMW	7 series	486	317
Fiat	Croma	44	
Toyota	Crown	25	
Toyota	Supra	249	95
Toyota	Lexus		248
Jaguar/Daimler		1055	500
Honda	Legend	1412	837
Holden	Caprice		471
Ford	Ltd.	836	748
Mazda	929 6	2227	1515
Mazda	RX 7		127
Mercedes	190s	450	319
Mercedes	230E/TE	562	
Mercedes	300s	531	1604
Mercedes	260E/300E	1222	
Mercedes	420/560	542	
Mercedes	S Class		626

VEHICLE CLASSES BY MAKE, MODEL AND TYPE OF BODY, FOR PMVs SOLD IN 1988 AND 1990.(1) - 4 of 4

		Total PMVs	
Make	**Model**	**1988**	**1990**
Maserati			16
Peugeot	505 S/Wagon	129	96
Rover	825/827	208	143
Porsche		300	322
Renault	21/25	136	3
Saab	900T/9000	1107	883
Volvo	740/760	1960	1531
V W	Cabriolet		11
Ferrari		55	11
Rolls Royce/Bently		56	69
Others		111	158
TOTAL UPPER LUXURY		16713	15857

Source: PAXUS Australia Pty Ltd, Bulletin - New Motor Vehicle Registrations, 1988.

Note: (1) There are no PMV derivatives included in this table.

WORKING PAPER NO. 2

TECHNICAL FEASIBILITY OF INTRODUCING FUEL EFFICIENT TECHNOLOGY

PREPARED FOR:
NELSON ENGLISH, LOXTON AND ANDREWS PTY LTD

PREPARED BY:
ENERGY AND ENVIRONMENTAL ANALYSIS, INC.
1655 NORTH PORT MYER DRIVE, ARLINGTON, VIRGINIA, USA

MARCH, 1991

TABLE OF CONTENTS

PAGE NO.

LIST OF TABLES

LIST OF FIGURES

CONTEXT

Within the context of developing a comprehensive policy response to the Government's planning target to reduce greenhouse gas emission, the Department of Transport and Communications acting in concert with a number of other government agencies commissioned Nelson English, Loxton and Andrews Pty. Ltd. (NELA) to assess the potential to reduce fuel consumption by new passenger cars sold in Australia.

Interim information is being presented to the Steering Committee by way of a series of seven Working Papers as follows:

Working Paper No.	Title
1	Available Options for Fuel Efficient Technology
2	**Technical Feasibility of Introducing Fuel Efficient Technology**
3	Economic Feasibility of Introducing Fuel Efficient Technology
4(a)	Outlook for Fuel Consumption
4(b)	Implications of Likely Directions in Other Motor Vehicle Design and Operation Regulations
5	Report on International Conference on Tomorrow's Clean and Fuel-Efficient Automobile, Berlin, 25-28 March, 1991
6	Review of Policy Instruments Available to Governments
7	Impact Analysis - Process and Procedures

1. INTRODUCTION

Fuel economy improvements in cars can be accomplished in two basic ways - first by reducing the size or performance of the car, and second, by improving the technology of a car. The first option obviously impacts the attributes that consumers desire in a car, and a wide variety of choices in size and performance levels are available in Australia. Hence, the first method is conceptually identical to moving consumers into smaller models already available in the market. Such a move involves forcing consumers to buy vehicles different from one's they would normally choose, and does not involve any technological questions.

The second, improving technology to enhance fuel economy, is the topic considered in this report. It is possible to increase fuel economy significantly by upgrading vehicle technology without impacting consumer attributes that are defined as interior room, acceleration performance and accessory options such as automatic transmission, power steering and power brakes.

This report documents the technologies that can be used to improve the fuel economy of Australian vehicles. The documentation provides an understanding of the technology and the engineering basis for its estimated fuel economy benefit, as well as a documentation of the sources of data from which the benefit was estimated. Most of these technologies described in the report are already available commercially in some cars and their fuel efficiency benefit can be (in some cases) estimated from comparisons of otherwise identical vehicles with and without the technology.

Unfortunately, such comparisons are rarely possible because of differences in the attributes of cars as well as the fact that multiple technologies are usually incorporated into new models, making it difficult to estimate the benefits of each technology.

An underlying assumption behind this analysis is that cars and technologies are similar throughout the world, and that data derived from U.S. cars are applicable to cars in Australia. If the technology benefits are carefully referenced to baseline technologies, this can be proved to be true as the same laws of physics hold. Moreover, the car is a very mature product and cars the world over are technologically quite similar. Adjustments for Australian emissions and safety regulations will be necessary, since these do impact fuel economy and the applicability of certain specific engine technologies.

EEA has collected data over the last decade on specific technological improvements possible to enhance fuel economy from a variety of sources. The Society of Automotive Engineers publishes a large number of papers on individual technologies; however, the technology data may not be specific to an actual vehicle application. The best source for detailed vehicle data has been through the U.S. Corporate Average Fuel Economy (CAFE) program, where manufacturers were required to submit data to the U.S. Department of Transportation (DOT).

Over the years, EEA has obtained access to these submissions and they are extensively referenced in this report. EEA has also held several meetings with all of the world's largest manufacturers in Japan, Germany and the U.S., and direct input obtained from the technical staff has been utilised in this report. Lastly, the trade press is also a source of useful information on this topic.

Section 2 of this report provides an overview of the calculation method used to forecast fuel economy improvements when one or more new technologies are used to improve a vehicle. Sections 3 through 9 describe the range of technologies available to improve car and light truck fuel economy.

2. METHODOLOGY TO CALCULATE BENEFITS

2.1 OVERVIEW

The fuel economy behaviour of a vehicle is dependent not only on the individual technologies employed on a vehicle, but also in how they are applied, and to some extent, what other technologies are present simultaneously. As noted in the introduction, the fuel economy benefit due to technology changes to a given automobile is always calculated on the basis of holding vehicle size as measured by interior volume, and vehicle performance constant. The second term is more complex to define, but each technology that affects the power, torque or weight of the engine/vehicle is examined in detail, and the appropriate set of tradeoffs to measure fuel economy benefit on a constant performance basis are identified and defined.

Individual technology benefits are defined relative to a base technology and are estimated in terms of percent benefits to fuel economy. If the technology represents a change to a continuous variable e.g., weight, the impact of a specific (e.g. 10) percent change in the variable a fuel economy is estimated. If the technology represents a discrete technology, the percent benefit for that technology is defined relative to replacing a base technology (e.g., 4- valve engine over 2-valve engine) holding the size and performance parameters constant. Table 2.1 provides a list of technologies documented in this report and the baseline technology against which benefits are measured.

Of course, no technology will be used in isolation and synergistic and non- additivity constraint must be recognized. Non-additivity is handled simply by recognizing the fact that the sum of market penetration of two non-additive technologies can never exceed 100 percent, i.e., both technologies cannot be present in the same car. Synergy is recognized from engineering analysis which identifies technologies that simultaneously contribute to the reduction of the same source of energy loss. The computational methodology uses a linearised form of the exact engineering equation, and it is described below.

Clearly, the method is an approximation to make the calculations relatively simple, yet yields results that have been accurate to q0.2 MPG, historically. In projecting a maximum technology boundary case for the post-2000 time frame it is believed that these approximations could cause larger errors and a more rigorous engineering model is required. The current model is described below.

2.2 ENGINEERING MODEL

The model follows the work of Sovran[1/2] who produced a detailed analysis of tractive energy requirements on the EPA fuel economy test schedule, i.e., the city cycle and the highway cycle. Each driving cycle specifies speed as a function of time.

TABLE 2.1: TECHNOLOGY DEFINITIONS

Technology	Definition
Front Wheel Drive	Benefits include effect of weight reduction and engine size reduction starting from a late-1970's rear-wheel drive vintage design.
Drag Reduction I	Based on CD decreasing from 0.375 in 1987 to 0.335 in 1995, on average.
Drag Reduction II	Based on CD decreasing from 0.335 to 0.30 in 2001, on average.*
Torque Converter Lock-up	Lock-up in gear 2-3-4 compared to open converter.
4-Speed Auto Transmission	3-speed auto transmission at same performance level.
Electronic Transmission Control	Over hydraulic system, with electronic control of shift schedule and lock-up of torque converter.
Accessory Improvements	Improvements to power steering pump, alternator, and water pump over 1987 baseline.
Lubricants (5W-30)	Over 10W-40 oil.
Overhead Camshaft	OHV engine of 44-45 BHP/litre replaced by OHC engine of 50-52 BHP/litre but with smaller displacement for constant performance.
Roller Cam Followers	Over sliding contact follower.
Low Friction Pistons/Rings	Over 1987 base (except for select engines already incorporating improvement).
Throttle Body Fuel Injection	Over carburettor (includes air pump elimination effect).
Multi-Point Fuel Injection	Over carburettor. Includes effect of tuned intake manifold, sequential injection and reduced axle ratio for constant performance.
4-Valve Engine (OHC/DOHC)	Over two-valve OHC engine of equal performance. Includes effect of displacement reduction and compression ratio increase from 9.0 to 10.0.

* To exploit the benefits of drag reduction, the top gear must have a lower (numerical) ratio to account for the reduced aerodynamic horsepower requirement.

TABLE 2.1: TECHNOLOGY DEFINITIONS - Continued

Technology	Definition
Tires	Over 1987 tires, due to improved construction.
Intake Valve Control-	Lift and Phase Control for intake valves. Includes effect of engine downsizing to maintain constant performance.
Advanced Friction Reduction	Includes composite cam road, titanium valve springs, light weight reciprocating components.

The force required to move the vehicle over the driving cycle is easily derived from Newton's laws of motion:

$F = M\,dv/dt + R + D$
where F = the force required
M = the vehicle mass
dv/dt = the acceleration rate
R = the tire rolling resistance
D = the drag force

From the knowledge of physics, it can be shown that:

$$F = Mdv/dt + gMCRV + \frac{CD\,A\rho\,V^2}{2} \quad \text{-- (1)}$$

where CR is the rolling resistance co-efficient
CD is the drag coefficient
g, ρ are the gravitational acceleration and air density respectively.
V is the vehicle speed

Over the fuel economy test, V is specified as V(t), and the energy required is the integral of

$$E = F.\,ds = F.\,V.\,dt.$$

In the car, energy is provided only when F is greater than zero, while energy during deceleration is simply lost to the brakes.

Taking these factors into account, Sovran and Bohn$_2$ showed that energy per unit distance (S)

$$E/S = a\,MCR + b\,CDA + c\,M \quad \text{--- (2)}$$

where a, b and c are constants virtually independent of vehicle characteristics, but are different for the city and highway cycle. In essence, each term represents one component of the total force, the first representing energy to overcome tire rolling resistance, E_R, the second to overcome aerodynamic drag, E_A, and the third to supply kinetic energy of acceleration, E_k. In the absence of acceleration (during steady speeds) E_k is zero. Figure 2.1 shows the drag and the rolling resistance forces for a typical car at steady state cruise, as well as the driveline loss described below.

Sovran[1/] also related tractive energy to fuel consumption by adding the work required to drive accessories, and the energy wasted by the engine during idle and braking. He defined the average engine brake specific fuel consumption over the test cycle as bsfc, and derived the following equation

$$FC = \frac{bsfc}{\eta_d} [Er + EA + Ek] + bsfc\ EAC + Gi\ (ti + tb) \ldots\ldots (3)$$

where η_d is the drive train efficiency
E_{AC} is the accessory energy consumption
G_i the idle fuel consumption rate
t_i, t_b the time at idle and braking in the test cycle.

The above equation shows that reductions in rolling resistance, mass, drag and accessory energy consumption, and idle fuel consumption cause additive reductions in fuel consumption.

The engine output energy is supplied to match the tractive energy requirements. If total energy required is defined as

$$E = \frac{1}{\eta_d} [EA + ER + Ek] + EAC \ \ldots \qquad (4)$$

then $E = \overline{BHP}.t$ (engine power output)

Engine output power can be further decomposed to provide explicit recognition of engine internal losses. There are no conventions regarding the nomenclature of such losses. In general, the engine has two types of losses, one arising from the thermodynamic efficiency of combustion and heat recovery, and the second due to friction, both mechanical and aerodynamic. Aerodynamic friction is more usually referred to as pumping loss.

A third component that is sometimes excluded from the engine efficiency equation is the power required to drive some internal accessories such as the oil pump and the distributor. Items such as the water pump, alternator and fan are usually (though not always) classified under accessory power requirements. In this analysis, power for all accessories - both internal and external - are classified under accessory power requirements, and the following relationship holds:

$$BHP = IHP\ (1 - P - Fr) \ \ldots \qquad (5)$$

Where IHP is power generated by the positive pressure in the cylinder
P is the pumping loss fraction
Fr is the mechanical friction loss fraction

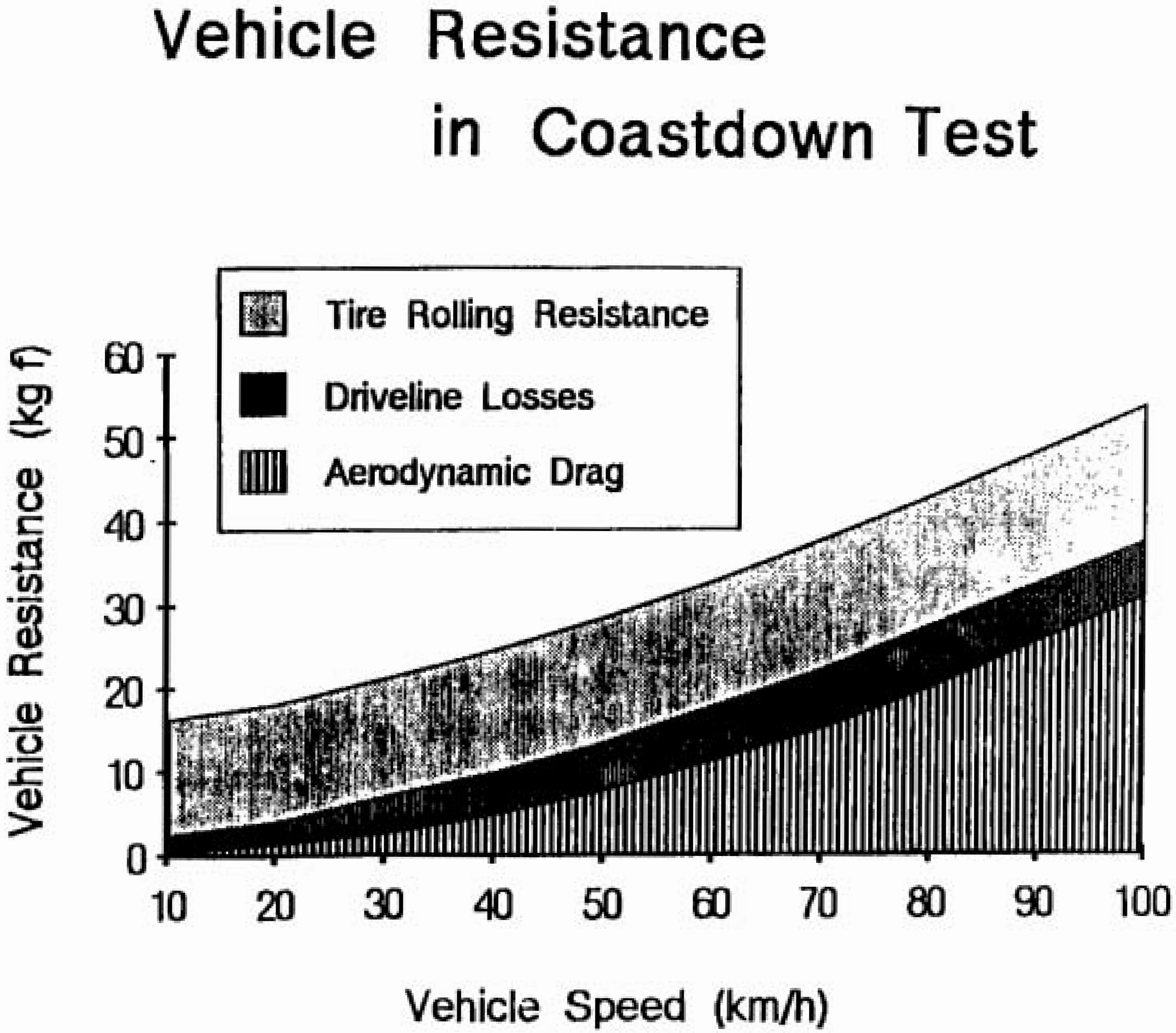


FIGURE 2.1: VEHICLE RESISTANCE IN COASTDOWN TEST

Since fuel consumption, FC, can be written as

$$FC = \overline{bsfc}.BHP.t = \overline{isfc}.IHP.t$$

$$\overline{bsfc} = \frac{\overline{isfc}}{(1-P-Fr)} \quad . \; . \; . \qquad (6)$$

Substituting equation (6) into (3) we obtain

$$FC = \frac{\overline{isfc}}{1-P-Fr} [ER + EA + Ek + \eta d\ Eac] + Gi\ [ti + tb] \; \ldots\ldots\ldots (7)$$

The isfc is principally a function of combustion chamber design and compression ratio of the engine, and to a lesser degree, the air fuel ratio. Since nearly all cars operate at stoichiometry, the air fuel ratio is currently not a factor but could become one if "lean-burn" concepts are utilized.

Pumping losses are dependent principally on the relative load of the engine over the cycle. The larger the engine for a given car weight, the lower the load factor and the higher the pumping loss due to throttling. Pumping losses are also incurred in the intake and exhaust manifolds and valve orifice. The use of tuned intake and exhaust manifolds, and greater valve area (e.g. by utilizing 4 valves/cylinder) reduce pumping losses. Losses other than throttling loss are not unimportant in the contribution to overall pumping loss.

Engine mechanical friction is associated with the valve train losses, piston and connecting rod friction, as well as the crankshaft friction. At low RPM, valve train friction is quite large as a percent of total friction, but decreases at higher RPM, while piston/connecting rod friction increases rapidly with increasing RPM. Total engine friction increases non-linearly with engine RPM.

Idle fuel consumption is also affected by changes in engine parameters. At idle, all of the fuel energy goes into driving the accessories and overcoming pumping and friction loss, since there is no output energy requirement. Hence, decreases in pumping loss or mechanical friction result in much larger percentage reduction in fuel consumption at idle than at load.

Mitsubishi data on the general components of friction of the engine is shown in Figure 2.2. The pumping loss shown is due to internal airflow and not due to throttling. At closed throttle idle pumping loss is approximately equal to frictional loss.

Equation 7 also shows the general structure of the calculation procedure. A simple differentiation of (7) yields:

$$\frac{dFC}{FC} = \frac{d(\overline{isfc})}{isfc} + \frac{P}{1-P-Fr} \cdot \frac{dP}{P} + \frac{Fr}{1-P-Fr} \cdot \frac{dFr}{Fr}$$

$$+ \frac{E_A}{E_A+E_R+E_k + d\ E_AC} \cdot \frac{dE_A}{E_A} + \; . \; . \; . + \; . \; . \qquad (8)$$

where each derivative is expressed as a percentage change. Thus, a one percent change in isfc translates to a one percent change in fuel economy, but a one percent change in pumping loss must be weighted by the fraction that pumping loss is of total output energy. Similarly, aerodynamic tractive energy change must be weighted by the fraction that aerodynamic energy loss is of total tractive energy.

Two observations are required at this point. First, equation (8) assumes that the vehicle can be reoptimized for any change, so that engine variables are not affected by tractive energy requirements. As pointed out by Sovran, this is not always possible.

For example, aerodynamic losses are near zero at low speed but high at high speed. Hence, an engine cannot be simply downsized as aerodynamic loss is reduced, since the smaller engine will not have enough power at low speed. As a result, a higher gear must be added along with engine downsizing to achieve a correct compromise. In theory, it is possible to reoptimize the entire drivetrain, but in practice compromises cause significant losses in fuel economy from the attainable maximum. In the long run, as for 2010, some factors can indeed be optimized to yield the full predicted value, while other factors cannot. For example, it appears unlikely that predicted friction loss reduction related fuel savings can be obtained as the engine cannot be downsized to the point where low speed torque is compromised. On the other hand, rolling resistance decreases may provide the predicted fuel savings as its effect is felt uniformly throughout the speed range.

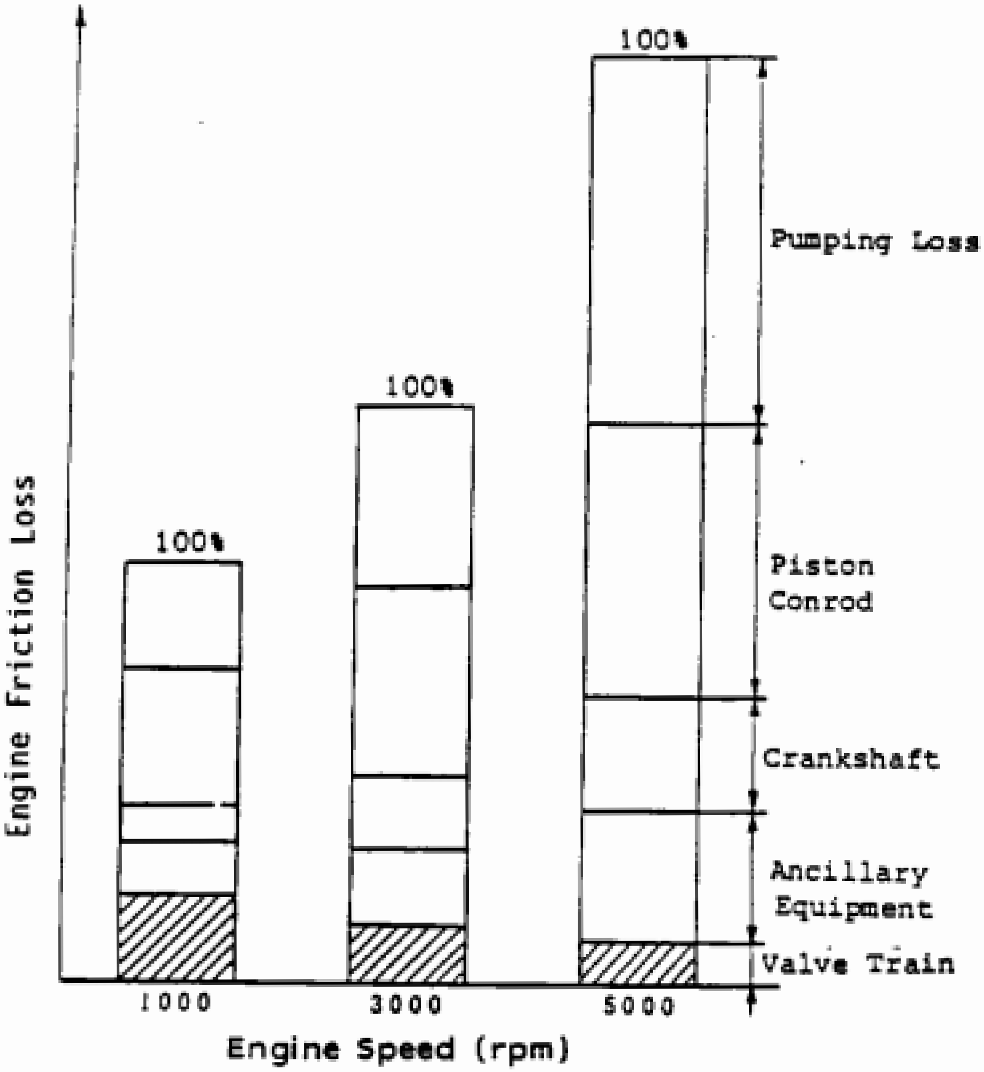
2.3 CALCULATION PROCEDURE

Methods to increase the fuel economy (reduce fuel consumption) must rely on reduction of energy contributed by each of the terms shown in Equation (7). Equation (8) is useful if the change in factors is small, but not applicable for the large changes. Focusing on the terms in equation (7) it is easily seen that fuel consumption is decreased by:

- decreasing friction and pumping loss;
- decreasing weight;
- decreasing drag;
- decreasing rolling resistance;
- decreasing accessory power consumption;
- decreasing idle fuel consumption

Of course, a given technology can act on more than one of these factors simultaneously. Table 2.2 shows the relationships between individual technologies and the terms listed in equation (7). Drivetrain efficiency, d is not major factor in the benefits associated with multi speed transmissions; rather, the reduction in pumping and frictional losses are the biggest factor.

FIGURE 2.2: **PROPORTION OF ENGINE FRICTION DUE TO VALVE TRAIN**



Proportion of Engine Friction Due to Valve Train

With Roller-Cam Followers

It should also be noted that all engine improvements affect idle fuel consumption, so that idle consumption can be approximated as:

$$FC = \frac{\overline{isfc} \quad [ER + EA + EK + \eta d\ (EAC + EI)]}{\eta d\ [1-P-Fr]} \ldots \qquad (9)$$

Where EI is an "equivalent" energy at idle to drive the accessories and torque converter. EI is simply a mathematical artifact to make the analysis simpler for forecasting.

The relationship between fuel consumption and vehicle variables can be derived from equation 7 in exact terms if the co-efficients are evaluated for the FTP and HIGHWAY driving cycles.

In fact, Sovran utilized a detailed evaluation of these cycles to derive the sensitivity of fuel consumption to vehicle weight, aerodynamic drag and tire rolling resistance coefficient. The general characteristics of the two cycles are shown in Table 2.3.

One striking factor is that nearly 41 percent of the time on the FTP is spent in deceleration or at idle. In comparison, less than 10 percent of the time on the highway cycle is spent in braking or at idle. This difference, coupled with the different speeds and average acceleration rates in each cycle, leads to substantially different sensitivities between the two cycles.

In order to evaluate the sensitivity of fuel consumption to changes in vehicle parameters, information is required on the fuel consumption at idle and braking as well as the fuel consumed by driving accessory loads. Sovran utilized data on 1979/1980 GM cars and found that idle and braking fuel consumption was proportional to engine size.

As an approximation, he assumed idle + braking consumption to be a constant fraction of total fuel consumed and estimated this fraction at 16 percent for the FTP and 2 percent for the highway cycle. He utilized a similar assumption for the accessory fuel consumption fraction, holding it constant at 10 and 9 percent respectively.

This is equivalent to the approach in Equation (9) where the term [EAC + EI] . bsfc is replaced by a constant. Utilizing these assumptions, he derived sensitivity coefficients that were dependent on the drag to mass ratio and the rolling resistance coefficient. Using typical value for the average 1988 car, with a mass of 1400 kg (3100 lb), CD of 0.37, frontal area of 1.9 m2 and tire rolling resistance co-efficient of 0.01, the fuel consumption sensitivity coefficients are as follows:

C_D = 0.28
Weight= 0.54
C_R = 0.24

The weight reduction sensitivity co-efficient above does not incorporate the effect of engine downsizing, which reduces idle/braking fuel consumption proportionally. The coefficients assume that the engine and drivetrain are adjusted to provide

TABLE 2.3: FUEL ECONOMY CYCLE CHARACTERISTICS

	Urban	Highway
Speed (average) kmh	38.4	77.6
Speed (max) kmh	91.5	96.8
Distance, km	12.0	16.5
Time at idle (s)	249	3
Time of braking (s)	311	57
Total time for cycle (s)	1373	765
Percent of time at idle and braking	40.8	9.84

constant bsfc, (a factor which may not be realized in practice) but do not account for engine downsizing. Second, the constants are dependent to a certain extent on the assumptions for the fraction of fuel consumed at idle + braking, and by accessory power demands. (The smaller these fractions, the larger the sensitivity coefficients).

Table 2.4 provides a summary of the estimates of the EEA estimated sensitivity coefficients that is attained in actual practice, as opposed to the estimates derived purely from equation (8). In the application of these coefficients, it should be recognized that they can be used only for modest variations for any of the variables involved.

TABLE 2.4: ESTIMATED FUEL CONSUMPTION SENSITIVITY COEFFICIENTS(1)

Variable	FC Sensitivity	F/E Sensitivity
Weight reduction	0.62 (0.54)	0.66
Drag reduction (CD)	0.22	0.23
CR reduction	0.23	0.24
Thermal efficiency	1.00	1.00
Pumping loss	0.23	0.24
Friction loss	0.23	0.24
Drivetrain efficiency	0.78	0.81
Accessory power	0.10	0.11

Note: 1. Percent reduction in fuel consumption per percent reduction in independent variable.)

When large reductions of any variable are likely to occur the preferred form of analysis is to use equation (7) with a "slippage" factor to account for the fact that theoretical benefits cannot be attained in actual practice for some variables of concern.

The methodology used to calculate the fuel economy benefit due to the application of any set of technologies to the automobile is as follows. First, the technology set is examined to identify which energy use factors are affected, and areas of overlap are examined for synergy. Second, the net reduction in each specific energy use area are estimated and the benefits to fuel consumption calculated with equation (8). In general, synergies occur primarily in pumping loss reduction, with smaller synergies in the area of friction reduction.

REFERENCES FOR SECTION 2

1. Gino Sovran and Mark S. Bohn, "Formulae for the Tractive Energy Requirements of Vehicles Driving the EPA Schedule", SAE Paper 810184, February 1981.

2. Gino Sovran, "Tractive-Energy-Based Formulae for the Impact of Aerodynamics on Fuel Economy Over the EPA Driving Cycle", SAE Paper 830304.

3. WEIGHT REDUCTION

3.1 ENGINEERING DESCRIPTION

One of the most important determinants of vehicle fuel economy is vehicle weight. Lower vehicle reduces the forces required to accelerate a car, which in turn reduces fuel consumption. There are four principal methods to reduce vehicle weight, namely:

- o Conversion to front-wheel drive
- o Downsizing
- o Material substitution
- o Use of unit body construction

Conversion to front-wheel drive reduces weight because: 1) the driveshaft and rear axle are eliminated, and 2) a vehicle of given interior room can have smaller exterior dimensions due to more efficient packaging.

Downsizing reduces vehicle weight by decreasing the size. This process, however, does not conserve interior room for cars, and results in a loss of consumer utility. It is not considered in this report, since its effects can be simulated as a changed mix of size classes.

Material substitution requires the substitution of high strength steel, aluminum, magnesium alloys or plastics for plain carbon steel, which accounted for over 45 percent of 1988 vehicle weight. In most cases, this involves redesign of the part to optimize for strength.

Unit body construction refers to the elimination of the conventional chassis/body structure. Prior to 1978, most vehicles utilized a separate chassis that carried all vehicle loads, and the body was suspended on the chassis. Unit body vehicles utilize the body panels as stressed members that carry the vehicle load.

Elimination of the chassis results in a 5-8 percent reduction in vehicle empty weight. Between 1980 and 1983, many U.S. domestic cars have incorporated all four methods of weight reduction described below. All front wheel drive cars now feature unit body construction.

Conversion to front-wheel drive began in the U.S. with the introduction of the Omni/Horizon in 1978 and the GM X-car in 1979. In general, most of these conversions have maintained interior volume in comparison to their rear-wheel drive predecessors, thus permitting comparisons of fuel economy gains and cost changes.

Downsizing occurred primarily during the 1975-1980 era in the U.S. Even though the exteriors of the cars are now much smaller, interior volume declined only modestly. (This downsizing does not account for "mix shift" which is treated separately). More recently, cars are being upsized and recent cars have even increased in exterior dimensions in almost all countries around the world.

3.2 FRONT-WHEEL DRIVE

In front wheel drive (FWD) vehicles, the engine/transmission output shaft is directly connected to the front-wheels, and the most common placement of the engine is in the transverse position, so that the crankshaft is parallel to the driveshaft. In contrast, the engine/transmission in rear wheel drive (RWD) vehicles is placed longitudinally. The output shaft is connected to the rear axle by a propeller shaft that runs from the front to the rear. The pair is transmitted to the wheels via the differential. The advantages of FWD over RWD designs are:

(1) The transverse engine placement allows more compact packaging of the drivetrain, eliminating the propeller shaft, differential and rear axle.

(2) The vehicle's exterior dimension can be reduced significantly when the engine is packaged transversely, without impacting passenger room. In addition, FWD eliminates the hump in the floor required to accommodate the drive shaft, enhancing legroom.

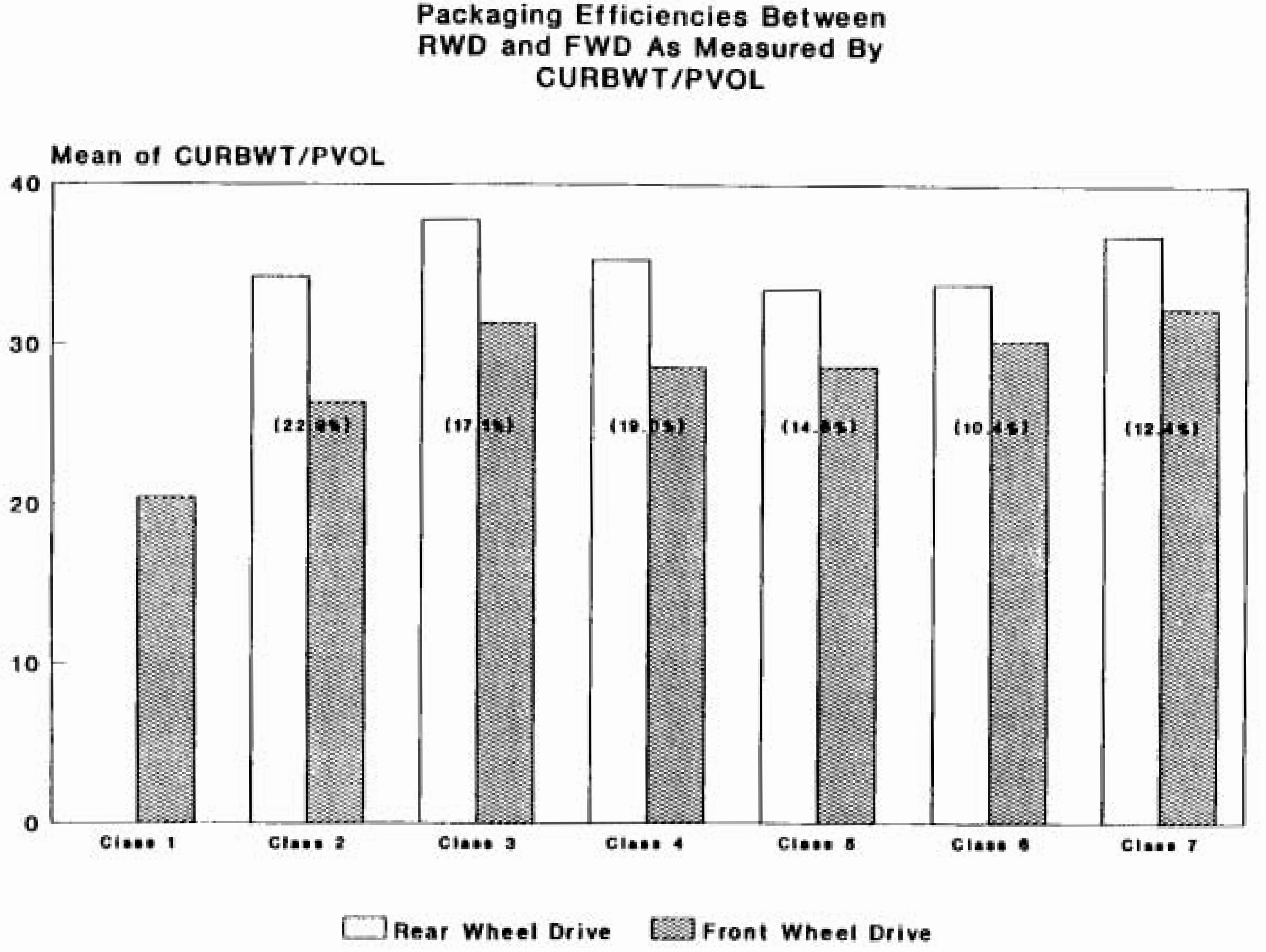
(3) The drivetrain is made more efficient by the elimination of the less efficient hypoid gears in the rear drive axle with the helical gears used in the transaxle. EEA's analysis of front-wheel drive versus rear wheel drive compares the benefits at equal interior volume. Two factors affect fuel economy - the increased drivetrain efficiency, and the weight reduction through improved packaging of the car.

DOT had extensively investigated the improvements of drivetrain efficiency between RWD and FWD designs in the late 1970's and early 1980's. They concluded that the reduced drivetrain losses in the FWD design would lead to a 1.5 percent improvement in fuel from this factor alone.

The weight reduction afforded by FWD designs over RWD can be gauged by several methods. The weight of the drive shaft, rear differential and rear axle weigh 150 to 160 lbs, which is the minimum weight reduction that can be expected, partially offset by the transaxle which weight 30-50 lbs in FWD vehicles. (Transmission weights are also slightly lower for FWD vehicles). The minimum net weight reduction of 100-120 lbs is not representative, as the packaging benefits are more significant.

One method to estimate the total weight reduction from FWD is simply to observe the weight/volume ratios for the current 1988 fleet. Since RWD is used in few cars, simple fleet averages would be unrepresentative. Rather, the fleet is divided into "market" classes, where each market class consists of vehicles with similar interior volume, performance levels and price. (The last two variables separate market class from size class, as it allows recognition of sports and luxury vehicles).

In general all of the vehicles in one market class are considered as substitutable choices for a consumer, and vehicle attributes show relatively small variances among models within a market class, with the exception of the luxury class. (Luxury class is simply defined as all cars costing over $25,000 in 1988, and incorporates a wide variety of models.) Figure 3.1 shows the WT/VOL comparison. In virtually every case the weight of an FWD



PVOL = Passenger Volume
CURBWT = Curb Weight
Percent Difference (RWD-FWD/RWD) in ()

FIGURE 3.1: PACKAGING EFFICIENCIES BETWEEN RWD AND FWD AS MEASURED BY CURBWT/PVOL

vehicle is 10.5 to 19 percent lower at the same interior volume. No value for subcompact and minicompact cars is shown since all cars in these classes were already FWD in 1988.

The domestic manufacturers had only a handful of RWD models in 1988, and some of these have been replaced by FWD models by 1991. Table 3.1 shows the weight reduction available by comparing it with the actual replacement model weight or the weight of a similar competing vehicle of near equal volume and performance.

The analysis is dependent to some degree on the comparison, especially for the sports cars. However, EEA does not anticipate that the Camaro/Firebird and Mustang will be converted to FWD.

For all other RWD vehicles, we have utilized a mean value of 13 percent weight reduction. Some of this gain is due to the conversion from body-on-chassis type structure to unit body construction. The 13 percent weight reduction potential translates to a 8.5 percent improvement in fuel economy. The total benefit of FWD conversion for both weight reduction and driveline efficiency improvement is estimated at 10 percent. This includes the effect of conversion to unit body construction.

3.3 MATERIAL SUBSTITUTION

Material use in domestic cars changed sharply in the late 1970's and early 1980's, and material substitution was launched with the new Chevrolet Impala/Caprice for model year 1977. Relative to previous cars, the weight of the Chevrolet was lower by 600 to 700 lbs, while interior room was largely unchanged. On average, the fleet average weight decreased by over 500 lbs in the 1976 to 1984 timeframe. Since 1984, the pace of material substitution has slowed significantly.

In fact, the 1977 Chevrolet was sold through model year 1990 with only cosmetic updates and very minor changes to material content. Table 3.2 shows the progression of material use in domestic cars during the 1976-1988 period. Between 1988 and 1990 weights of some cars have actually climbed, due to less weight conscious design.

In the near term, competition between plastics and HSLA will be intense, and cost considerations will dictate the specific winner in the absence of regulatory forces. According to Dr. Peter Beardmore[1], most plastic composites are more expensive than steel in high volume applications, but can be competitive in low volume specialty applications. The situation is changing rapidly as plastic structural component manufacturing technology and the materials evolve to become more manufacturable and meet consistency requirements.

In 1989, few plastics for exterior panels were in use in the car market with the sole exception of the Chevrolet Corvette. Typically, plastics are currently being used in limited applications such as front fascias and spoilers, with fender applications only in the Cadillac. Of course, plastics are widely used for interior applications such as the dashboard and door moldings.

TABLE 3.1: WEIGHT REDUCTION THROUGH FWD CONVERSION

1988 RWD Model	Body Type	Weight	Comparable FWD Model	Weight	Savings
GM					
Chevrolet Caprice	Chassiss	3803	Olds 88	3296	10.8
Cadillac Broughan	Chassiss	4282	N/A	--	15.1*
Camaro/Firebird	Unibody	3357	Probe Turbo	2990	11.0
Monte Carlo	Chassiss	3270	'89 Regal/Supreme	2953	9.7
Ford					
Crown Vic/Gd. Marquis	Chassis	3780	Olds 98	3330	12.0
Thunderbird/Cougar	Unibody	3215	'89 Regal/Supreme	2953	8.2
Mustang V-8	Unibody	3190	Probe Turbo	2990	6.3
Chrysler					
Fifth Avenue	Chassis	3760	'90 Fifth Avenue	3215	

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* Estimated from similar vehicle volume/wt ratio for Cadillac FWD

TABLE 3.2: WEIGHT REDUCTION THROUGH MATERIAL SUBSTITUTION

	Base*	HSLA	Plastics	Aluminum	GRP
Small Car	2150	1821 (15%)	1794 (16.5)	1561 (28.5)	1467 (31.8)
Compact Car	2600	2310 (14.4)	2265 (12.9)	2040 (22.5)	1870 (28.1)
Large Car	3586	3022 (15.3)	2979 (16.9)	2781 (22.5)	2429 (32.3)

* Baseline
Small car: Ford Escort
Compact car: Chevrolet Citation
Large car: Chevrolet Impala/Caprice

Plastic components are not yet used for any structural (load bearing) parts.

Material substitution is likely to accelerate in pace in the post-1991 timeframe. The major materials considered for substitution are:

- High strength low alloy steel (HSLA) ;
- Reinforced Injection Molded (RIM) Plastic Components ;
- Sheet-Molding Compound (SMC) for body panels with Glass Fiber Reinforced Plastic;
- Aluminum;
- Graphite Fiber Reinforced Plastics (GRP);
- Advanced Composites

Other materials such as zinc and magnesium also will be used, but in lesser quantities. Costs associated with these materials vary by the particular requirement for the component, e.g., stiffness, bending strength, formability. In general, HSLA is the lowest cost increment and is compatible with tooling equipment used for plain carbon steel. Plastics (RIM and SMC) also are fairly low in cost but require new manufacturing and finishing techniques. Aluminum represents a fairly high cost option but also is capable of producing large reductions in weight. GRP and advanced composites represent the highest cost option and produce the greatest weight savings.

DOT and GM had published some detailed studies in the early 1980's on the weight benefits and costs of using increased amounts of plastics and high- strength low alloy steels in the designs. The studies are still relevant largely because of the pace of material substitution slowed in the mid and late 1980's. The price of glass-fiber SMC has dropped since the time these papers were completed from $1.20/lb to $0.80 - 0.90/lb in 1990, while sheet steel prices have climbed by 15 to 20 percent in absolute terms over the same period.

GM researchers[2] found that, at $1.20/lb, the cost per pound saved using SMC body panels over a range of applications, was $0.30/lb saved. They also found a very similar cost penalty for aluminum. In recent times, the cost of penalty of glass SMC designs have ranged from near zero to $0.20/lb saved, while aluminum has increased to $0.40/lb saved. (These figures were derived by scaling the GM estimates based on 1989/90 prices for materials). The fact that SMC is being used in some vehicles is proof of its cost-effectiveness.

The Department of Transportation (DOT) has performed detailed studies[2] of weight reductions possible in 3 different size classes of cars for four cases--HSLA dominant, Reinforced Plastics dominant, Aluminum dominant, and GRP dominant. The resulting weight reductions are detailed in Table 3.2. Although no one case will be representative of any manufacturer's strategy, EEA believes that the lowest cost materials will be used first in the 1990- 2000 timeframe.

This indicates that the most likely weight range will like near those predicted for the HSLA and Reinforced Plastics cases. In the post- 2000 period, Aluminum and GRP may be used in specific components if the costs can be justified in fuel savings. Researchers from ALCOA[6] found even large weight reduction potential with aluminum. They reported that an X-body car could have weight reduced from its 2700 lbs (in 1982) to 1550 lbs with an aluminum intensive design.

The DOT weight savings estimates includes all of the secondary weight benefits associated with material substitution. For example, as the weight of the body structure is reduced, a smaller engine is required, and the suspension and tires can be reduced in weight also.

The DOT study used historical data to compute secondary weight reductions, but many feel that their estimates are too optimistic to be realized in production as it does not account for the need to maintain ride quality, or the inability of drivetrain engineers to adjust drivetrain parameters to account for all primary weight changes.

Table 3.2 indicates that a 15 percent weight reduction is possible in the near term, but the industry consensus appears to be closer to 10 percent. VW[4] has published recent estimates for their Golf vehicle (which is representative of most modern FWD subcompact/compact cars) and concluded that a 10 percent weight reduction was both possible and likely by 2000. Another confirmation comes from the Automotive Material Conference held in December 1989 where Donald Smith, professor at the University of Michigan and a panel composed of specialists in the industry projected weight reduction potential in excess of 225 lb through material substitution.

William Risk, president of Autopolymer Design Inc. reported that existing product programs would increase plastics use from 220 lb in 1988 to 360 lbs by the mid-1990's. In contrast, the ALCOA[6] study seems to indicate reductions to levels not supported by other work.

Hence, EEA has projected a 10 percent weight reduction potential for all cars in the 1990-2001 timeframe, equivalent to an average weight reduction of close to 300 lbs.

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4. IMPROVEMENTS IN AERODYNAMICS

4.1 ENGINEERING DESCRIPTION

Aerodynamic drag is a resistance force on a moving car's surface areas caused by wind intensity and direction. Aerodynamic drag is a function of a car's frontal area and body shape. The drag coefficient is a measure of the streamlining of the car body.

The higher the coefficient, the greater the drag; the larger a car's frontal area, the higher the drag. Drag-related power requirements are a cubic function of a car's speed through the air. Drag has a minimal effect at low speeds and a strong impact at high speeds, so that reduction in drag affects highway fuel economy much more than city fuel economy.

Aerodynamic drag cannot be reduced without affecting the styling characteristics of the automobile. Since drag depends on body shape and frontal area, a change in drag characteristics can impact the vehicle's interior volume and its utility to the consumer.

For example the drag force could be significantly reduced by narrowing the car width to accommodate two people per seat instead of three. However, this would affect the car's carrying capacity. Streamlining of the vehicle's shape is subject to these limitations, as well as public acceptance of highly aerodynamic shapes.

Since aerodynamic drag is so inextricably related to vehicle design, it is not feasible to distinguish the application of improved aerodynamics from styling in current vehicles. There is no question that greater attention is being paid to the vehicle's drag coefficient, but this has always been compromised by styling requirements as discussed below.

The measured of drag co-efficient can be influenced by the measurement as well as is the design of the wind tunnel itself, and some researchers believe that automanufacturer claims for several models may be based on different measurement methods.

Nevertheless, the only sources of data on vehicle drag co-efficients (or C_D) are from the manufacturers themselves. Table 4.1 shows the drag co-efficients of several domestic used imported cars in 1988. Data on the CD of some vehicles especially those with high drag co-efficients) are unavailable. From publicly available data on most cars, in combination with some unofficial estimates for vehicles where data is unavailable, EEA estimates that the average C_D in 1988 was in the 0.37 - 0.39 range.

4.2 DRAG REDUCTION POTENTIAL

Since 1986, several vehicles with low drag co-efficients have been introduced. The first aerodynamic U.S. domestic car was Ford's Taurus/Sable with drag coefficients of 0.33, and several other cars have followed suit. GM's Olds Cutlass Supreme for 1989 boasts a C_D of below 0.30, and some recent (1990) GM models

TABLE 4.1: DRAG CO-EFFICIENTS FOR SELECTED 1988 VEHICLES

DOMESTIC CARS

Make	Best Model	Cd	Frontal Area (sq. ft.)	Worst Model	Cd	Frontal Area (sq. ft.)
AMC/Renault	Medallion 4-dr.	0.34	21.2	Alliance 4-dr.	0.39	20.5
Chrysler	LeBaron Coupe	0.35	N.A.	Fifth Avenue	0.48	N.A.
Plymouth	N.A.	N.A.	N.A.	Horizon	0.42	N.A.
Dodge	Daytona Shelby Z	0.35	N.A.	Omni	0.42	N.A.
Ford	Taurus	0.33	22.7	Crown Victoria	0.50	24.4
Lincoln-Mercury	Sable	0.32	22.7	Grand Marquis	0.50	24.4
Buick	Riviera	0.37	22.3	Regal	0.46	24.5
Cadillac	Allante*	0.34	22.3	Brougham	0.46	24.5
Chevrolet	Camaro Z-28	0.33	N.A.	Caprice	0.45	N.A.
Oldsmobile	Calais 2-dr.	0.37	20.7	Customer Cruiser Wagon	0.45	27.4
Pontiac	Trans-Am**	0.35	21.4	Safari Station Wagon	0.45	27.4

NOTES: * With hardtop ** With aero package.

TABLE 4.1: DRAG CO-EFFICIENTS FOR SELECTED 1988 VEHICLES - Continued

IMPORT CARS

Make	Best Model	Cd	Frontal Area (sq. ft.)	Worst Model	Cd	Frontal Area (sq. ft.)
Acura	Legend	0.32	N.A.	Integra	0.34	N.A.
Alfa Romeo	Milano	0.37	20.0	Spider	0.40	18.0
Audi	5000S	0.32	N.A.	4000CS Quattro	0.42	N.A.
Austin Rover	Sterling	0.33	21.2	N.A.	N.A.	N.A.
BMW	735i	0.32	N.A.	N.A.	N.A.	N.A.
Honda	CRX	0.32	18.5	Civic Sedan, Wagon	0.39	20.1*
	Accord Sedan		20.5	4wd Wagon		21.9*
Hyundai	Excel	0.36	N.A.	N.A.	N.A.	N.A.
Jaguar	XJ-6	0.37	21.3	XJ-S Cabriolet	0.41	20.1
Mazda	RX-7	0.29	N.A.	323 Sedan	0.38	N.A.
Mercedes-Benz	26C & 300E	0.31	22.4	560SL	0.43	20.2
Mitsubishi	Cordia	0.33	18.7	Mirage 2-dr.	0.39	19.2
Nissan	300-ZX	0.31	N.A.	Maxima Wagon	0.39	N.A.
Porsche	924S, 944 Turbo	0.33	N.A.	911 Carerra Turbo, 928S	0.39	N.A.
Saab	9000	0.34	22.0	900	0.41	21.0
Subaru	XT Coupe	0.29	19.7	Station Wagon	0.38	20.6
Toyota	Celica GT-S	0.33	N.A.	Van	0.39	N.A.
Volkswagen	Golf GT, GTI, Jetta	0.36	N.A.	Cabriolet, Fox	0.46	N.A.
Volvo	760 GLE**	0.37	N.A.	N.A.	N.A.	N.A.

NOTES: * Depending on model ** 1983 European model

This chart lists each auto manufacturer's most aerodynamic and least aerodynamic models, their coefficients of drag (Cd) and frontal areas. All figures are based on manufacturers' claims. In some cases, vehicle frontal areas are not available (N.A.)

SOURCE: Automotive News.

have C_D values in the 0.31 range. The most aerodynamic cars sold in the U.S. in 1990 are the Lexus LS400 and the Subaru XT. In Europe, the most aerodynamic car sold in the Opel Calibra with a C_D of 0.26.

Analysis of product plans of the manufacturers show that most new models will emphasize aerodynamics, while some luxury vehicles may still retain the "formal" look that leads to high C_D. Nevertheless, by 1995, it appears that the average C_D will be 0.33 - 0.34 corresponding to a 10 percent reduction in drag with reference to the 1988 average. (Some models like the Taurus will see no reduction at all, while other like the Crown Victoria will experience a 20-25 percent reduction).

Given that there are some cars already available with drag coefficients of 0.29, it appears reasonable to project that the 2001 fleet average will be 10 percent lower than 1995's with a C_D of 0.29 ~ 0.30. These levels of drag reduction are not expected to alter vehicle attributes significantly$_1$. No reduction in frontal area is forecast for either time- frame, in keeping with the analytical requirements of constant interior volume.

It should be noted that the reduction of drag co-efficient <u>must</u> be accompanied by other changes to match the drivetrain to the reduced horsepower demand. If only the drag co-efficient is changed, the load on the engine is reduced.

While overall fuel consumption will be reduced, operating at a lower load factor will increase bsfc$_2$. To compensate, the engine speed must be reduced by reducing the N/V ratio in top gear. As a result, the engine RPM is lowered so that the new operating point has <u>at least</u> the bsfc of the original pre drag reduction operating point. It is also possible to actually improve the bsfc since at the same speed, the engine will be running at lower RPM, decreasing frictional loss. This effect is captured in EEA's analysis as the overdrive gear effect (please see section 7).

The cost of aerodynamic improvements are associated primarily with the expenses related to research the body styling and trim details to lower the drag coefficient. The essential inseparability of aerodynamic drag co-efficients and styling requirements make it difficult to allocate precise "costs" to drag reduction.

At C_D levels of 0.33-0.34, there are no significant variable costs associated with drag reduction. At lower levels of C_D (in the 0.30 range), manufacturing costs increase because of the need to maintain better tolerances for body parts and improved fit and finish quality. (The use of a covered underbody is not expected to be necessary to meet the 0.29- 0.30 target). Flush windows also impose some variable cost penalties. However, these quality of fit-and-finish improvements are also required to be competitive in the current marketplace, so that it is difficult to allocate costs to aerodynamic drag reduction alone.

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5. TYRES, LUBRICANTS AND ACCESSORIES

Small gains in fuel economy can be attributed to:

- Decreases in the rolling resistance coefficients of tyres;
- Decreased viscous and frictional losses due to the use of synthetic lubricants;
- Reductions in power losses in accessory drives.

5.1 TYRES

The use of radial tires has spread across the entire new car fleet. However, radial tires of more advanced designs manufactured from rubber compounds with lower hysterisis losses can reduce the rolling resistance of all tires. In a study reported in 1981, researchers from the EPA[1] found that fiberglass belted tires had 5 percent lower rolling resistance than steel belted tires, and that "all season" treads have 5.6% higher rolling resistance than conventional treads.

Studies on tire inflation pressure by B.F. Goodrich[2] showed that rolling resistance continues to decrease to inflation pressures of up to 40 psi, but is not affected above that pressure. However, it is also well known that tire performance is a complex function of design variables and that handling characteristics and traction and often adversely affected by the design factors that decrease rolling resistance[3].

No detailed data on current tire rolling resistance coefficients (C_R) are available publicly, but tire companies suggest that the average C_R is around 0.01. In recent years, there has been a tread towards high performance tires of low aspect ratio, that have had impacted rolling resistance unfavorably for fuel economy.

However, EEA contacts with tire companies' staff[4] indicate that rolling resistance will decline by 10 percent over the next decade on a "same tire" basis but the trend towards higher performance tires will negate half the benefit. Hence, a total of reduction of 5 percent in rolling resistance is forecast over the next decade through:

- improved tread and shoulder design;
- use of different high performance belt materials, such as arramed fiber;
- improved rubber compounds.

Others have suggested that the benefit could be as high as a 10 percent reduction in rolling resistance.

Lubricants

Synthetic axle and engine lubricants have been available for several years[5], but have not found wide acceptance because of the substantial cost premium for small fuel economy benefits[6]. It is unlikely that the situation will change over the next decade, and their benefits are not likely to be seen in the fleet. However, 5W-30 oil has recently come into use in some U.S. vehicles as a factory fill oil, and automanufacturer submissions to DOT have claimed a 0.5 percent fuel economy benefit, on average, by replacing 10W-30 with 5W-30 oil.

There may be other small benefits associated with approved axle and differential lubricants, but these benefits may be only in the 0.1 to 0.2 percent range.

5.2 ACCESSORIES

Accessory drives absorb power from the engine and their influence is inversely related to engine size. In cars, the cooling fan, water pump, alternator, power steering pump, and air conditioner (when used) can account for a major (15 percent) penalty in fuel consumption.

Efficiency improvements in all of these accessories and conversion to thermostatically operated electronic cooling fans can provide up to a 3 percent improvements in fuel economy. All of these improvements have been already incorporated during the 1980-1990 time period.

An additional 5 percent improvement in fuel economy is possible through redesign of the drives and improvements in fan blades coupled with reduced heat rejection from the engine (which may be necessary for meeting exhaust emissions standards). These improvements will be phased in during the 1990- 2000 period. Costs for such improvements (except the electric fan) are small, typically amounting to about $10.00 per vehicle.

The variable speed accessory drive has been researched extensively by DOE[7]. However, their cost-effectiveness is poor if the vehicle features an electric fan as all FWD vehicles do. Ford was ready to introduce such a drive in the mid-1980's but cancelled the introduction due to durability problems, and difficulty in matching the alternator load requirements under some conditions. As a result, EEA does not foresee the use of these devices in the next decade.

The power steering pump absorbs a significant fraction of accessory energy, especially at low speeds. An electric power steering system has been developed and recently commercialized. Due to electrical power requirements, it is best suited for small cars. Such a system would increase fuel economy by 1 percent when the hydraulic pump is eliminated. The electric power steering system has been recently commercialized in Japan.

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6. SPARK IGNITION ENGINE TECHNOLOGY

6.1 OVERVIEW

The spark ignition (SI) piston engine is expected to be the dominant form of motive power in the next decade. Although the S.I. engine has been in existence for a 100 years, steady and continuous improvements are being made. As noted in Section 2, the areas where technical improvements are possible are:

- Increased thermodynamic efficiency
- Decreased pumping loss
- Decreased mechanical friction loss

Any new type of engine incorporates improvements in all three areas. We have discussed specific engine types and specific component changes that may cause improvements in any or all of the three areas.

Prior to 1980, Ford was the only manufacturer that offered even one overhead cam engine among the domestics, and all other domestically manufactured engines were of the overhead valve (OHV) type. All pre-1980 engines were carburetted with the sole exception of the Cadillac 350 CID V-8 offered in the Eldorado and Seville. OHV engines continue to dominate the domestic car fleet in 1988, although most engines are now fuel injected. As a reference, the 1988 carburetted OHV engine serves as a baseline for comparison of OHC and 4- valve engines. Detailed data on the few remaining engines of this type showed that they typically produced 32~35 BHP/litre, and 67-70 N-m/litre of torque.

The categories of engines now in the marketplace are as follows.

Advanced OHV Engines are a recent phenomenon as domestic car manufacturers have updated older engines with new "fast-burn" heads, improved piston and ring designs, better manufacturing tolerances of the cylinder base, noise reduction and improved airflow. The engine block retains the same basic dimensions of the older OHV designs. Such engines have outputs of 42-45 BHP/litre and torque ratings of 74-76 N-m/litre.

Overhead Cam Engines of older designs are roughly equivalents in specific output and specific torque to the advanced pushrod engines. These older designs are represented by the Chrysler 2.2/2.5 litre 4 cylinder engines designed 10 years ago and the Ford 2.3L that dates from the early 1970's but has been updated since. More modern OHC engine have specific outputs of 50-54 HP/L and torque of 80-82 N-m/L. High performance engines have increased specific outputs of 60-63 BHP/L with only slight reduction in torque.

However, both the torque peak and HP peak are realized at much higher RPM.

4-valve engines are only of the overhead cam type, some featuring single overhead cam (SOHC) while others have double overhead cams (DOHC). The four valves permit improved breathing and a more compact combustion chamber with a central spark plug that allows for higher compression ratios (CR). Typically 4-valve engines can have a CR of 10.0 without being knock limited while most OHV/OHC engines have CR's of 8.8 to 9.2. The specific output of a modern 4- valve engine optimized for fuel economy is 60 to 65 BHP/L with torque of 88-90 N-m/l.

If optimized for high end performance, the maximum torque decreases only slightly but maximum output increases to 75-80 BHP/L, with RPM at peak torque and peak horsepower increasing. A summary of engine classifications is provided in Table 6.1.

Fuel injection can also improve the specific output of engines. The simpler throttle-body (or single-point) injection provides only modest gains in specific output as it does not allow a redesign of the intake manifold to maximize airflow. Multi-point fuel injection offers the benefit of being adaptable to tuned intake manifolds and more accurate fuel delivery that is matched to requirements of the engine during transients.

Throttle-body and multipoint fuel injection are widely used in the 1988 fleet, and carburettors were restricted to just one engine family for Chrysler and GM (in the 318 V-8 and the 307 V-8 respectively) in 1988. All Ford engines were fuel injected.

Variable Valve Timing can provide reduction of pumping loss by closing the intake and potentially to exhaust valves, depending on the speed and load. Valve timing is known to have favourable effects on engine output across the RPM range, largely because the current system of fixed valve timing is largely a compromise for the range of load are speed conditions encountered. The problem has always been the lack of good mechanisms to vary valve timing.

Most schemes have proved unreliable mechanically and/or caused such large increases in mechanical friction that the pumping loss benefits were overwhelmed. More recently, a simple mechanism suitable for DOHC engines that changes the timing of intake valves, but not lift or duration has been commercialized by Nissan and Mercedes. In 1990, Honda introduced a more sophisticated system that varies timing, lift and duration between two fixed sets of values, one for low speed and the other for high speed.

Engine mechanical friction reduction is an ongoing effort and evolutionary improvements in friction are being realized constantly. The level of friction in an engine is characterized in normalized terms as friction mean effective pressure (fmep). A typical advanced OHV or OHC engine has a brake mean effective pressure at wide open throttle of 930 kPa (135 psi), while the fmep is 170 KPa. Major components contributing to friction are piston/rings, valvetrains, crankshaft/seals and oil pump, in order of importance. Considerable work has gone into designs of these components to reduce friction. Friction reduction is usually incorporated into modern engine designs.

The specific fuel economy benefits associated with engine design type and through fuel injection and friction reduction are documented below. The overhead valve engine is used as a comparison baseline.

TABLE 6.1: ENGINE CLASSIFICATION

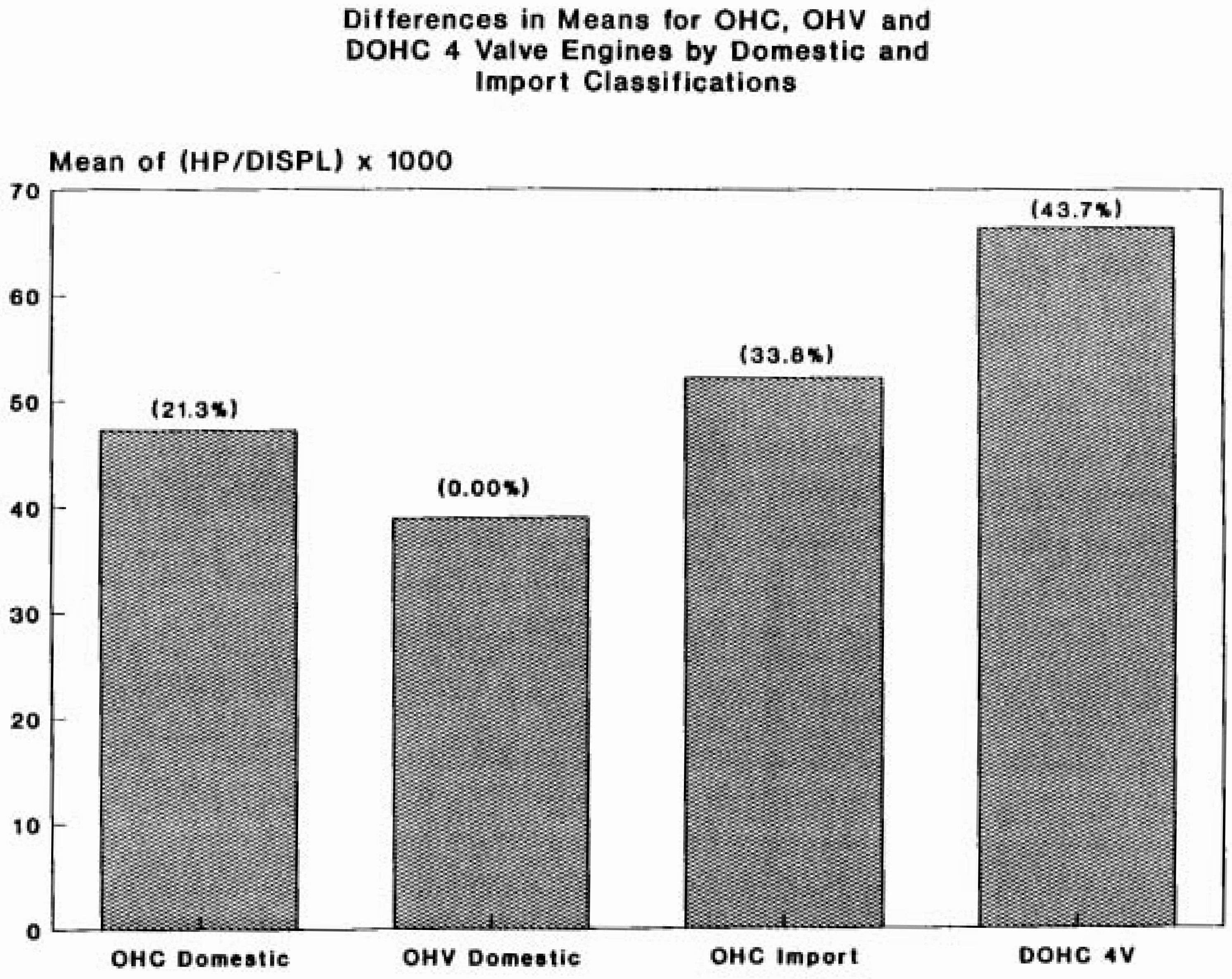
		Specific Power	Specific Torque	
Class	**Valves/cyl**	**(HP/L)**	**(N-m/L)**	**Examples**
OHV (old design)	2	30-35	67-70	Ford 302 V-8
Advanced OHV and OHC	2	44-46	74-76	Ford 181V-6 GM 3300/3800 V-6
Modern OHC	2	50-54	80-82	Most Japanese engines
Modern OHC (High performance)	2	58-60	78-80	Mercedes 3 litre, I-6 BMW 3.5 litre I-6
Modern 4-valve	4	62-65	90-92	GM Quad-4
Modern 4-valve (High performance)	4	70-75	88-90	Ford/Yamaha 3L V-6

6.2 OVERHEAD CAM ENGINES

As noted, overhead cam engines can have valve timing adjusted to provide up to 60 BHP/L in high performance applications. In the more common application where fuel economy is important, discussions with manufacturers and current design practice suggest that 50-52 BHP/L is the optimal range. Figure 6.1 shows the actual 1988 averages for OHV, domestic OHC, import OHC and 4 valve engine specific outputs. The domestic OHV output figures aggregate the two sub-classes of advanced OHV and old OHV. If the import OHC average is used as a representative figure (since they are more modern designs than domestic OHC engines) for the specific output, it coincides with the general comments obtained from manufacturers.

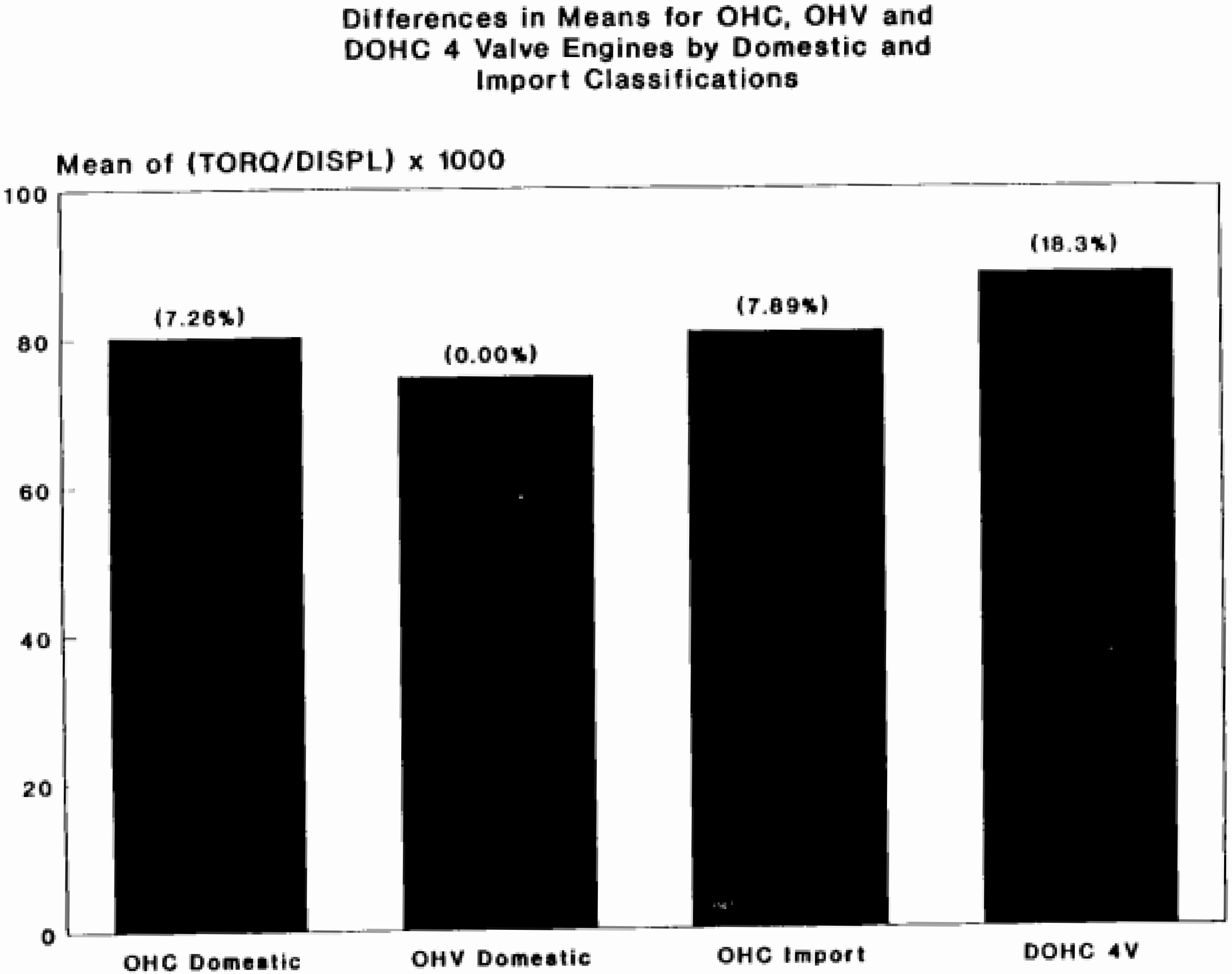
Figure 6.2 shows the specific torque ratings for 1988 engines. It appears that modern OHC designs offer an 8 percent benefit over the average OHV engines. The more appropriate comparison is against the advanced OHV engine, where the torque benefit is 6 percent.

In the EEA analysis of fuel economy potential, the case considered is an advanced OHV engine of 44 BHP/L being replaced with an OHC engine of 52 BHP/L output. Torque will increase 6 percent from 75 N-m/L to 80 N-m/L. To maintain constant performance, the OHC engine is assumed to be downsized by 10 percent. Peak horsepower will increase a 6-percent but torque will decrease by 4.5 percent. In order to compensate for the low end torque loss, axle ratio must be increased by 5 percent. This maintains the same "launch feel" and top gear gradeability.



Difference in () with OHV Dom. as base.

FIGURE 6.1: DIFFERENCES IN MEANS FOR OHC, OHV AND DOHC 4 VALVE ENGINES BY DOMESTIC AND IMPORT CLASSIFICATONS



Difference in () with OHV Dom. as base.

FIGURE 6.2: DIFFERENCES IN MEANS FOR OHC, OHV AND DOHC 4 VALVE ENGINES BY DOMESTIC AND IMPORT CLASSIFICATONS

The OHC engine has a more rigid valve train, which allows reduced valve spring tension, as well as higher valve accelerations, relative to an OHV engine. This results in reduced engine friction, improved combustion and reduction in pumping loss. Ford[1] has estimated the net benefits of OHC engines over OHV (2-valve) engines at constant displacement to be 1%. At constant performance, the net benefit is calculated by EEA as follows:

OHC to OHV benefit	**1%**
10 percent CID reduction	**3.8%**
5 percent axle ratio increase	**- 1.1%**

Total benefit	**3.7 percent**

Ford1/ has used slightly different factors in their assessment of the effect of displacement decrease and axle ratio increase, but has arrived at a similar net benefits estimate of 3.5 percent.

6.3 4-VALVE ENGINES

The calculation of DOHC 4-valve engine benefit is similar conceptually to that of the OHC engine to OHV engine benefit calculation shown above. It can be shown from actual 1988 data that a 4-valve engine of modern design is capable of producing 90 N-m of torque per litre and 60 to 65 BHP per liver of specific output. These values represent a 10 percent increase in torque and a 20 percent increase in peak power over an OHC 2-valve design.

The 4-valve engine has other features that impact fuel economy. First, the increased number of valves (4 vs. 2) causes some increase in valve train friction. The friction is not doubled because each valve is much smaller and lighter, and the valve spring tension is lower. Second, the 4-valve engine allows a better combustion chamber design, with a central spark plug.

For maximum fuel efficiency, Toyota[2] has developed a compact combustion chamber with a narrow included angles between intake and exhaust valves. Higher performance designs sacrifice this feature to maximize airflow and feature a large included angle between intake and exhaust valves.

Third, the central spark plug location and improved airflow characteristics allow the use of higher compression ratios. Many currently available 4-valve engines such as the GM Quad-4 and the Infiniti 2 litre already utilize a compression ratio of 10:1 which is one point higher than the ratios used in current OHC and OHV engines.

The constant performance comparison between OHC/2 valve and DOHC/4-valve requires that the 4-valve engine be 10 percent smaller than the 2-valve engine. Peak torque is constant while peak horsepower increases by 10 percent in this comparison. However, low-end torque (at 1500 RPM) is reduced in this comparison and axle ratio must be raised to preserve launch from rest.

The components of the fuel economy benefit estimate are as follows:

10 percent CID decrease	+ 3.8%
5 percent axle ratio increase	- 1.1%
Increase thermodynamic efficiency	+ 2.5%
Increase valve-train friction	- 0.5%
Decreased aerodynamic friction	+ 0.5%

Net benefit	+ 5.2%

In submissions to the OTA, Toyota[3] has suggested a 5.0 percent benefit for the 4-valve engine, consistent with the above estimate.

GM has provided[4] a very detailed comparison between two engines of near equal performance, in this case the advanced OHV 2.8 litre V-6 rated at 130 HP and the DOHC 4-valve 2.3 L (Quad 4) engine. Both engines were offered in 1988 in the same car (Pontiac Grand Am) with the same transmission and axle ratio. (Note that the EEA computations allow an increase in axle ratio to preserve low speed acceleration). In this case, the comparison is between a V-6 are a 4-cylinder engine which allows a further reduction in engine friction (see Section 6.4). The power and torque curves of the two engines are shown in Figure 6.3.

The 2.8L V-6 engine provided a fuel economy of 26.3 MPG composite while the Quad 4 was rated at 32.L MPG composite, a total increase of 22.4 percent. The GM detailed analysis allowed a breakout of the individual contributions associated with displacement reduction, improved thermodynamic efficiency and reduced friction. GM's estimates are compared to the EEA standardized estimates below:

	GM Estimate F/E Benefit	**EEA F/E Benefit**
Displacement reduction	12.0%	7.6%
Compression Ratio	2.2%	2.5%
Compact Chamber Design	2.4%	
4 vs. 6 cylinder Friction	2.4%	3.0%
OHV vs. Pushrods	2.4%	1.0%
Other	0.8	2.0*
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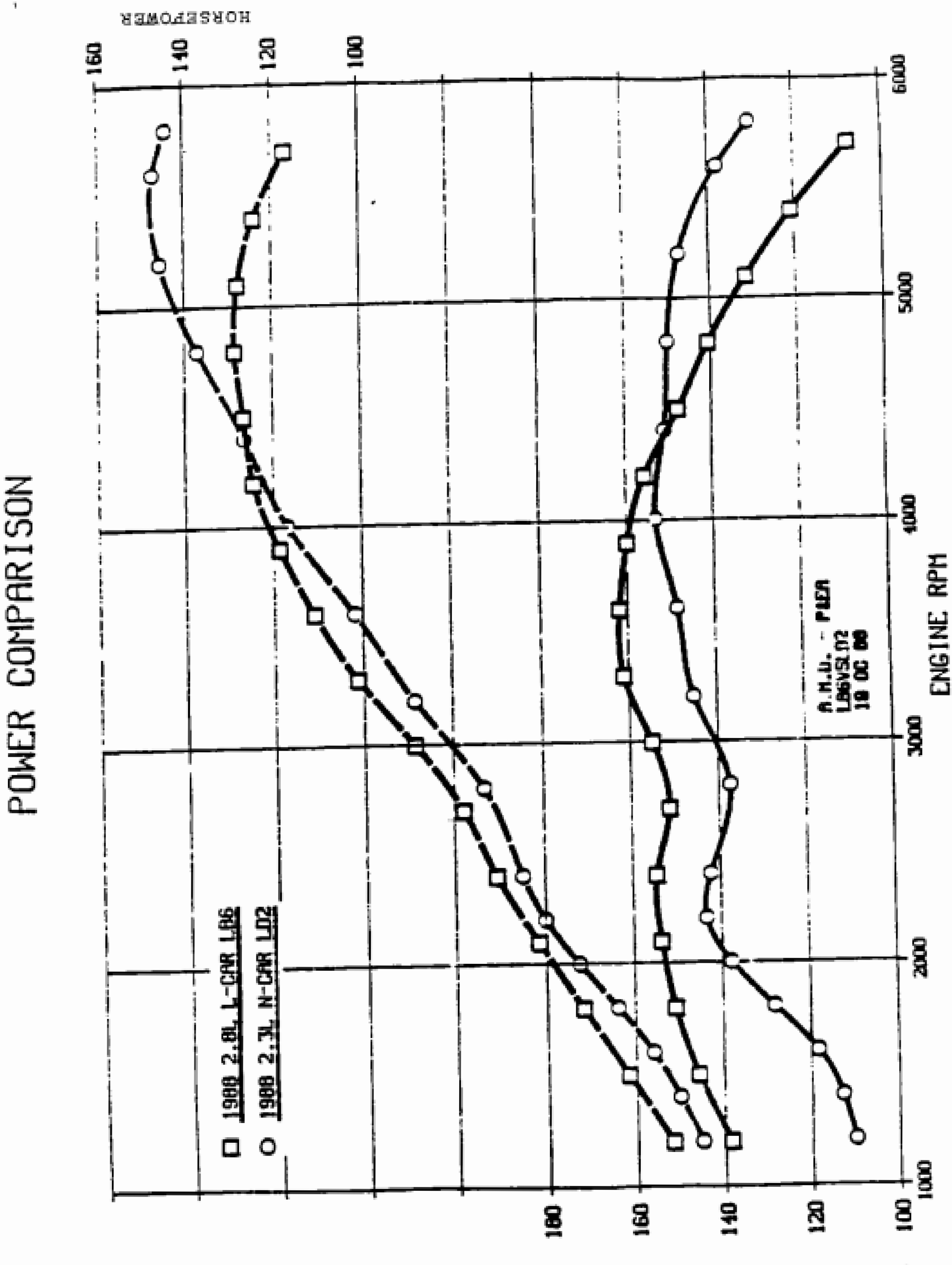
TOTAL	22.4	16.1

* EEA's estimate of friction reduction from more modern design.

FIGURE 6.3: POWER COMPARISON



The EEA estimate agrees with GM's in the total friction benefit but appears to significantly understate the benefit of displacement reduction and combustion chamber design improvement. This may be partially due to the fact that 2.8L V-6 is not one of GM's most efficient designs, but it clearly shows that the EEA estimates are conservative.

In addition, the EEA estimate allows for an axle ratio increase by 10 percent for the particular case examined by GM (5 percent for OHV to OHC/2V and another 5 percent for OHC/2V to OHC/4V), and it is noted that actual cars on sale do not necessarily follow this practice, as illustrated by GM's N-car. However, this is not a true constant performance comparison.

In EEA's comparison, the OHV 2.8L V-6 with a 2.84 axle and three speed automatic transmission can be replaced on OHC 2.5L V-6 with a 2.98 axle ratio, or DOHC 4-valve 2.3L engine with a 3.13 axle ratio. At 2000 RPM, it can be seen from Figure 6-3 that the Quad 4 provides 10 percent lower torque, which is exactly offset by the 10 percent axle increase ratio.

6.4 FUEL INJECTION

There are two types of fuel injection (FI) - single point (or throttle-body) injection (SPI) and multipoint fuel injection (MPI). SPI is used in all naturally aspirated 4-cylinder engines made by GM and Chrysler, as well as in a few low cost Japanese models and the Ford Escort in 1988. Most other vehicles use MPI. Carburettors are used in entry level Japanese models and Korean models in 1988, as well as in 2 old design V-8 engines among the domestic models.

The benefit of SPI over the carburettor has been documented in several submissions by the manufacturers to DOT in the early 1980's. A significant part of the gain in fuel economy is associated with the ability to eliminate the air pump required by carburetted vehicles to meet the emission standards. The air pump absorbs power from the engine and raises exhaust back pressure. It's elimination can result in a fuel economy benefit of 2 percent.

In addition, the SPI system results in reduced cold start enrichment requirements and less acceleration enrichment due to improved fuel atomization. These effects provide another 1 percent benefit, for a total of 3 percent. Many carburetted vehicles used pulse-air systems, so that their conversion to SPI did not include the benefit associated with air pump elimination, but did provide a modest back pressure decrease. For such vehicles, EEA has estimated a total benefit of 1.5 percent due to SPI largely from paired comparisons of 1984-1986 vehicles when conversion to SPI was the only change between otherwise identical vehicles in that time frame.

Multipoint fuel injection places the fuel injectors close to the intake valves of the engines, allowing very precise delivery of fuel to each cylinder. This results in further decreases to cold start enrichment and acceleration enrichment, and significantly improved control of fuel delivery during deceleration. These factors provide a 1.2 to 1.5 percent fuel economy gain, based on data provided by the manufacturers.

However, MPI also allows the use of a tuned intake manifold optimized for airflow. Such a manifold can provide a significant benefit to maximum torque. Torque benefits are available even without a tuned manifold since no intake air heating is required to vaporize fuel, and a colder denser air change increase the engine output. Regression analysis of 1988 engines showed the following benefits for MPI in specific output and specific torque relative to SPI, controlling for compression ratio:

	BHP/L	N-m/L
OHC	9.3%	2%
OHV	9.3%	3.4%

The OHC comparison is biased by the fact that more high performance engines (tuned for maximum BHP) utilize MPI rather than SPI. As a result, MPI shows a very significant rise in peak output of nearly 10 percent but only a 2 percent increase in torque. A more controlled comparison shows that MPI can provide a 3 percent increase in torque and a 6 percent increase in output. For a constant performance comparison, axle ratio must be reduced by 3 percent relative to an SPI engine of the same displacement.

Complete shutoff of fuel during deceleration is also possible with MPI. Some manufacturers believe that deceleration fuel shutoff causes unacceptable driveability, but it is used by others. Deceleration fuel shutoff can provide a one percent benefit in fuel economy. Accordingly, the total benefit of MPI over SPI is as follows:

Reduced cold-start and acceleration enrichment	1.20 to 1.50%
Decrease axle ratio by 3 percent	0.67%
Deceleration fuel shutoff	1.00%
Total	2.8 to 3.17%

EEA utilizes a 3 percent benefit estimate as an average. In 1986, when GM converted their 2.8L V-6 from a carburetted fuel system to a multipoint fuel injection system, they publicly claimed[5] a benefit of 7 percent in fuel economy. This is in good agreement with the 3+3 percent (6%) estimated by EEA.

6.5 ENGINE FRICTION REDUCTION

Engine friction reduction is an ongoing effort and is made possible by evolutionary improvements to all parts in the engine that contribute to friction. At an engine speed of 3000 RPM, the major components accounting for total frictional losses are pistons/rings, valve train, crankshaft and oil pump, in that order. While the friction losses of most components increase non-linearly with engine RPM, valve train friction actually declines slightly in absolute terms and significantly as a percentage of total friction.

Because of its larger contribution to total friction at low speeds, valve train friction reduction provides large benefits on the test cycle where engine speeds are typically in the 1000-2000 RPM range. Roller cam followers provide very significant reduction in friction, and most domestic OHV engines have (by 1990) utilized this technology. Detailed analysis by DOT and manufacturer submissions to DOT show that the use of roller cam followers can provide a 1.5 to 3 percent improvement in fuel economy.

This confirms an earlier (1982) analysis by Ford[6], that showed a 2.9 percent fuel economy improvement due to roller cams at an engine speed of 1500 RPM. The use of roller cams in OHC engines is more recent, and has been adopted by Chrysler and Mitsubishi.

Mitsubishi[7] provided data on an OHC engine as shown in Figure 6.4, an it is claimed that the EPA test cycle fuel economy benefit is over 4 percent. Other manufacturers have suggested that the benefit is sensitive to the base (non-roller) design, and a median benefit estimate of 2 percent has been adopted by EEA.

Piston redesign and decreases in ring tension and ring width contribute to a reduction in friction. Ring tension reduction and redesign alone has contributed to a 1.5 percent increase in fuel economy in some engines already. Improved piston design and lighter weight pistons have contributed to an additional 0.5 percent.

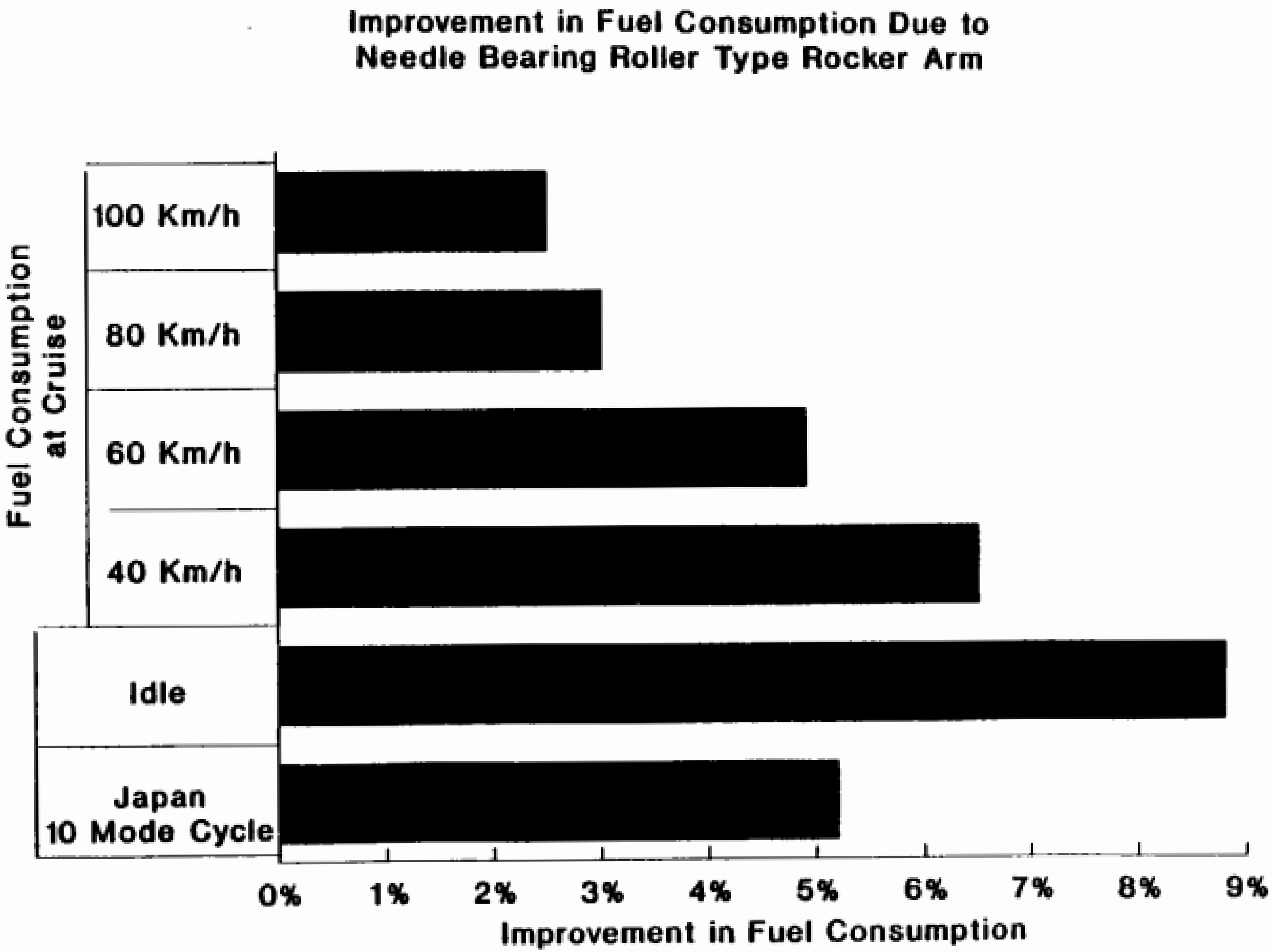
Typically, a 1988 4-cylinder engine has a friction mean effective pressure of 12 to 13 psi at 1500 RPM. Piston and ring redesign along with improvements such as:

- lightweight valves
- titanium valve springs
- composite lightweight connecting rod
- use of 2 rings instead of three
- half-speed oil pump
- low friction crankshaft seals

will all contribute to a 20 percent reduction in friction by 2001 (of course, individual engines may have larger or smaller reductions). A special low friction engine constructed by Ford[8] recorded a 4.3 psi reduction in friction even without a 2-ring piston, with a claimed fuel economy benefit of 6.5%. EEA forecasts a total benefit of 4 percent through improved design and an additional 2 percent through the use of roller cam followers over the 1988- 2001 period, consistent with Ford's estimate.

A separate issue centres around the reduction in number of cylinders. As engines of higher specific output and lower displacement are used, it would be reasonable to assume that a reduction in the number of cylinders is both feasible and likely. Consider a vehicle with an OHV 3.0L V-6 with an engine output of 135 BHP and 225 N-m of torque.

FIGURE 6.4: IMPROVEMENT IN FUEL CONSUMPTION DUE TO NEEDLE BEARING ROLLER TYPE ROCKER ARM



SOURCE: Mitsubishi

This can be replaced by an OHC V-6 of 2.7L displacement providing 140 BHP and 220 N-m of torque, or by DOHC/4V engine of 2.4L displacement producing 149 BHP and 216 N-m of torque. The 2.4L engine can either be a V-6 or an I-4, and the I-4 would have lower friction. Based on friction data collected from different engines EEA estimated that the friction benefit could be 14 to 15 percent, to provide a 3 percent benefit in fuel economy.

Ford[9] provided a detailed comparison of friction data for 2.3L engine in 4, 6 and 8-cylinder form. They also found that the larger bore of the 4-cylinder results in some thermal efficiency improvement. A similar comparison for a 4.5L V-6 vs. a 4.5L V-8 was provided and the data are shown in Table 6.2. The BSFC change for the smaller engine supports EEA's projections, but Ford claimed that the 4-cylinder would have higher idle and lug RPM levels than a V-6, negating this 3 percent benefit. (The same effect was claimed for the V- 6 to V-8 comparison). EEA has examined available idle RPM data from 4 and 6 cylinder engines and found significantly smaller difference than claimed by Ford.

In addition, we found that the 4-cylinder engine typically weighs 40-50 lbs. less than V-6 of equal displacement, and Ford had not considered this effect.

As a result, EEA has retained the 3 percent benefit estimate for reduction in number of cylinders. It is clear that 4-cylinder has inferior vibration characteristics relative to a V-6, and EEA recognises that the fuel economy benefit does result in some reduction to consumer attributes. However, we note that other technologies for engine mounts may counteract this effect completely.

The use of balance shafts on four cylinder engines will, however, negate the benefits of reduction in number of cylinders.

TABLE 6.2: EFFECT OF NUMBER OF CYLINDERS ON FUEL ECONOMY

	4-cylinder	6-cylinder	8-cylinder
2.3 Litre			
Thermal Efficiency	0.366	0.363	0.358
Friction MEP (psi)	12.4	13.9	15.1
% Change in BSFC	Base	-3.2	-6.2
4.5 Litre			
Thermal Efficiency	--	0.366	0.366
Friction MEP (psi)	--	11.5	12.5
% Change in BSFC	--	Base	-1.6

Source: Ford Motor Co.

Note: For Ford's comments see text on idle and lug speed capability.

REFERENCES FOR SECTION 6

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6. Kovach, T.J., et al, "Engine Friction Reduction for Improved Fuel Economy", SAE Paper 820085, 1982.

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8. Kovach, et al, Ibid.

9. Ford Motor Co., Technical Analysis Paper provided to DOE, July 1990.