Electric Cars

Report

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BUREAU OF TRANSPORT ECONOMICS

ELECTRIC CARS

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FOREWORD

It is becoming clear that the community will not accept the rising levels of air pollution caused by motor vehicles. One way of tackling the problem would be to use the electric car as a replacement for the ordinary motor car. This would also reduce noise in cities.

Two reports have been prepared in the BTE to review the state of knowledge in the field of alternative road vehicle technologies (the other being a report on liquefied petroleum gas as a motor vehicle fuel). This report, dealing with electric cars, has been prepared by W.P. Egan of the Transport Engineering Branch.

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Director

Bureau of Transport Economics,
Canberra,
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SUMMARY

The question of alternatives to the conventional car has assumed considerable importance in view of increasing concern about the effects of atmospheric pollution, traffic noise and energy resource allocation. While there are many possible measures which might reduce reliance on the internal-combustion car (not the least of such possibilities being improved public transport), the electric car is one alternative which appears to offer clean and quiet personal transport within the existing road traffic framework.

The BTE has undertaken a study of the possible introduction of electric cars in Australia. The results are presented in this report.

Basically, the report establishes the patterns of motor vehicle ownership and use in Australia, examines the technical and operational features of electric cars, and assesses the environmental and economic impacts of a significant swing to such vehicles.

The particular aspects of electric cars which are treated in detail are their performance characteristics and their effects on atmospheric pollution, noise, energy resources and the economic infrastructure of transport. In order to establish performance and energy use characteristics in an authoritative manner, considerable emphasis has been placed on the likely design parameters of battery cars which could have a significant market appeal. The actual performance of such cars is analysed by modelling techniques.

The general conclusion of the report is that, despite limitations on range and performance, battery cars could be acceptable, for some types of urban travel, in their present state of development. However, under existing market conditions, it is unlikely that such vehicles would gain wide public acceptance. This situation could be reversed by deliberate regulation, by significant technical improvements in battery cars, or by increased operating costs for conventional cars.

Widespread use of electric cars would assist substantially in reducing pollution and noise in urban areas without depriving the community of the personal convenience of private motor cars.

CHAPTER 1 INTRODUCTION

In a limited history of some three-quarters of a century, the motor car and its derivatives (trucks, buses, motor cycles and the like) have secured a central and dominant role in the transport activities of the modern world. At all steps in its development, the car has been subject to various types of criticism. In the early stages, it was suggested that man could not survive at the speeds envisaged for car travel, and that the effects on horses would be detrimental to the society of the times. More recently, there has been a growing awareness of the social and economic evils associated with the widespread and growing use of car travel. In particular, the effects in urban areas of emissions from internal-combustion engines have come to be regarded as a pressing problem which requires urgent solution. Other adverse effects of automotive travel are the growing expenditure of national resources on providing facilities (roads and parking areas, amongst others), the materials (particularly oil) which are utilised in a relatively inefficient manner, and the increasing economic reliance on the production of motor vehicles. The heavy toll of road accidents is another serious disadvantage of road travel in its present form.

There is a widespread tendency to emphasise the demerits of the car and its position in society without giving due weight to its considerable beneficial effects. At present, the car and its associated road system provide an extremely flexible method of transport at a realistic cost. Alternative systems currently available suffer from either reduced flexibility or increased cost - in some cases, both. Some emerging transport technologies promise to provide flexibility acceptably close to that of the car, at similar cost, but such systems are unproven as yet. The major favourable attribute of the car is, therefore, its capability of providing a very large proportion of the population with a relatively inexpensive method of transport which is flexible and highly demand-oriented. In the words of Sir Colin Buchanan:

'Individual manufacturers obviously seek to promote the sale of one make of car rather than another, but I have no doubt that the real reason why people buy cars is because they are such extraordinarily useful and attractive things.

Status-seeking, "keeping up with the Joneses", are irrelevant side-tags - it is the sheer convenience of the car that is its own best salesman. We ignore this fact at our peril.'(1)

Like most useful devices, the car has a number of drawbacks, some of them severe. As a result, there is a continuous effort on the part of various sectors of the community to alleviate some of these disadvantages. In the extreme, some of these attempts are aimed at complete elimination of the car, at least in certain circumstances. These efforts ignore the degree to which modern transport depends on automobile-based equipment of one type or another. A more logical approach is to attempt to eliminate, or at least diminish, some of the more significant disadvantages of the present type of motor car. In the long term, the car in its present form may well be supplanted by some completely different alternative technology, but the concept of a personal, flexible transport system is likely to be retained.

In considering alternatives to internal-combustion automobiles, there is one perennial favourite - the electric car. While this type of vehicle might have no substantial effect on road congestion, accidents or the resources involved in automobile manufacture, its introduction in substantial quantities would certainly bring about a significant, dramatic

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(1) From an address to a conference organised by the Institutions of Highway Engineers and Structural Engineers, 1973. Professor Buchanan is author of Traffic in Towns, a milestone in the public presentation of the problems of urban traffic. However, in this address he presses for moderation of the current vociferous attack on motor vehicles as a form of transport.

and permanent reduction in urban atmospheric pollution. It could also use a readily available resource for its motive power - off-peak electricity. The electric car is, therefore, an extremely attractive proposition, at least at first glance.

However, these advantages would be obtained at a considerable price. Although electric-powered (and particularly battery-powered) vehicles have established a firm position in certain specialised applications (e.g. milk delivery trucks, industrial trucks and golf carts), their general application is inhibited by severe deficiencies in performance. Although current and future developments will possibly enhance their performance considerably, it is unlikely that cars powered by batteries alone will approach the performance capabilities of internal-combustion vehicles within the foreseeable future. Nevertheless, battery-powered vehicles of various types are already operating in considerable numbers, and the possibility of successful development of battery cars of adequate performance for a specific range of personal transport tasks clearly cannot be overlooked.

In this report, many of the central issues in electric car development are appraised. The emphasis of this appraisal is deliberately oriented to the car, since this particular class of vehicle occupies such a predominant position in a modern transport system. Although electric power may be applicable as an alternative power source for other vehicles (such as buses and trucks) in certain circumstances, the most significant pollution and energy resource problems in transport are clearly those of the car.

Consideration of any alternative to the car in its present form must involve many factors. Some of these factors are economic, but the technical and social implications of an alternative technology are clearly important, as well. A major part of this report is devoted to a parametric analysis of the levels of performance likely to be achieved by battery cars.

The analysis, used in conjunction with considered estimates of vehicle parameters, would be useful in planning the development of such cars, and also gives substantial data on related factors such as electrical power consumption. Although there is considerable emphasis, in the report, on the power consumption of electric vehicles, a wide range of other related topics is treated, including:

- car ownership, use patterns, characteristics and emission properties in Australia;
- characteristics of different electric vehicle systems;
- implications of a substantial conversion to electric cars as an alternative to internal-combustion cars;
- research and development requirements for electric car implementation; and
- possible advanced electric vehicle systems which might merit further investigation.

The electric car has generated wide publicity because there are many experimental vehicles in existence. This is a function of the fact that limited-performance electric vehicles of various types can be assembled from readily available components, even by amateur effort. This is at once an advantage and a disadvantage, since it leads to a notion that electric car technology is simple, without giving due weight to the many serious limitations and complications involved in wide public acceptance of such vehicles. A further result is that there is a large body of literature on the subject which is uncoordinated and, in some cases, misinformed. This report represents an attempt to clarify at least some of the issues involved.

CHAPTER 2 CARS IN AUSTRALIA

The importance of the car as a universal and flexible method of transport has already been asserted. However, a useful assessment of the impact of alternatives to the internal-combustion car involves some comparison with quantitative properties of the car, both as an item of equipment and as a social and economic phenomenon. In this Chapter, relevant details of the motor car in Australia are presented.

CAR REGISTRATION

At the present time, the total motor vehicle registration of Australia is approaching 6 million vehicles, of which approximately 80 per cent are classified as cars or station wagons[1]. The number of cars has been growing in recent years at a rate in excess of 5 per cent per annum, which is over 2.5 times the rate of growth of the nation's population in a similar period. It is interesting to note that the annual numerical growth in cars is currently closely parallel to that of the population.

The numbers of motor vehicles on register[2] and the population of Australia[3], for the period 1930 to 1973 (and extrapolated to 1980), are shown in Figure 2.1. On the basis of these figures, it can be reasonably postulated that the total number of motor vehicles in Australia will exceed 7 million by 1980, and that almost 6 million of these vehicles will be cars (including station wagons). While it is extremely unlikely that these trends will continue indefinitely, it is clear that the car occupies an important position in the national transport network, and that this position is unlikely to be eroded significantly in the near future.

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(1) Australian Bureau of Statistics, Motor Vehicle Registrations 1972, May 1973.

(2) Actual values from: Australian Bureau of Statistics, Transport and Communications Bulletin No. 61, July 1971.

(3) Actual values from: Australian Bureau of Statistics, Year Book - Australia 1972, December 1972.

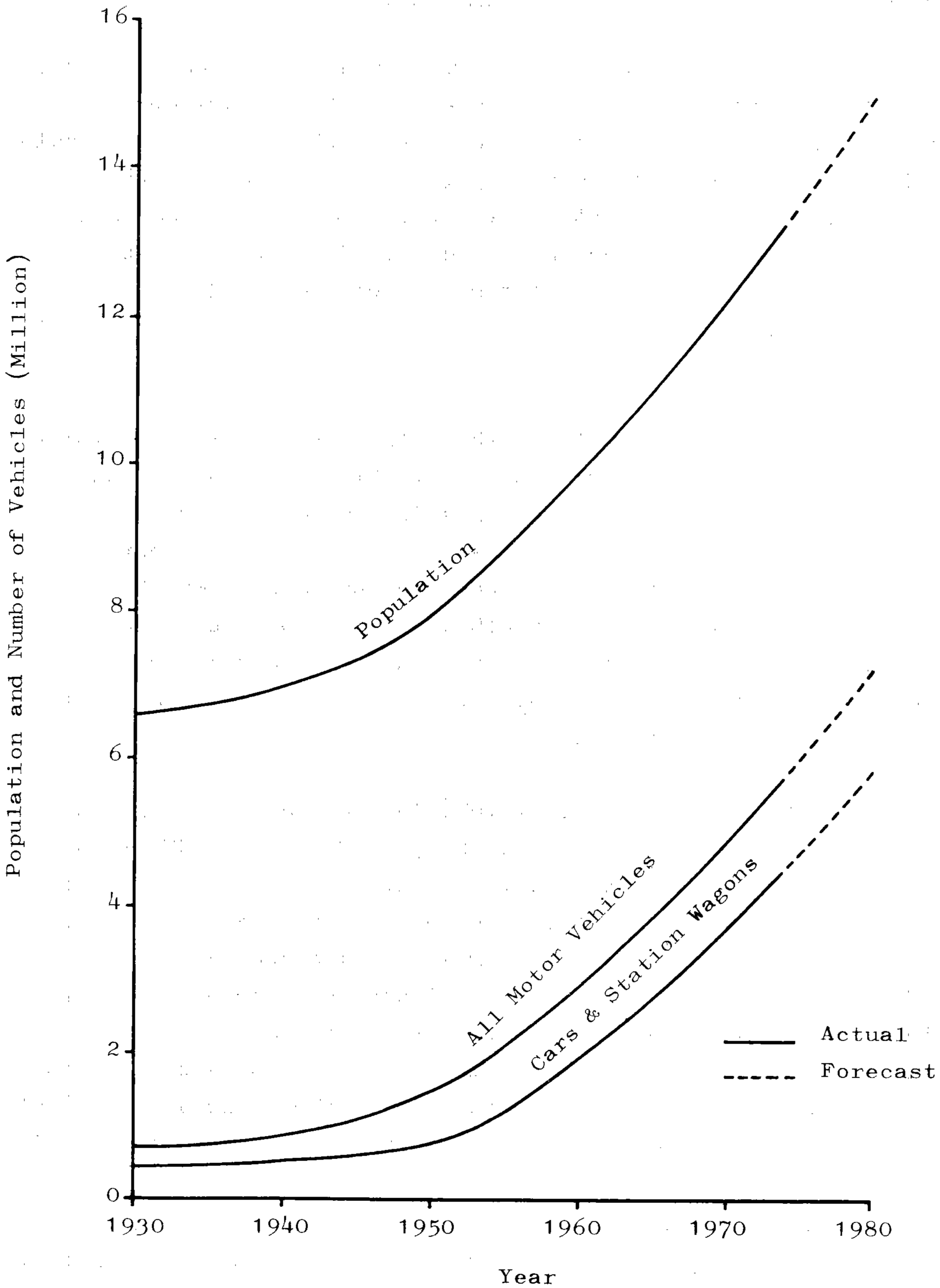

FIGURE 2.1 - POPULATION AND MOTOR VEHICLES, AUSTRALIA

MOTOR VEHICLE MANUFACTURE

The magnitude of motor vehicle manufacturing operations is shown by the fact that the value added in production of motor vehicles and parts amounted to $623m, or 7.5 per cent of the total value added in all production by Australian manufacturing establishments in the year 1969-70.[1] The value of output in the motor vehicle sector is a much higher figure again. Associated with the actual production of motor vehicles, of course, is a very high level of expenditure on petroleum products, road maintenance and construction, and repairs to vehicles.

OWNERSHIP PATTERNS

The growth in the number of cars per head of population is shown in Figure 2.2. Although this index of motor vehicle ownership cannot be expected to continue to rise indefinitely at the present rate, it is likely that its value will be in the vicinity of 0.40 by 1980.

Geographically, most cars are situated in major population centres. Australia is highly urbanised, with 65 per cent of the population dwelling in ten major population centres (i.e. centres of more than 100,000 residents)[2]. As a consequence, the bulk of the vehicle population is concentrated in relatively few areas. To an even greater extent, the problems associated with the car as a means of transport are largely concentrated in these areas. Of all new motor car and station wagon registrations in 1972, two-thirds were recorded in the six capital cities and the Australian Capital Territory[3].

An important measure in assessing the acceptability of alternative car propulsion systems is the distribution of cars

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(1) Australian Bureau of Statistics, Manufacturing Establishments 1969-1970, April 1973.

(2) Year Book - Australia 1972, op. cit.

(3) Motor Vehicle Registrations 1972, op. cit.

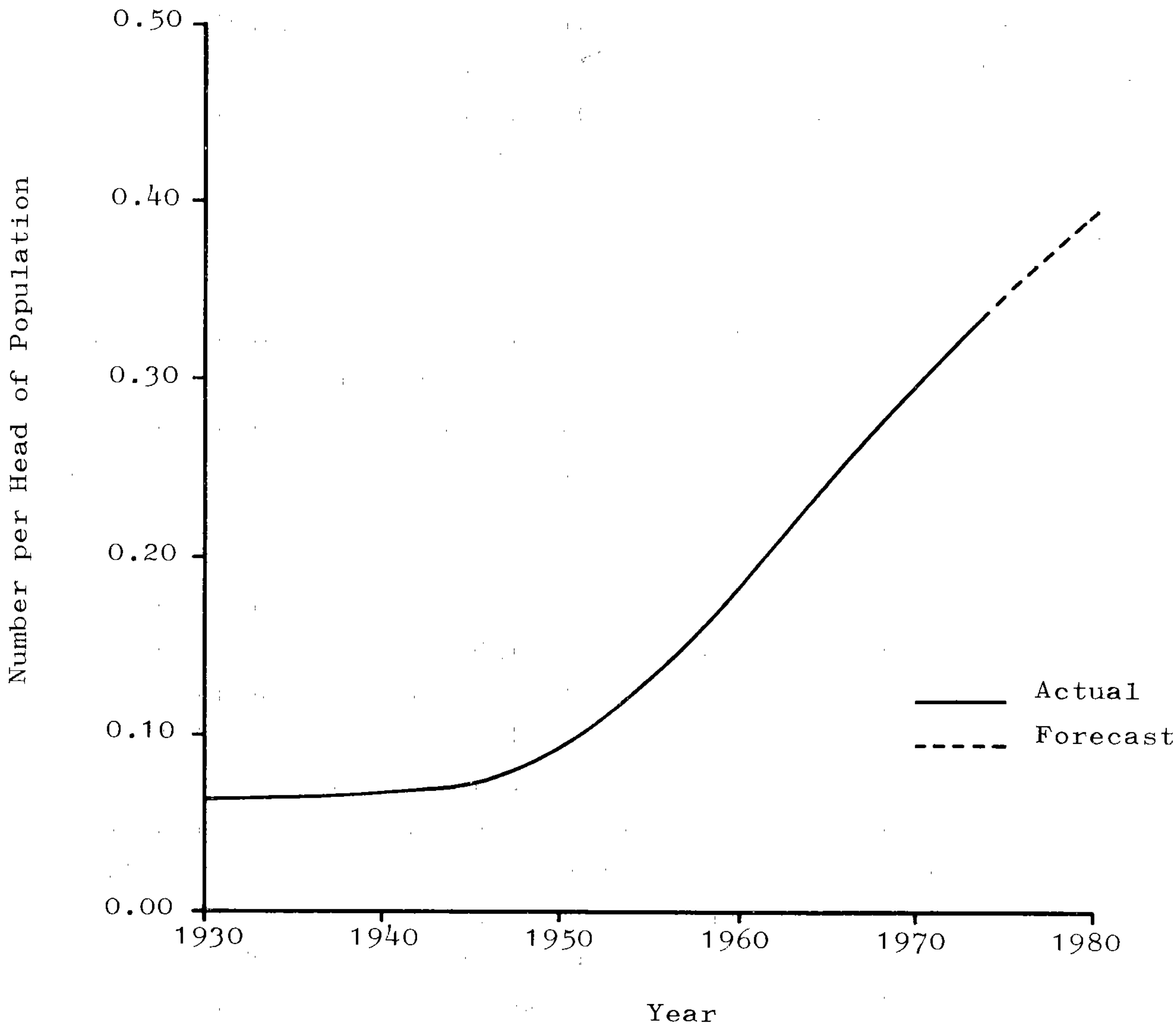

FIGURE 2.2 - MOTOR CARS AND STATION WAGONS PER HEAD OF POPULATION

amongst households. It is anticipated that 'second' and subsequent cars owned by a household are the prime targets for replacement by an alternative form of automotive transport. A distribution of car ownership for 1971, together with a projected distribution for the year 1980(1), is shown in Figure 2.3. From these figures, it is possible to estimate the number of 'first' and subsequent cars which are included in the overall privately-owned car fleet. Values for these quantities are given in Table 2.1.

TABLE 2.1 - DISTRIBUTION OF FIRST AND SUBSEQUENT CARS

	Proportion of Cars	
	1971	1980
	%	%
First cars	68.1	64.7
Second cars	24.8	27.5
Third cars	5.6	6.2
Fourth or subsequent cars	1.5	1.6
TOTAL	100.0	100.0
Cars per household	1.16	1.30

The significance of these figures is that the number of first (and presumably all-purpose) cars on register will drop somewhat as a proportion of all cars, over the next decade. The scope for an alternative technology for subsequent cars is therefore increasing with time.

CAR CHARACTERISTICS

The economic and market mechanisms which are involved in manufacture and sales of cars are quite complex, but the actual sales follow a quite distinct pattern. In the absence of a readily available body of information on the characteristics

(1) Derived from values in: Commonwealth Bureau of Roads, Report on Roads in Australia 1973, November 1973.

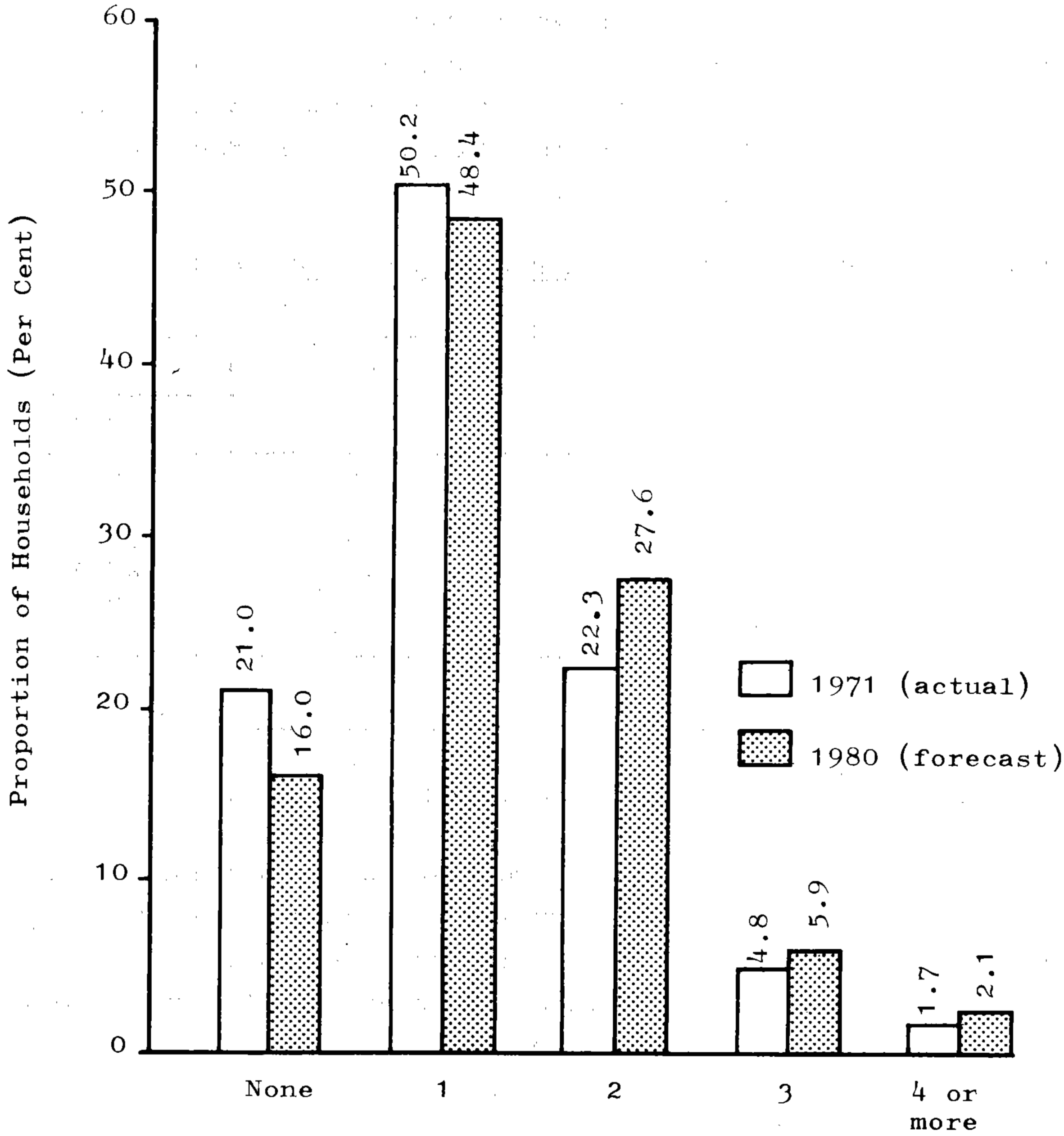

FIGURE 2.3 - DISTRIBUTION OF CAR OWNERSHIP

of cars in Australia, the BTE undertook a limited survey of particulars of cars newly registered in 1972[1]. In the context of replacing cars with an alternative, it is useful to have a measure of the size and power of the present vehicle types.

On the basis of data obtained from the sample of 1972 cars registered in Australia, the distribution of overall car lengths shown in Figure 2.4 was obtained. The major implication of this distribution is that there is a marked preference for larger cars. While the cars comprising the largest market share are not nearly so large as their United States counterparts, they are, nevertheless, fairly large by world standards. At the same time, smaller cars are gaining an increasing share of the new car market in Australia. This latter fact is somewhat misleading, however, since the relatively small car in Australia today (i.e. a car around 4 metres in overall length) is larger than a car which might have been considered small in the past.

Hand in hand with the tendency towards ownership of larger cars is the high proportion of cars with large engines. In the sample assessed by BTE, fully 64 per cent of the cars were powered by engines of 6 or more cylinders. A distribution of the number of cylinders for the 287,881 cars included in the sample is shown in Figure 2.5. The advertised powers of the cars were also considered, and a distribution of this parameter is shown in Figure 2.6.

This information indicates that current Australian cars are both relatively large and high-powered. These characteristics are reflected in fuel consumption statistics. Typical fuel consumption values under a range of driving conditions are given in Table 2.2[2]. Although there is

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(1) The sample comprised the best-selling 81 per cent of new car registrations in 1972. A more complete description of the sample, together with further characteristics of the cars, is given in Annex D.

(2) Periodically published road test figures produced by the National Road Motorists Association (NRMA).

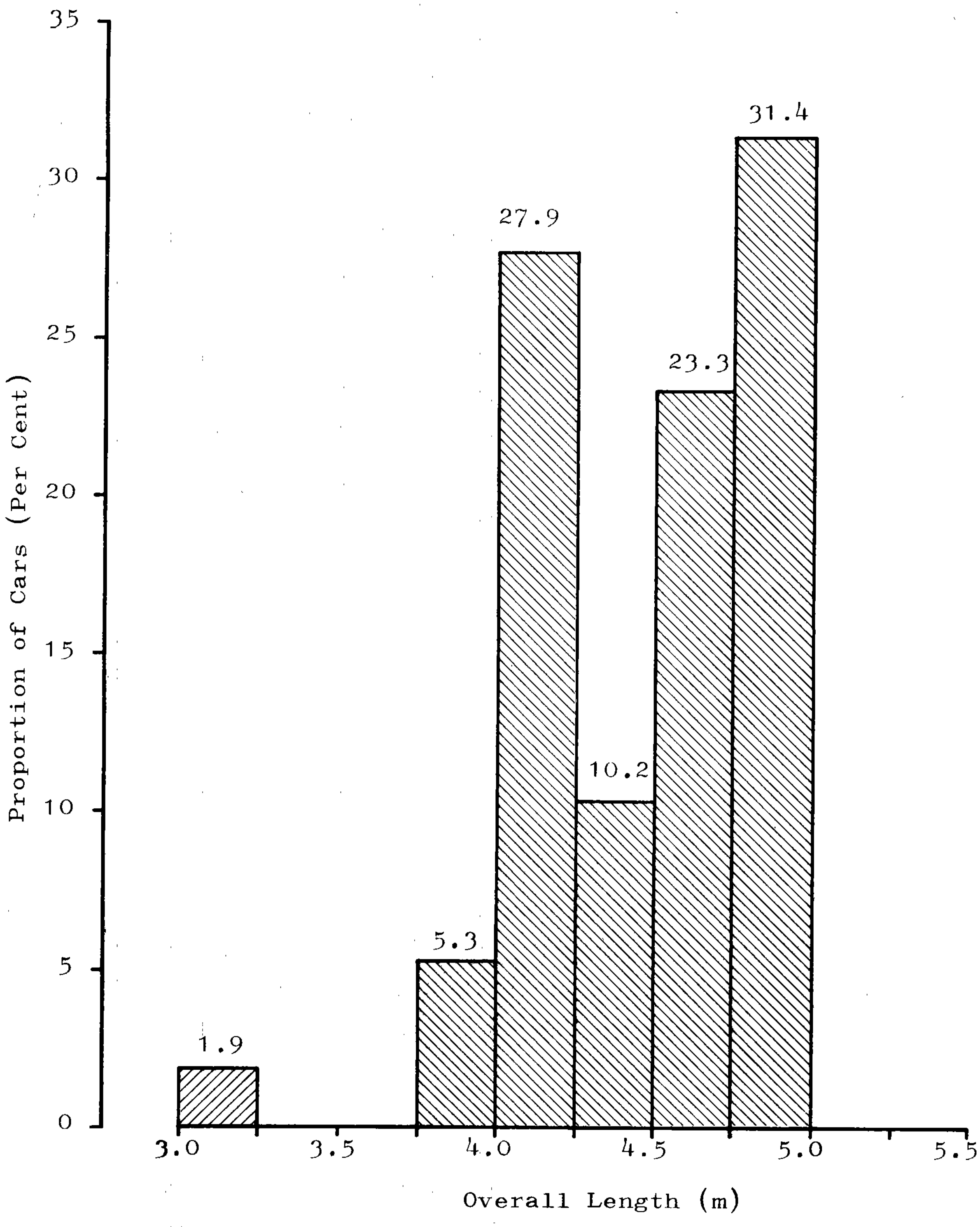

FIGURE 2.4 - DISTRIBUTION OF OVERALL LENGTH OF CARS (1972 MODELS)

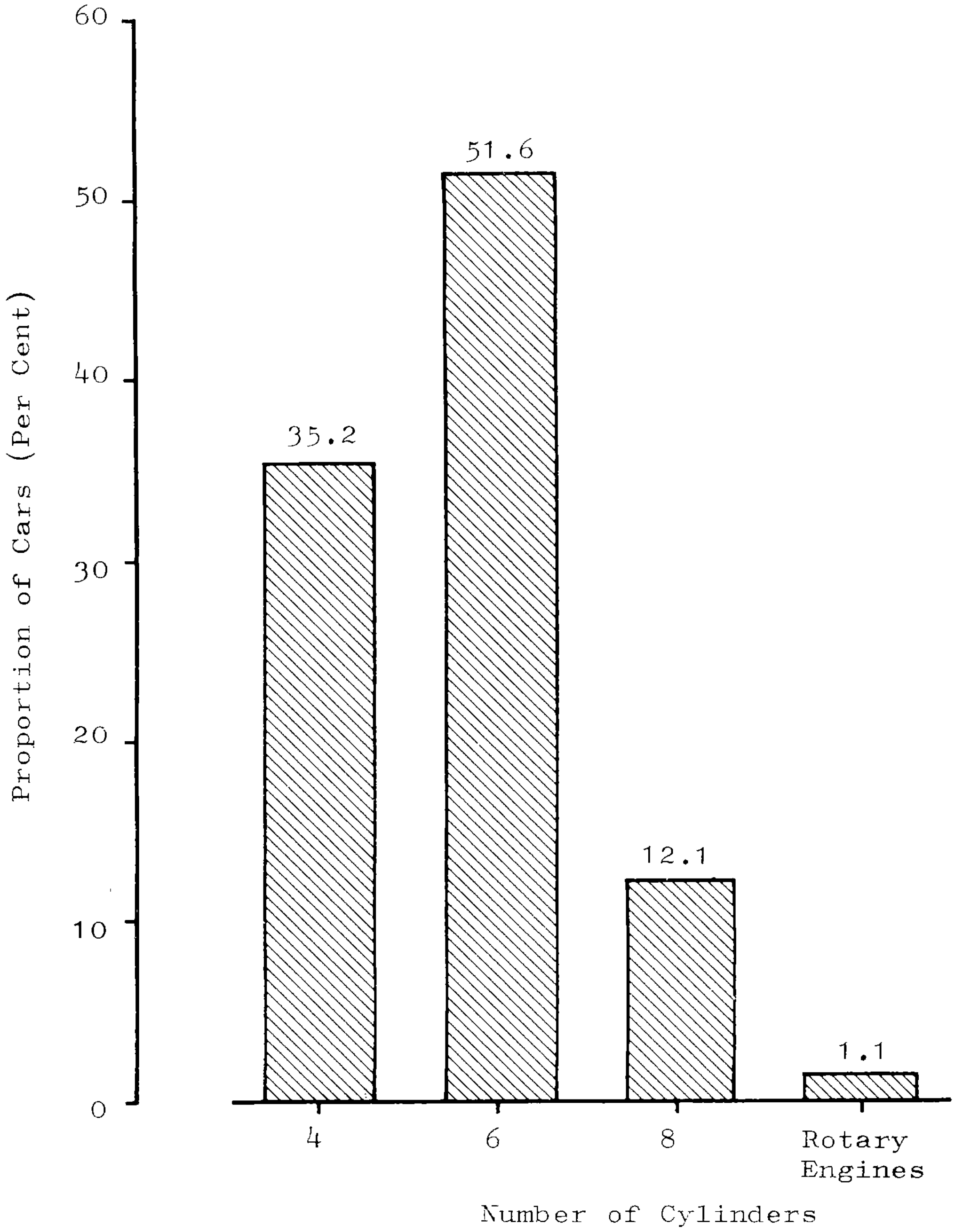

FIGURE 2.5 - DISTRIBUTION OF NUMBER OF CYLINDERS (1972 MODELS)

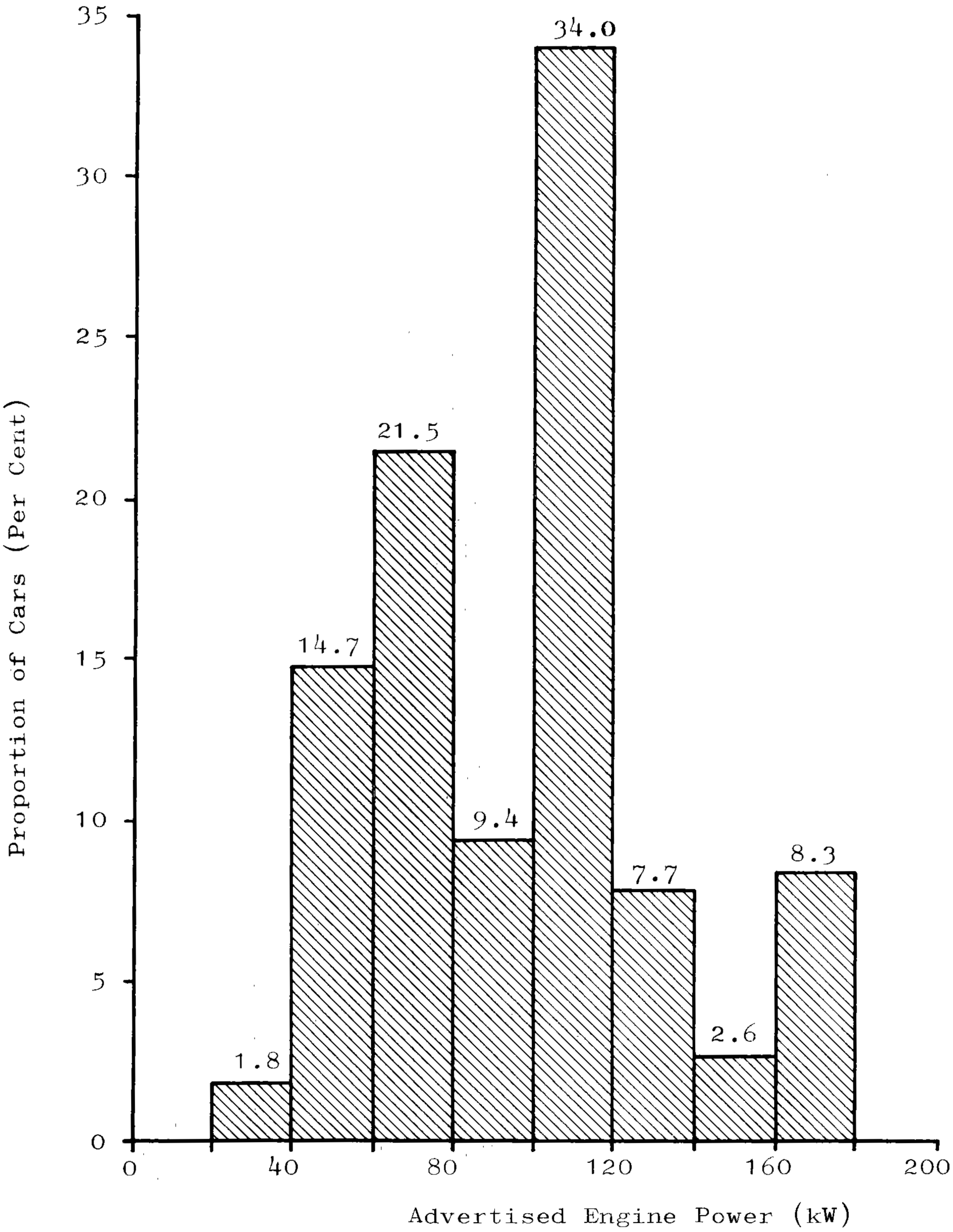

FIGURE 2.6 - DISTRIBUTION OF ADVERTISED ENGINE POWER (1972 MODELS)

obviously a substantial variation of actual consumption with variations in driving conditions, the ranges given are reasonably representative of figures likely to be obtained.

TABLE 2.2 - TYPICAL FUEL CONSUMPTION FIGURES

No. of cylinders	Consumption (km/litre)
2	14 - 18
4	8 - 13
6	6 - 9
8	4 - 7

A survey of all Australian States in 1971[(1)] indicated that the overall average fuel consumption for cars and station wagons was around 8 km/litre. This average figure is compatible with the consumptions indicated in Table 2.2 when the preponderance of 6-cylinder cars is taken into account. In fact, application of the distribution in Figure 2.5 to the central points of the consumption ranges in Table 2.2 yields an average value quite close to 8 km/litre.

The performance capabilities of most cars marketed in Australia are undoubtedly well in excess of their performance requirements. The majority of cars have top speeds in excess of 150 km/h, when the trend in legislation is towards absolute rural speed limits of 100-115 km/h. Equally, the acceleration capabilities of many of the cars available could well be dangerous if applied in normal traffic conditions. As a comparison, acceleration curves for representative 4-cylinder, 6-cylinder and 8-cylinder cars produced recently[(2)] are shown in Figure 2.7. The practical operating range of Australian cars is generally of the order of 350 km on a single tank of fuel. However, the operating range of internal combustion vehicles can be readily extended if required.

(1) Australian Bureau of Statistics, Survey of Motor Vehicle Usage 1971, September 1973.

(2) Published newspaper road test figures.

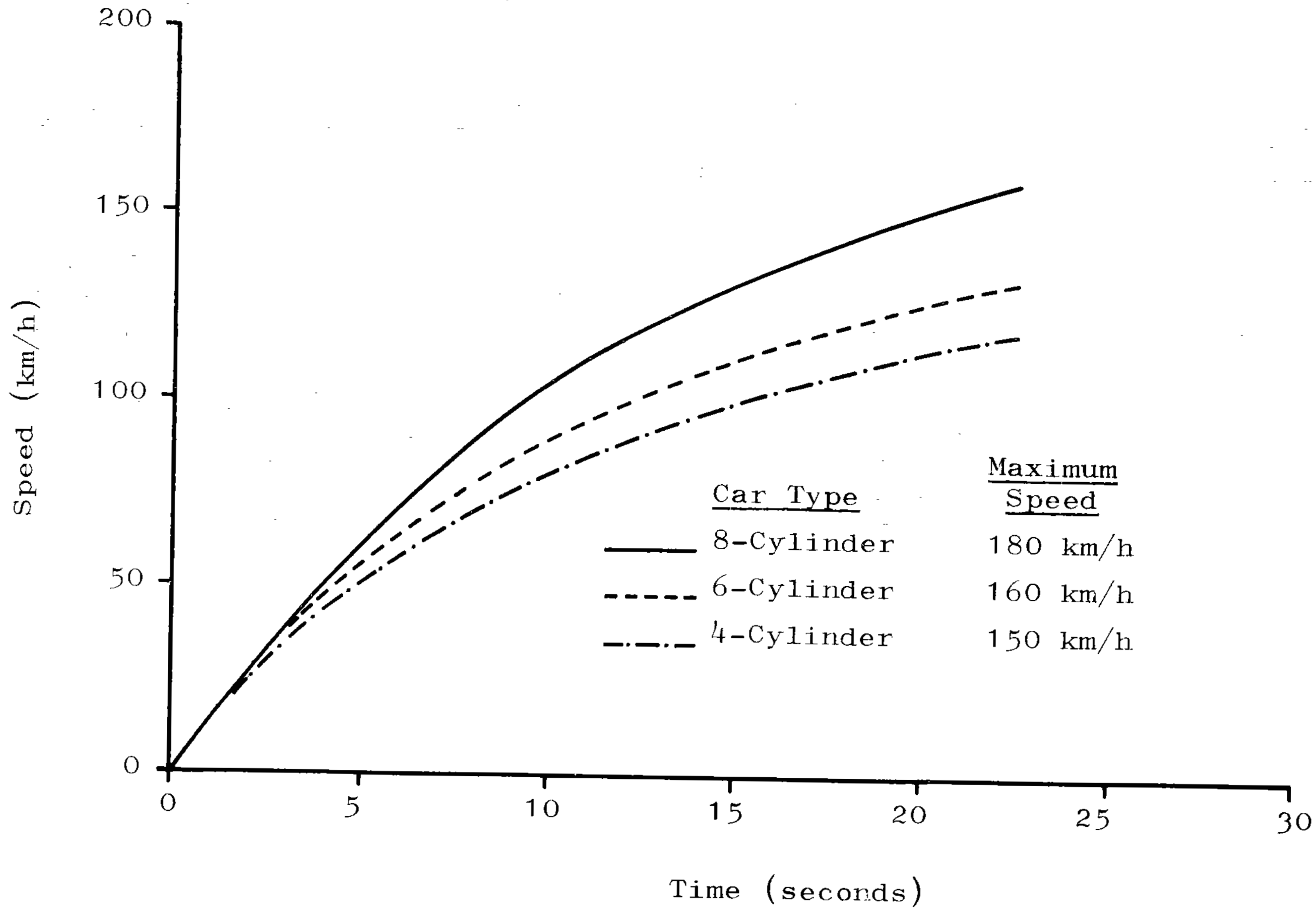

FIGURE 2.7 - REPRESENTATIVE ACCELERATION CURVES (1973 MODELS)

CAR USE PATTERNS

The latest available information[1] suggests that the total annual distance travelled by all vehicles on the Australian road system was approximately 80.5 x 10^9 km in 1970-1971. Of this total travel, 42.6 x 10^9 km (or 53 per cent) was performed in the capital city urban areas[2]. A further 6.5 x 10^9 km was performed in provincial urban areas. In the same period, 3.99 million cars and station wagons were registered in Australia, and the average annual distance travelled by these vehicles in capital cities amounted to 8,370 km. On the basis of these figures, it can be deduced that over 78 per cent of all motor vehicle travel in capital cities was performed in cars (including station wagons). The overall average distance travelled by cars (on an Australia-wide basis) was around 15,900 km. The use of cars outside urban areas was therefore quite high. Of all road travel in Australia (measured on a vehicle-kilometre basis), almost 80 per cent was performed in cars or station wagons. Detailed travel statistics relating to car usage in Australia are set out in Table 2.3.

TABLE 2.3 - DISTANCES TRAVELLED BY MOTOR VEHICLES, 1970-71

Area of operation	Cars[a]	Other	Total
TOTAL DISTANCES TRAVELLED (10^9 KM)			
Capital cities[b]	33.4	9.2	42.6
Provincial	5.1	1.4	6.5
Other areas	25.0	6.4	31.4
Total	63.5	17.0	80.5
PROPORTION OF DISTANCE TRAVELLED (PER CENT)			
Capital cities[b]	41.5	11.4	52.9
Provincial cities	6.3	1.7	8.0
Other areas	31.1	8.0	39.1
Total	78.9	21.1	100.0

(a) Includes station wagons. (b) Includes A.C.T. and Darwin.

(1) Derived from: Survey of Motor Vehicle Usage 1971, op.cit.

(2) Includes the Australian Capital Territory and Darwin.

The major emphasis of this report is centred on replacements for the car, specifically in the urban context. It is not envisaged that the electric car, in particular, will threaten the internal-combustion car for extra-urban or inter-urban travel for some considerable time. Accordingly, it is necessary to consider the nature of trips undertaken by cars, in urban areas, in some detail.

The primary sources of coherent information on urban travel are the transport studies carried out in major cities. To date, such studies have been carried out in five of the six Australian State capitals (Sydney is the exception - its study was not complete by March 1974). Amongst a great deal of information relating to travel patterns of all kinds, such studies usually contain information on the length of trips undertaken in cars. The lengths are generally organised on a time basis. This information was examined by BTE to obtain a picture of the nature of car trips in the major Australian cities. Since the information was not presented in a standard manner, it has been subjected to some manipulation, and the values obtained can only be regarded as approximate. Similarly, the studies were carried out at different times, which means that they are not strictly comparable. Nevertheless, they serve to illustrate the nature of car trips in major Australian cities.

In this analysis, the lengths of car trips have been considered on a vehicle (as opposed to occupant) basis, so that the actual operation of the vehicle has been considered. Trips of all purposes are aggregated, so that the figures represent all types of trips (work, social, etc.). Cumulative trip length distributions on this basis are shown in Figure 2.8 for Melbourne(1), Brisbane(2), Perth(3) and Hobart(4). Appropriate information to generate a trip length distribution for Adelaide was not readily available.

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(1) Wilbur Smith and Associates, Melbourne Transport Study - Volume 1: Survey, 1969.

(2) Wilbur Smith and Associates, South-East Queensland - Brisbane Region Public Transport Study, 1970.

(3) Perth Regional Transport Study, 1970.

(4) Wilbur Smith and Associates, Hobart Area Transport Study - Volume 1, 1965.

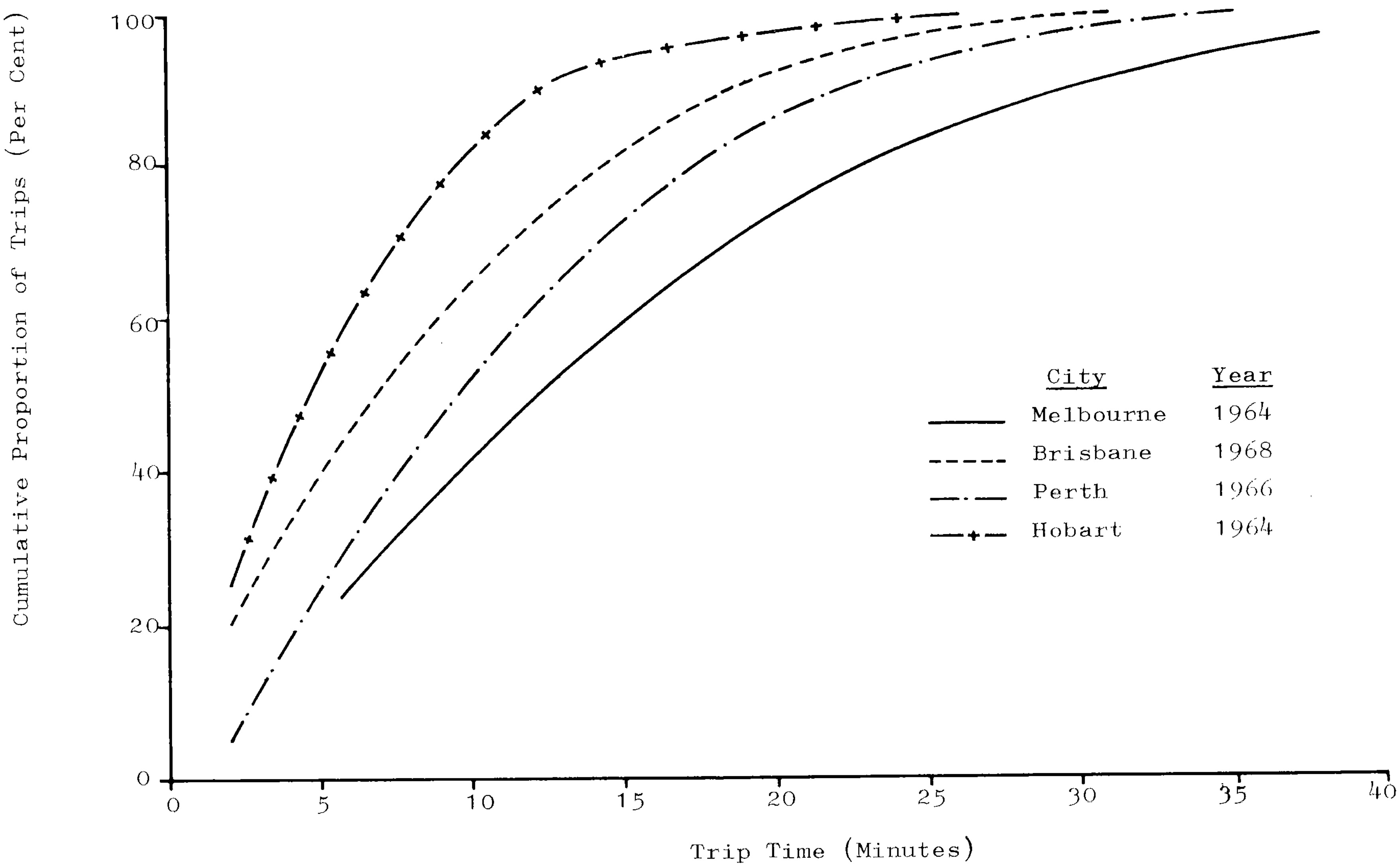

FIGURE 2.8 - CUMULATIVE DISTRIBUTION OF CAR TRIP LENGTHS

The outstanding feature of these distributions is that they demonstrate that individual car trips are extremely likely to be of short duration. Average trip times, together with the times corresponding to particular points on the cumulative trip length distributions, are shown in Table 2.4 for each of the four cities considered.

TABLE 2.4 - REPRESENTATIVE CAR TRIP LENGTH CHARACTERISTICS

	Melbourne	Brisbane	Perth	Hobart
Study year	1964	1968	1966	1964
1971 population (million)	2.39	0.82	0.64	0.13
Average trip length (minutes)[a]	12.0	11.5	14.3	7.6
50% point (minutes)[b]	12.5	7.0	10.0	5.0
75% point (minutes)[b]	21.0	13.0	16.0	9.0
90% point (minutes)[b]	30.0	19.0	22.0	13.0

(a) Estimated value for Perth. Study values for Melbourne, Brisbane and Hobart. (b) These figures should be regarded with caution, since the widely differing methods of presenting the basic figures caused considerable approximation in their derivation.

Although the average times for trips undoubtedly increase with growth in population and other time-dependent urban characteristics, it is clear that the range demands of many automobiles, in day-to-day urban travel situations, are certainly not excessive. While travel speeds depend on road network traffic conditions and other factors, it is probably correct to state that individual car trips of greater than 15 km in length are the exception, rather than the rule. The values derived here are not, incidentally, atypical of overseas experience. For example, a 1967 study[1] in the United Kingdom indicated that:

(1) Mary Lee, 'Electric Vehicles', Science Journal, March 1967.

'Approximately 80% of cars on the road travel less than 30 km per day, and this (distance) figure is decreasing.'

A similar study in Greater London showed that 700,000 commuter cars made average daily journeys of less than 8 km to work, with an average car occupancy of 1.2.

A major problem in determining car usage patterns is that averages do not give a complete picture. For instance, the figures provided in Table 2.4 indicate the overwhelming proportion of short car trips. Nevertheless, an outstanding feature of the modern car is its ability to act as a combined cargo and passenger transport medium for longer trips (e.g. holidays). Although such trips are a small fraction of all car trips, they are undoubtedly important in the eye of the consumer. In terms of marketing an alternative power unit for cars, it is essential that expanded information on car travel patterns should be obtained. Particular facets of car use patterns which warrant in-depth examination (perhaps by a special survey on an appropriate sample) are:

- overall daily use patterns for individual cars in various ownership categories (e.g. private, business);
- longer term (weekly and monthly) use patterns for individual cars; and
- estimates of the longest trips ever likely to be made by individual cars.

The emphasis on individual cars in this list of suggested research is a result of the general-purpose nature of cars. The aggregated values provided by transport studies are oriented towards transport facilities planning, and they can only provide a guide to the nature of actual car usage patterns. In particular, the fact that average car trip lengths for a city may be a certain value implies little about the likely extreme uses of individual cars in specific categories.

Nevertheless, the information available suggests that the major urban uses of cars are not particularly demanding in terms of range performance. Several methods are available for increasing the attractiveness of car engine alternatives which may be adequate in this limited role, but deficient in certain other, less frequent, roles. Some of these methods are described in Chapter 4.

Two further characteristics which bear directly on alternatives to the car in its present form are its seating requirements and the number of trips it is likely to make in a day. As a rule, transport studies give such data for work-day travel, and derived values for the five Australian State capitals for which studies have been performed are presented in Table 2.5.

TABLE 2.5 - CAR OCCUPANCY AND TRIPS PER DAY

City	Study year	Average occupancy	Trips per day(a)
Melbourne	1964	1.41	1.99
Brisbane	1968	1.62	3.09
Adelaide	1965	1.49	2.69
Perth	1966	1.35	3.49
Hobart	1964	1.65	1.85

(a) Trips by cars, not person trips in cars.

Again, these figures suffer from the fact that the real situation is not well-described by average values. In common with the trip characteristics given in Table 2.4, they are affected by the disadvantage of ignoring the socially important week-end trips. Nevertheless, they are valuable in determining the actual nature of the uses to which cars are applied in normal circumstances, and the occupancy figures, in particular, are revealing.

ATMOSPHERIC POLLUTION

The internal combustion car is universally regarded as a major source of undesirable emissions to the atmosphere, particularly in large urban areas. The mechanisms by which cars produce atmospheric pollutants are extremely complex, but the pollutants themselves fall into three major categories and several subsidiary ones. The major categories, and very brief descriptions of their production mechanisms, are as follows:

(a) Hydrocarbons (HC), which are produced both by incomplete fuel combustion (giving exhaust-borne hydrocarbons) and by evaporation from the engine crankcase and the fuel system (evaporative hydrocarbons).

(b) Carbon monoxide (CO), which is produced by incomplete fuel oxidation during the combustion process.

(c) Nitrogen oxides (NO_x), which are a direct product of high-temperature combustion processes involving air.

These three types of emission, together with particulate matter and oxides of sulphur, are considered the major atmospheric pollutants encountered in large urban areas. The car in its present form is a major contributor to the atmospheric content of hydrocarbons, carbon monoxide and nitrogen oxides, but does not add significantly to the volume of sulphur oxides and particulates (although some of the latter produced by cars are particularly noxious). The low emissions of sulphur compounds are a result of the use of fuels with low sulphur contents. In the case of particulate matter, the car (and not necessarily the engine) contributes relatively small quantities of the following products, amongst others:

- asbestos, as a result of braking operations;
- rubber, produced by tyre abrasion; and
- lead compounds, which are a result of the addition of tetra-ethyl lead to petrol to enhance its combustion properties.

Other (minor) pollutants resulting from motor vehicle operation include ozone (from generators and starter motors) and miscellaneous products from battery charging and other subsidiary automotive operations.

While this list is by no means exhaustive, it shows that the present form of car is a mobile generator of a wide variety of noxious substances. If an even broader view is taken, the infrastructure of the car as a mode of transport includes manufacturing operations, road construction, petroleum products refining and administrative arrangements, all of which generate atmospheric pollution. Motor vehicle operation and infrastructure also contribute significantly to changes in the biosphere, and even the non-toxic byproducts of driving (such as carbon dioxide) are important in this way.

In terms of the five major pollutant categories, the contribution of motor car operation, together with an approximate pro-rated share of petroleum refining processes, to total atmospheric pollution in Australia is shown in Figure 2.9[1]. Approximate contributions of other transport operations to the overall pollutant levels are also illustrated in Figure 2.9.

Although it is particularly difficult to assess the actual ultimate effects of motor vehicle emissions (or, indeed, emissions from any source), it is generally agreed that they can be an important contributory factor, in particular circumstances, to illness or even death. In addition, they have deleterious effects on plant and animal life and man-made structures, and

(1) Derived from: D.A. Thomson and W. Strauss, 'Total Emissions to the Australian Atmosphere', Clean Air, February 1973.

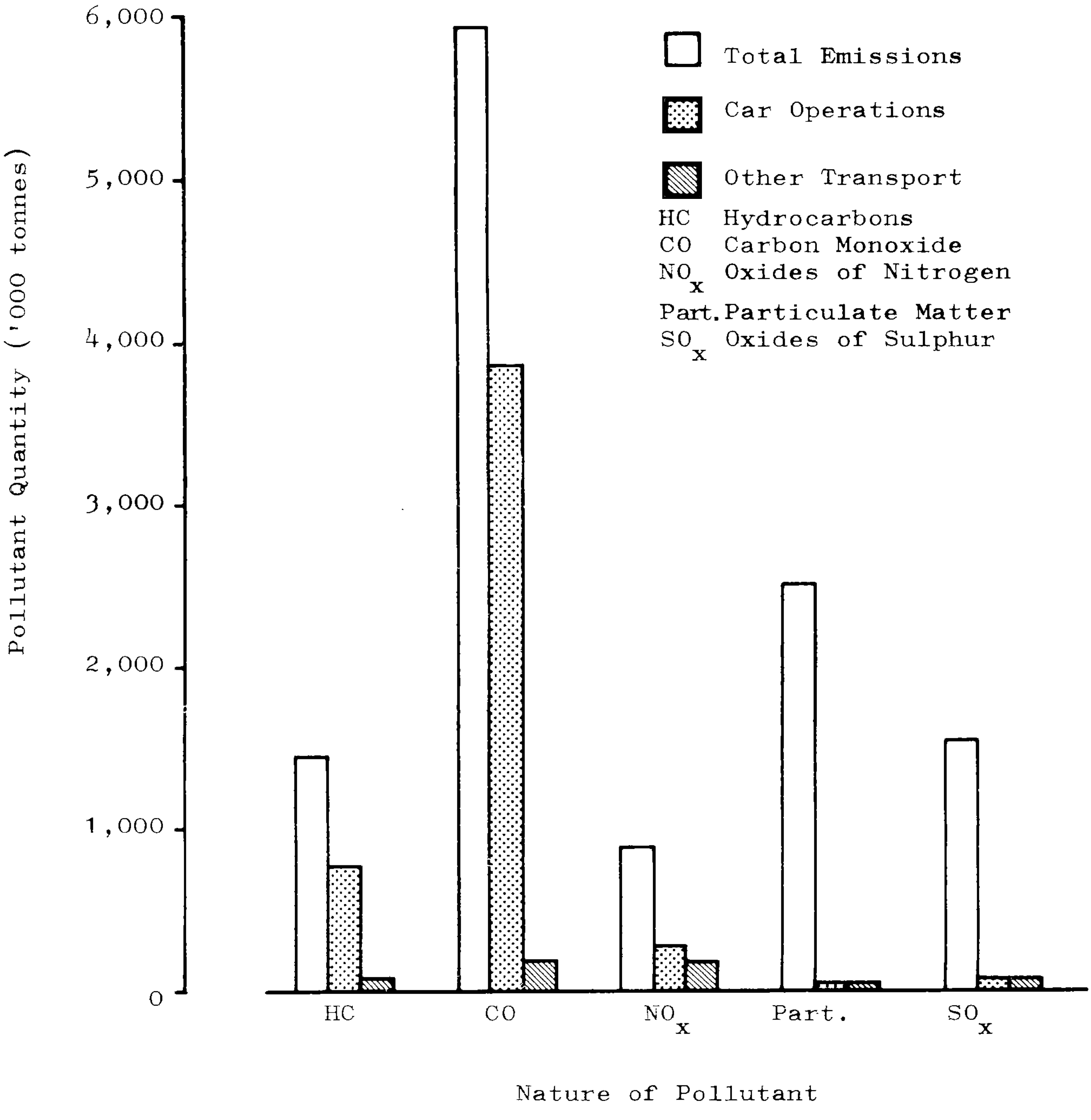

FIGURE 2.9 - MAJOR EMISSIONS TO THE ATMOSPHERE: AUSTRALIA, 1971

thus lead to an undefinable but undeniable reduction in the quality of life. It has been estimated(1) that motor vehicle emissions in Australian urban areas could have been a major contributor to as many as 660 deaths in 1969. In addition, they could have been a prime factor in 800,000 days of illness in that year.

The major problem encountered in assessing the levels of emissions from cars is that these levels vary widely with driving conditions. Not only is the total quantity of emissions from an individual vehicle dependent on the driving and traffic conditions, but the actual composition of the emissions varies with these parameters. Some details of this variation are given in Figure 2.10, for United States cars observed(2) before the widespread introduction of emission control legislation.

New emission control legislation will undoubtedly engender a significant change in the emissions from individual cars. However, this improvement is likely to be accompanied by a parallel growth in the number of cars and worsening of general traffic conditions. It is therefore probable that the net effect will be an initial improvement in total emission levels, followed by a decline(3). The aggregate effect will depend, in part, on the stringency of future controls on emissions. At present, overseas emission control legislation has been posted for the period to 1976, and the US (Federal) standards for that year have met with considerable industry resistance(4). The possibility of significant improvements beyond those standards is not yet established.

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(1) Report from the Senate Select Committee on Air Pollution: Part II, Submission by the Commonwealth Bureau of Roads, 1970.

(2) G.I. Clearly, 'Air Pollution and the Automobile', Clean Air, June 1967.

(3) A more detailed analysis of these interactive effects is given in: R.P. Murphy, Air Pollution and the Motor Vehicle, SAE National Convention, Melbourne, October 1971.

(4) A detailed comparison of Australian and overseas legislation is presented in: J.P. Soltam, and R.J. Larbey, The Sampling and Measurement of Exhaust Emissions from Motor Vehicles, Associated Octel Report OP72/2, April 1972.

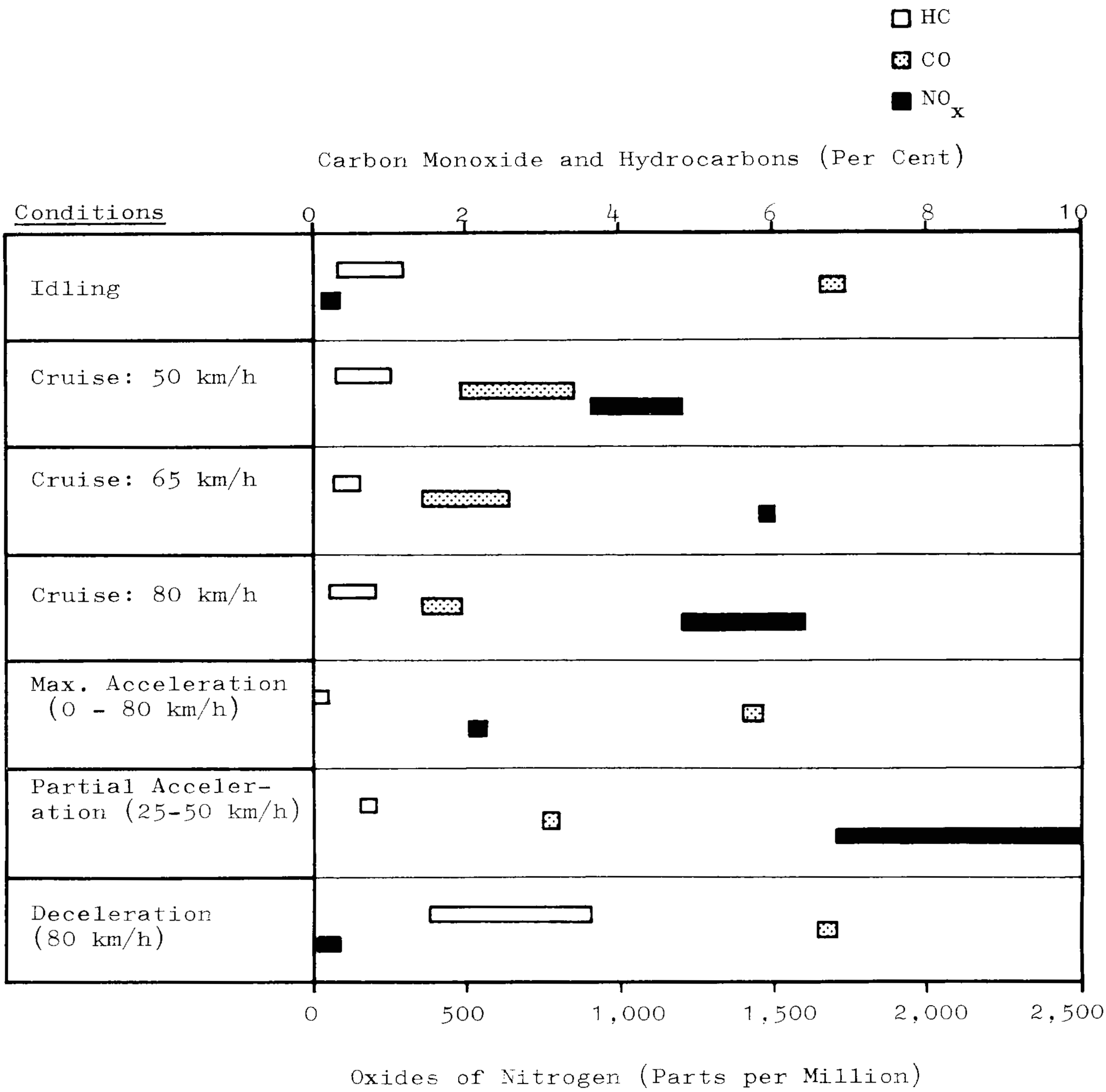

FIGURE 2.10 - COMPARISON OF EMISSIONS UNDER VARIOUS CONDITIONS, UNCONTROLLED CARS

As an indication of the improvements engendered in the regulations already posted up until 1976, the US (Federal) standards from 1973 until that year are compared in Figure 2.11. The Australian regulations for 1976 are identical to the 1973-1974 US (Federal) standards. It should be noted that emission control regulations in different countries are not directly comparable, since they are framed in relation to specific test conditions.

A further important point related to emissions and emission control procedures is that motor vehicle emissions are both geographically variable and indiscriminate. The combination of intense traffic density and high-density development can result in extreme pollution problems in urban areas, particularly in business centres at peak travel times. A coherent assessment of pollution effects is difficult to obtain, partly because of lack of measured data, and also because pollution concentrations vary markedly with both horizontal and vertical distance from the source and with prevailing atmospheric conditions. However, in some circumstances, the pollutant levels in some Australian cities are already at danger level. As an indication, the first recorded instance of photo-chemical smog in Australia was encountered in the recent past[1]. While the motor car is not solely to blame for this situation, it is certainly a major contributor to it.

The indiscriminate nature of the effects of air pollution of all types may be socially important. Pollution is typically most intense in the central areas of large cities where high levels of industrial activity both lead to direct pollution from fixed sources and engender pollution indirectly by attracting a high level of road traffic. However, inner city residents are typically in lower income groups, and are less likely to reap the benefits of the polluting activities, particularly those due to private car operation. A further

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(1) In November 1971, in Sydney: Total Emissions to the Australian Atmosphere, op.cit.

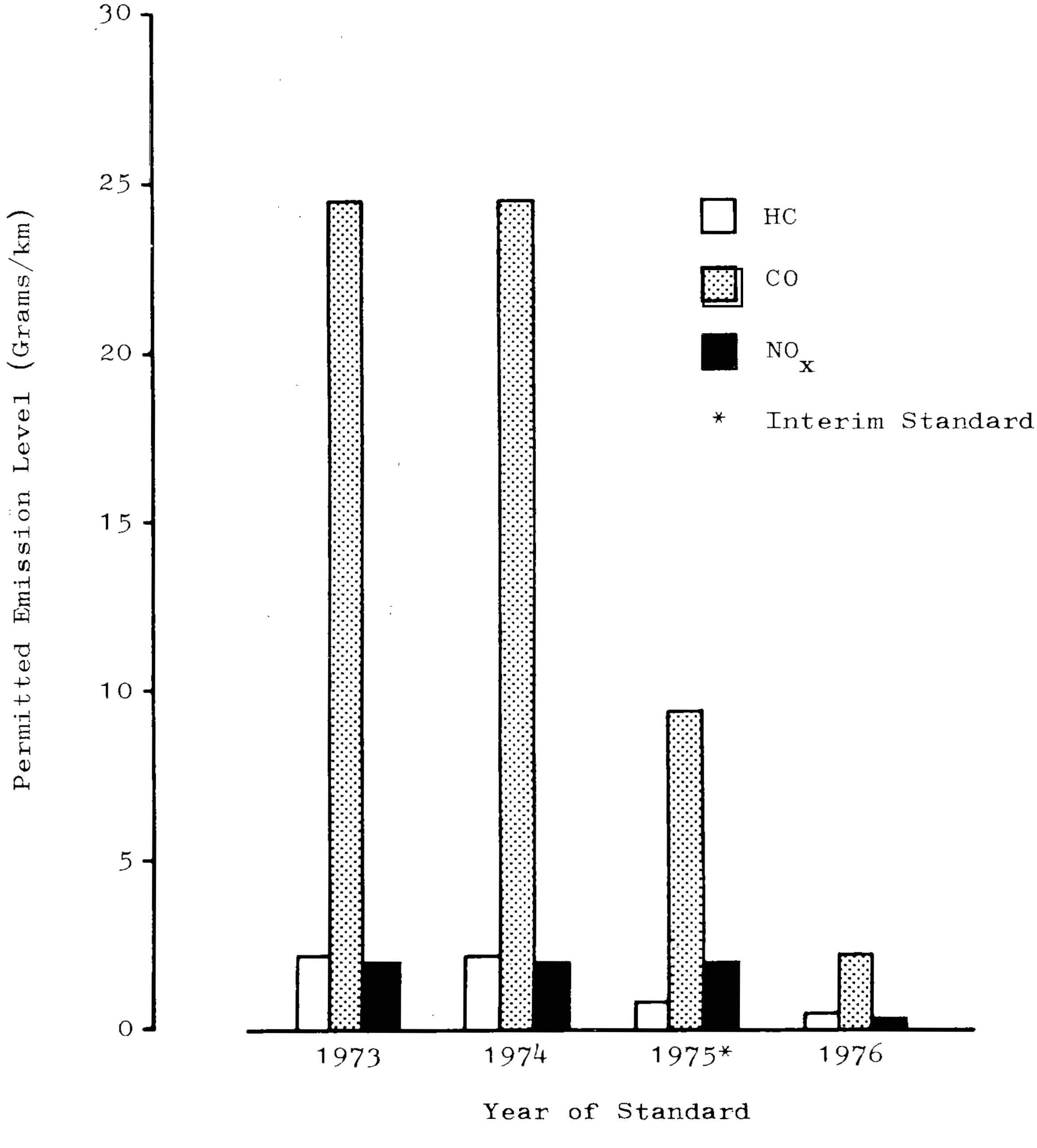

FIGURE 2.11 - US (FEDERAL) EMISSION STANDARDS

social inequity is that those whose health is most likely to be adversely affected as a result of air pollution are the very young and the very old, neither of whom can be considered responsible for much pollution from motor vehicles, at least.

In summary, the available facts indicate that the motor car is a substantial contributor to atmospheric pollution in Australian cities. Other transport media are relatively insigificant by comparison. While the effects of motor vehicle emission legislation (in conjunction with greater efforts by motor vehicle manufacturers) will certainly improve the emission performance of individual cars, growth in traffic and changes in urban development patterns will tend to counteract these improvements. Further, while vehicle pollution may be reduced in the limited areas which currently have near-saturation traffic levels, since the traffic volumes will not change greatly, total motor vehicle emissions to the atmosphere in major cities could revert to current levels within a relatively short time. The car in its present form does not appear capable of development far beyond emission levels envisaged by legislation already proposed, without severe degradation of performance or greatly increased cost. In these circumstances, the question of an alternative car technology is both relevant and timely.

Since any alternative to the motor car in its present form is extremely unlikely to make an appearance in appreciable quantities in Australia for some years, it is useful to assess the likely levels of emissions of cars in the future. If present trends in Australian car ownership continue until at least 1980, and if Australian emission legislation follows the US (Federal) model, only some 10 per cent of Australian cars in 1980 will be equipped to US 1976 standards. Around 30 per cent may be equipped to <u>at least</u> Australian 1976 (or US 1973) standards, and the remainder will be controlled to lesser standards, or effectively uncontrolled. It would be extremely complicated to compute pollution levels at that stage, since so many factors are involved[1].

As an indication, however, Australian cars in 1980 are likely to be roughly equivalent in emission performance to those equipped to US 1973 standards. The position beyond 1980 is dependent on whether current patterns of car ownership and use are continued, and on other factors such as whether standards beyond the US 1976 ones are introduced. These questions are considered unanswerable at this stage. If no standards are introduced after the US 1976 standards (assumed for this purpose to be introduced in Australia in 1979), then almost all cars in Australia would reach this standard in the 1990's. The fact that a car is a relatively long-life item (with an estimated life expectancy of around 12 years[2] - albeit markedly skewed) introduces a severe damping effect on any measures designed to increase its acceptability from an emission viewpoint.

NOISE

In assessing the effects of vehicle noise, it is necessary to make a distinction between noise levels experienced inside the vehicle and those outside. In this respect, modern cars are generally substantially quieter inside than outside (a situation which does not, incidentally, apply universally to all motor vehicles - some commercial vehicles tend to be extremely noisy inside). Also, the internal noise level is, to an extent, caused by and borne by the same people. Accordingly, the major social problem created by car noise is a function of its external effects. This noise originates in a variety of areas:

---

(1) Including car life, actual emission levels for uncontrolled cars, annual distance travelled as a function of car age, and so on. It is clear that even the likely effects of emission controls on total vehicle emissions (let alone emissions under specific conditions of location and atmospheric conditions) could not be assessed without a very large and costly research effort.

(2) Estimated from motor vehicle registration figures.

- engine noise, which is caused by the combustion process, valve gear, various pumps, fans and ancillary equipment, and by general vibration and roughness;

- exhaust system noise;

- air intake noise;

- transmission system noise;

- braking noise;

- chassis and body structure noise, which is caused by vibration and resonances within the car structure;

- coasting noise, which is predominantly caused by tyres, although aerodynamic noise may also be significant under some circumstances; and

- door slamming.

A major difficulty in assessing car noise is that of comparing objective measurements of noise with the subjective effects of such noise. This problem is overcome by fitting measuring equipment with filter networks which tailor the characteristics of the equipment to the sensitivity of the human ear for particular noise frequencies. The measurements are based on a logarithmic decibel (dB) scale, on which a doubling of sound intensity corresponds to a measured increase of 3 dB in sound level. The threshold of hearing is 0 dB, while a measurement of 120 dB approximates the threshold of pain. A further difficult factor in assessing car noise is the distance at which the noise is measured.

Estimated noise levels for US passenger cars[1] are shown as a function of distance and speed in Figure 2.12. In this case, the noise level is expressed in PNdB (perceived noise dB, corresponding to the effect on the human ear). A slightly different weighting system, resulting in a modified measurement scale (dB(A)) has been proposed[2] in Britain, and a maximum noise level, for cars, of 85 dB(A) is in force. In practice, noise measurements for individual vehicles do not reflect the intensity or frequency of noise which are characteristic of traffic operations. The overall noise effect of road traffic depends on speed, traffic volumes, distance from source, screening and meteorological conditions, amongst other factors.

Two features of the internal-combustion car tend to make it inherently noisy, particularly in urban operation. Firstly, the engine idles when the car is not in motion, which leads to comparatively high noise levels at certain times and places. The second, and more important, feature is that engine noise increases with power, while other major sources of noise in the vehicle increase with speed. Since high power levels may be experienced at low speed (as, for instance, when accelerating), low-speed operation is inherently noisy. The annoying quality of gear-changing noise can reinforce this effect.

The noise levels of individual cars are probably not significant causes of danger to health, but aggregated traffic noise may approach danger levels. Similarly, modern cars are comparatively quiet, and this fact masks the deterioration in ambient noise levels caused by their increasing numbers. In terms of an alternative technology,

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(1) A. Cohen, 'Location-Design Control of Transportation Noise', Urban Planning and Development Division Journal, ASCE, December 1967.

(2) Cars for Cities, HMSO, 1967.

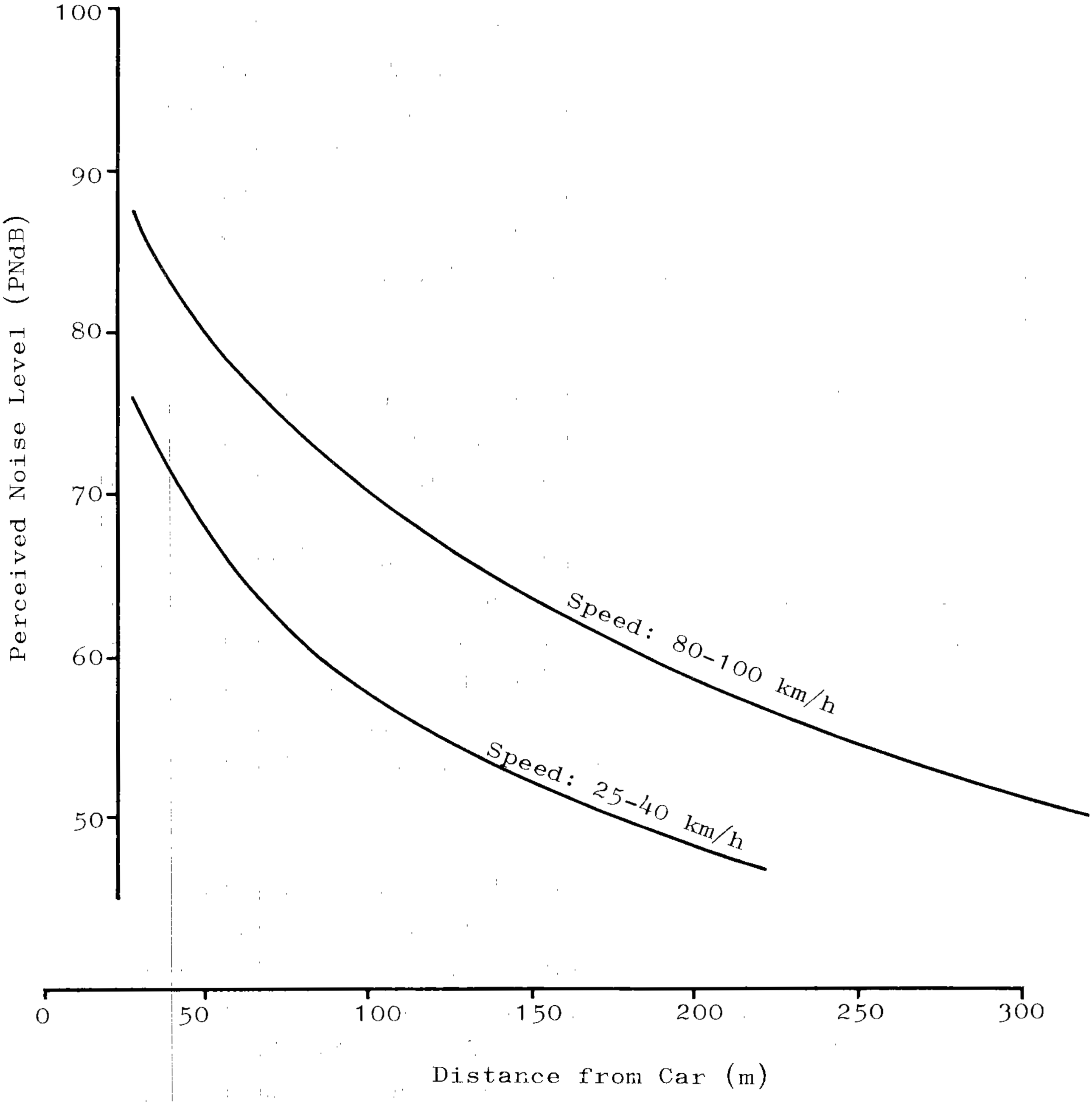

FIGURE 2.12 - CAR NOISE LEVELS AS A FUNCTION OF SPEED AND DISTANCE

the most promising development in car noise abatement would be a system which reduces or eliminates the predominance of engine noise at comparatively low speeds. In view of the great exposure of the community to noise emanating from urban traffic, any system which can reduce low-speed car noise to a level approaching coasting noise would represent a significant improvement in the quality of urban living.

ENERGY RESOURCES

As with atmospheric pollution, the allocation of energy resources between various energy users is a complex issue and is currently under close scrutiny[1]. The results of a preliminary investigation by the BTE indicate that petroleum products account for almost one half of the energy available in combustible products consumed, for energy conversion purposes, in Australia at the present time[2]. A distribution of Australian energy consumption is shown in Figure 2.13.

Readily available statistics[3] on the consumption of petroleum indicate that motor spirit (i.e. petroleum products refined to standards appropriate to motor vehicle use) accounts for over one third of total petroleum consumption in Australia. A distribution of petroleum product consumption by broad categories is shown in Figure 2.14.

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(1) Amongst other Australian investigations, the BTE is currently examining transportation energy requirements.

(2) This figure must be regarded as approximate, and interpreted with caution. In particular, energy equivalent values at the fuel consumption stage are misleading.

(3) Australian Department of Minerals and Energy, Australian Petroleum Statistics 1972-1973, September 1973.

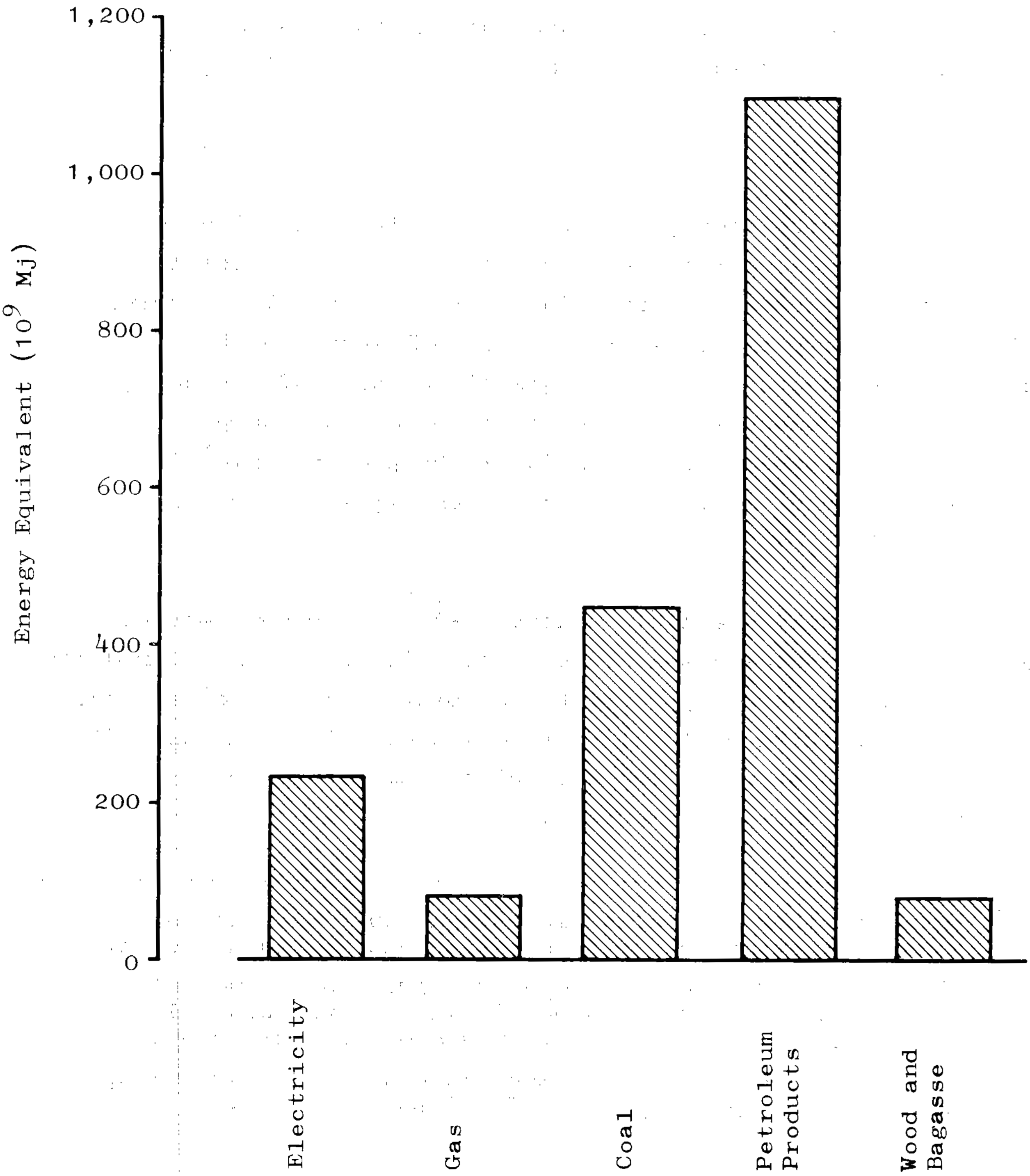

FIGURE 2.13 - DISTRIBUTION OF ENERGY SOURCES: AUSTRALIA, 1972

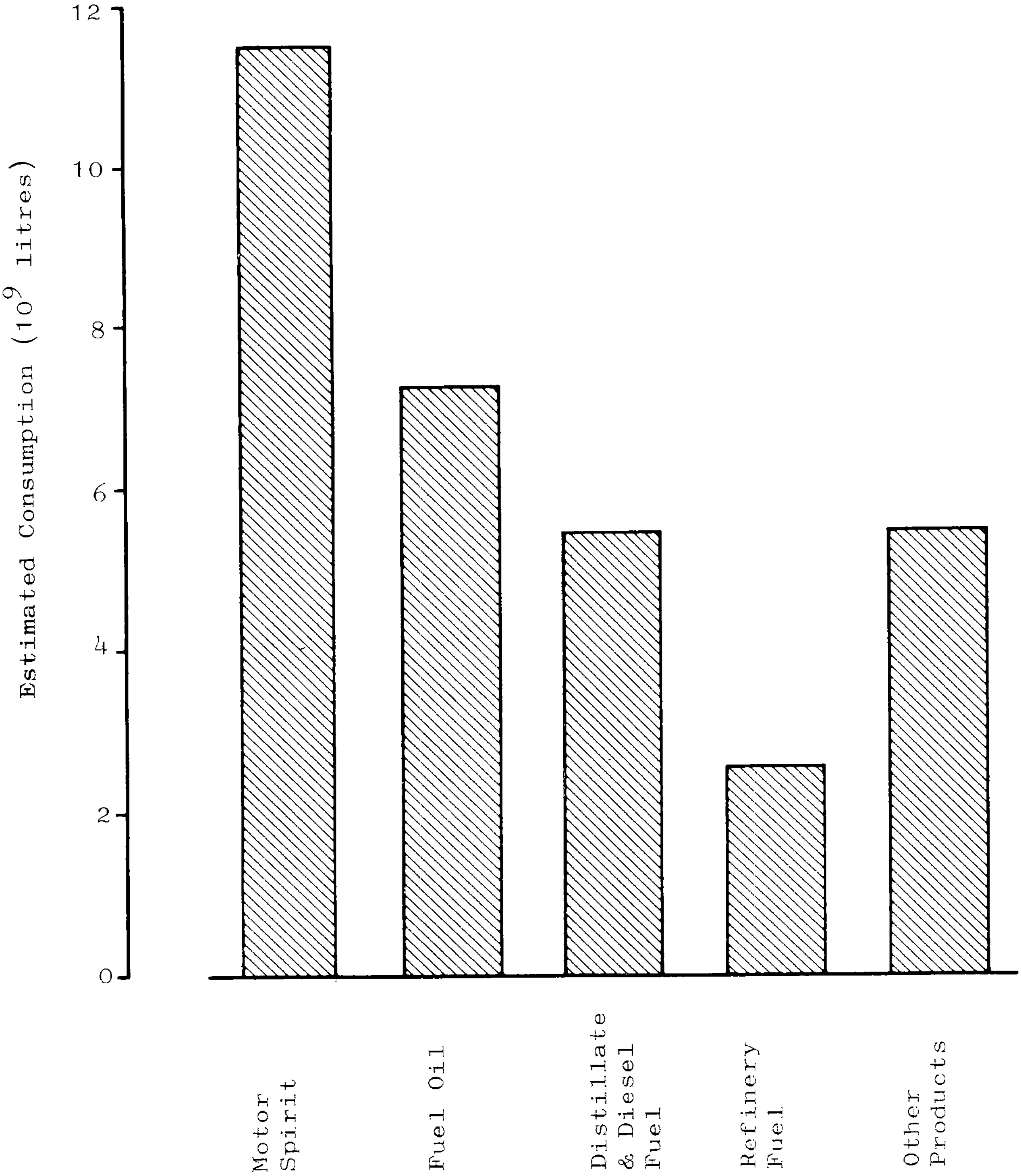

FIGURE 2.14 - ESTIMATED PETROLEUM PRODUCTS CONSUMPTION: AUSTRALIA, 1972-1973

On the basis of 1971 statistics[1] of car usage, motor cars and station wagons accounted for an annual consumption of 7.81×10^9 litres of motor spirit out of an Australian total consumption of 10.38×10^9 litres. Thus, cars account for 75 per cent of all motor spirit consumption, and 28 per cent of all petroleum products consumption (on a volumetric basis).

It is clear that the car is an important consumer of petroleum products. In view of current developments in energy resource availability and control, the prospect of an alternative system which is not specifically dependent on petroleum products is particularly attractive. Although Australia is reasonably self-sufficient at present in the production of petroleum products suitable for refining to motor spirit standards, this is not true for the whole spectrum of petroleum products. While the nation may not face an 'energy crisis' in the near future, at least in the automotive sphere, any substantial shift in the emphasis of car fuels away from motor spirit would at least increase the options available in allocating the available petroleum resources.

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(1) Survey of Motor Vehicle Usage 1971, op. cit.

CHAPTER 3 ELECTRIC CARS

GENERAL CONSIDERATIONS

The development of widespread reticulation of mains electricity in this century has resulted in a social and economic system which accepts this particular form of energy as a fundamental element. In the transport sphere alone, electric power is widely used, directly or indirectly. Some uses are closely related to the performance of specific transport tasks (such as electric railways, conveyor systems and battery-powered submarines). In other cases, electric power is a significant contributor to the transport infrastructure (for example, in the manufacture of transport equipment).

One transport field on which electric power has made little significant impact is that of motor vehicle operation [(1)]. While the reasons for this situation are apparently simple, they warrant some examination.

Any transport system which is under single ownership and operates on a fixed track (a railway, for instance) is a prime contender for electrification, since it is relatively simple and safe to reticulate electricity so that it may be collected by the vehicle. Even so, system electrification is expensive and is normally only justified, economically, in certain circumstances. Motor vehicles, particularly cars, are a different proposition altogether. One of the greatest contributors to the car's popularity is its extreme flexibility. Clearly, an electrical reticulation system which would permit cars to travel over the exceedingly diverse routes which they now traverse would be prohibitively expensive, as well as unsightly and probably dangerous. Universal collection of electricity from wayside structures is thus out of the question. The future of the electric car therefore depends on either on-board storage of electrical energy, on-board energy conversion, or partial system operation.

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(1) This has not always been the case. At the beginning of the 20th Century, electric cars outnumbered their internal-combustion counterparts.

Electric car development has largely favoured on-board energy storage, in which a battery is charged at a stationary outlet connected to the normal electric mains system. On-board conversion from chemical or heat energy to electric energy has undergone substantial experimentation, with no promising results to date. Partial system operation could involve either privately owned vehicles using an electrified route in particular urban areas, while operating independently on other roads, or special small vehicles confined to a network of guideways covering major routes within a city. These latter possibilities are not explored in depth in this report, which is focussed on the potential of electric cars operating with very much the same inherent flexibility as present internal-combustion cars.

Electric vehicle operation is not altogether uncommon even now. In cases where a particular vehicle operates over a limited area, and is always in relatively close proximity to appropriate charging outlets, battery vehicles have found considerable acceptance. For example, there are approximately 50,000 battery vehicles [1] registered for use on public roads in the United Kingdom. A high proportion of these vehicles are in milk delivery and refuse collection fleets, in which the daily distance travelled is not great. In certain other areas, a marked trend towards battery vehicles for special purposes is also noticeable. Again in the United Kingdom, electric industrial trucks (primarily fork-lift trucks) have gained supremacy over those powered by internal-combustion engines. Production figures for both types are shown in Figure 3.1. Similarly, large numbers of electric golf-carts operate throughout the world. Electric buses are used in airport operation and in certain limited inner-city distribution systems.

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(1) A.S. Duncan, 'Battery Electric Road Vehicles Past and Present', presented at the Australian Lead Development Association Symposium on Electric Vehicles - Current Developments and the Future, September 1972.

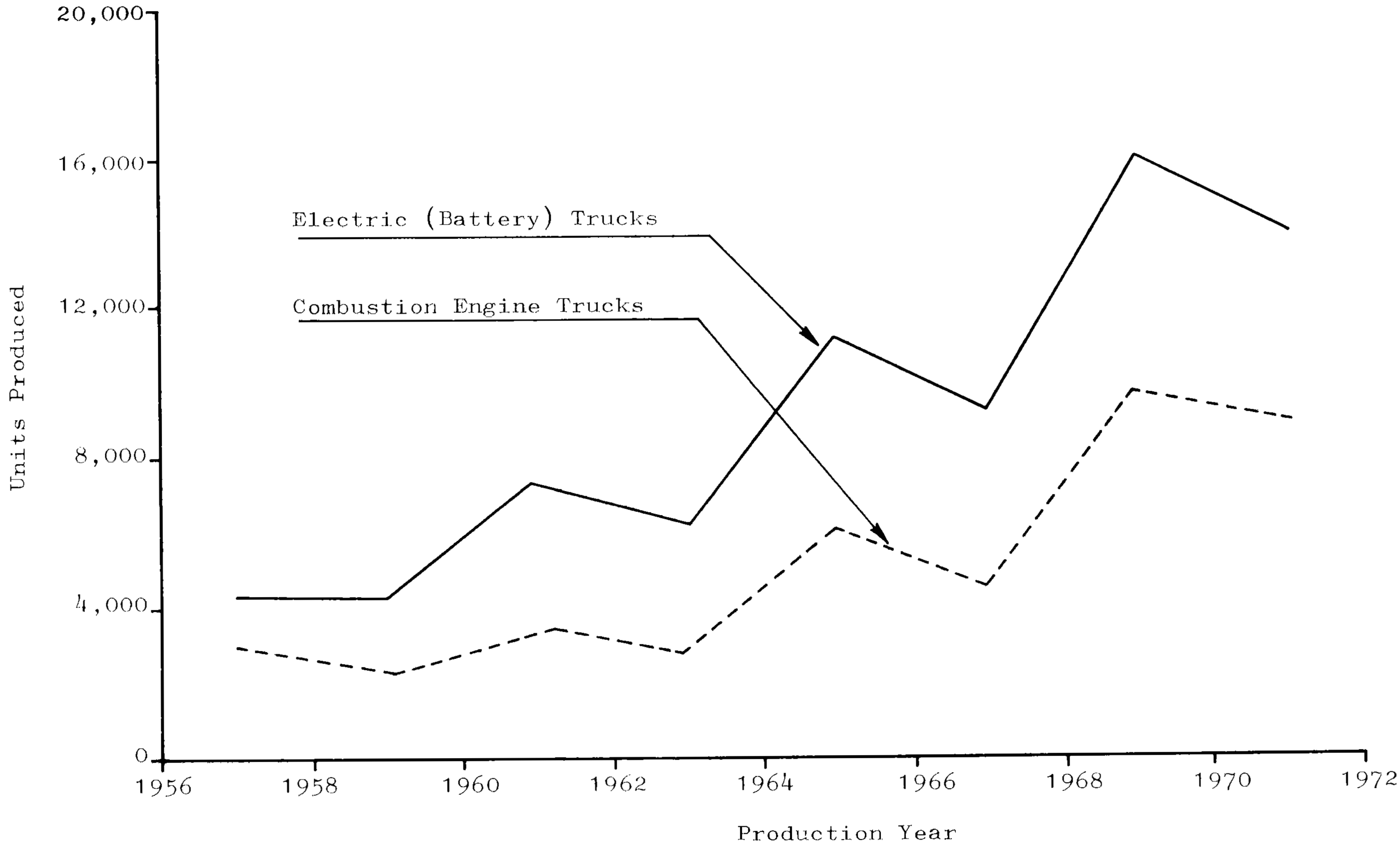

FIGURE 3.1 - PRODUCTION OF INDUSTRIAL (FORK-LIFT) TRUCKS IN UNITED KINGDOM

ELECTRIC CAR SYSTEMS

Propulsion systems for electric cars range from pure energy-storage systems to hybrid systems, which effectively use an electric power transmission system for an internal-combustion engine, with a battery for storing excess energy and supplying peak energy demands. Clearly, it is difficult to generalise about systems which range between these extremes, but it is useful to consider electric cars in four major categories:

(a) complete energy storage systems (battery cars) which have no energy source other than the battery;

(b) energy conversion systems (fuel-cell cars), in which chemical energy is converted to electric energy;

(c) hybrid systems, which use batteries and internal-combustion engines to propel the car through an electrical transmission system; and

(d) miscellaneous systems.

Battery Cars

Notionally, battery cars are the most simple form of electric car, and they are also the most popular and numerous form. The battery car contains a bank of batteries which is used to drive an electric motor. The motor, in turn, drives the car's wheels. The process is controlled by a control system, which may be quite simple or exceedingly complex. An outline of a battery car's essential equipment is shown in Figure 3.2.

The predominant attribute of a battery car system is its simplicity. It is exceedingly reliable and requires little maintenance. At present, at least, it is heavy and as a result, limited in performance. Its range is strictly limited by the capacity of its battery, and operation is governed by the

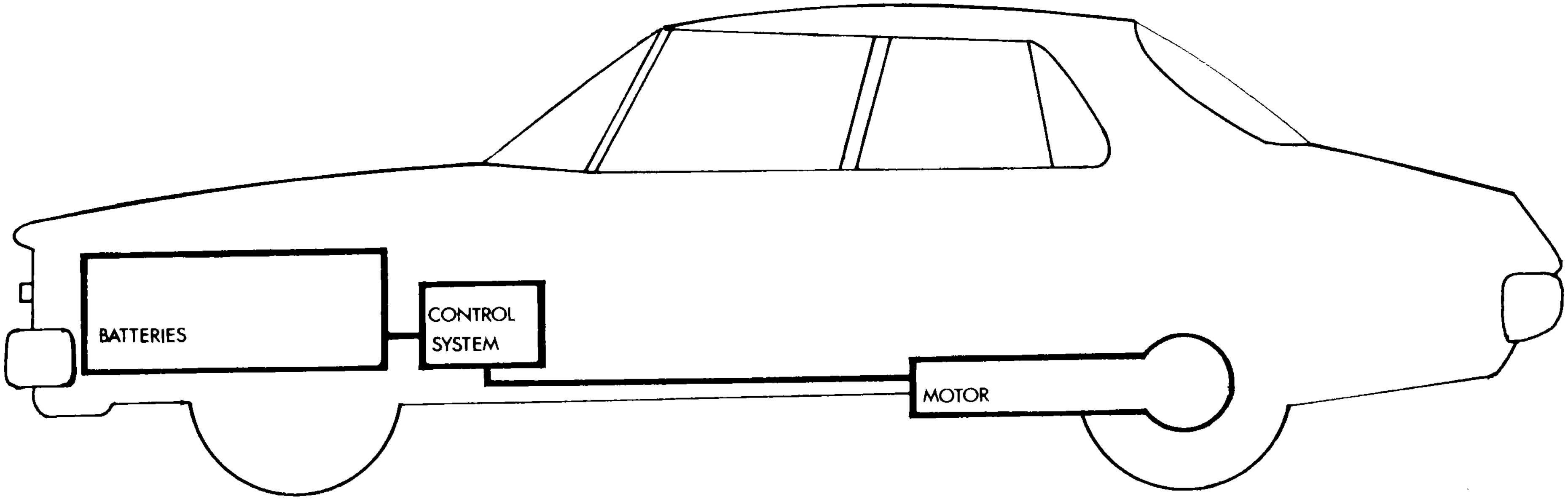

FIGURE 3.2 - BATTERY CAR

proximity of suitable charging outlets or battery exchange stations. Nevertheless, early attempts to introduce electric cars in substantial numbers are very likely to be based on battery cars, and the attributes of these cars are explored in greater depth later in this report.

<u>Fuel-Cell Cars</u>

A fuel-cell is in some ways analogous to a battery, since it generates electricity by electrolytic processes. However, the fuel-cell operates continuously, as long as the appropriate chemical compounds are fed to it. It is not used for storing electric energy, as in a battery, but rather for generating it. A fuel-cell car therefore consists of the cell itself, suitable equipment for feeding it with the required fuel, a control system and an electric motor. The latter two items are essentially similar to those required for a battery car. The primary components of a fuel-cell car are shown in Figure 3.3.

Fuel-cells, at present, can have various features which are a disadvantage for automotive application. These include the following:

(a) Fuel-cells are likely to be expensive, due to the use of exotic materials in their construction.

(b) Although the use of common petroleum products as fuel is possible, some experimental fuel-cells produced to date have used unusual and even toxic fuels (for example, hydrazine and ammonia).

(c) The products of fuel-cells may themselves be pollutants.

(d) A fuel-cell may require feeding with both a fuel and an oxidant, which would thus cause duplication (and hence complication) of the feed system. This characteristic would be avoided in fuel-cells using air as the oxidant.

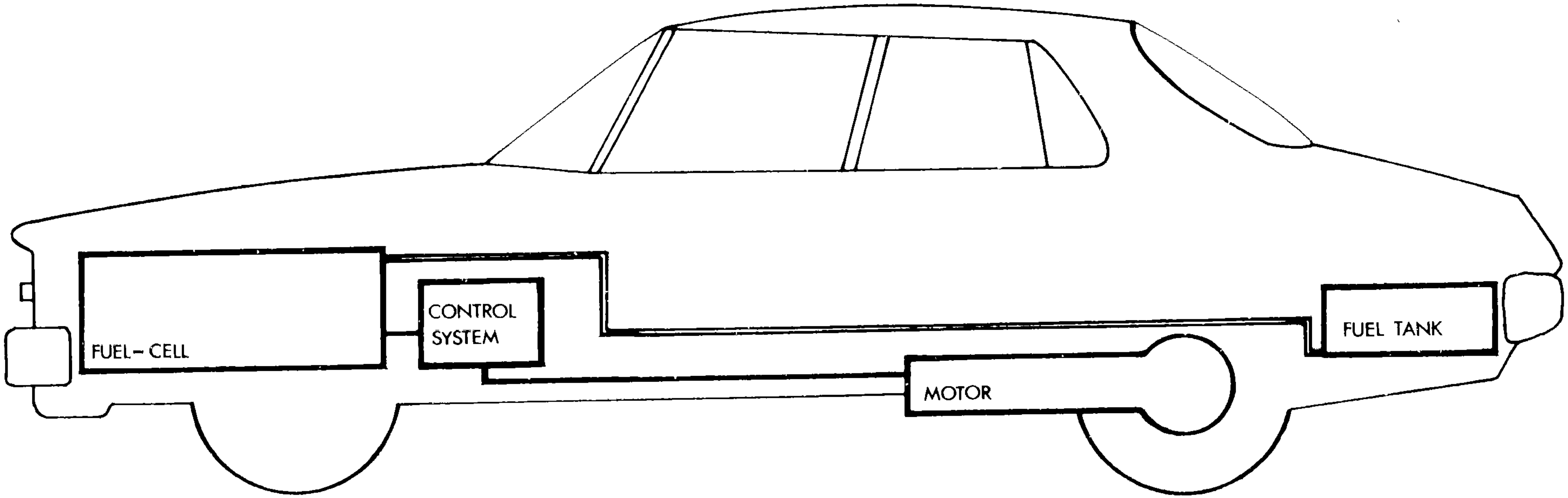

FIGURE 3.3 - FUEL-CELL CAR

(e) Although fuel-cells are continuous producers of energy (at least as long as the fuel is supplied), they are still heavy and bulky.

All these considerations indicate that the fuel-cell has certain inherent disadvantages for automotive applications at this stage. However, fuel-cell technology is of a nature which presents the possibility of important breakthroughs in the future. If such breakthroughs occur, the fuel-cell may quickly become pre-eminent as a future automotive power plant.

Fuel-cells have been used extensively for on-board generation of electricity in spacecraft. In this application, the high cost of the cells and fuel is compensated by other desirable characteristics. Several experimental motor vehicles have been built (1), but the early application of fuel-cell technology to general automotive transport appears rather unlikely. For this reason the technology of fuel-cells is not examined in depth in this report (2).

Hybrid Cars

The term 'hybrid' applied to electric cars can have several meanings. Cars containing both fuel-cells and batteries are often referred to as hybrid vehicles, while the same term is also used in connection with cars using combinations of battery types. The major use of the term is, however, in relation to vehicles combining battery energy storage with an internal-combustion engine. A schematic diagram of such a system is shown in Figure 3.4. In principle, the internal-combustion engine drives a generator, which can supply electric power to

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(1) One such vehicle is the General Motors ELECTROVAN (using a hydrogen/oxygen fuel-cell). A description is given in: H.A. Wilcox, 'Electric Vehicle Research', presented at a Symposium: Power Systems for Electric Vehicles (US Department of Health, Education and Welfare), April 1967.

(2) A comprehensive survey of fuel-cell characteristics is given in: R.U. Ayres, and R.P. McKenna, Alternatives to the Internal-Combustion Engine, John Hopkins University Press, Baltimore, USA, 1972.

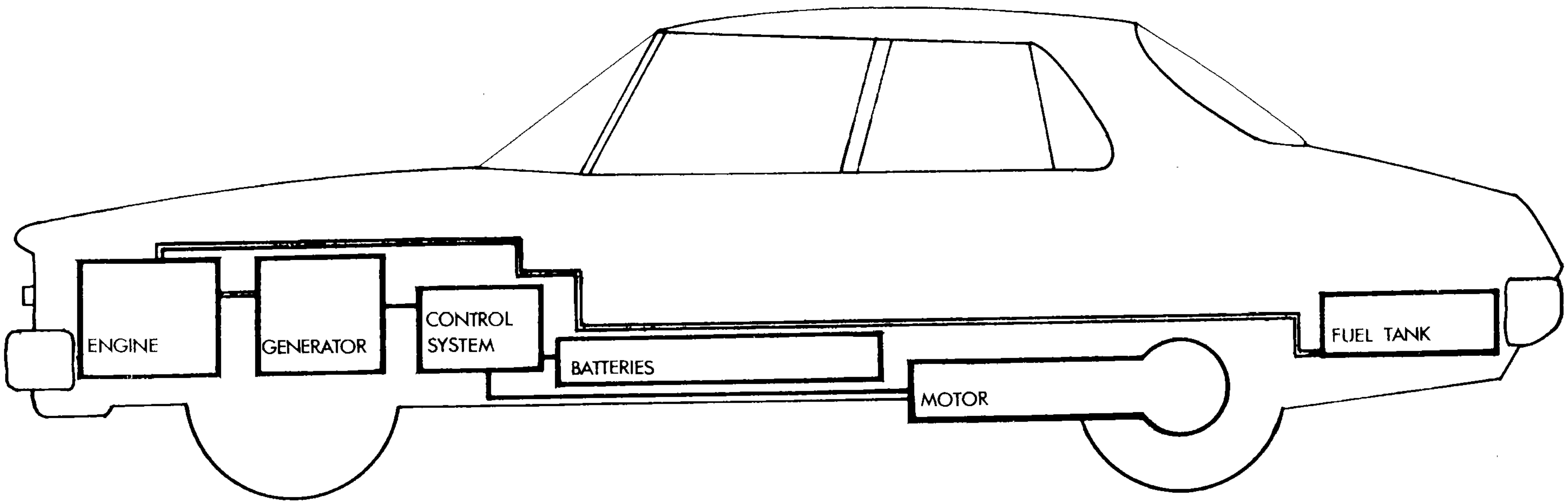

FIGURE 3.4 - HYBRID CAR

both the car's driving motor and its battery. At times when the engine is lightly loaded (low-speed cruising, for instance), part of the output of the generator is diverted from the motor to the battery, thus recharging it. For high acceleration, or other high-power conditions, the motor is driven by the full output of the generator, in conjunction with the battery.

In this form of hybrid car, the battery serves as an averaging device for the engine. The rationale of the hybrid car is that full-power demands on a normal car engine are relatively infrequent and of short duration. Thus, the hybrid car has a somewhat smaller engine and uses the battery to meet peak demands. A further advantage of this system is that the engine may be designed to operate at constant speed, which gives the designer considerably more latitude in reducing noise and exhaust emission. The fact that the car can run on either the battery or the engine is a further valuable feature, as it reduces the probability of complete system failure, and would permit bans to be imposed on non-electric vehicles in specified areas.

The hybrid car is clearly flexible, since its range and performance capabilities can be comparable to those of current cars (although the added electrical equipment weight would diminish its capabilities to some extent). However, under normal operating conditions, its performance in regard to exhaust emissions can only be regarded as marginally superior to that of normal cars with advanced emission control systems. In fact, in certain circumstances, it may well be worse. In city centre driving conditions, for example, a stationary hybrid car may well be operating its engine at high power levels for battery recharging, thus contributing greater exhaust emissions and noise than its normal, internal-combustion counterpart.

It is difficult to generalise about the value of hybrid cars, since they can be designed for operation within such a wide variety of conditions. For example, one particular car might have a large engine and small battery, and may run predominantly on its engine, with the battery available for peak demands or very limited engine-off cruising. At the other extreme, a predominantly battery car may have only a very small charging engine, and may have to stop to recharge the batteries, either by its own engine or by connection to a mains supply. However, this design flexibility certainly allows for construction of vehicles which are optimised for particular types of operations. In fact, a degree of optimisation for particular purposes might be built into an individual vehicle's control system. Thus, the system might be programmed for several driving modes, and selection of the appropriate mode could alter the balance between engine drive, battery drive and battery recharging.

The major likely disadvantage of hybrid cars is their complication. An inspection of the engine compartment of even the smallest conventional car will reveal a complex maze of wires, pipes and items of equipment. If an electric generator and motor, a battery and a relatively bulky and complicated control system are added, the maintenance and accessibility problems of such a car could well become acute. On this basis alone, a general redesign of engines appears to be a prerequisite of a commercially successful hybrid car. The situation would certainly improve if many of the ancillary items of engine equipment (e.g. distributor, water pump and oil pump) could be incorporated into one removable module.

The whole question of the usefulness of hybrid cars cannot be resolved without considerably more research into the driving patterns required of cars in various situations. With the availability of substantial data on this subject, parametric analyses of hybrid car design and operation could provide a basis for postulating the characteristics of the car (and, more particularly, of the engine/battery trade-off). Until this is done, the value of the hybrid car must remain open to doubt.

Its successful development also appears to hinge on a reappraisal of conventional engine design, although some hybrid car concepts have included the use of unconventional engines (e.g. Stirling-cycle engines).

Miscellaneous Systems

Although most of the current developments in electric cars fall into the three categories treated above, there are at least two other systems worthy of mention. Both of these relate to direct thermal generation of electricity, as opposed to electrochemical storage or conversion.

The first system is based on the phenomenon of electricity generation when cells comprised of dissimilar metals are heated[(1)]. The heat is supplied by a simple burner system, and the 'engine' is subject to normal thermodynamic laws. Although this system appears simple, its theoretical efficiency is much less than that of an internal-combustion engine. Experimental versions have been built, but are considered unsatisfactory for automotive use[(2)].

The second direct process for thermal/electric conversion is magneto-gas-dynamics (MGD). In this process, a high-temperature stream of ionised gases is subjected to a magnetic field, which separates it into positive and negative streams. Current may be collected from electrodes inserted in these streams. Although extensive research has been carried out in this area, it is not considered that MGD will be a serious competitor in the automotive field in the foreseeable future.

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(1) There are two separate phenomena involved: the Seebeck effect (a voltage differential across a junction when the ends are at a different temperature to that of the junction), and the Peltier effect (a current flow across a junction due to a temperature differential).

(2) Research on thermo-electric generators of the junction type has been performed at the Battelle Institute.

BATTERY CAR CHARACTERISTICS

The previous remarks on electric car systems have indicated that the battery car is the only type of electric vehicle which is at an adequate stage of development to be considered as a serious contender to the internal-combustion car. It is well known that battery cars are deficient in range performance, but the degree of this deficiency relative to actual car requirements has received little consideration. In this report, a thorough investigation of the likely characteristics of battery cars is undertaken. First, however, the elements of battery cars are considered in some detail.

Batteries

There are two basic types of batteries - primary cells and secondary cells. The primary cell generates electrical energy by chemical reactions between its elements, but this process cannot readily be reversed. Thus, the primary cell cannot be recharged in the usual sense. It may be possible, in some cases, to continue the reaction process (even indefinitely) by replenishment of the appropriate reactants, in which case the primary cell is closely analogous to a fuel-cell. Although certain primary cells may be suitable for automotive purposes eventually, they are of little real interest at present.

Secondary cells, on the other hand, are readily recharged by connection to an appropriate electrical supply. Thus, they are true energy storage systems. The ideal secondary cell would be one which could:

- store high quantities of electrical energy in light-weight, low-volume modules;
- accept full charging quickly and conveniently;
- attain high power levels on demand;
- have energy capacity which is relatively insensitive to power demands;

- use safe, low-cost reactants; and

- be intrinsically a long-life device, capable of sustaining many discharge/recharge cycles.

Unfortunately, many of these objectives are mutually exclusive. It is usually found that batteries with high energy densities, for instance, are composed of expensive or dangerous materials, and are correspondingly uneconomic or undesirable. Owing to a variety of such problems with alternatives, the lead-acid battery has become the most common type of secondary cell in general use. For example, the millions of automobiles in the world use such batteries almost exclusively for starting, lighting and ignition purposes. Its components are relatively inexpensive, readily obtainable and long-lasting. However, its energy density and energy/power characteristics are relatively poor.

While a complete description of the processes involved in energy storage and release in a comprehensive range of battery types is outside the scope of this report, it should be noted that many combinations of elements have been tried in efforts to improve battery capabilities. Among the more likely candidates for automotive battery applications are the following:

lead-acid batteries (with various additives to improve energy and power densities and discharge/recharge capabilities)

nickel-cadmium batteries

nickel-zinc batteries

silver-zinc batteries

zinc-air batteries

sodium-sulphur batteries

lithium-chlorine batteries

The last three of these battery types have moving parts, involving a process such as the pumping of electrolyte. This adds some complexity (and corresponding cost) to their operation. The sodium-sulphur and lithium-chlorine batteries operate only at elevated temperatures (from 350°C to 650°C). High-temperature operation raises questions of warming-up periods, while the elements used in these particular batteries are potentially dangerous. Sodium, for example, ignites spontaneously on contact with the air. In vehicle collisions such a property could be catastrophic.

Sufficient information is not available for the BTE to make an objective judgment of the overall desirability of particular battery systems for automotive purposes. For present purposes, however, a somewhat subjective assessment of the capabilities of alternative battery types is given in Table 3.1 under seven headings:

- energy density (the storage capacity of the battery system on a weight and volume basis)
- power density
- ease of recharging
- life (measured by the number of discharge/ recharge cycles which the battery can sustain)
- availability of component materials
- cost
- safety

TABLE 3.1 - BATTERY SYSTEM CHARACTERISTICS

System	Energy density	Power density	Ease of re-charging	Life	Materials	Cost	Safety
Lead-acid	P	G	G	G	E	E	G
Nickel-cadmium	P	E	E	E	P	P	G
Nickel-zinc	G	G	G	F	G	F	G
Silver-zinc	F	E	P	P	P	P	G
Zinc-air	G	F	G	F	E	G	G
Sodium-sulphur	E	E	E	E	E	E	P
Lithium-chlorine	E	E	E	E	G	G	P

NOTE: Ratings

E = Excellent G = Good
F = Fair P = Poor

From this table, it can be seen that no specific battery system is universally better than the others. The advanced batteries under current development (sodium-sulphur and lithium-chlorine) score highly on most counts, but must be considered potentially poor in safety for general automotive use although, with appropriate shielding and operational precautions, they may prove satisfactory for other transport applications.

There is one further feature of battery systems which requires consideration. The energy capacity of a particular battery is a function of the rate at which energy is drawn from it. Thus, a battery which is capable of supplying, say 1kW for 10 hours is not capable of supplying 10 kW for 1 hour. The actual capacity of the battery at the higher power level will be somewhat less, the difference depending on the battery type.

The lead-acid battery is particularly poor in this regard. As a comparison, capacity-power curves(1) for batteries of the same weight, but of several types, are shown in Figure 3.5.

In summary, the situation for batteries is somewhat similar to that for fuel-cells - a technological breakthrough may well cause a revolution in battery systems for electric vehicles. However, there is one important difference in the case of batteries - several workable systems are already available. Of the currently available batteries, the lead-acid type appears the most suitable for use in cars, largely due to its low cost and long life(2). Accordingly, it is used in this report as a basis for the evaluation of electric car operation.

<u>Motors</u>

Motor technology for battery cars is largely based on experience gained in the design and construction of other traction systems. The major criteria for motor selection for cars are:

- suitable power-speed characteristics
- light weight and low volume
- high reliability
- low cost

As with batteries, there is a substantial degree of disagreement about the direction in which battery car motor

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(1) Values mainly derived from: Ayres and McKenna, <u>Alternatives to the Internal-Combustion Engine</u>, op.cit.

(2) Many of the factors involved in battery systems for electric vehicles are explored in: <u>Second International Electric Vehicle Symposium - Proceedings,</u> November 1971.

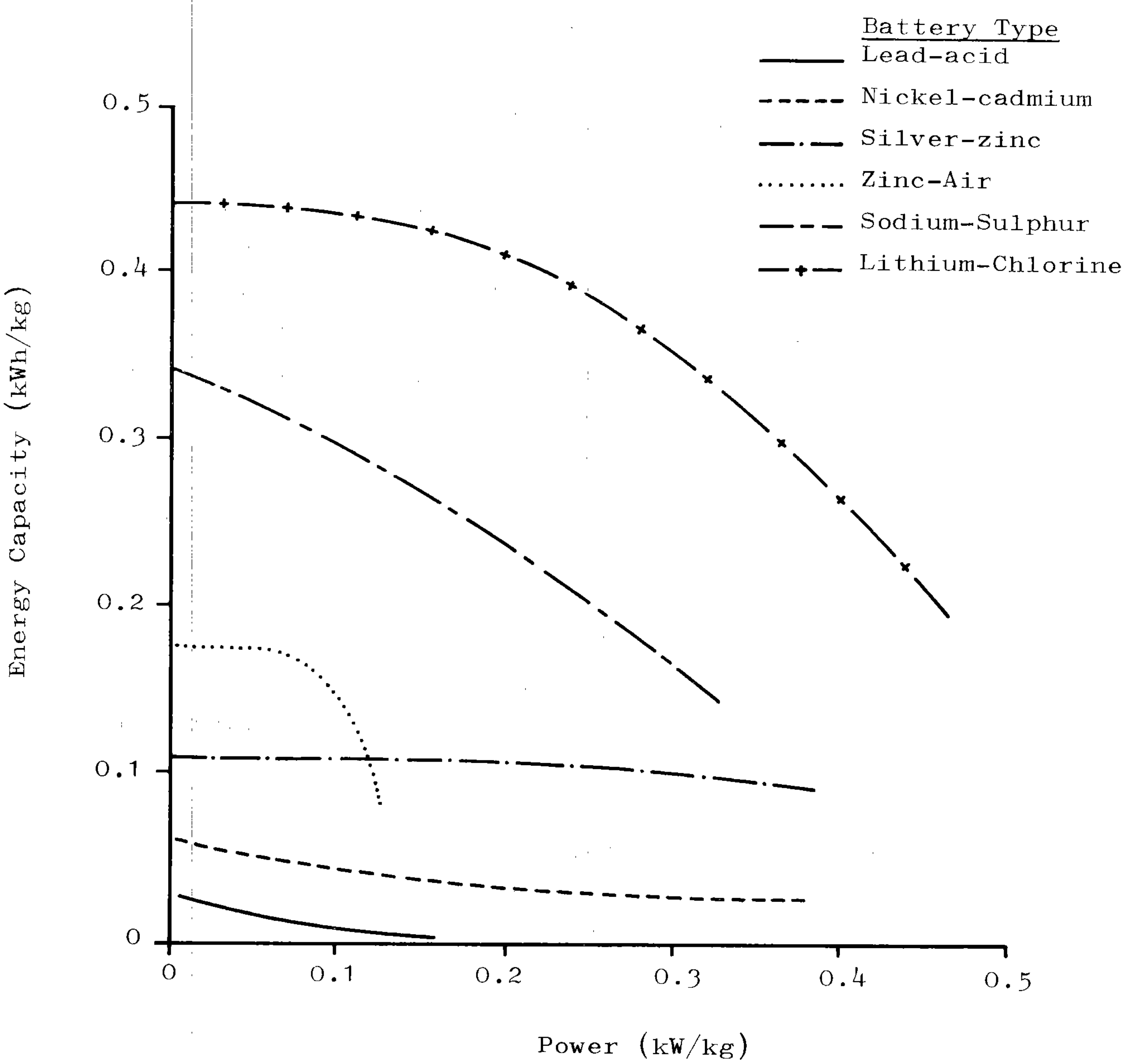

FIGURE 3.5 - CAPACITY-POWER RELATIONSHIPS FOR VARIOUS BATTERY TYPES

development should proceed. Many developmental vehicles use direct-current (DC) series motors, which have the advantages of being readily available, proven, and of comparatively low cost. However, they are also heavy, and their power-speed characteristics are far from ideal for automotive purposes. More modern developments of DC series-wound motors are lighter in weight and have improved characteristics, but their cost is somewhat higher.

The General Motors electric research vehicles[(1)] used alternating-current (AC) motors which gave very high power/weight ratios at high speeds. In general, higher speed motors have improved power/weight ratios, but may require complex transmission mechanisms and advanced cooling systems (for example, oil cooling).

Two Australian developments in battery car motors are of interest. In the first, Flinders University (South Australia) experimenters[(2)] use a fixed-speed DC parallel-wound motor which is connected to a hydraulic pump. The output of the pump is controlled by a suitable hydraulic mechanism and drives a series of hydraulic motors connected to the wheels. The major advantages claimed of this system are that an infinite speed control is obtained, regenerative efficiency is high and battery current is kept low (thus enhancing battery life). The motor is of printed-circuit construction. No electrical control system is required (except for an isolating switch), since the hydraulic mechanism provides all necessary control functions.

The second interesting Australian development is that of the Sydney firm, Electro Dynamics Corporation[(3)]. In

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(1) H.A. Wilcox, Electric Vehicle Research, op. cit.

(2) The Flinders University Electric Research Vehicle - Report No.2, School of Physical Sciences, Flinders University of South Australia, April 1973.

(3) Discussions with members of Electro Dynamics Corporation.

essence, the development consists of a motor comprised of a multitude of windings, which may be connected to provide optimum performance characteristics. While the motor is complex in operation[(1)], it promises high efficiency and low weight, together with extremely flexible characteristics. At the same time, its functional elements can be rearranged (by a simple switching mechanism) to form an inbuilt battery charger. The characteristics of the motor are largely governed by the control system, which is a thyristor type.

While the DC series-wound motor remains the major contender for battery cars at this stage, it is encouraging to note that other significant developmental work is in progress. A further point is that rapid advances in control systems for electric motors tend to cloud the traditional distinctions between different motor types. The major developments likely in battery car motors are increased power/weight ratios (probably obtained at the expense of complex transmission and cooling systems) and a more complete integration of the motor design with that of the control system and other parts of the vehicle. In particular, many switching functions currently carried out by such devices as motor commutators are likely to be relegated to the control system, where electronic components will perform the functions with improved reliability and flexibility.

Mechanical design of actual motors may follow aircraft experience, where the importance of conserving weight and space focussed particular attention on these aspects of design. Electro-mechanical equipment items used in aircraft

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(1) A description of the motor is given in: C.StJ. Lamb, 'New Approach to Battery Powered Vehicles', Electrical Engineer, August 1973.

have power/weight ratios in excess of five times as great as those for comparable ground-based equipment. While this improvement is obtained at high cost, it is clear that there is considerable scope for improvement in the design of battery car motors.

A feature of battery cars which makes motor and transmission design rather complex is the possibility of regenerative braking (in which the motor acts as a generator, and feeds braking energy to the battery). Although regenerative braking cannot completely supplant normal braking systems, it is clearly useful in extending range. However, both motors and transmissions must be designed for the loads involved. For example, effective regenerative braking could depend on a front-wheel drive system to overcome reduced braking efficiency due to the lifting tendency of rear wheels under braking conditions.

Control Systems

There are four favoured control systems for battery cars, but their applicability depends largely on the type of motor used and the specific performance requirements of the vehicle.

Battery switching: The simplest method of control is battery switching, in which various sections of the battery are switched in or out of the motor circuit as required. While this type of control is reasonably efficient, it suffers from the drawback that acceleration is not smooth. It also tends to draw unequal currents from different sections of the battery, which has a deleterious effect on battery life. It appears to have little application for automotive use.

Resistive control: This is perhaps the most common form of control for DC traction motors. In this system, a variable resistance is connected in series with the motor (although other, more complex, systems are also possible). Although this type of control is simple and smooth, it is also very inefficient. If the resistance is not fully reduced (and it would normally only be fully reduced during high acceleration or at high speed), energy losses are experienced through heating of the resistor banks. This system is not particularly amenable to regenerative braking, although dynamic braking (resulting in further heating of the resistors) is possible, within limits. The loss of energy in both driving and braking modes is very undesirable in a road vehicle, so resistance control is basically unsatisfactory for battery cars. However, it is used in some small experimental electric cars.

Chopper control: The most promising control system at this stage appears to be silicon-control-rectifier (SCR) or 'chopper' control. In this system, current is supplied to the motor as a series of pulses of constant peak voltage but varying frequency (frequency switching). At low power levels, the pulses are relatively infrequent, leading to a low average voltage across the motor. Conversely, at high power levels, the pulses are frequent and yield a high average voltage. A similar effect may be obtained by generating constant frequency pulses, but by varying their width (pulse-width modulation). Either system, if suitably designed, permits regenerative braking, with braking energy stored in the battery, and is also extremely flexible. Chopper control is also well suited for use with advanced motor systems. Chopper control systems, at present, are both heavy and costly, but the advantages gained in control flexibility and regeneration appear to outweigh these disadvantages.

Mechanical control: Another system for controlling battery cars is mechanical control, in which the motor inputs are not directly controlled at all. Control of power to the wheels is performed by an appropriate mechanical drive, such as gears or hydraulic transmission. Such systems have certain advantages, but they are relatively complex, with consequent cost and maintenance disadvantages, and do not make full use of the capabilities of electric motor systems.

The optimum control system for battery cars is largely a matter of design and performance requirements. At present, chopper control appears to offer significant advantages over other systems, although incurring some weight and initial cost penalties. The general growth in the field of electronics and the remarkable history of reductions in electronic component costs strongly suggest that the balance of advantages for electronic control will improve with time. The fact that some advanced and promising motor systems rely heavily on the availability of electronic control systems[(1)] is another factor favouring the use of this type of control for battery cars.

BATTERY CAR DESIGN

Assessments of emerging technologies tend to be qualitative by nature, and the discussion of battery car components in this report is no exception. Although certain characteristics of battery cars have been investigated in great detail, particularly in the United States, little coherent information is available about such cars as a whole. Only a few experimental models have been subjected to rigorous testing[(2)] and, of these, few correspond to classes of cars presently in common use in Australia. Accordingly, it is useful to postulate some of the likely characteristics of a 'state-of-the-art' battery car which would have reasonable marketing prospects in competition with, or as a supplement to, conventional cars.

Such a car should be of comparable size and passenger-carrying capacity to at least some existing cars in Australia (that is, ranging in length between 3 and 5 metres, and with corresponding width and height). Although the electric car would be heavy, this should not be apparent in its appearance.

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(1) For example, the system proposed by Electro Dynamics Corporation, which was discussed previously (page 57).

(2) One of the few battery cars of size comparable to existing models for which serious testing efforts appear to have been made is the Electric Fuel Corporation (US) X-144.

The car is likely to be a front-wheel drive vehicle, to take maximum advantage of regenerative braking potential and provide maximum flexibility for equipment layout. An electronic control system would be used to take advantage of regenerative braking and superior control characteristics.

The batteries would probably be long-life lead-acid types (placed in removable battery modules so that changeover batteries could be fitted quickly and conveniently) and would occupy a large volume within the vehicle. However, the batteries could be distributed to minimise the impact on available space. A major advantage of such battery modules would be that improved battery systems could be fitted if they became available within the life of the car.

The battery system would need to allow for slow re-charging at home, and also for at least occasional rapid charging (to perhaps 80 per cent of full capacity within one hour) without undue loss of battery life. This implies use of an additive (such as cobalt) to the lead-acid battery, and suitable supply wiring to carry heavy currents. A system whereby a vehicle could be driven directly onto a charging facility, without requiring manual connection to the power supply, should be feasible (and would certainly be desirable).

The actual performance requirements of the electric car are rather difficult to specify, but it should be capable of a top speed in excess of 100 km/h. It should also be able to accelerate from rest to 50 km/h in under 10 seconds, on a level road. A hill-climbing capability of grades of 1 in 10 should be provided. These characteristics are judged as acceptable to a substantial number of potential owners, not too detrimental to general traffic operation, and attainable at acceptable cost in a state-of-the-art electric car.

The car should be designed in accordance with normal automotive practice, and all relevant safety standards should be observed. In view of the inherent longevity of some of the more expensive tractive components in an electric car, the body should be designed for somewhat longer than normal life. The car should have all normal equipment (e.g. windscreen wipers and fans), but a special type of heating system may have to be developed, since resistive heating would severely limit the operating range. A heat-storage system, charged in conjunction with main battery recharging, might be used in winter, although efficient oil-burning heaters may be more appropriate.

BATTERY CAR PERFORMANCE

In order to examine the likely performance of a battery car designed in accordance with the postulated requirements, a parametric model of battery vehicle performance was developed. Although this model was largely intended for use in assessing the performance of battery cars, it is equally applicable to other types of battery-powered vehicles. The analytical background to the model is given in Annex A, a listing of the computer program is presented in Annex B and a typical set of results is shown in Annex C.

The central analysis involved in the study was the estimation of likely parametric values for electric cars designed on the state-of-the-art lines suggested above. This involved intensive examination of the characteristics of a range of cars currently marketed in Australia, to determine their physical characteristics. Further investigation was necessary to determine the weight and other characteristics of possible comparable battery cars. A complete description of the methodology is given in Annex D. It should be emphasised that the parametric values given in that Annex relate specifically to battery cars which are comparable in design to current internal-combustion cars in every aspect, except the drive system and performance. In other words, they are not 'unusual' in appearance, size or layout. The results of the analysis are consistent with currently available data on actual battery vehicles.

The performance model and parametric estimation procedures were applied to three postulated battery cars, which were categorised by their respective lengths (3, 4 and 5 metres). Other physical properties of these cars were selected by the procedures detailed in Annex D, together with informed estimates of the sizes of motors, control systems and batteries which could be accommodated within the car structures. The results of the analyses are presented in Annex E.

Each car would be capable of approaching or meeting the postulated performance characteristics for maximum speed, acceleration and hill climbing. The range of cars, as expected, would drop off substantially with increases in cruising speed and the gradient being traversed. However, the crucial point is that each vehicle would be capable of a reasonable operating range under reasonable conditions. On account of its limited battery-carrying capacity, the 3-metre car would have significantly worse range characteristics under all conditions than its larger counterparts. Again, because of its relatively low power/weight ratio, it would be somewhat inferior in overall performance. The maximum level-road speed of the 3-metre car would be approximately 92 km/h, and it would accelerate from rest to 50 km/h in 13.8 seconds. By comparison, a conventional 4-cylinder car, of the type whose performance characteristics are shown in Figure 2.7, has a top speed of 150 km/h and a 0-50 km/h acceleration time of around 6 seconds. The 3-metre battery car would be markedly inferior on both counts. The 4-metre battery car, which is a more appropriate comparison, would have corresponding values of 102 km/h and 10.9 seconds. While these figures are still inferior to those for the conventional car, they are better than those for the 3-metre car, suggesting that electric car design should be aimed at developing a medium size car rather than a very small car. Acceleration characteristics for the three battery cars and the 4-cylinder car are shown in Figure 3.6.

Operating Range

The crucial feature of battery car performance is the operating range before recharging. The parametric model results in Annex E give range versus speed for each car, under various

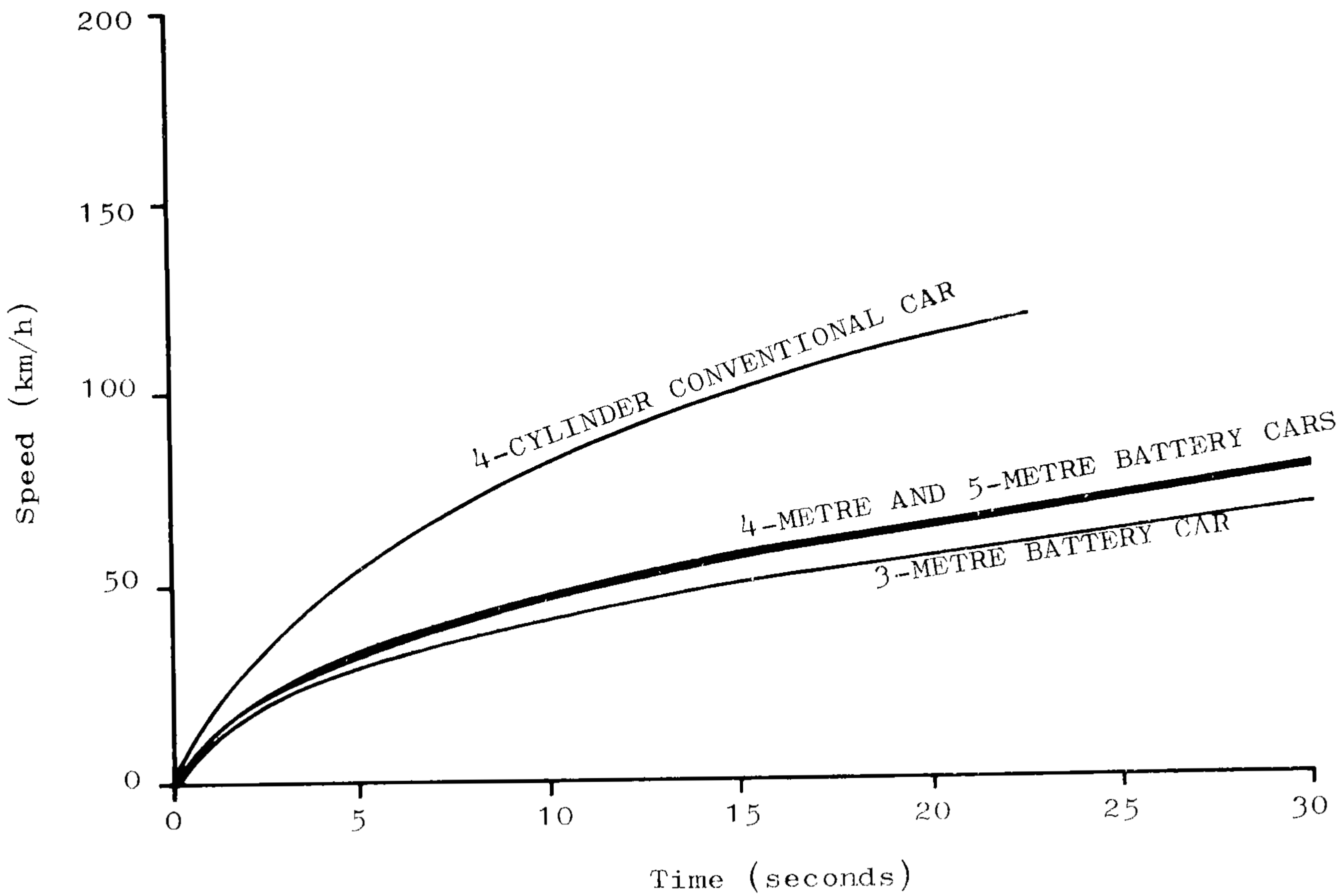

FIGURE 3.6 - COMPARATIVE ACCELERATION RATES (LEVEL ROADS)

grade conditions. In Figure 3.7, the level-road, constant-speed range characteristics of the three battery cars are compared, showing that the larger the car, the further its range under these conditions. This is a function of the size of the batteries which may be fitted into the cars. The figures presented do not take into account the fact that the battery cannot be used to complete exhaustion. Practical extreme ranges might be of the order of 80 to 90 per cent of the values quoted in Figure 3.7. Nevertheless, it appears that battery cars designed along the lines of those suggested in this report would have ranges between 50 and 100 km at constant speeds between 40 and 60 km/h.

The range of battery cars is seriously reduced by frequent stopping. While the performance model does not directly assess the effects of stop-start operation, it does provide sufficient information for an estimate of range degradation due to this factor. Such an estimate was made for the postulated 3-metre battery car, on the assumption that the vehicle travelled on a level road. The vehicle was assumed to accelerate from rest to a certain cruising speed, continue at that speed, and then decelerate in one-half of the distance covered during acceleration. The distances covered in these phases were adjusted to give the nominated number of stops per kilometre (with due regard to acceleration capabilities and other physical constraints).

The results of the analysis are shown in Figure 3.8. The energy consumption, rather than range, is shown, since the latter is difficult to estimate accurately in this type of analysis due to the effects of power output on battery capacity. It may be seen that stopping frequency has only a marginal effect on energy consumption at low speeds, but that the effect becomes marked at high speeds. Under heavily-congested urban conditions, it appears that energy consumption may be doubled or trebled on a distance basis, since a peak speed of 40 km/h and a stopping frequency of 4-5 stops/km might be experienced in such circumstances. In general, higher stopping frequencies are associated

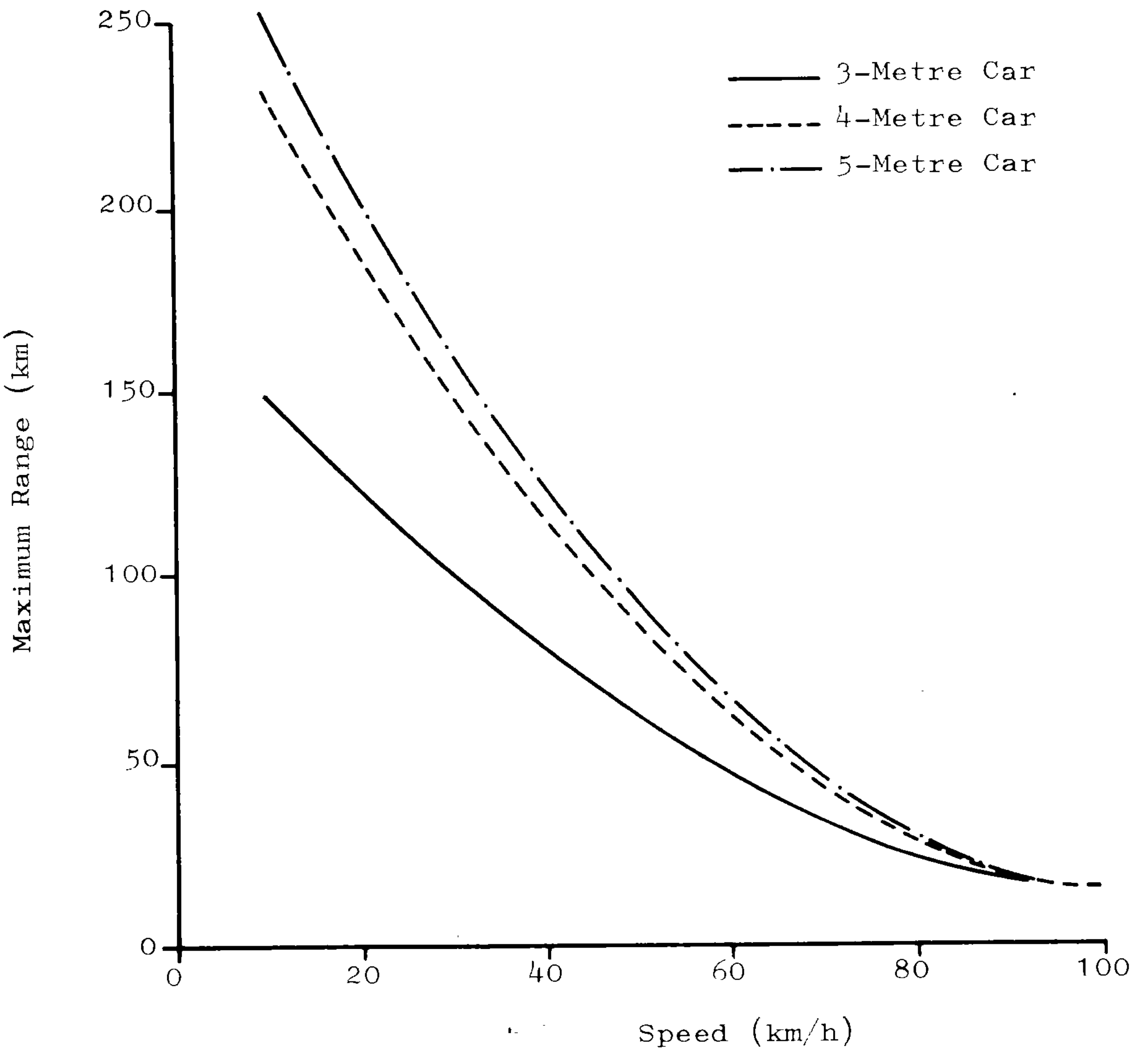

FIGURE 3.7 - COMPARATIVE RANGE-SPEED CURVES FOR BATTERY CARS (CONSTANT-SPEED, LEVEL ROAD)

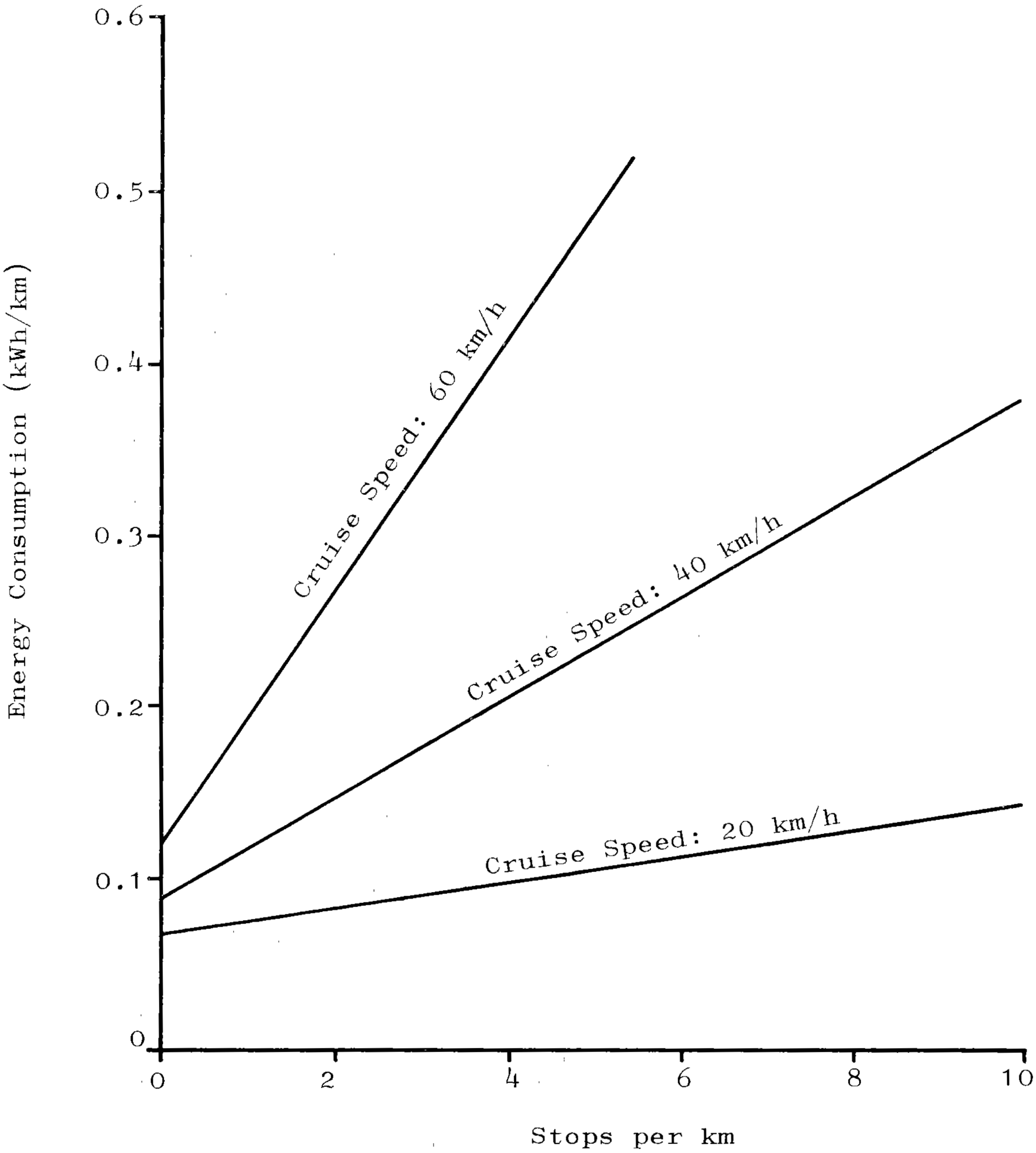

FIGURE 3.8 - EFFECTS OF STOPPING ON ENERGY CONSUMPTION - 3-METRE BATTERY CAR (LEVEL ROAD)

with lower peak speeds, so that most urban driving corresponds with the lower part of Figure 3.8. In addition, the distances travelled under such circumstances are not likely to be great, so that the range penalty for stop-start driving of a battery car may be acceptable for typical urban journeys. It should be noted that the values in Figure 3.8 relate to maximum acceleration; reduced acceleration would lower the energy consumption in most circumstances. As with conventional cars, 'furious' driving would result in very high energy consumption.

APPRAISAL OF BATTERY CARS

It is clear from the foregoing remarks that a successful battery car development is feasible within the limits of present technology. Although it could emulate the appearance and carrying capacity of conventional cars, a battery car would be heavier, and would have a much more limited performance. In this respect, it must be concluded that near-term battery cars are likely to be fairly leisurely methods of transport. Their acceleration and maximum speeds would not match those of current internal-combustion cars. As an illustration, they might perform rather like an early post-war small car.

The crucial question affecting battery car use is range. It has been shown that a state-of-the-art battery car, using appropriate lead-acid batteries, could have a range between 60 and 100 km at a constant speed of about 50 km/h. Under very congested conditions these range values might well be reduced by as much as one-half. It must therefore be concluded that the range of near-term battery cars is insufficient for any but a rather limited category of urban motorist. The fact that batteries now available can be recharged relatively rapidly (perhaps in one hour) alleviates the range problem to some extent, but still does not suggest general suitability for urban motoring.

Nevertheless, if battery car performance is related to data on car trip-length characteristics (Figure 2.8, for example), it is clear that even the limited range available to battery cars is adequate for a very large proportion of individual trips in urban areas. The crucial question relates to the number of such trips made in a particular day (or at least between suitable recharging times) by individual cars. Some light is thrown on this matter by overall statistics of motor vehicle use, which indicate that cars travel an average distance of around 9,000 km per annum in urban areas in Australia(1). On this basis, the average distance travelled per day is only 25 km. Thus, battery cars are capable of meeting average car requirements for urban areas. It must be emphasised, however, that average figures are misleading in such cases, and a realistic estimate of the possible penetration of battery cars would require considerably deeper research into the subject of individual car use patterns.

To the overall question of battery car usefulness in urban transport, the answer must be guardedly optimistic (in view of performance limitations). It has already been noted that specialised commercial battery vehicles have gained wide acceptance, and it is likely that buses and other personnel-carrying vehicles may be suitable targets for battery operation in some circumstances. On the other hand, it appears extremely unlikely that battery operation will be suitable for heavy trucks, unless a significant technological breakthrough occurs.

At this stage, the only possible judgments about the applicability of battery cars to urban automotive travel are qualitative. On a performance basis, the battery car appears adequate for many work journeys, within limited distances, since the requirements for such journeys are not particularly arduous. It is probably more than adequate for typical 'second car' applications. The requirements of many commercial and government vehicles could also be met by battery cars. However, battery cars are certainly not capable of meeting all the requirements of every individual car in these categories.

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(1) Survey of Motor Vehicle Usage 1971, op.cit.

SOCIAL AND ECONOMIC EFFECTS

The preceding sections of this report have dealt with the position of the motor car in Australia, and with the basic characteristics and likely performance of battery cars which could be introduced to general service in the near future. The results of this appraisal have shown that battery cars are unlikely to be competitive, on performance grounds, with internal-combustion cars under current circumstances. So far no account has been taken of the social and economic effects of the introduction of battery cars.

Vehicles powered by on-board electrical generation or storage equipment have frequently been hailed as progenitors of completely pollution-free, quiet personal transport. This acclamation is partly warranted, but requires closer examination. Additional aspects of battery car operation which merit examination are their effects on road safety, road networks, traffic patterns, energy resources and manufacturing processes. Of necessity, estimates of the ramifications of battery car use in these areas are qualitative, since it is virtually impossible, with current information, to predict the likely penetration of battery vehicles into the car market.

Battery Car Emissions

Although lead-acid battery vehicles do not produce normal atmospheric pollutants at their point of operation, their use would result directly in increased emissions from thermal power stations. Although such emissions are concentrated in specific sources, and are hence easier to control than automotive emissions, they are nevertheless significant in quantity.

It has been found particularly difficult to derive quantitative estimates of the reduction of pollutant levels which might be experienced if battery cars were to be introduced in substantial quantities. Certainly, carbon monoxide (CO) and hydrocarbon (HC) emissions to the atmosphere in urban areas would be reduced significantly, since the internal-combustion car is a major contributor to these emissions (as shown in Figure 2.9). If battery cars found great use in inner city areas, the local levels of these particular emissions would be reduced even more significantly. Both of these changes would be worthwhile. It is also expected that direct production of nitrogen oxides (NO_x) by cars would be dramatically reduced. However, this effect would be somewhat negated, in the overall picture, by the fact that oxides of nitrogen are produced in relatively large quantities by thermal power stations. The question of control of this particular source of NO_x emissions is beyond the scope of this report, but it is felt that widespread use of battery cars might well result in an overall increase in the levels of these particular pollutants, although the distribution would be much more acceptable.

The other major atmospheric pollutants (particulate matter and sulphur oxides) would certainly be increased in quantity by extensive use of electric cars, under present power-generation conditions. However, these conditions are certain to improve as emission controls on thermal power stations are progressively updated. In Australia, pollution control is aided by the fact that most thermal power stations use coal, and Australian coal is relatively low in sulphur content.

In terms of other pollutants, battery cars have both positive and negative effects. While generation of asbestos emissions should decrease (due to regenerative braking), rubber emissions are likely to increase due to the extra weight of such cars. Similarly, electric motor operations will involve deposition of copper compounds and particles, although these could be controlled at their source. Motors also generate ozone, but it is anticipated that production of this pollutant would be minimised with advanced motor systems. Battery charging operations also generate emissions (in particular, hydrogen in lead-acid batteries), but these should be readily controllable. With the exception of rubber and asbestos particles, it is anticipated that battery car emissions will be predominantly non-toxic and relatively simple to control.

In summary, a significant penetration of electric cars as substitutes for internal-combustion vehicles would have two major effects:

(a) An immediate and permanent reduction in local emission problems (such as those encountered in inner-city areas and other high traffic density areas).

(b) A decrease in overall emission levels of CO and HC, and a likely increase in SO_x and particulate levels, with an indeterminate effect on NO_x levels.

Maintenance of these advantages would, of course, involve an increasing share of the car market by battery cars. In many ways, the problem is an analogy to that involved in emission controls for conventional cars - if the number of cars continues to grow, improved individual performance will be overwhelmed by increasing numbers.

Battery Car Noise

A further desirable social aspect of battery cars is their reduced noise level under certain conditions. Although automobile noise falls into many classes, the prevailing sources under low-speed conditions are the engine, exhaust system and transmission. In urban areas, where substantial proportions of driving time are spent under idling and acceleration conditions, these noise sources become particularly marked.

In battery cars, the motor is almost silent, and thus engine and exhaust noises are virtually eliminated. Since battery cars may not require gear-changing mechanisms, their transmissions should also be particularly silent. The fact that battery car motors do not 'idle', in the usual sense, also reduces their noise levels. These effects are significant at lower speeds, but in all cars coasting noise becomes predominant at speeds in excess of 50 km/h. At speeds of this order, battery cars may be noisier than conventional cars due to their greater weight.

In extreme urban driving conditions (as, for instance, inner-urban traffic), widespread use of battery cars would substantially reduce traffic noise. Under freeway conditions they could be slightly noisier than their conventional counterparts.

Travel Patterns

Substantial usage of vehicles with strictly limited range might well result in changes in urban travel patterns and, in the longer term, to changes in land use. Legislative action (particularly bans on non-electric cars in specific areas) could reinforce and hasten such changes.

Safety

A gradual introduction of low-performance cars amongst the normal road traffic is likely to result in increased accident rates. No information is currently available for assessing the magnitude of such increases, but they may well be significant. The causes of additional accidents could be classified in the following ways:

(a) Direct accidents, caused by unexpectedly low performance which could confuse drivers of faster-accelerating vehicles.

(b) Indirect accidents, caused by general worsening of traffic flows due to substantial numbers of low-performance vehicles.

As penetration of battery vehicles increases, accidents due to these causes should decrease, due to increased driver awareness and more uniform car performance capabilities.

Road Construction and Design

Current urban road design procedures are closely related to the composition of existing road traffic. The advent of battery cars in substantial quantities could ultimately affect such procedures in several ways:

(a) The increased weight of battery cars would lead to increased road wear. This effect is not considered major, since roads are primarily designed for trucks, which have wheel loadings considerably greater than battery cars.

(b) Design gradients, particularly for interchanges and flyovers, would presumably have to be reduced to compensate for the reduced capabilities of battery cars. This would result in increased construction costs and could increase land requirements.

(c) The reduced performance of battery cars may well lead to reduced road capacities (in the same way as capacities are reduced by the presence of heavy vehicles). In turn, this may result in increased road construction requirements.

These changes to road construction and design are, of course, distant, since battery cars are unlikely to constitute a significant proportion of urban traffic for some considerable time. Nevertheless, they must be considered as likely future disbenefits of the introduction of battery cars.

Energy Resources

In view of recent disturbances in the market for petroleum products, the value of any transport technology development which leads to a reduction in petroleum product consumption is clearly significant. The commodity required for battery vehicle propulsion is electricity, and the basic fuels for such vehicles are those fuels which are used to produce electricity. In Australia, the majority of electrical power is generated by thermal power stations, which are predominantly coal-fired. The nation also possesses large hydro-electric power generating facilities, which are mainly used to supply peak load requirements. Some power stations use petroleum products and natural gas for their operations, but these are in a minority[1].

It is frequently asserted that battery cars could be operated by night-time recharging on off-peak power (which is supplied at extremely low tariffs). This assertion has been challenged on two grounds:

(a) It is likely that many battery cars will require recharging during the day (typically during lunch periods) to carry out their functions. Since such recharging would be at a high rate, the actual power levels required at such times would be heavy.

(b) Off-peak electric power will only remain inexpensive while it is in relatively low demand.

In 1970-71, the total installed power of electrical generating equipment in Australia approached 16,000 MW. It is estimated that the total possible generation of electric power during that year could have been approximately 10^8 MWh[2]. In fact, Australian consumption amounted to only 45 per cent of that figure. It is clear that there is considerable unused generating capacity available.

On the basis of the performance estimates derived previously for battery cars (Figure 3.8), a consumption figure of 0.40 kWh/km is regarded as a reasonable estimate for battery cars under general urban conditions. If such cars perform similar travel in urban areas to present cars (i.e. an average of 8370 km per annum), each car would require

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(1) This information and other details of electric power generation in Australia are taken from: Year Book - Australia 1972, op.cit.

(2) Assuming plant availability of 80 per cent for thermal power plants, and limited hydro-electric generation.

approximately 5,000 kWh(1) of electrical energy each year. At this consumption level, even the 1970-1971 excess generating capacity appears easily capable of supporting the urban operations of several million battery vehicles, if recharging can be organised so that it does not interfere with peak electricity production. Given this situation, there appears to be little justification for substantial off-peak electricity price rises, at least until battery vehicles have appeared in very considerable numbers. Recharging batteries during periods of relatively high loading would be charged at appropriate rates and may, in fact, be charged at higher than normal rates if such operations were likely to entail construction of additional electric generation facilities.

The question of coal resources for electricity generation has not been examined in detail. It is generally held that Australia has very considerable coal reserves, so a substantial use of electric cars is not likely to unduly strain energy resources. A relative increase in the price of coal may be expected, even without electric cars, but in itself this is unlikely to materially influence electric car usage. A more significant issue is whether or not there would be excise on electricity used for automotive purposes. If off-peak electrical tariffs remain at relatively low levels, battery cars will enjoy a considerable margin of economy over internal-combustion engined cars (at least in direct operating costs). However, this advantage would be eliminated by the imposition of an excise comparable to that on petroleum products.

Although Australia currently depends heavily on coal-fired thermal generation of electricity, its options for other forms are considerable. In addition to expanded hydro-electric generation, the following alternative or supplementary power sources could be attractive in the long term:

- tidal power

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(1) Assuming recharging efficiency of 70 per cent.

- solar generation
- natural gas or LPG generation
- nuclear generation

In summary, it appears that energy resources for electric power generation are varied and readily available. Although current generation methods use resources which are finite and subject to price variations in response to world demands, future possibilities include resources which are both abundant and not subject to such considerations. By the nature of electrical supply and demand, considerable excess plant capacity is available, and power for cars using storage systems should be relatively inexpensive in the near and medium future.

In terms of overnight recharging, the power capacity of present suburban and household wiring systems should be adequate to meet battery car demands. Fast recharging (e.g. one hour) may require more substantial circuitry.

Manufacturing Operations

The widespread use of battery cars would have a major disruptive effect on existing car manufacturing operations. Although much of the bodywork, suspension and structure of such cars would not be substantially different from those of present cars, most other components would be completely new to automotive manufacturers. Similar problems would occur throughout the entire process of selling, repairing and maintaining cars. It is obvious that substantial retraining for people in the industry and major restructuring of manufacturing plant would be required. The magnitude of these changes would depend on the rate of conversion to electric car usage.

Similar problems in the petroleum industry would be felt even more acutely if battery cars appeared quickly and in large quantities. The situation would be that the motor spirit market would diminish, with consequent underutilisation of refineries and unemployment in production and sales operations. However, the effects would not be great if the total number of internal-combustion cars remained relatively constant for a considerable time.

Manufacturing Materials

Current cars are manufactured predominantly from iron and steel, with lesser quantities of other metals and materials. Battery cars, on the other hand, would require the same materials for bodywork and similar structures, but would use considerable amounts of lead and copper. Lead-acid 4-metre battery cars might contain approximately 0.3 tonnes of lead and 0.1 tonnes of copper. Although the copper in such cars would be in long-life equipment (such as motors and control systems), the batteries would only last for around three years (although they could be largely reclaimed after that time).

In 1971, Australian production(1) of lead amounted to approximately 400,000 tonnes, of which almost 55 per cent was exported. Since the total domestic consumption of lead per year is of the order of 200,000 tonnes (or the equivalent of some 600,000 new battery cars), it appears unlikely that such cars would cause problems in lead production, particularly if efficient reclamation processes could be adopted.

Again in 1971, the total contained copper in Australian mine production was approximately 177,000 tonnes. This production level is also sufficiently high to ensure that battery car production would not cause a serious supply problem, at least for a considerable time.

The fact that battery cars tend to be substantially heavier than conventional cars requires greater strength in body and suspension components. This, in turn, dictates that

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(1) Bureau of Mineral Resources, Geology and Geophysics, Australian Mineral Industry, March 1973.

they would use larger quantities of conventional construction materials per unit of production. The materials most affected by this aspect of battery car construction are steel and rubber.

In general, it is anticipated that the advent of battery cars in significant numbers would exert pressure on prices for the materials mentioned. However, it is not envisaged that these problems would be severe, and they are not likely to be encountered for some years, even if battery cars begin to appear immediately.

Battery Car Costs

The question of specific costs for battery cars has so far been largely avoided, since meaningful information on this aspect is particularly scarce. Cars currently available in very small quantities exhibit a wide range of initial prices (ranging from 1.5 to 5 times the prices of comparable internal-combustion cars). It is estimated that battery cars might be produced, in quantity, at price levels approximately 25 per cent greater than those for conventional high-volume cars. Obviously, the actual price levels would depend on philosophies adopted in defraying developmental and plant-conversion expenditure, and the extent of governmental participation would also affect these factors. It does not appear likely that the initial price of battery cars, at least in the near term, can be reduced to the level of comparable conventional cars (without such Government action as sales tax or import duty remissions).

One advantage claimed for battery cars is that they are low in maintenance. Although the BTE has not examined the question in detail, it is felt that engine maintenance is not a predominant factor in overall car maintenance. Although electric motors and batteries require little maintenance, the general requirements for body, chassis and transmission servicing will disguise this advantage in the overall cost of routine maintenance. In addition, battery cars may require separate recharging systems which would require occasional checking and service. The motors used in battery cars are inherently long-life items, but batteries require replacement at regular intervals.

In terms of direct operating costs, battery cars would be particularly attractive at current off-peak electric power tariffs. While a 4-metre conventional car might have a fuel consumption of around 11 km/litre under urban conditions (a fuel cost of approximately $0.011/km at current capital city motor spirit prices), its battery counterpart could have electricity costs as low as one-third of this figure, in some cases. This advantage would be somewhat mitigated by increased tyre wear due to greater weight, and by battery replacement costs, but the battery car would still have a clear advantage if electricity prices remain at current relative levels. If petroleum prices rise relative to coal, the attractiveness of the battery car would be further enhanced.

It is not considered appropriate to make direct comparisons between battery and conventional car operating costs, since many of the characteristics of the former are not fully known. However, it appears that battery cars are attractive if they can be produced at initial price levels which are not greatly higher than those of conventional high-volume cars, if the price relativity between electricity and motor spirit can be maintained, and if there is no excise on electricity for cars.

CHAPTER 4 ELECTRIC CAR RESEARCH AND DEVELOPMENT

Although various aspects of electric car design and operation have been investigated in this report, it is clear that several important questions remain unanswered and further research into the characteristics and operations of such vehicles is warranted. At various stages of the report, certain topics relating to areas of doubt have been pointed out, and these topics, together with other specific research and development requirements, are discussed in the following paragraphs. Particular planning activities related to battery car introduction are also noted.

CAR USE RESEARCH

Efforts to obtain consistent information on patterns of car use, particularly in urban areas, have failed to produce useful results. In a serious program to replace internal-combustion cars, in large quantities, it is imperative that the use patterns for individual cars should be known. The obvious method of determining such patterns is to conduct a limited survey of a sample of urban motorists. The results of such a survey would provide valuable data on the performance required of car alternatives, and would highlight any legislative actions which might improve acceptance of any performance deficiencies of such vehicles.

Battery Car Performance Assessments

The modelling procedures described in this report are useful in assessing the likely performance of battery cars, but are fairly limited in scope. Although the results of such a parametric model could be made more realistic by inclusion of a wider range of driving conditions, this may well be a poor substitute for actual trials involving battery cars designed in accordance with the latest available procedures. The battery car is a transport medium which attracts considerable interest from all sectors of the community, and particular organisations and individuals frequently put forward proposals for various developments in this field. Although many of these proposals are clearly unworkable, some are based on reasonable technical grounds, and it appears that selective expenditure on development could well be warranted. Such support could be largely directed towards the development of specific car concepts, with the aim of proving or disproving the merits of battery cars in Australian conditions. Early information on some important aspects of this research could be obtained by importing a limited number of overseas-designed battery cars for trial purposes.

One other aspect of battery car performance research is that of research into specific components (in particular, batteries and motors). This type of research could, again, originate with individuals, but its successful completion would probably require the resources of relatively large research or industrial institutions. Although avenues for transport hardware development are somewhat limited in Australia, there is a clear need for their establishment, and a limited program of research into battery vehicle components may be an appropriate starting point[1].

EFFECTS ON EXISTING TRANSPORT

The introduction of battery cars in large quantities would have some general effects on roads and traffic operation. Particular aspects which would warrant attention include:

- design rules for collision safety;
- road design standards; and
- traffic control measures.

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(1) In this respect, some of the work previously outlined as being undertaken within Australian Universities, firms and other organisations may well be worthy of support.

ECONOMIC ASPECTS

Once the technical feasibility of battery cars as replacements for conventional cars has been demonstrated, even in limited form, economic questions relating to the introduction of such cars assume major importance. Although some of these questions have been treated arbitrarily in this report, it is clear that a successful program of battery car development and implementation would involve major changes of a general economic nature. The question of the feasibility of such shifts, regardless of the technical feasibility of battery cars themselves, is one of considerable importance. Specific areas in which research is required are:

(a) The basic effects on manufacturing industry of a shift from internal-combustion cars to battery cars.

(b) Economic aspects of altered use patterns for electricity.

(c) Effects on prices of changes in demand for basic materials required for battery car manufacture.

(d) Effects of diminished demand for petroleum products.

(e) Effects on car ownership.

(f) Effects on travel demand (car and public transport).

(g) The trade-offs between higher cost travel, reduced mobility, reduced air pollution and reduced noise.

(h) The public facilities which would be required for convenient battery charging.

These research areas would involve considerable resources. Nevertheless, the intrinsic merit of an automobile replacement which offers a reasonable promise of alleviating both atmospheric pollution and energy resource problems must be regarded as worthy of a substantial research effort.

GOVERNMENT ACTION

Although research and development are not normally taken to include assessments of possible government action, legislative or administrative controls of the use of cars could have a major effect on the market penetration of battery cars. Avenues by which battery cars might be made more attractive than conventional cars, despite the performance limitations of the former, include:

(a) Selective closures of areas of cities to vehicles other than battery cars.

(b) Advantageous parking rates (and tolls, where applicable) for battery cars.

(c) Differential sales tax rates on new-car purchases to overcome the likely higher initial price of battery cars.

(d) Preservation of low off-peak electricity tariffs for battery car use (perhaps financed by increases in motor spirit excise rates).

(e) Not imposing excise on electricity used for battery cars.

In addition to direct legislative action, there are other spheres of battery car development and operation in which government participation may be warranted. A major deterrent to the introduction of battery cars is their inability to perform all the functions required of normal cars. This difficulty might be overcome by providing owners of battery cars with limited access to hired conventional cars at subsidised rates. For longer journeys (for example, annual holidays), low-rate air or rail travel, with availability of a battery car at the journey's end, may provide a considerable incentive for people not to own conventional cars. However, the feasibility and cost of such schemes would require careful assessment.

A further area in which government action might be desirable is in establishing networks of recharging stations or battery-exchange facilities. Although battery cars would be recharged mostly at the owners' premises, using low charging rates, there would be occasions on which external recharging or battery exchange would be required. Such facilities could be incorporated in publicly assessible locations where suitable charging tariffs could be imposed.

ADVANCED ELECTRIC CAR CONCEPTS

The majority of this report has dealt with battery cars, although certain details of other electric car types have been presented. It is felt that electric car technology is an area in which dramatic advances might occur, either as a result of general technological advance or as a direct by-product of the quantity production of battery cars. Such advances are likely to be in battery and motor technology, and the development of battery systems which are safe, simple and efficient is one facet of battery car research in which breakthroughs would be highly advantageous.

There is one related concept which should be mentioned. Any captive transport system is either limited in coverage or highly expensive, and it is unlikely that a universal car-based system using reticulated electric power (collected by the vehicle) would be economically feasible. However, a compromise system, in which cars run on batteries for limited periods, and on electric power from wayside structures, where these are available, seems promising as a long-term objective. In its simplest form, the vehicle would be a battery car, equipped with an appropriate collection mechanism (a possible design is shown in Figure 4.1). Freeways and major arterial roads might be equipped with perhaps one electrified lane, and suitably-equipped cars could travel considerable distances without drawing power from their batteries. They could even recharge batteries by using the collected power. The power level available from the road installation might be made higher than that normally available from batteries, so that in the captive mode the car could have true freeway performance.

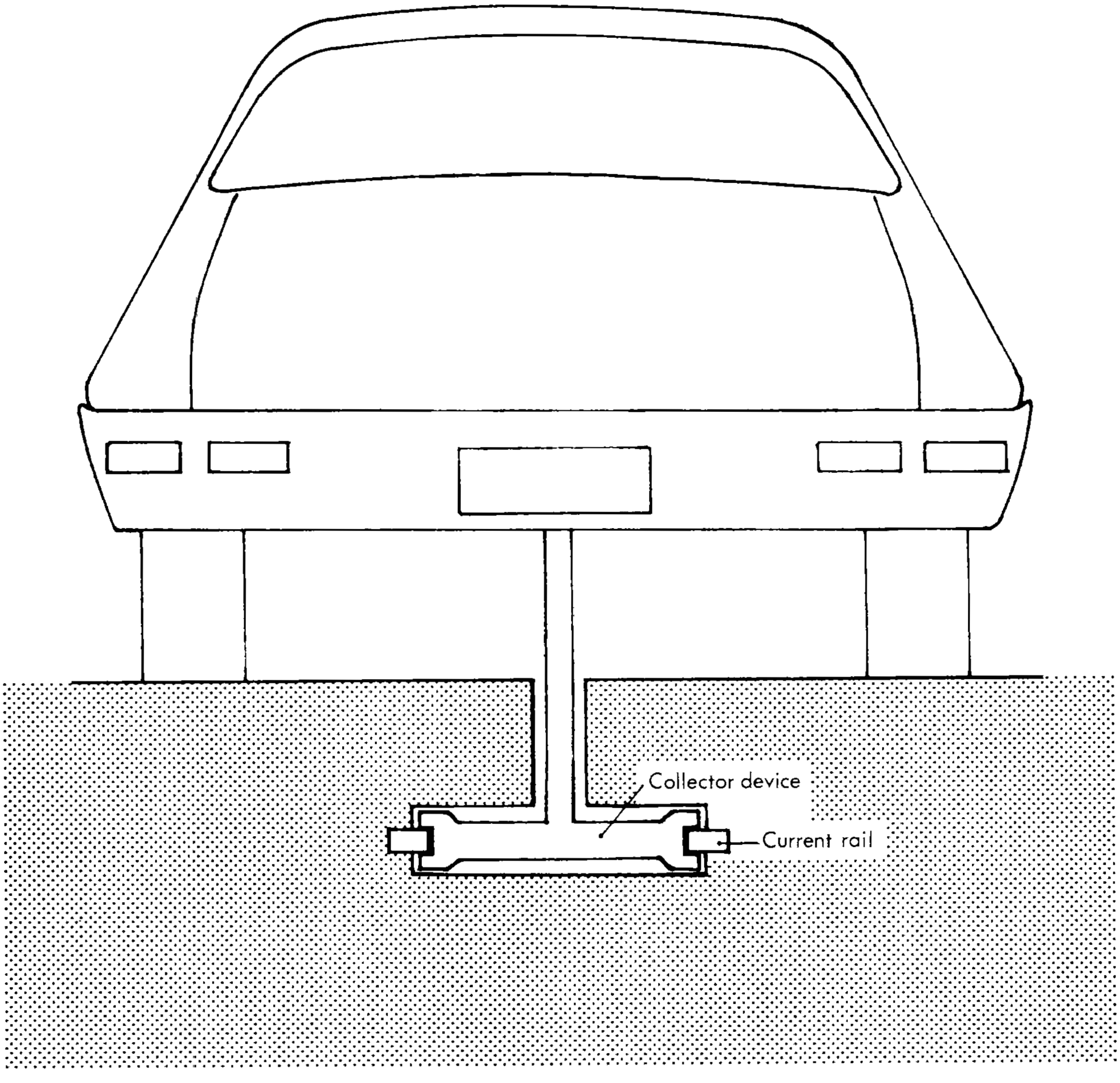


FIGURE 4.1 - SEMI-CAPTIVE ELECTRIC CAR

Although a system of this type clearly requires considerable development, it offers the potential for long-range electric vehicle driving, with limited capabilities off major roads. Since vehicles would be connected to the road by electrical means (and probably mechanically as well) during major-road travel, the concept can be readily adapted to automatic control, which could offer many advantages of driver communication, safety and road capacity. A semi-captive vehicle system of this type would involve even greater technological and economic changes than the introduction of battery cars, and would require extensive investigation. Nevertheless, the technological base for the system already exists, and it must be regarded as a possible contender for a significant share of future urban travel.

CHAPTER 5

CONCLUSIONS

In this report, many aspects of the design, performance and potential of electric cars have been examined at varying depth. This examination was carried out on the basis that electric vehicles are already regarded as acceptable in limited specialised applications (e.g. industrial trucks, milk and refuse delivery and collection services, golf carts, airport apron vehicles and inner-city buses). However, the considerable social advantages of such vehicles will not be fully exploited unless they are accepted as substitutes for the conventional motor car. Essentially, it is concluded that battery cars of state-of-the-art design are adequate for many urban driving demands, and that they could have considerable beneficial effects in reducing atmospheric pollution, traffic noise and reliance on petroleum-based fuels. At the same time, considerable numbers of battery cars could be manufactured and operated in Australia without exerting undue pressure on key resources such as coal, lead and copper.

Other electric car types are not considered ready for introduction at this stage, although they may have potential for the future. Further, the battery car in its present form is unsuitable for operation outside urban areas. Other disadvantages of the introduction of battery cars as replacements for conventional cars are that they may increase traffic collisions, impede traffic flows and disrupt the motor car and petroleum industries.

As with any new technological development, it is difficult to provide a quantitative assessment of the overall merit of the introduction of battery cars. From a potential buyer's point of view, battery cars are likely to be expensive initially, but comparatively low in operating costs. Although the magnitudes of these factors cannot be determined without research into actual urban conditions, it is likely that there would be some net user disutility involved in purchasing and operating a battery car rather than a conventional car (at least, under present sales tax, import duty and excise provisions). However, these factors may well be overshadowed by the reduced flexibility of battery cars in regard to performance, particularly with respect to range. On the other hand, battery cars offer significant reductions in both local and overall pollutant levels, and they may well be the only method of powered personal transport to offer this advantage within the foreseeable future. Additional advantages to the community would stem from noise reduction and energy resource conservation.

In view of these competing factors in battery car acceptability, it could be useful to postulate a scenario in which battery cars could eventually find large-scale acceptance. A progressive schedule of circumstances might include all or most of the following:

(a) Importation and scientific trial by government agencies of a range of battery cars currently available overseas.

(b) Imports of small quantities of the most promising type (or types) of battery car to be marketed at costs reasonably comparable to those of corresponding conventional cars (allocation of cars could be selective and conditional on continuing provision of cost and travel data for research purposes).

(c) Exemplary action by government agencies in using battery cars wherever the pattern of car usage is reasonably consistent with battery operation.

(d) Stimulation of the development and manufacture of suitable battery cars in Australia.

(e) Establishment of levels of import duty, sales tax and electricity tariff so that the initial cost and running costs of battery cars are reduced below those of conventional cars.

(f) Progressive development of a convenient network of battery recharging and exchange stations.

(g) Development of parking fee structures and regulations to discriminate in favour of battery cars in central city areas.

(h) Selective and progressive bans on internal-combustion cars in specified areas (particularly city and major suburban centres).

(i) Introduction of taxes to discourage multiple ownership of internal-combustion cars, so that multiple-car households would tend to use a battery car for inner urban travel and a conventional car for suburban and inter-urban travel.

(j) Development of measures for relieving the disadvantage of battery car ownership for long distance travel.

In preparing information for this report, the BTE gained the impression that some of the battery car technology under development in Australia has particular merit, and warrants co-ordination and support to encourage it towards early fruition. The data assembly and analyses also led to the strong impression that battery car usage in Australia should be based on vehicles which are reasonably similar in size, styling and (as far as possible) performance to conventional cars. The introduction of very small 'city cars' in Australia is unlikely to encourage a trend towards battery car usage, and may actually be counter-productive.

In conclusion, the BTE considers that there is a case for serious exploration and testing of the proposition that battery car use by certain categories of car owners in major cities is practicable and in the community interest.

ANNEX A

BATTERY VEHICLE PERFORMANCE ANALYSIS

A basic consideration in establishing the acceptability of vehicles of any type is the performance of such vehicles relative to other vehicle types with which they must compete. In this Annex, the fundamental attributes of battery-powered vehicles are investigated, and an analytical model of battery vehicle performance characteristics is postulated. The model is developed as a computer program, which is listed in Annex B. For this report, use of the model is based largely on parametric analysis, which is considered the appropriate medium for investigating battery vehicles at this stage.

ANALYSIS REQUIREMENTS

The basic requirement of any analysis of vehicle performance is to provide details of performance under various specific conditions of travel (in some ways, this requirement is similar to that of 'road tests' given in motoring magazines and newspapers). In addition, an analysis of vehicle performance under simulated conditions representing those encountered in normal travel is desirable, but the processing required to amalgamate and collate details of road travel in Australian cities was of such magnitude that it was not possible to undertake this activity in the time available for preparing this report. Therefore, the analysis described in this Annex is confined to investigation of the following vehicle attributes:

- constant-speed energy consumption, range and similar characteristics;
- maximum speed capability;
- full-power acceleration capability;
- hill-climbing capability; and
- regenerative energy-conservation capability.

In addition, the sensitivity of vehicle performance to variations in basic parameters is considered.

BASIC THEORY

The fundamental linear equation of motion of a motor vehicle consists simply of balancing the accelerating force against the difference of driving and retarding forces on the vehicle, with the difference resolved in the direction of vehicle motion:

$$M\,a(v) = D(v) - R(v) \qquad (A.1)$$

where M is the vehicle mass,
$a(v)$ is acceleration at speed v,
$D(v)$ is drive force at speed v, and
$R(v)$ is retarding force at speed v.

A general diagram of the forces acting on a vehicle is shown in Figure A.1.

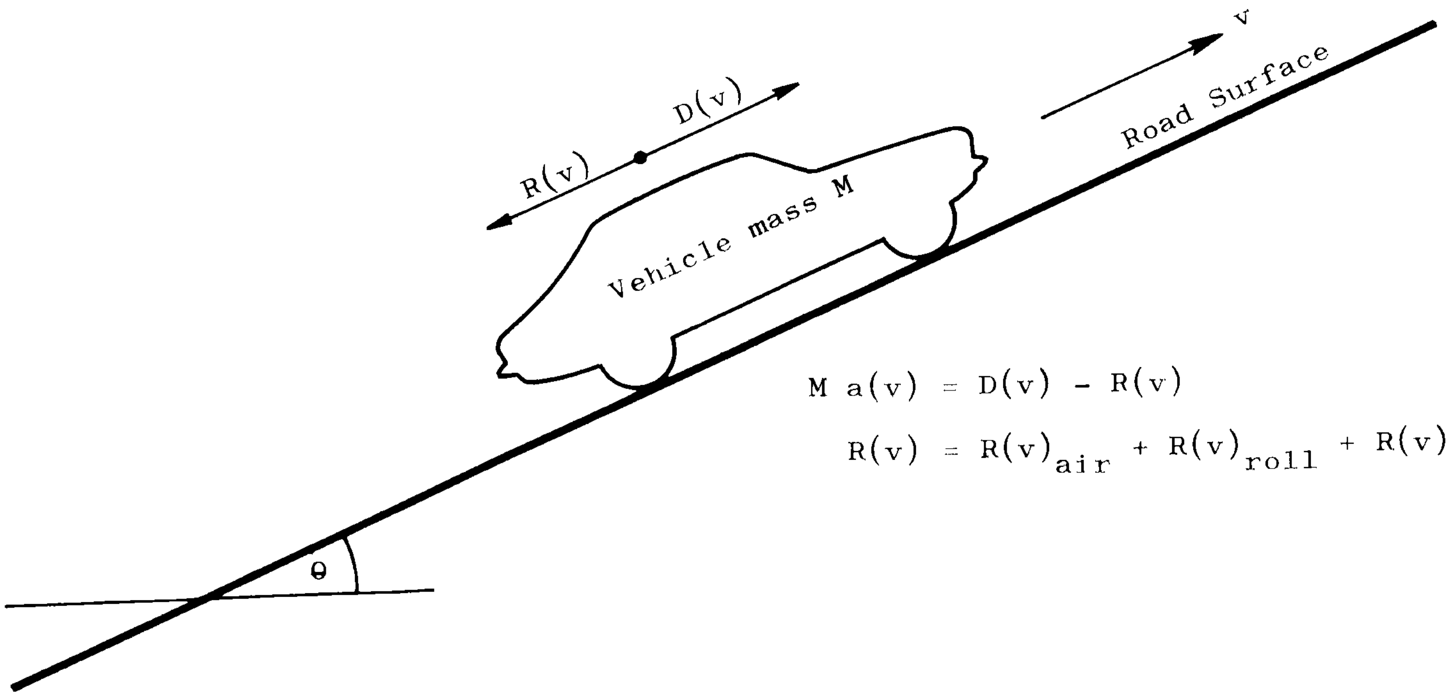
Although the drive force is a complex function of inter-actions between vehicle driving components, it may be computed quite readily on a parametric basis. Since an electrically-propelled vehicle does not normally contain a speed-changing transmission mechanism, the maximum available drive force is:

$$D(v)_{max} = \frac{P(v)_{max}\,\eta(v)}{v} \qquad (A.2)$$

where $D(v)_{max}$ is maximum drive force at speed v,

$P(v)_{max}$ is maximum power available at speed v, and

$\eta(v)$ is conversion efficiency at speed v.



$$M\,a(v) = D(v) - R(v)$$

$$R(v) = R(v)_{air} + R(v)_{roll} + R(v)_{grade}$$

FIGURE A.1 - GENERALISED VEHICLE FORCES DIAGRAM

The parametric representation of drive force given in equation (A.2) is valid for positive and non-zero values of speed. However, a notional difficulty arises as speed approaches zero, since power at zero speed is, in general, zero, and the drive force at zero speed is therefore indeterminate. This problem is overcome by defining a limiting (or critical) speed, below which the available drive force has a constant value. This solution to the problem is also in line with the physical performance of electric motors, which are current-limited at low speeds, and power-limited at higher speeds. Thus, a more general form of available drive force variation is as follows:

$$D(v)_{max} = \frac{P(V_L)_{max}\,\eta(V_L)}{V_L} \qquad (v \leqslant V_L) \qquad (A.3)$$

$$D(v)_{max} = \frac{P(v)_{max}\,\eta(v)}{v} \qquad (v > V_L) \qquad (A.4)$$

where V_L is the limiting speed of the constant-force regime.

The nature of available drive force variation with speed for a given power-speed variation, according to equations (A.3) and (A.4), is shown in Figure A.2.

Retarding force is a complex function of vehicle, road and driving conditions, but may be treated quite readily in a parametric analysis. Traditionally, the retarding force for linear vehicle motion is considered as composed of three identifiable components:

(a) Aerodynamic drag, due to atmospheric resistance to motion.

(b) Rolling resistance, due to frictional losses involved in tyre motion on road surfaces.

(c) Grade retardation, due to gravitational forces encountered in ascending hills.

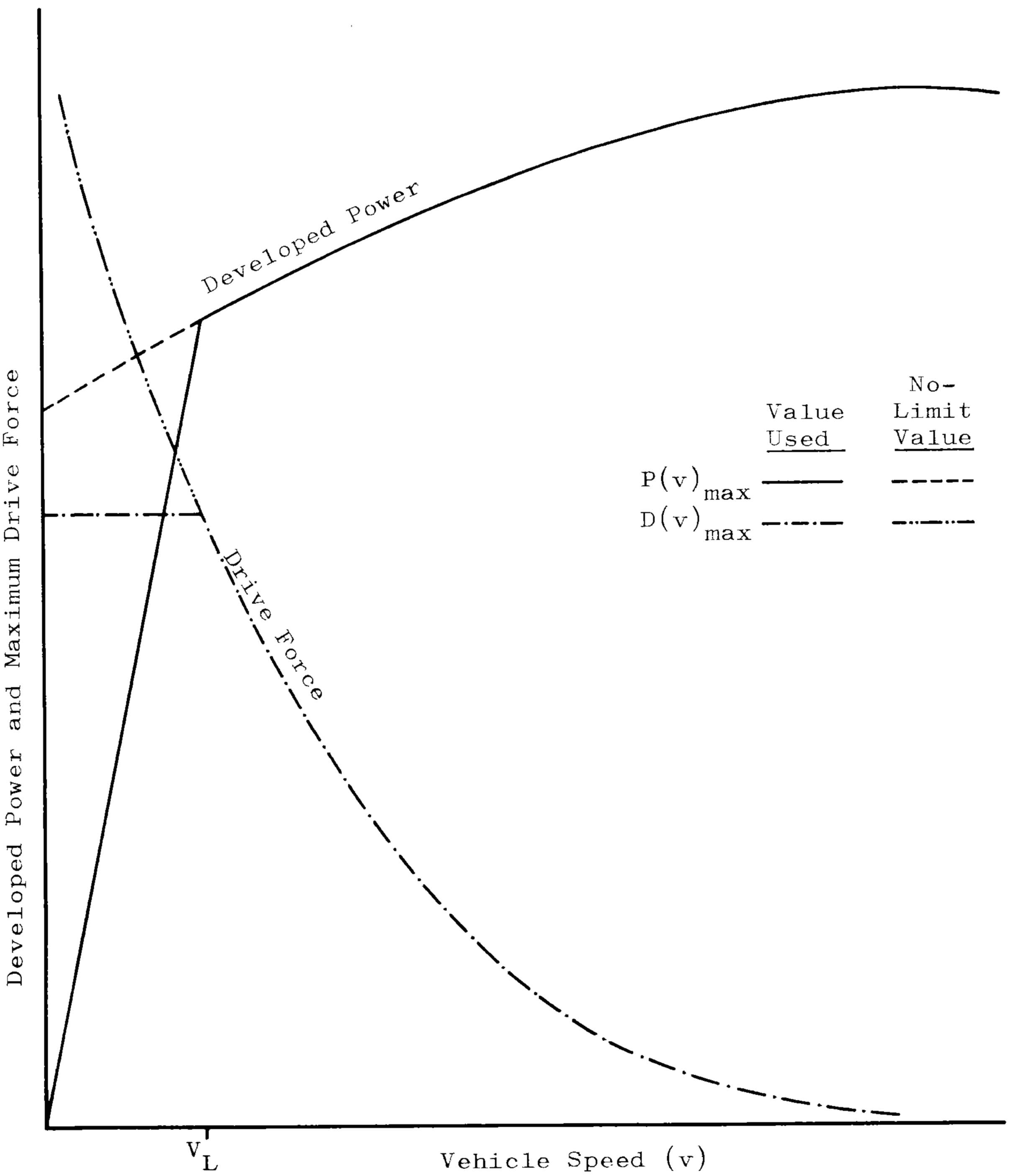


FIGURE A.2 - POWER AND DRIVE FORCE VARIATIONS

By nature, aerodynamic drag is perhaps the most complex of these phenomena, and is usually considered as varying with air density, frontal area and the square of speed. An aerodynamic drag coefficient is introduced into the drag equation to allow for the form of the body in motion. However, aerodynamic drag is influenced by a mixture of effects (dynamic pressure, skin friction and turbulence, among others) and the magnitude of these separate influences varies according to conditions. Predominantly, speed is the prime factor in variation, and the aerodynamic drag coefficient is normally considered a function of speed to cater for these effects. This leads to an expression for aerodynamic drag in the following terms:

$$R(v)_{air} = \tfrac{1}{2}\,\rho(z)\;C_D(v)\;A\;v^2 \qquad (A.5)$$

where $R(v)_{air}$ is aerodynamic drag at speed v,

$\rho(z)$ is atmospheric density at altitude z,

$C_D(v)$ is the aerodynamic drag coefficient at speed v, and

A is a representative frontal area.

Rolling resistance is basically dependent on vehicle weight (or, more precisely, on road reaction to vehicle weight). There is some variation of rolling resistance with speed[1]. In a parametric analysis, it is convenient to include the speed variation in a rolling resistance coefficient which, when multiplied by road reaction to vehicle weight, will produce the rolling resistance force:

(1) Ayres and McKenna, Alternatives to the Internal Combustion Engine, op. cit.

$$R(v)_{roll} = M\ C_R(v)\ \cos\theta \qquad (A.6)$$

where $R(v)_{roll}$ is rolling resistance at speed v,

$C_R(v)$ is the rolling resistance coefficient at speed v, and

θ is the angle of the grade which the vehicle is traversing.

Grade retardation is a simple function of the grade being traversed, and is expressed as:

$$R(v)_{grade} = M\ g(z)\ \sin\theta \qquad (A.7)$$

where $R(v)_{grade}$ is the grade retardation at speed v, and

$g(z)$ is gravitational acceleration at altitude z.

The total retarding force on the vehicle is therefore given by the sum of the forces shown in equations (A.5), (A.6) and (A.7). Thus:

$$R(v) = R(v)_{air} + R(v)_{roll} + R(v)_{grade} \qquad (A.8)$$

PERFORMANCE ESTIMATION

The major performance characteristics required of this analysis are energy consumption, range and duration at constant speed. For constant speed conditions, the accelerating force is zero, and the drive force must be just sufficient to overcome retarding forces at the required speed. Thus:

$$D(V_c) = R(V_c) \qquad \text{(from equation A.1)}$$

where $D(V_c)$ is the minimum drive force to maintain V_c, and

V_c is the chosen constant speed.

It should be noted that $R(V_c)$ may be negative (when descending hills), and regenerative power may therefore be available to a battery vehicle equipped to utilise it. There are, as a consequence, two possible power situations to consider:

$$P(V_c) = \frac{V_c\, R(V_c)}{\eta(V_c)} \qquad (R(V_c) \geq 0) \qquad (A.9)$$

$$P'(V_c) = -\, V_c\, R(V_c)\, \eta(V_c) \qquad (R(V_c) < 0) \qquad (A.10)$$

where $P(V_c)$ is the driving power required to maintain speed V_c,

$P'(V_c)$ is regenerative power available at speed V_c, and

$\eta(V_c)$ is conversion efficiency at speed V_c.

In equation (A.10), it is assumed that the regenerative efficiency of the battery/motor/drive train system is identical to its normal conversion efficiency at the same speed. While this assumption is only marginally valid, it is adequate for an analysis of this type.

The duration and range of the vehicle at a given speed only have significance if the driving condition requires consumption of energy (as in equation (A.9)). Duration is clearly a function of battery capacity, which is, itself, a generally-decreasing function of the power drawn from the battery. Thus:

$$d(V_c) = \frac{C(P(V_c))}{P(V_c)} \qquad (A.11)$$

where $d(V_c)$ is the duration at speed V_c, and

$C(P(V_c))$ is the battery capacity at the power level required to maintain V_c.

The vehicle's range at speed V_c is then obtained as:

$$r(V_c) = V_c\, d(V_c) \qquad (A.12)$$

where $r(V_c)$ is the range at speed V_c.

The full-power (or 'emergency') acceleration available at speed V_c may be calculated by considering application of all available power to driving the vehicle:

$$a(V_c) = \frac{D(V_c)_{max} - R(V_c)}{M} \qquad (A.13)$$

where $a(V_c)$ is acceleration available at speed V_c,

$D(V)_{max}$ is the available drive force at speed V_c, as derived in equations (A.3) and (A.4), and

$R(V_c)$ is the retarding force at speed V_c.

Maximum Speed

The vehicle's maximum speed under specific conditions may be found by solving the maximum-power equation of motion with acceleration set to zero. The equation to be solved is:

$$D(v)_{max} - R(v) = 0 \quad \text{at} \quad v = V_{max} \qquad (A.14)$$

While it is not intended to outline the solution of this equation in detail, it would normally be solved by an iterative process. In certain cases (involving low-order variations of parameters with speed) an analytical solution of equation (A.14) is possible without resort to approximation.

Acceleration Capabilities

The question of acceleration capabilities is a more complex one, particularly if the time taken to accelerate from one speed to another is considered. The general form of available acceleration is as shown in equation (A.1), rearranged in the following manner:

$$a(v) = \frac{D(v)_{max} - R(v)}{M}$$

$$\text{or} \quad \frac{dv}{dt} = f(v) \qquad (A.15)$$

where $f(v)$ is a generalised expression giving the instantaneous acceleration at speed v.

The time (t_{ij}) required to accelerate from speed V_i to speed V_j, under full power, is then obtained as follows:

$$dt = \frac{dv}{f(v)}$$

$$\text{and } t_{ij} = \int_{V_i}^{V_j} \frac{dv}{f(v)} \qquad (A.16)$$

The expression on the right side of equation (A.15) is not readily integrated, except in special circumstances which do not apply to the general case treated in this Annex. As an alternative, equation (A.15) may be integrated by numerical analysis techniques to provide values of speed at specific values of time. The table thus generated may then be used to obtain values of t for specific values of v, by interpolation. If a sufficiently small time increment is used for this numerical integration, the resultant error in interpolated values of time will not be significant. A similar process may be used to obtain the distances travelled and energy consumed in acceleration.

MODEL FORMULATION AND OPERATION

The preceding sections of this Annex have presented the theoretical background to studies of battery vehicle performance. The remaining step is to convert these theoretical considerations into a unified mathematical model of performance which may be used to probe the performance of various postulated vehicle configurations. In view of the complexity of some of the calculations involved, the performance model was programmed for solution on a digital computer[1]. The basic terms of reference of the model are:

(a) Accept, as input, values of parameters required for fundamental performance analysis.

(b) Produce values of energy consumption, range, duration and available acceleration for selected road gradients at specified cruising speeds.

(c) Produce maximum speed values and range at maximum speed, for selected gradients.

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(1) An IBM System 360/67 installation; the programming language used was FORTRAN IV - Level G.

(d) Produce acceleration performance and associated characteristics for the selected gradients.

(e) Investigate range sensitivity to variations in vehicle efficiency, aerodynamic drag coefficient, rolling resistance coefficient and weight for the selected gradients and specified speeds.

(f) Produce more detailed reports on specific vehicle characteristics, on demand.

Parametric Values and Model Input

The model requires specification of several values and sets of values of certain basic parameters used in the equations previously derived. In addition, the program and subprograms comprising the model require certain control values to modify or delete specified model operations. The major parametric inputs are as follows:

- vehicle weight
- vehicle frontal area
- operational altitude
- power overload factor
- rated power (at three values of speed) to form the basis of a power-speed parametric representation, together with a value for the limiting speed for the constant-force regime
- conversion efficiency (at three values of speed)

- aerodynamic drag coefficient (at three values of speed)
- rolling resistance coefficient (at three values of speed)
- battery capacity (at three values of power)

The multiple values of power, efficiency, aerodynamic drag coefficient, rolling resistance coefficient and battery capacity are a result of the fact that the model uses quadratic variations of these values with speed (or power, in the case of battery capacity). While these parameters are subject to complex, and in some cases immutable, physical laws, a parametric analysis can only include them in an arbitrary fashion. In this case, perusal of published information indicates that most of the parametric variations used in the model are only known as fairly vague experimental results, and any attempt to model them accurately would be ingenuous, at best. The points specified as inputs to the model may be chosen to represent a wide range of variations, including (but not limited to) constants, linear variations and square-law variations. The power overload factor is included to compensate for the fact that electric motor characteristics (such as weight) are related to a rated continuous power level, whereas the motors are actually capable of operation at substantially higher power levels. The quadratic power variation refers to rated power, which is multiplied by the overload factor to obtain actual power available.

Operational altitude is used to compute appropriate values of atmospheric density and gravitational acceleration. Since standard atmospheric parameters are not suitable for application to the predominantly warm Australian climate, these parameters are calculated by an approximation to the US Standard Atmosphere Supplement - Subtropical 30°N (July)[1].

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(1) W.P. Egan, A Computer Program for Simulating the US Standard Atmosphere and Supplements, Australian Department of Supply Technical Memorandum CSE2, June 1970.

TABLE A.1 PERFORMANCE MODEL INPUT DATA FORMATS

Card	Field	Bytes	Format	Units	Contents
1	1	01-08	I8	kg	Vehicle Weight
	2	09-16	F8.0	m^2	Vehicle Frontal area
	3	17-24	I8	m	Operational altitude
	4	25-26	-	-	Not used
	5	27	I1	-	Table key - parameter variation[(a)]
	6	28	I1	-	Table key - forces variation[(a)]
	7	29	I1	-	Table key - capacity-power variation[(a)]
	8	30	I1	-	Table key - speed-time variation[(a)]
	9	31-32	-	-	Not used
	10	33	I1	-	Table key (1:10 grade)[(b)]
	11	34	I1	-	Table key (1:20 grade)[(b)]
	12	35	I1	-	Table key (1:50 grade)[(b)]
	13	36	I1	-	Table key (level road)[(b)]
	14	37	I1	-	Table key (-1:50 grade)[(b)]
	15	38-40	-	-	Not used
	16	41-80	10A4	-	Alphanumeric title
2	1	01-08	F8.0	kW	Power at first speed reference
	2	09-16	I8	km/h	First speed reference[(c)]
	3	17-24	F8.0	kW	Power at second speed reference
	4	25-32	I8	km/h	Second speed reference[(c)]
	5	33-40	F8.0	kW	Power at third speed reference
	6	41-48	I8	km/h	Third speed reference[(c)]

Card	Field	Bytes	Format	Units	Contents
2	7	49-56	I8	km/h	Constant-force speed limit[d]
	8	57-64	F8.0	-	Power overload factor (fraction)
	9	65-80	-	-	Not used
3	1	01-08	F8.0	-	Efficiency at first speed reference
	2	09-16	I8	km/h	First speed reference
	3	17-24	F8.0	-	Efficiency at second speed reference
	4	25-32	I8	km/h	Second speed reference
	5	33-40	F8.0	-	Efficiency at third speed reference
	6	41-48	I8	km/h	Third speed reference
	7	49-80	-	-	Not used
4	1	01-08	F8.0	-	Air drag coefficient at first speed reference
	2	09-16	I8	km/h	First speed reference
	3	17-24	F8.0	-	Air drag coefficient at second speed reference
	4	25-32	I8	km/h	Second speed reference
	5	33-40	F8.0	-	Air drag coefficient at third speed reference
	6	41-48	I8	km/h	Third speed reference
	7	49-80	-	-	Not used
5	1	01-08	F8.0	N/kg	Rolling resistance coefficient at first speed reference
	2	09-16	I8	km/h	First speed reference

Card	Field	Bytes	Format	Units	Contents
5	3	17-24	F8.0	N/kg	Rolling resistance coefficient at second speed reference
	4	25-32	I8	km/h	Second speed reference
	5	33-40	F8.0	N/kg	Rolling resistance coefficient at third speed reference
	6	41-48	I8	km/h	Third speed reference
	7	49-80	-	-	Not used
6	1	01-08	F8.0	kWh	Battery capacity at first power reference
	2	09-16	I8	kW	First power reference
	3	17-24	F8.0	kWh	Battery capacity at second power reference
	4	25-32	I8	kW	Second power reference
	5	33-40	F8.0	kWh	Battery capacity at third power reference
	6	41-48	I8	kW	Third power reference
	7	49-80	-	-	Not used

(a) A value of 0 for any of these keys will result in suppression of the corresponding table. Any other value will cause generation of the table.

(b) These keys may range in value from 0 to 2, and any value outside this range will be set automatically to 1. The effects of these key values are as follows:

Value	Result
0	No tables generated for this grade value
1	Performance table generated
2	Performance and sensitivity tables generated

(c) For this and other parameter variations, the three values of the independent variable <u>must</u> be unequal.

(d) The value entered <u>must</u> be greater than 0.

The model is programmed for batch-processing, with physical input in the form of punched cards. The program is organised in such a manner that several individual sets of data may be analysed consecutively in one run. Each set of data relates to a particular set of vehicle characteristics, and consists of six cards. The parameter values are entered on these cards in the format shown in Table A.1, and the overall deck structure is as shown in Figure A.3. The model uses metric (SI) units throughout, and the units for input values are also shown in Table A.1.

Model Operation and Results

The first stage in operation of the model program is to enter required parametric values and check them for validity. Errors in this stage cause immediate termination of execution, and involve failure to meet the minor constraints outlined in the footnotes to Table A.1. If this phase is successfully completed, a page of printed results is produced, giving a summary of the parametric values supplied to the program, together with the following computed values:

- Quadratic coefficients for use in estimating parametric values at points intermediate to those specified in the model input.

- Atmospheric density and gravitational acceleration at the selected operational altitude.

- The maximum drive force available at the limiting speed (V_L) of the constant-force regime.

The program then uses the specified and computed values to compute maximum speed under level-road conditions[(1)].

(1) To avoid errors caused by undue extrapolation of fitted parametric values, the maximum speed is taken as the actual maximum or the maximum of all the speed reference values supplied for the parametric variations, whichever is less. Accordingly, some care must be exercised in stipulating the speed reference values.

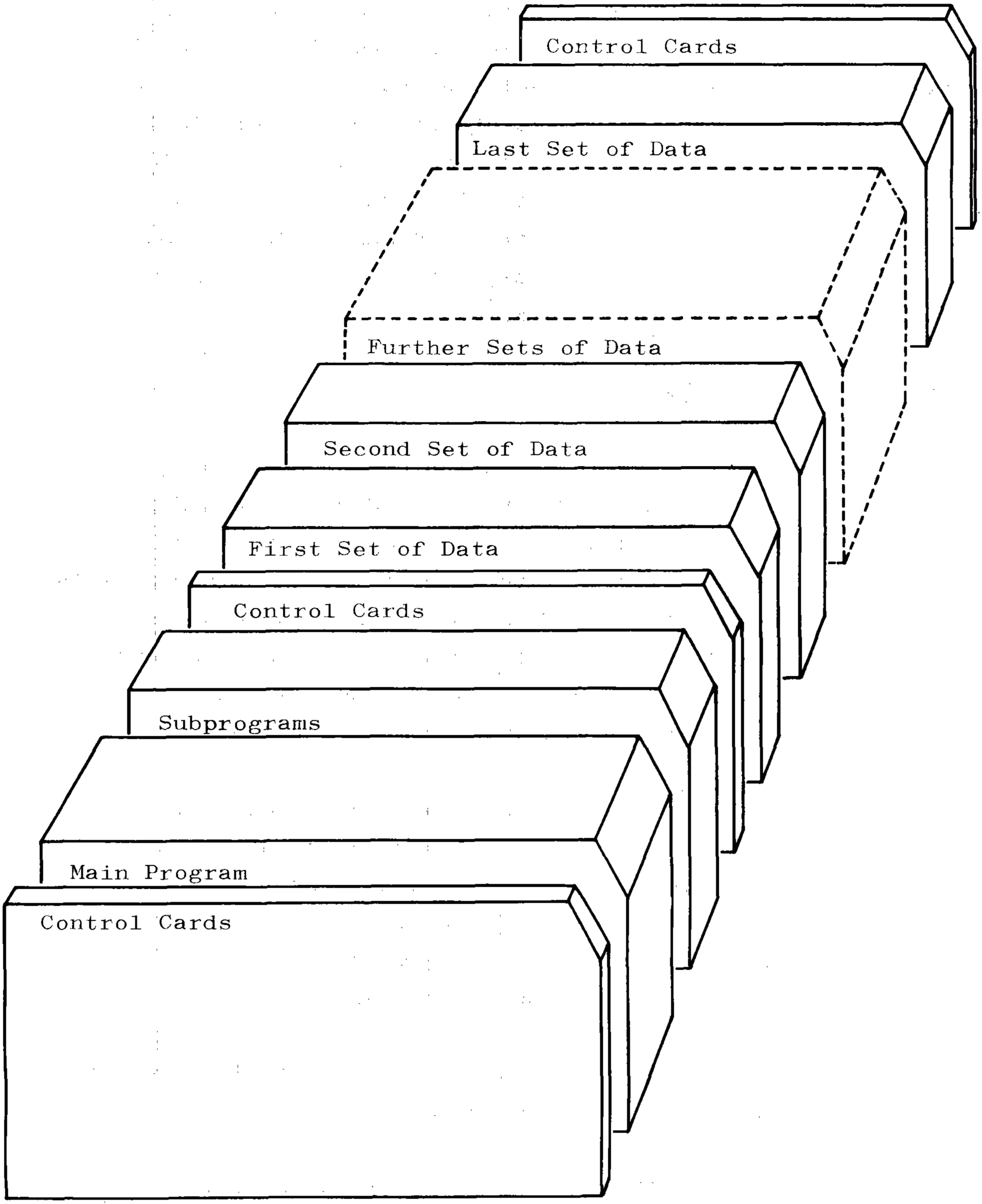

FIGURE A. 3 - PERFORMANCE PROGRAM JOB DECK STRUCTURE

This value is used to determine the length of subsequent tables produced by the program, and is also used for various internal purposes. The program then performs the steps involved in generating two tables, either or both of which may be suppressed at the user's discretion (by a suitable specification of the appropriate table keys outlined in Table A.1). The tables are:

(a) Variation of the available power, conversion efficiency, aerodynamic drag coefficient and rolling resistance coefficient with speed. This table is generated by evaluating the appropriate quadratics at various speed values.

(b) Variation of forces on the vehicle with speed under full-power, level-road conditions. The forces are categorised as drive force, aerodynamic drag, rolling resistance and total retarding force. The available acceleration at particular speeds is also tabulated.

These tables, if generated, are computed at 1 km/h intervals from 0 km/h. Each table terminates at the nearest 1 km/h below the vehicle's maximum level-road speed, and an entry representing the values at maximum speed is appended to the end of the table. Forces are expressed in newtons (N), while acceleration values are expressed as multiples of gravitational acceleration (g).

A table of variation of battery capacity with power requirements is then generated, if the appropriate option is exercised. The heading of this table gives the maximum power on the power-speed variation, together with the speed at which this value is attained. The battery capacity at zero power (a notional quantity) is also listed. The table gives battery capacity as a function of power at 1 kW intervals up to the maximum power or 35 kW, whichever is less. Power is also expressed as a fraction of maximum power, and capacity as a fraction of zero-power capacity, as an aid to comparison.

The next table available at the user's option is a tabulation of full-power, level-road acceleration capabilities. In this table, the vehicle's speed at given times is presented, assuming that the vehicle is at rest at zero time. The distance travelled and energy used up to the particular time are also presented, together with the available acceleration at that time. The values used in this table are computed by using numerical integration of vehicle acceleration over time increments of 0.1 seconds to obtain speeds. Distance travelled and energy used are obtained by using the means of speed and power over the time interval. The integration process used is the fourth-order Runge-Kutta technique, and integration continues until either:

(a) available acceleration reduces to a level below 0.01 m s^{-2} (approximately 0.001g); or

(b) a time of 100 seconds is exceeded.

The interval at which tabulated values are presented is computed automatically, according to the maximum time attained in the integration process. The intervals available are:

Maximum Time (seconds)	Reporting Interval (seconds)
00.0 - 20.0	0.1
20.1 - 50.0	0.2
more than 50.0	0.5

The next phase of program operation produces the central results of the analysis - performance characteristics on various grades. In this case, there are basically five sets of results, and they relate to road grades of the following magnitudes:

grade of 1:10
grade of 1:20
grade of 1:50
level road
grade of -1:50

For each grade, the user has three options available. The first is to ignore the particular grade completely, and pass on to the next. The other options are to produce a table of basic performance without sensitivity testing, or to produce both the performance table and the sensitivity table.

The first part of the performance characteristics consists of a tabulation of maximum speed[(1)] on the particular grade, together with the power and range at that speed. Cruising speed characteristics are then presented in a table which gives power (kW), specific energy consumption (kWh/km), range (km), duration (hours) and available acceleration (g) at various speeds. The speeds used range from 10 km/h to 100 km/h (or the nearest 10 km/h increment below maximum speed, whichever is less). In cases involving the possibility of regenerating energy, the entries in the table are flagged and range and duration are omitted (since they have no significance). In such cases, the energy consumption figure tabulated represents energy available through regeneration. In vehicles not equipped for regeneration, energy consumption in these cases would be zero (but braking might be required to limit speed to the specified value).

The next set of performance characteristics gives acceleration capabilities at full power for the current grade value. The time taken to accelerate from rest to specific speeds is given for speeds from 10 km/h to 100 km/h (or, again, the nearest 10 km/h increment below maximum speed, whichever

---

(1) The maximum speed computed is limited to a value less than or equal to the maximum speed reference value for parametric variations.

is less). For each speed value, the distance travelled (km) and energy (kWh) used to attain that speed under full power are presented, together with average speed (km/h) and average acceleration (g) during the acceleration phase. These values are computed by numerical integration in the manner described previously, with time-to-speed values obtained by linear interpolation.

If sensitivity testing is specified, the program produces a table of the sensitivity of vehicle range to variations in parametric values. The table consists of four parts, which test sensitivity to variations in the following parameters:

- conversion efficiency
- aerodynamic drag coefficient
- rolling resistance coefficient
- vehicle weight

Speed for sensitivity testing is varied from 10 km/h to the nearest 10 km/h increment below maximum speed, with a maximum of 100 km/h. Range is computed at the appropriate cruise speed and parametric values, and is expressed as a fraction of the value at zero parameter variation. Parameter values are varied from 80 per cent to 120 per cent of the original specified values, and in cases involving quadratic variations, the values are obtained by increasing or decreasing the whole curve by the required amount. Speed values involving power regeneration are ignored. Sensitivity to battery capacity variations is not explored, since it is a linear function of the magnitude of capacity variation.

When all grades have been considered, the program attempts to obtain a new set of vehicle data. If the appropriate cards are available in the input stream, the whole process is repeated. Otherwise, program execution is terminated.

The results of a test of a sample set of vehicle characteristics are shown in Annex C.

<u>Model Program Structure and Errors</u>

The program for computing vehicle performance characteristics consists of a main program and four sub-programs. The functions of these elements of the program are broadly as follows:

(a) MAIN PROGRAM: organisation of input and output, computation logic and non-recurring calculations.

(b) SUBROUTINE QFIT: checks on values entered for quadratic variations and generation of quadratic coefficients.

(c) SUBROUTINE SPDBAL: computation of speed at which drive force balances retarding forces; this function is performed by recursive computation of force components.

(d) SUBROUTINE FORCES: computation of drive and retarding force components at particular speeds.

(e) SUBROUTINE ACCINT: Runge-Kutta numerical integration of vehicle acceleration to determine speed changes and associated characteristics over a specified time increment.

An outline flow-chart of the model program is presented in Figure A.4, and shows the connection between major program elements.

Error-checking facilities included in the program are limited to the following:

(a) check on constant-force regime limiting speed; and

(b) check on inequality of independent variable values specified for quadratic variations.

Detection of errors results in an appropriate error message and immediate execution termination.

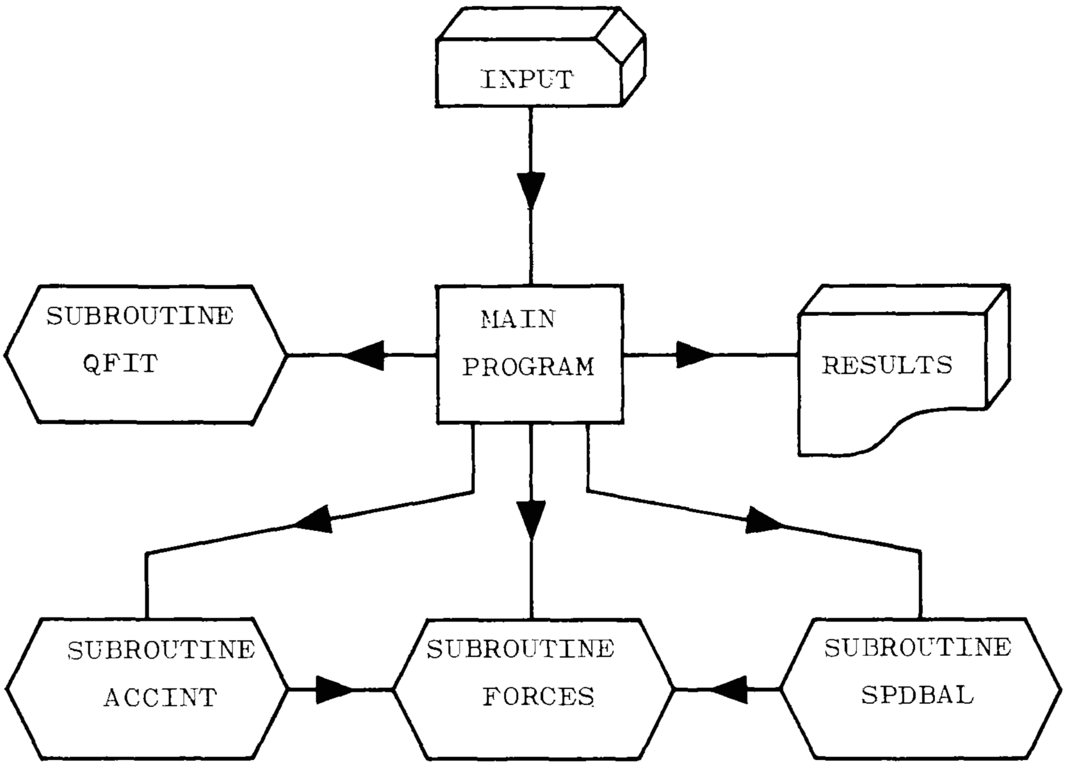

FIGURE A.4 - PERFORMANCE PROGRAM FLOW DIAGRAM

ANNEX B

PERFORMANCE MODEL LISTING

```
                              MAIN                 DATE = 74151

C     *****************************************************************
C     *                                                               *
C     *        PROGRAM FOR PERFORMING ANALYSIS OF ELECTRIC VEHICLE    *
C     *  PERFORMANCE.   THIS PROGRAM ACCEPTS DETAILS OF VEHICLE       *
C     *  WEIGHT, POWER, SIZE AND OTHER CHARACTERISTICS, AND OPERATES  *
C     *  ON THESE TO OBTAIN A STANDARD SET OF PERFORMANCE DATA.       *
C     *                                                               *
C     *        PROVISION IS INCLUDED FOR POSTULATION OF VARIOUS FORMS *
C     *  OF AIR DRAG, ROLLING RESISTANCE, POWER AND EFFICIENCY        *
C     *  VARIATIONS WITH SPEED.   SPEED-TIME CURVES ARE COMPUTED BY   *
C     *  THE RUNGE-KUTTA NUMERICAL INTEGRATION PROCESS.               *
C     *                                                               *
C     *****************************************************************
C
      DIMENSION TITLE(10),AATT(1000),EATT(1000),SATT(1000),VATT(1000)
      DIMENSION SENVAL(5),KGRADE(5)
      COMMON A0P,A1P,A2P,A0E,A1E,A2E,A0C,A1C,A2C,A0R,A1R,A2R
      COMMON IWT,AREA,IOPALT,IVLIM,FLIM,GRVACC,GTERM,ROEAIR,THETA
      COMMON IVVMAX
      DATA BLANK /' '/, ASTER /'*'/
 1000 FORMAT (I8,F8.0,I8,2X,4I1,2X,5I1,3X,10A4)
 1001 FORMAT ('1'/'1',
     * 9X,'****************************************'/
     *10X,'*                                      *'/
     *10X,'*  BUREAU OF TRANSPORT ECONOMICS       *'/
     *10X,'*                                      *'/
     *10X,'*  DEVELOPMENT SECTION                 *'/
     *10X,'*                                      *'/
     *10X,'*  ELECTRIC VEHICLE PERFORMANCE TESTS  *'/
     *10X,'*                                      *'/
     *10X,'****************************************'////
     *10X,'DESCRIPTION ...... ',10A4//
     *10X,'VEHICLE WEIGHT ...',I5,' KG'//
     *10X,'FRONTAL AREA .....',F5.2,' M**2'//
     *10X,'ALTITUDE .........',I5,' M')
 1002 FORMAT (3(F8.0,I8),I8,F8.0)
 1003 FORMAT (/10X,'DEVELOPED POWER                 ',I6,F9.3,'    A0 =',
     *F8.4/40X,I6,F9.3,'    A1 =',F8.4/40X,I6,F9.3,'    A2 =',F8.4)
 1004 FORMAT (/10X,'CONVERSION EFFICIENCY           ',I6,F9.3,'    A0 =',
     *F8.4/40X,I6,F9.3,'    A1 =',F8.4/40X,I6,F9.3,'    A2 =',F8.4)
 1005 FORMAT (/10X,'AERODYNAMIC DRAG COEFFICIENT    ',I6,F9.3,'    A0 =',
     *F8.4/40X,I6,F9.3,'    A1 =',F8.4/40X,I6,F9.3,'    A2 =',F8.4)
 1006 FORMAT (/10X,'ROLLING RESISTANCE COEFFICIENT',I6,F9.3,'    A0 =',
     *F8.4/40X,I6,F9.3,'    A1 =',F8.4/40X,I6,F9.3,'    A2 =',F8.4)
 1007 FORMAT (/10X,'CAPACITY - POWER VARIATION      ',I6,F9.3,'    A0 =',
     *F8.4/40X,I6,F9.3,'    A1 =',F8.4/40X,I6,F9.3,'    A2 =',F8.4)
 1008 FORMAT(/
     *10X,'LIMITING SPEED ...',I5,' KM/H'//
     *10X,'POWER OVERLOAD ...',F5.2////
     *10X,'QUADRATIC COEFFICIENTS FOR FITTED QUANTITIES.'//
     *10X,'                                 INPUT   INPUT     COMPUTED'/
     *10X,'FITTED QUANTITY                   (X)     (Y)    COEFFICIENTS'
     *)
```

```
1009 FORMAT (///
    *10X,'COMPUTED AIR DENSITY .......',F6.3,' KG/M**3'//
    *10X,'GRAVITY ACCELERATION .......',F6.3,' M/S**2'//
    *10X,'LIMITING DRIVE FORCE .......',I6,' NEWTONS'//)
1010 FORMAT ('1',
    * 9X,'****************************************'/
    *10X,'*                                      *'/
    *10X,'*  VARIATION OF PARAMETERS WITH SPEED  *'/
    *10X,'*                                      *'/
    *10X,'****************************************'///
    *10X,'                     CONVERSION    AERO DRAG    RESISTANCE'/
    *10X,'SPEED     POWER     EFFICIENCY   COEFFICIENT   COEFFICIENT'/
    *10X,'(KM/H)     (KW)    (FRACTION)                     (N/KG)')
1011 FORMAT (//10X,'* INDICATES CONSTANT-FORCE REGION.')
1012 FORMAT (' ')
1013 FORMAT (I14,F10.1,A1,F10.4,F14.4,F13.4)
1014 FORMAT (/F16.1,F8.1,F11.4,F14.4,F13.4)
1015 FORMAT (///10X,'***** CONSTANT-FORCE SPEED LIMIT INVALID.')
1016 FORMAT (/10X,'***** RUN AUTOMATICALLY TERMINATED.'/'1'/'1')
1017 FORMAT ('1',
    * 9X,'*********************************************'/
    *10X,'*                                           *'/
    *10X,'*  FULL-POWER, LEVEL-ROAD FORCES VARIATION   *'/
    *10X,'*                                           *'/
    *10X,'*********************************************'///
    *10X,'           DRIVE    AIR DRAG    ROLLING     TOTAL'/
    *10X,'SPEED      FORCE    RESIST.     RESIST.    RESIST.    ACC''N'/
    *10X,'(KM/H)      (N)       (N)         (N)        (N)        (G)')
1018 FORMAT (I14,F10.1,A1,F8.1,F11.1,F10.1,F9.3)
1019 FORMAT (/F16.1,F8.1,F9.1,F11.1,F10.1,F9.3)
1020 FORMAT ('1',
    * 9X,'**************************************************'/
    *10X,'*                                                *'/
    *10X,'*  FULL-POWER, LEVEL-ROAD SPEED-TIME VARIATION    *'/
    *10X,'*                                                *'/
    *10X,'**************************************************'///
    *10X,'                                            ENERGY'/
    *10X,'     TIME    SPEED    DISTANCE    ACC''N     USED'/
    *10X,'      (S)    (KM/H)     (KM)       (G)     (KW-H)')
1021 FORMAT (F18.1,F8.2,F11.4,2F9.3)
1022 FORMAT ('1',
    * 9X,'**************************************************'/
    *10X,'*                                                *'/
    *10X,'*  GENERAL VEHICLE PERFORMANCE CHARACTERISTICS    *'/
    *10X,'*                                                *'/
    *10X,'**************************************************'//)
1023 FORMAT (10X,'GRADE FOR THIS SET OF TESTS ...',I3,' IN ',I2//
    *10X,'MAXIMUM SPEED ATTAINABLE ......',F6.1,' KM/H'//
    *10X,'POWER AT MAXIMUM SPEED ........',F6.1,' KW'//
    *10X,'RANGE AT MAXIMUM SPEED ........',F6.1,' KM')
1024 FORMAT (10X,'GRADE FOR THIS SET OF TESTS ... LEVEL'//
    *10X,'MAXIMUM SPEED ATTAINABLE ......',F6.1,' KM/H'//
    *10X,'POWER AT MAXIMUM SPEED ........',F6.1,' KW'//
```

```
     *10X,'RANGE AT MAXIMUM SPEED ........',F6.1,' KM')
 1025 FORMAT (///10X,'CRUISE SPEED ENERGY CONSUMPTION, ETC.'//
     *10X,'                    ENERGY                          AVAILABLE'/
     *10X,'SPEED     POWER      USED       RANGE   DURATION      ACC''N'/
     *10X,'(KM/H)     (KW)    (KW-H/KM)     (KM)       (H)         (G)'/)
 1026 FORMAT (I14,F10.1,F10.4,F10.1,F10.2,F11.3)
 1027 FORMAT (I14,'       ....     .....        ....       ....       .....')
 1028 FORMAT (I14,F10.1,'*',F9.4,'*     .....       ....',F11.3)
 1029 FORMAT (/10X,'* INDICATES REGENERATIVE POWER.')
 1030 FORMAT (///10X,'ACCELERATION CHARACTERISTICS (FROM REST).'//
     *10X,'                                ENERGY   AVERAGE    AVERAGE'/
     *10X,'SPEED    TIME    DISTANCE     USED     SPEED       ACC''N'/
     *10X,'(KM/H)     (S)       (KM)      (KW-H)    (KM/H)       (G)'/)
 1031 FORMAT (I14,F9.2,2F11.4,F9.2,F11.3)
 1032 FORMAT (I14,'      .....      ......     ......     .....      .....')
 1033 FORMAT ('1'/'1')
 1034 FORMAT ('1',
     * 9X,'****************************************'/
     *10X,'*                                      *'/
     *10X,'*  VARIATION OF CAPACITY WITH POWER    *'/
     *10X,'*                                      *'/
     *10X,'****************************************'///
     *10X,'MAXIMUM POWER (LEVEL-ROAD) ...',F5.1,' KW'//
     *10X,'SPEED AT MAXIMUM POWER .......',I5,' KM/H'//
     *10X,'ZERO-POWER CAPACITY ..........',F5.1,' KW-H'///
     *10X,'             PART OF                   PART OF'/
     *10X,'POWER      MAXIMUM     CAPACITY      MAXIMUM'/
     *10X,' (KW)        POWER        (KW-H)      CAPACITY')
 1035 FORMAT (I14,F11.3,F12.3,F11.3)
 1036 FORMAT ('1',9X,'RANGE SENSITIVITY TO PARAMETER VARIATIONS')
 1037 FORMAT (I34,1X,5('   .....'))
 1038 FORMAT (I34,1X,5F8.3)
 1039 FORMAT ('+            CONVERSION')
 1040 FORMAT ('+            AERODYNAMIC DRAG')
 1041 FORMAT ('+            ROLLING RESISTANCE')
 1042 FORMAT ('+            GROSS VEHICLE')
 1043 FORMAT ('+            EFFICIENCY')
 1044 FORMAT ('+            COEFFICIENT')
 1045 FORMAT ('+            WEIGHT')
 1046 FORMAT ('+',51X,'(GRADE ...',I3,' IN',I3,').')
 1047 FORMAT ('+',51X,'(GRADE ... LEVEL).')
 1048 FORMAT (////
     *30X,'          MAGNITUDE OF PARAMETER VARIATION'/
     *30X,'SPEED'/
     *10X,'PARAMETER VARIED     (KM/H)   -20%    -10%      00%     +10%',
     *'     +20%')
    1 READ (5,1000,END=30) IWT,AREA,IOPALT,KTABA,KTABB,KTABC,KTABD,
     *KGRADE,TITLE
C
C      IWT ...... VEHICLE WEIGHT (KG).
C      AREA ..... VEHICLE FRONTAL AREA (M**2).
C      IOPALT ... BASIC OPERATIONAL ALTITUDE (M).
C      KTABA .... TABLE KEY - PARAMETER VARIATION.
```

```
C     KTABB .... TABLE KEY - FORCES VARIATION
C     KTABC .... TABLE KEY - CAPACITY-POWER VARIATION.
C     KTABD .... TABLE KEY - SPEED-TIME VARIATION.
C     KGRADE ... TABLE KEYS - PERFORMANCE CHARACTERISTICS.
C     TITLE .... 40-CHARACTER ALPHANUMERIC DESCRIPTION (OPTIONAL).
C
      WRITE (6,1001) TITLE,IWT,AREA,IOPALT
      READ (5,1002) P1,IV1,P2,IV2,P3,IV3,IVLIM,OPOW
C
C     P1 ...... POWER (KW) AT SPEED IV1 (KM/H).
C     P2 ...... POWER (KW) AT SPEED IV2 (KM/H).
C     P3 ...... POWER (KW) AT SPEED IV3 (KM/H).
C     IVLIM ... UPPER CONSTANT-FORCE SPEED (KM/H).
C     OPOW .... POWER OVERLOAD CAPABILITY (FRACTION).
C
      WRITE (6,1008) IVLIM,OPOW
      IF (IVLIM .GT. 0) GO TO 2
      WRITE (6,1015)
      WRITE (6,1016)
      STOP
    2 CALL QFIT (P1,IV1,P2,IV2,P3,IV3,A0P,A1P,A2P,1)
      WRITE (6,1003) IV1,P1,A0P,IV2,P2,A1P,IV3,P3,A2P
      A0P = OPOW * A0P
      A1P = OPOW * A1P
      A2P = OPOW * A2P
      IVVMAX = IV1
      IF (IVVMAX .LT. IV2) IVVMAX = IV2
      IF (IVVMAX .LT. IV3) IVVMAX = IV3
      READ (5,1002) E1,IV1,E2,IV2,E3,IV3
C
C     E1 ... EFFICIENCY (FRACTIONAL) AT SPEED IV1 (KM/H).
C     E2 ... EFFICIENCY (FRACTIONAL) AT SPEED IV2 (KM/H).
C     E3 ... EFFICIENCY (FRACTIONAL) AT SPEED IV3 (KM/H).
C
      CALL QFIT (E1,IV1,E2,IV2,E3,IV3,A0E,A1E,A2E,2)
      WRITE (6,1004) IV1,E1,A0E,IV2,E2,A1E,IV3,E3,A2E
      IF (IVVMAX .LT. IV1) IVVMAX = IV1
      IF (IVVMAX .LT. IV2) IVVMAX = IV2
      IF (IVVMAX .LT. IV3) IVVMAX = IV3
      READ (5,1002) C1,IV1,C2,IV2,C3,IV3
C
C     C1 ... AERODYNAMIC DRAG COEFFICIENT AT SPEED IV1 (KM/H).
C     C2 ... AERODYNAMIC DRAG COEFFICIENT AT SPEED IV2 (KM/H).
C     C3 ... AERODYNAMIC DRAG COEFFICIENT AT SPEED IV3 (KM/H).
C
      CALL QFIT (C1,IV1,C2,IV2,C3,IV3,A0C,A1C,A2C,3)
      WRITE (6,1005) IV1,C1,A0C,IV2,C2,A1C,IV3,C3,A2C
      IF (IVVMAX .LT. IV1) IVVMAX = IV1
      IF (IVVMAX .LT. IV2) IVVMAX = IV2
      IF (IVVMAX .LT. IV3) IVVMAX = IV3
      READ (5,1002) R1,IV1,R2,IV2,R3,IV3
C
C     R1 ... ROLLING RESISTANCE COEFF (N/KG) AT SPEED IV1 (KM/H).
```

```
C     R2 ... ROLLING RESISTANCE COEFF (N/KG) AT SPEED IV2 (KM/H).
C     R3 ... ROLLING RESISTANCE COEFF (N/KG) AT SPEED IV3 (KM/H).
C
      CALL QFIT (R1,IV1,R2,IV2,R3,IV3,A0R,A1R,A2R,4)
      WRITE (6,1006) IV1,R1,A0R,IV2,R2,A1R,IV3,R3,A2R
      IF (IVVMAX .LT. IV1) IVVMAX = IV1
      IF (IVVMAX .LT. IV2) IVVMAX = IV2
      IF (IVVMAX .LT. IV3) IVVMAX = IV3
      READ (5,1002) EC1,IP1,EC2,IP2,EC3,IP3
C
C     EC1 ... CAPACITY (KW-H) AT POWER IP1 (KW).
C     EC2 ... CAPACITY (KW-H) AT POWER IP2 (KW).
C     EC3 ... CAPACITY (KW-H) AT POWER IP3 (KW).
C
      CALL QFIT (EC1,IP1,EC2,IP2,EC3,IP3,A0EC,A1EC,A2EC,5)
      WRITE (6,1007) IP1,EC1,A0EC,IP2,EC2,A1EC,IP3,EC3,A2EC
C
C     COMPUTE AIR DENSITY AND GRAVITY AT OPERATING ALTITUDE.
C     FROM ... US STANDARD ATMOSPHERE SUPPLEMENT (SUBTROPICAL - JULY).
C
      ROEAIR = 1.159 - 0.905E-04 * IOPALT - 2.5E-09 * IOPALT**2
      GRVACC = 9.79324 - 3.09E-06 * IOPALT
C
C     COMPUTE DRIVING FORCE AT CONSTANT-FORCE SPEED LIMIT.
C
      PLIM  = A0P + IVLIM * (A1P + IVLIM * A2P)
      ELIM  = A0E + IVLIM * (A1E + IVLIM * A2E)
      FLIM  = 3600 * PLIM * ELIM / IVLIM
      IFLIM = FLIM
      WRITE (6,1009) ROEAIR,GRVACC,IFLIM
C
C     COMPUTE LEVEL-ROAD MAXIMUM SPEED.
C
      THETA  = 0.0
      GTERM = IWT * GRVACC * SIN(THETA)
      CALL SPDBAL (VLEVEL)
C
C     PRODUCE TABLE OF FITTED VALUES VERSUS SPEED, AND
C     TABLE OF FULL-POWER, LEVEL-ROAD FORCE VARIATIONS.
C
      IVMAX = VLEVEL + 1
      DO 5 IPASS=1,2
      IF ((IPASS .EQ. 1) .AND. (KTABA .EQ. 0)) GO TO 5
      IF ((IPASS .EQ. 2) .AND. (KTABB .EQ. 0)) GO TO 5
      IF (IPASS .EQ. 1) WRITE (6,1010)
      IF (IPASS .EQ. 2) WRITE (6,1017)
      KLIM  = 0
      LINES = 0
      DO 4 I=1,IVMAX
      IV = I - 1
      V  = IV
      CALL FORCES (V,POWER,EFFCY,CDRAG,CREST,DRIVE,DRAGA,DRAGR,
     *DRAGT,RESF,RACCN)
```

```
      ACC   = RACCN / GRVACC
      VOUT = BLANK
      IF (IV .LE. IVLIM) VOUT = ASTER
      IF (IV .LE. IVLIM) KLIM = 1
      IF (LINES .LE. 39) GO TO 3
      IF (KLIM .EQ. 1) WRITE (6,1011)
      IF (IPASS .EQ. 1) WRITE (6,1010)
      IF (IPASS .EQ. 2) WRITE (6,1017)
      KLIM  = 0
      LINES = 0
    3 IF (LINES .EQ. 00) WRITE (6,1012)
      IF (LINES .EQ. 10) WRITE (6,1012)
      IF (LINES .EQ. 20) WRITE (6,1012)
      IF (LINES .EQ. 30) WRITE (6,1012)
      IF (IPASS .EQ. 1) WRITE (6,1013) IV,POWER,VOUT,EFFCY,CDRAG,CREST
      IF (IPASS .EQ. 2) WRITE (6,1018) IV,DRIVE,VOUT,DRAGA,DRAGR,
     *DRAGT,ACC
      LINES = LINES + 1
    4 CONTINUE
      CALL FORCES (VLEVEL,POWER,EFFCY,CDRAG,CREST,DRIVE,DRAGA,DRAGR,
     *DRAGT,RESF,RACCN)
      ACC = RACCN / GRVACC
      IF (IPASS .EQ. 1) WRITE (6,1014) VLEVEL,POWER,EFFCY,CDRAG,CREST
      IF (IPASS .EQ. 2) WRITE (6,1019) VLEVEL,DRIVE,DRAGA,DRAGR,
     *DRAGT,ACC
      IF (KLIM .EQ. 1) WRITE (6,1011)
    5 CONTINUE
C
C     PRODUCE TABLE OF CAPACITY-POWER VARIATION.
C
      IF (KTABC .EQ. 0) GO TO 8
      PMAX  = 0.0
      CZERO = A0EC
      DO 6 I=1,IVMAX
      IV = I - 1
      POWER = A0P + IV * (A1P + IV * A2P)
      IF (POWER .LE. PMAX) GO TO 6
      IVPMAX = IV
      PMAX   = POWER
    6 CONTINUE
      WRITE (6,1034) PMAX,IVPMAX,CZERO
      LINES = 0
      IPMAX = PMAX + 2
      IF (IPMAX .GT. 36) IPMAX = 36
      DO 7 I=1,IPMAX
      IP    = I - 1
      CAP   = A0EC + IP * (A1EC + IP * A2EC)
      POWF = IP / PMAX
      CAPF = CAP / CZERO
      IF (LINES .EQ. 00) WRITE (6,1012)
      IF (LINES .EQ. 10) WRITE (6,1012)
      IF (LINES .EQ. 20) WRITE (6,1012)
      IF (LINES .EQ. 30) WRITE (6,1012)
```

```
      WRITE (6,1035) IP,POWF,CAP,CAPF
      LINES = LINES + 1
    7 CONTINUE
C
C     COMPUTE FULL-POWER, LEVEL-ROAD SPEED-TIME VARIATION.
C
    8 IF (KTABD .EQ. 0) GO TO 13
      VATT(1) = 0.0
      SATT(1) = 0.0
      EATT(1) = 0.0
      CALL FORCES (VATT(1),D1,D2,D3,D4,D5,D6,D7,D8,D9,AATT(1))
      DT = 0.1
      DO 9 IT=2,1000
      CALL ACCINT (VATT(IT-1),DT,VATT(IT),SATT(IT),EATT(IT),AATT(IT))
      SATT(IT) = SATT(IT-1) + SATT(IT)
      EATT(IT) = EATT(IT-1) + EATT(IT)
      ITMAX = IT
      IF (AATT(IT) .LT. 0.01) GO TO 10
    9 CONTINUE
C
C     PRODUCE TABLE OF SPEED-TIME VARIATION.
C
   10 IDT = 1
      IF (ITMAX .GT. 200) IDT = 2
      IF (ITMAX .GT. 500) IDT = 5
      WRITE (6,1020)
      LINES = 0
      DO 12 I=1,ITMAX,IDT
      TIME = (I - 1) / 10.0
      IF (LINES .LE. 39) GO TO 11
      WRITE (6,1020)
      LINES = 0
   11 IF (LINES .EQ. 00) WRITE (6,1012)
      IF (LINES .EQ. 10) WRITE (6,1012)
      IF (LINES .EQ. 20) WRITE (6,1012)
      IF (LINES .EQ. 30) WRITE (6,1012)
      ACCN = AATT(I) / GRVACC
      WRITE (6,1021) TIME,VATT(I),SATT(I),ACCN,EATT(I)
      LINES = LINES + 1
   12 CONTINUE
C
C     COMPUTE PERFORMANCE ON VARIOUS GRADES.
C
   13 DO 29 IGRADE=1,5
      KKGRAD = KGRADE(IGRADE)
      IF (KKGRAD .LT. 0) KKGRAD = 1
      IF (KKGRAD .GT. 2) KKGRAD = 1
      IF (KKGRAD .EQ. 0) GO TO 29
      IF (IGRADE .EQ. 1) IG = 10
      IF (IGRADE .EQ. 2) IG = 20
      IF ((IGRADE .EQ. 3) .OR. (IGRADE .EQ. 5)) IG = 50
      IGG = 1
      IF (IGRADE .GT. 4) IGG = -1
```

```
      GG = IGG
      G = IG
      THETA = 0.0
      IF (IGRADE .NE. 4) THETA = ATAN(GG/G)
C
C     COMPUTE PARAMETERS AT MAXIMUM SPEED.
C
      GTERM = IWT * GRVACC * SIN(THETA)
      CALL SPDBAL (VMAX)
      CALL FORCES (VMAX,POWER,D1,D2,D3,D4,D5,D6,D7,D8,D9)
      ECONS = POWER / VMAX
      CAP = A0EC + POWER * (A1EC + POWER * A2EC)
      RANGE = CAP / ECONS
      WRITE (6,1022)
      IF (IGRADE .NE. 4) WRITE (6,1023) IGG,IG,VMAX,POWER,RANGE
      IF (IGRADE .EQ. 4) WRITE (6,1024) VMAX,POWER,RANGE
C
C     COMPUTE CRUISE SPEED PARAMETERS.
C
      WRITE (6,1025)
      KREG = 0
      DO 16 IV=10,100,10
      V = IV
      IF (V .LE. VMAX) GO TO 14
      WRITE (6,1027) IV
      GO TO 16
   14 CALL FORCES (V,D1,EFFCY,D2,D3,D4,D5,D6,DRAGT,D7,RACCN)
      ACC = RACCN / GRVACC
      IF (DRAGT .GT. 0.0) GO TO 15
      KREG = 1
      POWER = -DRAGT * V * EFFCY / 3600
      ECONS = POWER / V
      WRITE (6,1028) IV,POWER,ECONS,ACC
      GO TO 16
   15 POWER = DRAGT * V / (3600 * EFFCY)
      ECONS = POWER / V
      CAP = A0EC + POWER * (A1EC + POWER * A2EC)
      RANGE = CAP / ECONS
      DUR = CAP / POWER
      WRITE (6,1026) IV,POWER,ECONS,RANGE,DUR,ACC
   16 CONTINUE
      IF (KREG .EQ. 1) WRITE (6,1029)
C
C     COMPUTE ACCELERATION PARAMETERS.
C
      WRITE (6,1030)
      IVCHEK = 10
      VATT(1) = 0.0
      SATT(1) = 0.0
      EATT(1) = 0.0
      CALL FORCES (VATT(1),D1,D2,D3,D4,D5,D6,D7,D8,D9,AATT(1))
      DT = 0.1
      DO 17 IT=2,1000
```

```
      CALL ACCINT (VATT(IT-1),DT,VATT(IT),SATT(IT),EATT(IT),AATT(IT))
      SATT(IT) = SATT(IT-1) + SATT(IT)
      EATT(IT) = EATT(IT-1) + EATT(IT)
      IF (AATT(IT) .LT. 0.01) GO TO 18
      IF (VATT(IT) .LT. IVCHEK) GO TO 17
      FRACT = (IVCHEK - VATT(IT-1)) / (VATT(IT) - VATT(IT-1))
      TIME = (IT + FRACT - 2) / 10.0
      DIST = SATT(IT-1) + FRACT * (SATT(IT) - SATT(IT-1))
      ENERGY = EATT(IT-1) + FRACT * (EATT(IT) - EATT(IT-1))
      VBAR = 3600 * DIST / TIME
      ABAR = (IVCHEK**2) / (25920 * DIST)
      ABAR = ABAR / GRVACC
      WRITE (6,1031) IVCHEK,TIME,DIST,ENERGY,VBAR,ABAR
      IVCHEK = IVCHEK + 10
      IF (IVCHEK .GT. VMAX) GO TO 18
      IF (IVCHEK .GT. 100) GO TO 18
   17 CONTINUE
   18 IF (IVCHEK .GT. 100) GO TO 20
      DO 19 IV=IVCHEK,100,10
   19 WRITE (6,1032) IV
C
C     COMPUTE RANGE SENSITIVITY TO PARAMETER VARIATIONS.
C
   20 IF (KKGRAD .EQ. 1) GO TO 29
      WRITE (6,1036)
      IF (IGRADE .NE. 4) WRITE (6,1046) IGG,IG
      IF (IGRADE .EQ. 4) WRITE (6,1047)
      WRITE (6,1048)
      DO 28 IPASS=1,4
      FEFFCY = 1.0
      FCDRAG = 1.0
      FCROLL = 1.0
      FVWGHT = 1.0
      WRITE (6,1012)
      DO 27 IV=10,100,10
      V = IV
      IF (V .LE. VMAX) GO TO 21
      WRITE (6,1037) IV
      GO TO 25
   21 DO 23 IPC=1,5
      FACTOR = 1.0 + (IPC - 3) / 10.0
      IF (IPASS .EQ. 1) FEFFCY = FACTOR
      IF (IPASS .EQ. 2) FCDRAG = FACTOR
      IF (IPASS .EQ. 3) FCROLL = FACTOR
      IF (IPASS .EQ. 4) FVWGHT = FACTOR
      KIWT = IWT
      A0E  = A0E * FEFFCY
      A1E  = A1E * FEFFCY
      A2E  = A2E * FEFFCY
      A0C  = A0C * FCDRAG
      A1C  = A1C * FCDRAG
      A2C  = A2C * FCDRAG
      A0R  = A0R * FCROLL
```

```
      A1R   = A1R * FCROLL
      A2R   = A2R * FCROLL
      IWT   = IWT * FVWGHT
      GTERM = IWT * GRVACC * SIN(THETA)
      CALL FORCES (V,D1,EFFCY,D2,D3,D4,D5,D6,DRAGT,D7,D8)
      A0E   = A0E / FEFFCY
      A1E   = A1E / FEFFCY
      A2E   = A2E / FEFFCY
      A0C   = A0C / FCDRAG
      A1C   = A1C / FCDRAG
      A2C   = A2C / FCDRAG
      A0R   = A0R / FCROLL
      A1R   = A1R / FCROLL
      A2R   = A2R / FCROLL
      IWT   = KIWT
      IF (DRAGT .GT. 0.0) GO TO 22
      WRITE (6,1037) IV
      GO TO 25
   22 POWER = DRAGT * V / (3600 * EFFCY)
      ECONS = POWER / V
      CAP   = A0EC + POWER * (A1EC + POWER * A2EC)
      SENVAL(IPC) = CAP / ECONS
   23 CONTINUE
      SMEAN = SENVAL(3)
      DO 24 IPC=1,5
   24 SENVAL(IPC) = SENVAL(IPC) / SMEAN
      WRITE (6,1038) IV,SENVAL
   25 IF (IV .NE. 10) GO TO 26
      IF (IPASS .EQ. 1) WRITE (6,1039)
      IF (IPASS .EQ. 2) WRITE (6,1040)
      IF (IPASS .EQ. 3) WRITE (6,1041)
      IF (IPASS .EQ. 4) WRITE (6,1042)
   26 IF (IV .NE. 20) GO TO 27
      IF (IPASS .EQ. 1) WRITE (6,1043)
      IF (IPASS .EQ. 2) WRITE (6,1044)
      IF (IPASS .EQ. 3) WRITE (6,1044)
      IF (IPASS .EQ. 4) WRITE (6,1045)
   27 CONTINUE
   28 CONTINUE
   29 CONTINUE
C
C     CHECK FOR FURTHER SETS OF DATA.
C
      GO TO 1
   30 WRITE (6,1033)
      STOP
      END
```

QFIT DATE = 74151

```
      SUBROUTINE QFIT (Y1,IX1,Y2,IX2,Y3,IX3,A0,A1,A2,NPASS)
C
C     *****************************************************************
C     *                                                               *
C     *        THIS SUBPROGRAM CALCULATES QUADRATIC COEFFICIENTS FOR  *
C     *  ARGUMENTS PRESENTED IN THE FOLLOWING FORM ...                *
C     *                                                               *
C     *             Y1 ... VALUE OF Y AT X = IX1.                    *
C     *             Y2 ... VALUE OF Y AT X = IX2.                    *
C     *             Y3 ... VALUE OF Y AT X = IX3.                    *
C     *                                                               *
C     *        THE QUADRATIC FITTED IS OF THE FORM ...                *
C     *                                                               *
C     *             Y = A0 + A1 * X + A2 * X**2                       *
C     *                                                               *
C     *        THE ARGUMENT NPASS IS A KEY USED FOR GENERATING ERROR  *
C     *  MESSAGES IF ERRORS ARE DETECTED.   ERRORS CAUSE IMMEDIATE    *
C     *  PROGRAM EXECUTION TERMINATION.                               *
C     *                                                               *
C     *****************************************************************
C
  100 FORMAT (///10X,'***** ERRORS IN FITTING ... ')
  101 FORMAT ('+',37X,'DEVELOPED POWER.')
  102 FORMAT ('+',37X,'CONVERSION EFFICIENCY.')
  103 FORMAT ('+',37X,'DRAG COEFFICIENT.')
  104 FORMAT ('+',37X,'ROLLING RESISTANCE COEFFICIENT.')
  105 FORMAT ('+',37X,'ENERGY CAPACITY.')
  106 FORMAT (/10X,'***** RUN AUTOMATICALLY TERMINATED.'/'1'/'1')
      IF (IX1 .EQ. IX2) GO TO 1
      IF (IX1 .EQ. IX3) GO TO 1
      IF (IX2 .EQ. IX3) GO TO 1
      GO TO 8
    1 WRITE (6,100)
      GO TO (2,3,4,5,6),NPASS
    2 WRITE (6,101)
      GO TO 7
    3 WRITE (6,102)
      GO TO 7
    4 WRITE (6,103)
      GO TO 7
    5 WRITE (6,104)
      GO TO 7
    6 WRITE (6,105)
    7 WRITE (6,106)
      STOP
    8 A2 = (Y1 - Y2) / (IX1 - IX2)
      A2 = (A2 - ((Y2 - Y3) / (IX2 - IX3))) / (IX1 - IX3)
      A1 = Y1 - A2 * IX1**2
      A1 = A1 - (Y2 - A2 * IX2**2)
      A1 = A1 / (IX1 - IX2)
      A0 = Y1 - A1 * IX1 - A2 * IX1**2
      RETURN
      END
```

SPDBAL DATE = 74151

```
      SUBROUTINE SPDBAL (VBAL)
C
C    ******************************************************************
C    *                                                                *
C    *       THIS SUBPROGRAM COMPUTES THE BALANCING SPEED UNDER      *
C    *  GIVEN SLOPE CONDITIONS.   THIS IS DONE BY ITERATIVE           *
C    *  SOLUTION OF THE DRIVING AND RETARDING FORCE EQUATIONS, WHICH  *
C    *  ARE COMPUTED IN SUBROUTINE FORCES.                            *
C    *                                                                *
C    *       VBAL IS THE RETURNED VALUE OF BALANCING SPEED.   IF A    *
C    *  SOLUTION IS NOT OBTAINED BELOW 200 KM/H, CONTROL IS RETURNED  *
C    *  TO THE CALLING PROGRAM SEGMENT.                               *
C    *                                                                *
C    ******************************************************************
C
      COMMON A0P,A1P,A2P,A0E,A1E,A2E,A0C,A1C,A2C,A0R,A1R,A2R
      COMMON IWT,AREA,IOPALT,IVLIM,FLIM,GRVACC,GTERM,ROEAIR,THETA
      COMMON IVVMAX
      NPASS = 1
      VBAL  = 0.0
      DV    = 1.0
    1 IF (VBAL .LT. IVVMAX) GO TO 2
      RETURN
    2 CALL FORCES (VBAL,D1,D2,D3,D4,D5,D6,D7,D8,D9,RACCN)
      IF (RACCN .LE. 0) GO TO 4
    3 VBAL = VBAL + DV
      GO TO 1
    4 IF (NPASS .GT. 2) GO TO 5
      NPASS = NPASS + 1
      VBAL  = VBAL - DV
      DV    = DV / 10.0
      GO TO 3
    5 RETURN
      END
```

FORCES DATE = 74151

```
      SUBROUTINE FORCES (V,POWER,EFFCY,CDRAG,CREST,DRIVE,DRAGA,DRAGR,
     *DRAGT,RESF,RACCN)
C
C     ****************************************************************
C     *                                                              *
C     *      THIS SUBPROGRAM COMPUTES THE MAGNITUDE OF THE POWER,    *
C     *  EFFICIENCY, DRAG COEFFICIENT AND ROLLING RESISTANCE AT A    *
C     *  SPECIFIC VALUE OF SPEED.   THE COMPONENTS OF DRIVING AND    *
C     *  RESISTANCE FORCES ARE ALSO COMPUTED.   THE ARGUMENTS OF THE *
C     *  SUBPROGRAM ARE AS FOLLOWS ...                               *
C     *                                                              *
C     *      V ........ SPEED (KM/H).                                *
C     *      POWER .... AVAILABLE POWER (KW).                        *
C     *      EFFCY .... CONVERSION EFFICIENCY (FRACTION).            *
C     *      CDRAG .... AERODYNAMIC DRAG COEFFICIENT.                *
C     *      CREST .... ROLLING RESISTANCE COEFFICIENT (N/KG).       *
C     *      DRIVE .... DRIVING FORCE (NEWTONS).                     *
C     *      DRAGA .... AIR RESISTANCE (NEWTONS).                    *
C     *      DRAGR .... ROLLING RESISTANCE (NEWTONS).                *
C     *      DRAGT .... TOTAL RESISTANCE (NEWTONS).                  *
C     *      RESF ..... RESULTANT FORCE (NEWTONS).                   *
C     *      RACCN .... RESULTANT ACCELERATION (M/SEC**2).           *
C     *                                                              *
C     *      THE VALUE OF ARGUMENT V IS SUPPLIED TO THE SUBPROGRAM,  *
C     *  WHILE THE REMAINDER ARE RETURNED AFTER EXECUTION IS         *
C     *  COMPLETED.                                                  *
C     *                                                              *
C     ****************************************************************
C
      COMMON A0P,A1P,A2P,A0E,A1E,A2E,A0C,A1C,A2C,A0R,A1R,A2R
      COMMON IWT,AREA,IOPALT,IVLIM,FLIM,GRVACC,GTERM,ROEAIR,THETA
      COMMON IVVMAX
      EFFCY = A0E + V * (A1E + V * A2E)
      CDRAG = A0C + V * (A1C + V * A2C)
      CREST = A0R + V * (A1R + V * A2R)
      IF (V .GT. IVLIM) GO TO 1
      DRIVE = FLIM
      POWER = DRIVE * V / (3600 * EFFCY)
      GO TO 2
    1 POWER = A0P + V * (A1P + V * A2P)
      DRIVE = 3600 * POWER * EFFCY / V
    2 DRAGA = ROEAIR * CDRAG * AREA * V**2 / 25.92
      DRAGR = IWT * CREST * COS(THETA)
      DRAGT = DRAGA + DRAGR + GTERM
      RESF  = DRIVE - DRAGT
      RACCN = RESF / IWT
      RETURN
      END
```

ACCINT DATE = 74151

```
      SUBROUTINE ACCINT (VO,DT,VF,DIST,ENERGY,ACCN)
C
C     ****************************************************************
C     *                                                              *
C     *      THIS SUBPROGRAM INTEGRATES ACCELERATION OVER AN         *
C     *  INTERVAL OF TIME TO OBTAIN THE FINAL SPEED.  THE ARGUMENTS  *
C     *  OF THE SUBPROGRAM ARE ...                                   *
C     *                                                              *
C     *      VO ....... INITIAL SPEED (KM/H).                        *
C     *      DT ....... TIME INCREMENT (SECONDS).                    *
C     *      VF ....... FINAL SPEED (KM/H).                          *
C     *      DIST ..... DISTANCE TRAVELLED IN DT (KM).               *
C     *      ENERGY ... ENERGY EXPENDED IN DT (KW-H).                *
C     *      ACCN ..... ACCELERATION AT END OF DT (M/SEC**2).        *
C     *                                                              *
C     *      ARGUMENTS VO AND DT ARE SUPPLIED TO THE SUBPROGRAM,     *
C     *  WHILE THE REMAINDER ARE RETURNED.  THE METHOD USED IS THE   *
C     *  RUNGE-KUTTA NUMERICAL INTEGRATION TECHNIQUE.                *
C     *                                                              *
C     ****************************************************************
C
      CALL FORCES (VO,POWO,EFFO,D1,D2,D3,D4,D5,D6,D7,ACC0)
      EST1 = 3.6 * DT * ACC0
      CALL FORCES ((VO+EST1/2),D1,D2,D3,D4,D5,D6,D7,D8,D9,ACC1)
      EST2 = 3.6 * DT * ACC1
      CALL FORCES ((VO+EST2/2),D1,D2,D3,D4,D5,D6,D7,D8,D9,ACC2)
      EST3 = 3.6 * DT * ACC2
      CALL FORCES ((VO+EST3),D1,D2,D3,D4,D5,D6,D7,D8,D9,ACC3)
      EST4 = 3.6 * DT * ACC3
      VF = VO + (EST1 + 2 * EST2 + 2 * EST3 + EST4) / 6.0
      CALL FORCES (VF,POWF,EFFF,D1,D2,D3,D4,D5,D6,D7,ACCF)
      DIST   = (VO + VF) * DT / 7200
      ENERGY = (POWO + POWF) * DT / 7200
      ACCN   = ACCF
      RETURN
      END
```

ANNEX C

PERFORMANCE MODEL - TYPICAL RESULTS

As an example of the scope of the results provided by the performance model, parameters for a particular car type were assessed. The car itself was 4 metres long, and it was assumed that a 20 kW (continuous rating) motor and 15 kWh (5-hour rating) lead-acid battery could be accommodated. Although these basic assumptions are the subject of variation, the values postulated are considered reasonable for an up-to-date design. The basic characteristics of such a car were estimated on the basis outlined in Annex D, and are tabulated in Table C.1.

The results provided by the performance model are appended. They consist of a tabulation of basic specified values, followed by tables of variations of the major parameters and forces with speed. The capacity-power variation is then presented, followed by a detailed listing of full-power, level-road acceleration capabilities. Finally, the results for each set of road grades are presented.

TABLE C.1 - PARAMETRIC VALUES FOR PERFORMANCE ANALYSIS EXAMPLE

Vehicle weight	1865 kg
Vehicle frontal area	1.92 m^2
Operational altitude	0 m
Constant force speed limit	10 km/h
Power overload factor	1.75
Options exercised	All

Title .... 4-METRE BATTERY AUTOMOBILE

	Speed	Value
Power-speed variation	0 km/h	16 kW
	60 km/h	20 kW
	120 km/h	18 kW
Efficiency-speed variation	0 km/h	0.6000
	60 km/h	0.6000
	120 km/h	0.6000
Aerodynamic drag coefficient variation with speed	0 km/h	0.5000
	60 km/h	0.4850
	120 km/h	0.4700
Rolling resistance coefficient variation with speed	0 km/h	0.1090 N/kg
	60 km/h	0.1260 N/kg
	120 km/h	0.1680 N/kg

	Power	Value
Capacity-power variation	1 kW	21.75 kWh
	15 kW	8.85 kWh
	40 kW	6.45 kWh

```
****************************************
*                                      *
*  BUREAU OF TRANSPORT ECONOMICS       *
*                                      *
*  DEVELOPMENT SECTION                 *
*                                      *
*  ELECTRIC VEHICLE PERFORMANCE TESTS  *
*                                      *
****************************************
```

DESCRIPTION ...... 4-METRE BATTERY AUTOMOBILE.

VEHICLE WEIGHT ... 1865 KG

FRONTAL AREA 1.92 M**2

ALTITUDE .... 0 M

LIMITING SPEED ... 10 KM/H

POWER OVERLOAD ... 1.75

QUADRATIC COEFFICIENTS FOR FITTED QUANTITIES.

FITTED QUANTITY	INPUT (X)	INPUT (Y)	COMPUTED COEFFICIENTS
DEVELOPED POWER	0	16.000	A0 = 16.0000
	60	20.000	A1 = 0.1167
	120	18.000	A2 = -0.0008
CONVERSION EFFICIENCY	0	0.600	A0 = 0.6000
	60	0.600	A1 = 0.0
	120	0.600	A2 = 0.0
AERODYNAMIC DRAG COEFFICIENT	0	0.500	A0 = 0.5000
	60	0.485	A1 = -0.0003
	120	0.470	A2 = 0.0000
ROLLING RESISTANCE COEFFICIENT	0	0.109	A0 = 0.1090
	60	0.126	A1 = 0.0001
	120	0.168	A2 = 0.0000
CAPACITY - POWER VARIATION	1	21.750	A0 = 22.9889
	15	8.850	A1 = -1.2601
	40	6.450	A2 = 0.0212

COMPUTED AIR DENSITY 1.159 KG/M**3

GRAVITY ACCELERATION 9.793 M/S**2

LIMITING DRIVE FORCE .... 6457 NEWTONS

```
****************************************
*                                      *
*  VARIATION OF PARAMETERS WITH SPEED  *
*                                      *
****************************************
```

SPEED (KM/H)	POWER (KW)	CONVERSION EFFICIENCY (FRACTION)	AERO DRAG COEFFICIENT	RESISTANCE COEFFICIENT (N/KG)
0	0.0*	0.6000	0.5000	0.1090
1	3.0*	0.6000	0.4997	0.1091
2	6.0*	0.6000	0.4995	0.1092
3	9.0*	0.6000	0.4992	0.1093
4	12.0*	0.6000	0.4990	0.1094
5	14.9*	0.6000	0.4987	0.1095
6	17.9*	0.6000	0.4985	0.1096
7	20.9*	0.6000	0.4982	0.1097
8	23.9*	0.6000	0.4980	0.1098
9	26.9*	0.6000	0.4977	0.1100
10	29.9*	0.6000	0.4975	0.1101
11	30.1	0.6000	0.4972	0.1102
12	30.2	0.6000	0.4970	0.1104
13	30.4	0.6000	0.4967	0.1106
14	30.6	0.6000	0.4965	0.1107
15	30.7	0.6000	0.4962	0.1109
16	30.9	0.6000	0.4960	0.1111
17	31.0	0.6000	0.4957	0.1113
18	31.2	0.6000	0.4955	0.1115
19	31.4	0.6000	0.4952	0.1117
20	31.5	0.6000	0.4950	0.1119
21	31.6	0.6000	0.4947	0.1121
22	31.8	0.6000	0.4945	0.1123
23	31.9	0.6000	0.4942	0.1126
24	32.1	0.6000	0.4940	0.1128
25	32.2	0.6000	0.4937	0.1130
26	32.3	0.6000	0.4935	0.1133
27	32.4	0.6000	0.4932	0.1136
28	32.6	0.6000	0.4930	0.1138
29	32.7	0.6000	0.4927	0.1141
30	32.8	0.6000	0.4925	0.1144
31	32.9	0.6000	0.4922	0.1147
32	33.0	0.6000	0.4920	0.1150
33	33.1	0.6000	0.4917	0.1153
34	33.3	0.6000	0.4915	0.1156
35	33.4	0.6000	0.4912	0.1159
36	33.5	0.6000	0.4910	0.1162
37	33.6	0.6000	0.4907	0.1165
38	33.7	0.6000	0.4905	0.1169
39	33.7	0.6000	0.4902	0.1172

* INDICATES CONSTANT-FORCE REGION.

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*                                      *
*  VARIATION OF PARAMETERS WITH SPEED  *
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SPEED (KM/H)	POWER (KW)	CONVERSION EFFICIENCY (FRACTION)	AERO DRAG COEFFICIENT	RESISTANCE COEFFICIENT (N/KG)
40	33.8	0.6000	0.4900	0.1176
41	33.9	0.6000	0.4897	0.1179
42	34.0	0.6000	0.4895	0.1183
43	34.1	0.6000	0.4892	0.1186
44	34.2	0.6000	0.4890	0.1190
45	34.2	0.6000	0.4887	0.1194
46	34.3	0.6000	0.4885	0.1198
47	34.4	0.6000	0.4882	0.1202
48	34.4	0.6000	0.4880	0.1206
49	34.5	0.6000	0.4877	0.1210
50	34.6	0.6000	0.4875	0.1214
51	34.6	0.6000	0.4872	0.1219
52	34.7	0.6000	0.4870	0.1223
53	34.7	0.6000	0.4867	0.1227
54	34.8	0.6000	0.4865	0.1232
55	34.8	0.6000	0.4862	0.1236
56	34.9	0.6000	0.4860	0.1241
57	34.9	0.6000	0.4857	0.1246
58	34.9	0.6000	0.4855	0.1250
59	35.0	0.6000	0.4852	0.1255
60	35.0	0.6000	0.4850	0.1260
61	35.0	0.6000	0.4847	0.1265
62	35.1	0.6000	0.4845	0.1270
63	35.1	0.6000	0.4842	0.1275
64	35.1	0.6000	0.4840	0.1280
65	35.1	0.6000	0.4837	0.1285
66	35.1	0.6000	0.4835	0.1291
67	35.1	0.6000	0.4832	0.1296
68	35.1	0.6000	0.4830	0.1302
69	35.1	0.6000	0.4827	0.1307
70	35.1	0.6000	0.4825	0.1313
71	35.1	0.6000	0.4822	0.1318
72	35.1	0.6000	0.4820	0.1324
73	35.1	0.6000	0.4817	0.1330
74	35.1	0.6000	0.4815	0.1336
75	35.1	0.6000	0.4812	0.1342
76	35.1	0.6000	0.4810	0.1348
77	35.1	0.6000	0.4807	0.1354
78	35.1	0.6000	0.4805	0.1360
79	35.0	0.6000	0.4802	0.1366

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*                                      *
*  VARIATION OF PARAMETERS WITH SPEED  *
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SPEED (KM/H)	POWER (KW)	CONVERSION EFFICIENCY (FRACTION)	AERO DRAG COEFFICIENT	RESISTANCE COEFFICIENT (N/KG)
80	35.0	0.6000	0.4800	0.1372
81	35.0	0.6000	0.4797	0.1379
82	34.9	0.6000	0.4795	0.1385
83	34.9	0.6000	0.4792	0.1391
84	34.9	0.6000	0.4790	0.1398
85	34.8	0.6000	0.4787	0.1405
86	34.8	0.6000	0.4785	0.1411
87	34.7	0.6000	0.4782	0.1418
88	34.7	0.6000	0.4780	0.1425
89	34.6	0.6000	0.4777	0.1432
90	34.6	0.6000	0.4775	0.1439
91	34.5	0.6000	0.4772	0.1446
92	34.4	0.6000	0.4770	0.1453
93	34.4	0.6000	0.4767	0.1460
94	34.3	0.6000	0.4765	0.1467
95	34.2	0.6000	0.4762	0.1475
96	34.2	0.6000	0.4760	0.1482
97	34.1	0.6000	0.4757	0.1489
98	34.0	0.6000	0.4755	0.1497
99	33.9	0.6000	0.4752	0.1505
100	33.8	0.6000	0.4750	0.1512
101	33.7	0.6000	0.4747	0.1520
102	33.7	0.6000	0.4745	0.1528
102.2	33.6	0.6000	0.4744	0.1529

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*  FULL-POWER, LEVEL-ROAD FORCES VARIATION  *
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SPEED (KM/H)	DRIVE FORCE (N)	AIR DRAG RESIST. (N)	ROLLING RESIST. (N)	TOTAL RESIST. (N)	ACC'N (G)
0	6457.5*	0.0	203.3	203.3	0.342
1	6457.5*	0.0	203.4	203.5	0.342
2	6457.5*	0.2	203.6	203.8	0.342
3	6457.5*	0.4	203.8	204.1	0.342
4	6457.5*	0.7	203.9	204.6	0.342
5	6457.5*	1.1	204.1	205.2	0.342
6	6457.5*	1.5	204.4	205.9	0.342
7	6457.5*	2.1	204.6	206.7	0.342
8	6457.5*	2.7	204.8	207.6	0.342
9	6457.5*	3.5	205.1	208.5	0.342
10	6457.5*	4.3	205.3	209.6	0.342
11	5904.5	5.2	205.6	210.8	0.312
12	5443.2	6.1	205.9	212.0	0.286
13	5052.3	7.2	206.2	213.4	0.265
14	4716.9	8.4	206.5	214.9	0.246
15	4425.7	9.6	206.8	216.4	0.230
16	4170.6	10.9	207.2	218.1	0.216
17	3945.1	12.3	207.5	219.8	0.204
18	3744.3	13.8	207.9	221.7	0.193
19	3564.3	15.3	208.3	223.6	0.183
20	3402.0	17.0	208.7	225.7	0.174
21	3254.8	18.7	209.1	227.8	0.166
22	3120.8	20.5	209.5	230.0	0.158
23	2998.1	22.4	209.9	232.4	0.151
24	2885.4	24.4	210.4	234.8	0.145
25	2781.4	26.5	210.8	237.3	0.139
26	2685.3	28.6	211.3	239.9	0.134
27	2595.9	30.9	211.8	242.7	0.129
28	2512.8	33.2	212.3	245.5	0.124
29	2435.2	35.6	212.8	248.4	0.120
30	2362.5	38.1	213.3	251.4	0.116
31	2294.3	40.6	213.8	254.5	0.112
32	2230.2	43.3	214.4	257.6	0.108
33	2169.8	46.0	215.0	260.9	0.105
34	2112.7	48.8	215.5	264.3	0.101
35	2058.7	51.7	216.1	267.8	0.098
36	2007.6	54.6	216.7	271.3	0.095
37	1959.0	57.7	217.3	275.0	0.092
38	1912.9	60.8	218.0	278.8	0.089
39	1868.9	64.0	218.6	282.6	0.087

* INDICATES CONSTANT-FORCE REGION.

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*  FULL-POWER, LEVEL-ROAD FORCES VARIATION *
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SPEED (KM/H)	DRIVE FORCE (N)	AIR DRAG RESIST. (N)	ROLLING RESIST. (N)	TOTAL RESIST. (N)	ACC'N (G)
40	1827.0	67.3	219.2	286.5	0.084
41	1787.0	70.7	219.9	290.6	0.082
42	1748.7	74.1	220.6	294.7	0.080
43	1712.1	77.7	221.3	298.9	0.077
44	1676.9	81.3	222.0	303.3	0.075
45	1643.2	85.0	222.7	307.7	0.073
46	1610.9	88.7	223.4	312.2	0.071
47	1579.8	92.6	224.2	316.8	0.069
48	1549.8	96.5	224.9	321.4	0.067
49	1520.9	100.5	225.7	326.2	0.065
50	1493.1	104.6	226.5	331.1	0.064
51	1466.2	108.8	227.3	336.1	0.062
52	1440.3	113.1	228.1	341.1	0.060
53	1415.2	117.4	228.9	346.3	0.059
54	1390.9	121.8	229.7	351.5	0.057
55	1367.4	126.3	230.6	356.8	0.055
56	1344.6	130.8	231.4	362.3	0.054
57	1322.5	135.5	232.3	367.8	0.052
58	1301.1	140.2	233.2	373.4	0.051
59	1280.2	145.0	234.1	379.1	0.049
60	1260.0	149.9	235.0	384.9	0.048
61	1240.3	154.9	235.9	390.8	0.047
62	1221.2	159.9	236.8	396.7	0.045
63	1202.5	165.0	237.8	402.8	0.044
64	1184.4	170.2	238.8	409.0	0.042
65	1166.7	175.5	239.7	415.2	0.041
66	1149.5	180.8	240.7	421.5	0.040
67	1132.6	186.2	241.7	428.0	0.039
68	1116.2	191.7	242.7	434.5	0.037
69	1100.2	197.3	243.8	441.1	0.036
70	1084.5	203.0	244.8	447.8	0.035
71	1069.2	208.7	245.9	454.6	0.034
72	1054.2	214.5	246.9	461.4	0.032
73	1039.5	220.4	248.0	468.4	0.031
74	1025.2	226.4	249.1	475.5	0.030
75	1011.1	232.4	250.2	482.6	0.029
76	997.4	238.5	251.3	489.8	0.028
77	983.9	244.7	252.4	497.2	0.027
78	970.7	251.0	253.6	504.6	0.026
79	957.7	257.3	254.7	512.1	0.024

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*  FULL-POWER, LEVEL-ROAD FORCES VARIATION  *
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SPEED (KM/H)	DRIVE FORCE (N)	AIR DRAG RESIST. (N)	ROLLING RESIST. (N)	TOTAL RESIST. (N)	ACC'N (G)
80	945.0	263.7	255.9	519.7	0.023
81	932.5	270.2	257.1	527.3	0.022
82	920.3	276.8	258.3	535.1	0.021
83	908.2	283.4	259.5	542.9	0.020
84	896.4	290.2	260.7	550.9	0.019
85	884.8	297.0	262.0	558.9	0.018
86	873.4	303.8	263.2	567.0	0.017
87	862.1	310.8	264.5	575.2	0.016
88	851.1	317.8	265.7	583.5	0.015
89	840.2	324.9	267.0	591.9	0.014
90	829.5	332.1	268.3	600.4	0.013
91	819.0	339.3	269.6	608.9	0.011
92	808.6	346.6	271.0	617.6	0.010
93	798.4	354.0	272.3	626.3	0.009
94	788.3	361.5	273.7	635.1	0.008
95	778.4	369.0	275.0	644.0	0.007
96	768.6	376.6	276.4	653.0	0.006
97	759.0	384.3	277.8	662.1	0.005
98	749.4	392.1	279.2	671.2	0.004
99	740.1	399.9	280.6	680.5	0.003
100	730.8	407.8	282.0	689.8	0.002
101	721.7	415.8	283.5	699.2	0.001
102	712.6	423.8	284.9	708.7	0.000
102.2	710.7	425.6	285.2	710.9	-0.000

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*  VARIATION OF CAPACITY WITH POWER *
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MAXIMUM POWER (LEVEL-ROAD) ... 35.1 KW

SPEED AT MAXIMUM POWER .... 70 KM/H

ZERO-POWER CAPACITY .... 23.0 KW-H

POWER (KW)	PART OF MAXIMUM POWER	CAPACITY (KW-H)	PART OF MAXIMUM CAPACITY
0	0.0	22.989	1.000
1	0.028	21.750	0.946
2	0.057	20.553	0.894
3	0.085	19.399	0.844
4	0.114	18.287	0.795
5	0.142	17.218	0.749
6	0.171	16.190	0.704
7	0.199	15.206	0.661
8	0.228	14.263	0.620
9	0.256	13.363	0.581
10	0.285	12.505	0.544
11	0.313	11.689	0.508
12	0.341	10.916	0.475
13	0.370	10.185	0.443
14	0.398	9.496	0.413
15	0.427	8.850	0.385
16	0.455	8.246	0.359
17	0.484	7.684	0.334
18	0.512	7.165	0.312
19	0.541	6.688	0.291
20	0.569	6.254	0.272
21	0.598	5.861	0.255
22	0.626	5.511	0.240
23	0.654	5.204	0.226
24	0.683	4.938	0.215
25	0.711	4.715	0.205
26	0.740	4.535	0.197
27	0.768	4.396	0.191
28	0.797	4.300	0.187
29	0.825	4.247	0.185
30	0.854	4.235	0.184
31	0.882	4.266	0.186
32	0.910	4.340	0.189
33	0.939	4.455	0.194
34	0.967	4.613	0.201
35	0.996	4.814	0.209

FULL-POWER, LEVEL-ROAD SPEED-TIME VARIATION

TIME (S)	SPEED (KM/H)	DISTANCE (KM)	ACC'N (G)	ENERGY USED (KW-H)
0.0	0.0	0.0	0.342	0.0
0.5	6.04	0.0004	0.342	0.001
1.0	11.89	0.0017	0.289	0.005
1.5	16.22	0.0036	0.214	0.009
2.0	19.63	0.0061	0.177	0.013
2.5	22.54	0.0091	0.154	0.018
3.0	25.12	0.0124	0.139	0.022
3.5	27.45	0.0160	0.127	0.027
4.0	29.60	0.0200	0.117	0.031
4.5	31.60	0.0243	0.109	0.036
5.0	33.47	0.0288	0.103	0.040
5.5	35.23	0.0335	0.097	0.045
6.0	36.90	0.0386	0.092	0.050
6.5	38.49	0.0438	0.088	0.054
7.0	40.01	0.0492	0.084	0.059
7.5	41.47	0.0549	0.081	0.064
8.0	42.86	0.0608	0.078	0.069
8.5	44.21	0.0668	0.075	0.073
9.0	45.50	0.0730	0.072	0.078
9.5	46.75	0.0794	0.070	0.083
10.0	47.96	0.0860	0.067	0.088
10.5	49.13	0.0928	0.065	0.092
11.0	50.26	0.0997	0.063	0.097
11.5	51.35	0.1067	0.061	0.102
12.0	52.42	0.1139	0.059	0.107
12.5	53.45	0.1213	0.058	0.112
13.0	54.46	0.1288	0.056	0.116
13.5	55.43	0.1364	0.055	0.121
14.0	56.38	0.1442	0.053	0.126
14.5	57.31	0.1521	0.052	0.131
15.0	58.21	0.1601	0.050	0.136
15.5	59.09	0.1682	0.049	0.141
16.0	59.94	0.1765	0.048	0.146
16.5	60.78	0.1849	0.047	0.150
17.0	61.60	0.1934	0.046	0.155
17.5	62.39	0.2020	0.045	0.160
18.0	63.17	0.2107	0.044	0.165
18.5	63.93	0.2195	0.043	0.170
19.0	64.67	0.2285	0.042	0.175
19.5	65.39	0.2375	0.041	0.180

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*  FULL-POWER, LEVEL-ROAD SPEED-TIME VARIATION  *
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TIME (S)	SPEED (KM/H)	DISTANCE (KM)	ACC'N (G)	ENERGY USED (KW-H)
20.0	66.10	0.2466	0.040	0.184
20.5	66.79	0.2559	0.039	0.189
21.0	67.47	0.2652	0.038	0.194
21.5	68.13	0.2746	0.037	0.199
22.0	68.78	0.2841	0.036	0.204
22.5	69.42	0.2937	0.036	0.209
23.0	70.04	0.3034	0.035	0.214
23.5	70.64	0.3132	0.034	0.219
24.0	71.24	0.3230	0.033	0.224
24.5	71.82	0.3329	0.033	0.228
25.0	72.39	0.3430	0.032	0.233
25.5	72.95	0.3531	0.031	0.238
26.0	73.49	0.3632	0.031	0.243
26.5	74.03	0.3735	0.030	0.248
27.0	74.55	0.3838	0.029	0.253
27.5	75.07	0.3942	0.029	0.258
28.0	75.57	0.4046	0.028	0.263
28.5	76.06	0.4152	0.028	0.267
29.0	76.55	0.4258	0.027	0.272
29.5	77.02	0.4364	0.027	0.277
30.0	77.49	0.4472	0.026	0.282
30.5	77.94	0.4580	0.026	0.287
31.0	78.39	0.4688	0.025	0.292
31.5	78.83	0.4797	0.025	0.297
32.0	79.26	0.4907	0.024	0.302
32.5	79.68	0.5017	0.024	0.306
33.0	80.09	0.5128	0.023	0.311
33.5	80.49	0.5240	0.023	0.316
34.0	80.89	0.5352	0.022	0.321
34.5	81.28	0.5465	0.022	0.326
35.0	81.66	0.5578	0.021	0.331
35.5	82.04	0.5691	0.021	0.336
36.0	82.40	0.5806	0.021	0.340
36.5	82.77	0.5920	0.020	0.345
37.0	83.12	0.6035	0.020	0.350
37.5	83.47	0.6151	0.019	0.355
38.0	83.81	0.6267	0.019	0.360
38.5	84.14	0.6384	0.019	0.365
39.0	84.47	0.6501	0.018	0.369
39.5	84.79	0.6619	0.018	0.374

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*   FULL-POWER, LEVEL-ROAD SPEED-TIME VARIATION     *
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TIME (S)	SPEED (KM/H)	DISTANCE (KM)	ACC'N (G)	ENERGY USED (KW-H)
40.0	85.10	0.6737	0.018	0.379
40.5	85.41	0.6855	0.017	0.384
41.0	85.72	0.6974	0.017	0.389
41.5	86.02	0.7093	0.017	0.394
42.0	86.31	0.7213	0.016	0.398
42.5	86.60	0.7333	0.016	0.403
43.0	86.88	0.7453	0.016	0.408
43.5	87.15	0.7574	0.016	0.413
44.0	87.43	0.7695	0.015	0.418
44.5	87.69	0.7817	0.015	0.423
45.0	87.95	0.7939	0.015	0.427
45.5	88.21	0.8061	0.014	0.432
46.0	88.46	0.8184	0.014	0.437
46.5	88.71	0.8307	0.014	0.442
47.0	88.95	0.8430	0.014	0.447
47.5	89.19	0.8554	0.013	0.451
48.0	89.42	0.8678	0.013	0.456
48.5	89.65	0.8802	0.013	0.461
49.0	89.88	0.8927	0.013	0.466
49.5	90.10	0.9052	0.012	0.471
50.0	90.32	0.9177	0.012	0.475
50.5	90.53	0.9303	0.012	0.480
51.0	90.74	0.9429	0.012	0.485
51.5	90.95	0.9555	0.012	0.490
52.0	91.15	0.9682	0.011	0.495
52.5	91.35	0.9808	0.011	0.499
53.0	91.54	0.9935	0.011	0.504
53.5	91.73	1.0063	0.011	0.509
54.0	91.92	1.0190	0.011	0.514
54.5	92.10	1.0318	0.010	0.519
55.0	92.28	1.0446	0.010	0.523
55.5	92.46	1.0574	0.010	0.528
56.0	92.64	1.0703	0.010	0.533
56.5	92.81	1.0831	0.010	0.538
57.0	92.97	1.0960	0.009	0.542
57.5	93.14	1.1090	0.009	0.547
58.0	93.30	1.1219	0.009	0.552
58.5	93.46	1.1349	0.009	0.557
59.0	93.62	1.1479	0.009	0.562
59.5	93.77	1.1609	0.009	0.566

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*                                               *
*  FULL-POWER, LEVEL-ROAD SPEED-TIME VARIATION  *
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TIME (S)	SPEED (KM/H)	DISTANCE (KM)	ACC'N (G)	ENERGY USED (KW-H)
60.0	93.92	1.1739	0.008	0.571
60.5	94.07	1.1870	0.008	0.576
61.0	94.21	1.2000	0.008	0.581
61.5	94.36	1.2131	0.008	0.585
62.0	94.50	1.2262	0.008	0.590
62.5	94.63	1.2394	0.008	0.595
63.0	94.77	1.2525	0.008	0.600
63.5	94.90	1.2657	0.007	0.604
64.0	95.03	1.2789	0.007	0.609
64.5	95.16	1.2921	0.007	0.614
65.0	95.29	1.3053	0.007	0.619
65.5	95.41	1.3185	0.007	0.623
66.0	95.53	1.3318	0.007	0.628
66.5	95.65	1.3451	0.007	0.633
67.0	95.77	1.3584	0.007	0.638
67.5	95.88	1.3717	0.006	0.642
68.0	95.99	1.3850	0.006	0.647
68.5	96.10	1.3983	0.006	0.652
69.0	96.21	1.4117	0.006	0.657
69.5	96.32	1.4250	0.006	0.661
70.0	96.42	1.4384	0.006	0.666
70.5	96.53	1.4518	0.006	0.671
71.0	96.63	1.4652	0.006	0.676
71.5	96.73	1.4787	0.006	0.680
72.0	96.82	1.4921	0.005	0.685
72.5	96.92	1.5056	0.005	0.690
73.0	97.01	1.5190	0.005	0.695
73.5	97.11	1.5325	0.005	0.699
74.0	97.20	1.5460	0.005	0.704
74.5	97.29	1.5595	0.005	0.709
75.0	97.37	1.5730	0.005	0.713
75.5	97.46	1.5865	0.005	0.718
76.0	97.54	1.6001	0.005	0.723
76.5	97.63	1.6136	0.005	0.728
77.0	97.71	1.6272	0.005	0.732
77.5	97.79	1.6408	0.004	0.737
78.0	97.87	1.6543	0.004	0.742
78.5	97.94	1.6679	0.004	0.747
79.0	98.02	1.6815	0.004	0.751
79.5	98.09	1.6952	0.004	0.756

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*                                                *
*  FULL-POWER, LEVEL-ROAD SPEED-TIME VARIATION   *
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TIME (S)	SPEED (KM/H)	DISTANCE (KM)	ACC'N (G)	ENERGY USED (KW-H)
80.0	98.17	1.7088	0.004	0.761
80.5	98.24	1.7224	0.004	0.765
81.0	98.31	1.7361	0.004	0.770
81.5	98.38	1.7497	0.004	0.775
82.0	98.45	1.7634	0.004	0.780
82.5	98.51	1.7771	0.004	0.784
83.0	98.58	1.7908	0.004	0.789
83.5	98.64	1.8045	0.004	0.794
84.0	98.71	1.8182	0.004	0.798
84.5	98.77	1.8319	0.003	0.803
85.0	98.83	1.8456	0.003	0.808
85.5	98.89	1.8593	0.003	0.813
86.0	98.95	1.8731	0.003	0.817
86.5	99.01	1.8868	0.003	0.822
87.0	99.06	1.9005	0.003	0.827
87.5	99.12	1.9143	0.003	0.831
88.0	99.17	1.9281	0.003	0.836
88.5	99.23	1.9419	0.003	0.841
89.0	99.28	1.9556	0.003	0.846
89.5	99.33	1.9694	0.003	0.850
90.0	99.38	1.9832	0.003	0.855
90.5	99.43	1.9970	0.003	0.860
91.0	99.48	2.0108	0.003	0.864
91.5	99.53	2.0247	0.003	0.869
92.0	99.58	2.0385	0.003	0.874
92.5	99.63	2.0523	0.003	0.878
93.0	99.67	2.0661	0.003	0.883
93.5	99.72	2.0800	0.003	0.888
94.0	99.76	2.0938	0.002	0.893
94.5	99.80	2.1077	0.002	0.897
95.0	99.85	2.1216	0.002	0.902
95.5	99.89	2.1354	0.002	0.907
96.0	99.93	2.1493	0.002	0.911
96.5	99.97	2.1632	0.002	0.916
97.0	100.01	2.1771	0.002	0.921
97.5	100.05	2.1910	0.002	0.925
98.0	100.09	2.2049	0.002	0.930
98.5	100.12	2.2188	0.002	0.935
99.0	100.16	2.2327	0.002	0.940
99.5	100.20	2.2466	0.002	0.944

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*                                                *
*  GENERAL VEHICLE PERFORMANCE CHARACTERISTICS   *
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GRADE FOR THIS SET OF TESTS ... 1 IN 10

MAXIMUM SPEED ATTAINABLE ...... 34.6 KM/H

POWER AT MAXIMUM SPEED .... 33.3 KW

RANGE AT MAXIMUM SPEED .... 4.7 KM

CRUISE SPEED ENERGY CONSUMPTION, ETC.

SPEED (KM/H)	POWER (KW)	ENERGY USED (KW-H/KM)	RANGE (KM)	DURATION (H)	AVAILABLE ACC'N (G)
10	9.4	0.9379	13.9	1.39	0.243
20	18.9	0.9454	7.1	0.36	0.074
30	28.7	0.9573	4.4	0.15	0.016
40	....	.....	....	....	.....
50	....	.....	....	....	.....
60	....	.....	....	....	.....
70	....	.....	....	....	.....
80	....	.....	....	....	.....
90	....	.....	....	....	.....
100	....	.....	....	....	.....

ACCELERATION CHARACTERISTICS (FROM REST).

SPEED (KM/H)	TIME (S)	DISTANCE (KM)	ENERGY USED (KW-H)	AVERAGE SPEED (KM/H)	AVERAGE ACC'N (G)
10	1.17	0.0016	0.0049	5.01	0.242
20	3.44	0.0117	0.0243	12.23	0.135
30	11.60	0.0711	0.0976	22.08	0.050
40	.....	......	......	.....	.....
50	.....	......	......	.....	.....
60	.....	......	......	.....	.....
70	.....	......	......	.....	.....
80	.....	......	......	.....	.....
90	.....	......	......	.....	.....
100	.....	......	......	.....	.....

RANGE SENSITIVITY TO PARAMETER VARIATIONS (GRADE ... 1 IN 10).

		MAGNITUDE OF PARAMETER VARIATION				
PARAMETER VARIED	SPEED (KM/H)	-20%	-10%	00%	+10%	+20%
CONVERSION EFFICIENCY	10	0.683	0.839	1.000	1.163	1.329
	20	0.598	0.783	1.000	1.239	1.496
	30	0.945	0.916	1.000	1.167	1.397
	40	.....	.....	.....	.....	.....
	50	.....	.....	.....	.....	.....
	60	.....	.....	.....	.....	.....
	70	.....	.....	.....	.....	.....
	80	.....	.....	.....	.....	.....
	90	.....	.....	.....	.....	.....
	100	.....	.....	.....	.....	.....
AERODYNAMIC DRAG COEFFICIENT	10	1.001	1.000	1.000	1.000	0.999
	20	1.004	1.002	1.000	0.998	0.996
	30	1.005	1.002	1.000	0.998	0.995
	40	.....	.....	.....	.....	.....
	50	.....	.....	.....	.....	.....
	60	.....	.....	.....	.....	.....
	70	.....	.....	.....	.....	.....
	80	.....	.....	.....	.....	.....
	90	.....	.....	.....	.....	.....
	100	.....	.....	.....	.....	.....
ROLLING RESISTANCE COEFFICIENT	10	1.033	1.017	1.000	0.984	0.968
	20	1.048	1.024	1.000	0.977	0.955
	30	1.029	1.014	1.000	0.987	0.976
	40	.....	.....	.....	.....	.....
	50	.....	.....	.....	.....	.....
	60	.....	.....	.....	.....	.....
	70	.....	.....	.....	.....	.....
	80	.....	.....	.....	.....	.....
	90	.....	.....	.....	.....	.....
	100	.....	.....	.....	.....	.....
GROSS VEHICLE WEIGHT	10	1.411	1.182	1.000	0.855	0.736
	20	1.622	1.265	1.000	0.804	0.658
	30	1.514	1.186	1.000	0.920	0.919
	40	.....	.....	.....	.....	.....
	50	.....	.....	.....	.....	.....
	60	.....	.....	.....	.....	.....
	70	.....	.....	.....	.....	.....
	80	.....	.....	.....	.....	.....
	90	.....	.....	.....	.....	.....
	100	.....	.....	.....	.....	.....

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*                                               *
*  GENERAL VEHICLE PERFORMANCE CHARACTERISTICS  *
*                                               *
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GRADE FOR THIS SET OF TESTS ... 1 IN 20

MAXIMUM SPEED ATTAINABLE ...... 58.6 KM/H

POWER AT MAXIMUM SPEED .... 35.0 KW

RANGE AT MAXIMUM SPEED .... 8.1 KM

CRUISE SPEED ENERGY CONSUMPTION, ETC.

SPEED (KM/H)	POWER (KW)	ENERGY USED (KW-H/KM)	RANGE (KM)	DURATION (H)	AVAILABLE ACC'N (G)
10	5.2	0.5192	32.8	3.28	0.292
20	10.5	0.5266	22.9	1.15	0.124
30	16.2	0.5385	15.1	0.50	0.066
40	22.2	0.5548	9.8	0.25	0.034
50	28.8	0.5754	7.4	0.15	0.014
60	....	.....	....	....	.....
70	....	.....	....	....	.....
80	....	.....	....	....	.....
90	....	.....	....	....	.....
100	....	.....	....	....	.....

ACCELERATION CHARACTERISTICS (FROM REST).

SPEED (KM/H)	TIME (S)	DISTANCE (KM)	ENERGY USED (KW-H)	AVERAGE SPEED (KM/H)	AVERAGE ACC'N (G)
10	0.97	0.0014	0.0040	5.01	0.291
20	2.56	0.0083	0.0176	11.64	0.190
30	5.78	0.0311	0.0465	19.37	0.114
40	11.80	0.0905	0.1023	27.62	0.070
50	24.73	0.2549	0.2254	37.10	0.039
60	.....	......	......	.....	.....
70	.....	......	......	.....	.....
80	.....	......	......	.....	.....
90	.....	......	......	.....	.....
100	.....	......	......	.....	.....

RANGE SENSITIVITY TO PARAMETER VARIATIONS (GRADE ... 1 IN 20).

PARAMETER VARIED	SPEED (KM/H)	MAGNITUDE OF PARAMETER VARIATION -20%	-10%	00%	+10%	+20%
CONVERSION EFFICIENCY	10	0.738	0.869	1.000	1.132	1.265
	20	0.668	0.831	1.000	1.173	1.349
	30	0.606	0.793	1.000	1.220	1.451
	40	0.634	0.791	1.000	1.248	1.525
	50	0.949	0.917	1.000	1.166	1.394
	60	.....	.....	.....	.....	.....
	70	.....	.....	.....	.....	.....
	80	.....	.....	.....	.....	.....
	90	.....	.....	.....	.....	.....
	100	.....	.....	.....	.....	.....
AERODYNAMIC DRAG COEFFICIENT	10	1.001	1.001	1.000	0.999	0.999
	20	1.005	1.003	1.000	0.997	0.995
	30	1.014	1.007	1.000	0.993	0.986
	40	1.026	1.013	1.000	0.987	0.975
	50	1.023	1.011	1.000	0.990	0.980
	60	.....	.....	.....	.....	.....
	70	.....	.....	.....	.....	.....
	80	.....	.....	.....	.....	.....
	90	.....	.....	.....	.....	.....
	100	.....	.....	.....	.....	.....
ROLLING RESISTANCE COEFFICIENT	10	1.050	1.025	1.000	0.976	0.954
	20	1.065	1.032	1.000	0.969	0.940
	30	1.082	1.040	1.000	0.962	0.925
	40	1.090	1.044	1.000	0.959	0.921
	50	1.054	1.025	1.000	0.978	0.960
	60	.....	.....	.....	.....	.....
	70	.....	.....	.....	.....	.....
	80	.....	.....	.....	.....	.....
	90	.....	.....	.....	.....	.....
	100	.....	.....	.....	.....	.....
GROSS VEHICLE WEIGHT	10	1.329	1.147	1.000	0.881	0.783
	20	1.429	1.190	1.000	0.849	0.725
	30	1.545	1.237	1.000	0.817	0.675
	40	1.621	1.260	1.000	0.817	0.692
	50	1.457	1.168	1.000	0.924	0.918
	60	.....	.....	.....	.....	.....
	70	.....	.....	.....	.....	.....
	80	.....	.....	.....	.....	.....
	90	.....	.....	.....	.....	.....
	100	.....	.....	.....	.....	.....

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*                                                  *
*  GENERAL VEHICLE PERFORMANCE CHARACTERISTICS     *
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GRADE FOR THIS SET OF TESTS ... 1 IN 50

MAXIMUM SPEED ATTAINABLE .... 83.0 KM/H

POWER AT MAXIMUM SPEED .... 34.9 KW

RANGE AT MAXIMUM SPEED .... 11.4 KM

CRUISE SPEED ENERGY CONSUMPTION, ETC.

SPEED (KM/H)	POWER (KW)	ENERGY USED (KW-H/KM)	RANGE (KM)	DURATION (H)	AVAILABLE ACC'N (G)
10	2.7	0.2661	74.4	7.44	0.322
20	5.5	0.2735	61.2	3.06	0.154
30	8.6	0.2854	48.2	1.61	0.096
40	12.1	0.3017	36.0	0.90	0.064
50	16.1	0.3223	25.4	0.51	0.044
60	20.8	0.3472	17.1	0.28	0.028
70	26.3	0.3764	11.9	0.17	0.015
80	32.8	0.4096	10.8	0.14	0.003
90	....	.....	....	....	.....
100	....	.....	....	....	.....

ACCELERATION CHARACTERISTICS (FROM REST).

SPEED (KM/H)	TIME (S)	DISTANCE (KM)	ENERGY USED (KW-H)	AVERAGE SPEED (KM/H)	AVERAGE ACC'N (G)
10	0.88	0.0012	0.0037	5.01	0.321
20	2.23	0.0071	0.0152	11.42	0.222
30	4.62	0.0239	0.0366	18.64	0.148
40	8.27	0.0597	0.0705	26.01	0.105
50	13.65	0.1274	0.1216	33.62	0.077
60	21.78	0.2524	0.2002	41.74	0.056
70	35.58	0.5036	0.3348	50.96	0.038
80	72.93	1.2944	0.6988	63.89	0.019
90	.....	......	......	.....	.....
100	.....	......	......	.....	.....

RANGE SENSITIVITY TO PARAMETER VARIATIONS (GRADE ... 1 IN 50).

		MAGNITUDE OF PARAMETER VARIATION				
PARAMETER VARIED	SPEED (KM/H)	-20%	-10%	00%	+10%	+20%
CONVERSION EFFICIENCY	10	0.770	0.885	1.000	1.115	1.231
	20	0.735	0.867	1.000	1.134	1.269
	30	0.694	0.845	1.000	1.157	1.316
	40	0.648	0.820	1.000	1.186	1.376
	50	0.606	0.794	1.000	1.220	1.450
	60	0.612	0.784	1.000	1.247	1.518
	70	0.794	0.851	1.000	1.215	1.480
	80	1.245	1.051	1.000	1.053	1.183
	90	.....	.....	.....	.....	.....
	100	.....	.....	.....	.....	.....
AERODYNAMIC DRAG COEFFICIENT	10	1.002	1.001	1.000	0.999	0.998
	20	1.008	1.004	1.000	0.996	0.992
	30	1.020	1.010	1.000	0.990	0.981
	40	1.039	1.019	1.000	0.981	0.963
	50	1.067	1.033	1.000	0.968	0.938
	60	1.100	1.048	1.000	0.955	0.913
	70	1.106	1.050	1.000	0.957	0.920
	80	1.023	1.007	1.000	1.003	1.014
	90	.....	.....	.....	.....	.....
	100	.....	.....	.....	.....	.....
ROLLING RESISTANCE COEFFICIENT	10	1.089	1.043	1.000	0.960	0.923
	20	1.102	1.049	1.000	0.954	0.912
	30	1.116	1.056	1.000	0.948	0.900
	40	1.134	1.064	1.000	0.941	0.886
	50	1.152	1.073	1.000	0.933	0.872
	60	1.162	1.077	1.000	0.931	0.868
	70	1.131	1.061	1.000	0.949	0.906
	80	1.022	1.006	1.000	1.003	1.013
	90	.....	.....	.....	.....	.....
	100	.....	.....	.....	.....	.....
GROSS VEHICLE WEIGHT	10	1.286	1.128	1.000	0.896	0.809
	20	1.324	1.145	1.000	0.882	0.784
	30	1.365	1.163	1.000	0.868	0.758
	40	1.412	1.184	1.000	0.852	0.730
	50	1.461	1.205	1.000	0.837	0.707
	60	1.491	1.214	1.000	0.837	0.713
	70	1.414	1.171	1.000	0.888	0.823
	80	1.127	1.032	1.000	1.020	1.081
	90	.....	.....	.....	.....	.....
	100	.....	.....	.....	.....	.....

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*                                               *
*  GENERAL VEHICLE PERFORMANCE CHARACTERISTICS  *
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GRADE FOR THIS SET OF TESTS ... LEVEL

MAXIMUM SPEED ATTAINABLE ...... 102.2 KM/H

POWER AT MAXIMUM SPEED .... 33.6 KW

RANGE AT MAXIMUM SPEED .... 13.8 KM

CRUISE SPEED ENERGY CONSUMPTION, ETC.

SPEED (KM/H)	POWER (KW)	ENERGY USED (KW-H/KM)	RANGE (KM)	DURATION (H)	AVAILABLE ACC'N (G)
10	1.0	0.0970	224.5	22.45	0.342
20	2.1	0.1045	195.7	9.79	0.174
30	3.5	0.1164	162.0	5.40	0.116
40	5.3	0.1327	127.4	3.18	0.084
50	7.7	0.1533	95.1	1.90	0.064
60	10.7	0.1782	67.0	1.12	0.048
70	14.5	0.2073	44.2	0.63	0.035
80	19.2	0.2406	27.3	0.34	0.023
90	25.0	0.2779	17.0	0.19	0.013
100	31.9	0.3194	13.6	0.14	0.002

ACCELERATION CHARACTERISTICS (FROM REST).

SPEED (KM/H)	TIME (S)	DISTANCE (KM)	ENERGY USED (KW-H)	AVERAGE SPEED (KM/H)	AVERAGE ACC'N (G)
10	0.83	0.0012	0.0034	5.02	0.341
20	2.06	0.0065	0.0140	11.30	0.244
30	4.10	0.0208	0.0322	18.28	0.170
40	7.00	0.0492	0.0591	25.31	0.128
50	10.89	0.0981	0.0961	32.43	0.100
60	16.03	0.1770	0.1458	39.75	0.080
70	22.97	0.3028	0.2135	47.46	0.064
80	32.89	0.5104	0.3102	55.87	0.049
90	49.27	0.8995	0.4685	65.72	0.035
100	96.87	2.1734	0.9196	80.77	0.018

RANGE SENSITIVITY TO PARAMETER VARIATIONS (GRADE ... LEVEL).

PARAMETER VARIED	SPEED (KM/H)	MAGNITUDE OF PARAMETER VARIATION -20%	-10%	00%	+10%	+20%
CONVERSION EFFICIENCY	10	0.789	0.895	1.000	1.105	1.211
	20	0.776	0.888	1.000	1.112	1.224
	30	0.759	0.880	1.000	1.121	1.242
	40	0.737	0.868	1.000	1.133	1.266
	50	0.706	0.852	1.000	1.150	1.301
	60	0.665	0.830	1.000	1.174	1.351
	70	0.620	0.803	1.000	1.207	1.421
	80	0.599	0.783	1.000	1.241	1.500
	90	0.727	0.824	1.000	1.232	1.507
	100	1.184	1.023	1.000	1.078	1.231
AERODYNAMIC DRAG COEFFICIENT	10	1.004	1.002	1.000	0.998	0.996
	20	1.017	1.008	1.000	0.992	0.983
	30	1.038	1.019	1.000	0.982	0.965
	40	1.065	1.032	1.000	0.970	0.941
	50	1.101	1.049	1.000	0.954	0.912
	60	1.147	1.070	1.000	0.936	0.877
	70	1.206	1.097	1.000	0.913	0.836
	80	1.274	1.126	1.000	0.892	0.799
	90	1.296	1.130	1.000	0.900	0.825
	100	1.122	1.039	1.000	0.998	1.028
ROLLING RESISTANCE COEFFICIENT	10	1.257	1.115	1.000	0.906	0.827
	20	1.254	1.114	1.000	0.905	0.825
	30	1.247	1.112	1.000	0.906	0.825
	40	1.240	1.110	1.000	0.906	0.825
	50	1.238	1.110	1.000	0.905	0.822
	60	1.243	1.113	1.000	0.902	0.815
	70	1.255	1.119	1.000	0.897	0.806
	80	1.264	1.122	1.000	0.895	0.804
	90	1.228	1.103	1.000	0.917	0.851
	100	1.065	1.022	1.000	0.995	1.006
GROSS VEHICLE WEIGHT	10	1.257	1.115	1.000	0.906	0.828
	20	1.254	1.114	1.000	0.905	0.826
	30	1.247	1.112	1.000	0.906	0.826
	40	1.240	1.110	1.000	0.906	0.825
	50	1.238	1.110	1.000	0.905	0.822
	60	1.243	1.113	1.000	0.902	0.816
	70	1.255	1.119	1.000	0.897	0.806
	80	1.264	1.123	1.000	0.895	0.804
	90	1.228	1.103	1.000	0.917	0.851
	100	1.065	1.023	1.000	0.995	1.006

```
*************************************************
*                                               *
*  GENERAL VEHICLE PERFORMANCE CHARACTERISTICS  *
*                                               *
*************************************************
```

GRADE FOR THIS SET OF TESTS ... -1 IN 50

MAXIMUM SPEED ATTAINABLE ...... 120.0 KM/H

POWER AT MAXIMUM SPEED .... 31.5 KW

RANGE AT MAXIMUM SPEED .... 16.4 KM

CRUISE SPEED ENERGY CONSUMPTION, ETC.

SPEED (KM/H)	POWER (KW)	ENERGY USED (KW-H/KM)	RANGE (KM)	DURATION (H)	AVAILABLE ACC'N (G)
10	0.3*	0.0259*	.....	....	0.362
20	0.5*	0.0233*	.....	....	0.194
30	0.6*	0.0190*	.....	....	0.136
40	0.5*	0.0131*	.....	....	0.104
50	0.3*	0.0057*	.....	....	0.084
60	0.5	0.0091	2457.5	40.96	0.068
70	2.7	0.0382	517.6	7.39	0.055
80	5.7	0.0715	230.5	2.88	0.043
90	9.8	0.1088	116.5	1.29	0.033
100	15.0	0.1502	58.8	0.59	0.022

* INDICATES REGENERATIVE POWER.

ACCELERATION CHARACTERISTICS (FROM REST).

SPEED (KM/H)	TIME (S)	DISTANCE (KM)	ENERGY USED (KW-H)	AVERAGE SPEED (KM/H)	AVERAGE ACC'N (G)
10	0.78	0.0011	0.0033	5.01	0.361
20	1.91	0.0060	0.0129	11.20	0.265
30	3.69	0.0185	0.0288	17.99	0.192
40	6.10	0.0420	0.0511	24.78	0.150
50	9.14	0.0802	0.0801	31.59	0.123
60	12.92	0.1380	0.1166	38.47	0.103
70	17.57	0.2222	0.1619	45.54	0.087
80	23.39	0.3438	0.2186	52.92	0.073
90	30.93	0.5223	0.2915	60.80	0.061
100	41.42	0.8001	0.3912	69.54	0.049

RANGE SENSITIVITY TO PARAMETER VARIATIONS (GRADE ... -1 IN 50).

PARAMETER VARIED	SPEED (KM/H)	MAGNITUDE OF PARAMETER VARIATION -20%	-10%	00%	+10%	+20%
CONVERSION EFFICIENCY	10	.....	.....	.....	.....	.....
	20	.....	.....	.....	.....	.....
	30	.....	.....	.....	.....	.....
	40	.....	.....	.....	.....	.....
	50	.....	.....	.....	.....	.....
	60	0.794	0.897	1.000	1.103	1.206
	70	0.769	0.885	1.000	1.116	1.231
	80	0.731	0.865	1.000	1.136	1.272
	90	0.677	0.836	1.000	1.167	1.336
	100	0.615	0.800	1.000	1.211	1.430
AERODYNAMIC DRAG COEFFICIENT	10	.....	.....	.....	.....	.....
	20	.....	.....	.....	.....	.....
	30	.....	.....	.....	.....	.....
	40	.....	.....	.....	.....	.....
	50	.....	.....	.....	.....	.....
	60	.....	.....	.....	.....	.....
	70	2.123	1.378	1.000	0.772	0.620
	80	1.710	1.280	1.000	0.804	0.659
	90	1.669	1.276	1.000	0.798	0.646
	100	1.738	1.306	1.000	0.777	0.613
ROLLING RESISTANCE COEFFICIENT	10	.....	.....	.....	.....	.....
	20	.....	.....	.....	.....	.....
	30	.....	.....	.....	.....	.....
	40	.....	.....	.....	.....	.....
	50	.....	.....	.....	.....	.....
	60	.....	.....	.....	.....	.....
	70	2.692	1.488	1.000	0.736	0.572
	80	1.678	1.270	1.000	0.809	0.667
	90	1.500	1.215	1.000	0.833	0.700
	100	1.453	1.201	1.000	0.839	0.709
GROSS VEHICLE WEIGHT	10	.....	.....	.....	.....	.....
	20	.....	.....	.....	.....	.....
	30	.....	.....	.....	.....	.....
	40	.....	.....	.....	.....	.....
	50	.....	.....	.....	.....	.....
	60	.....	.....	.....	.....	.....
	70	0.739	0.853	1.000	1.197	1.476
	80	0.833	0.910	1.000	1.103	1.224
	90	0.875	0.935	1.000	1.071	1.149
	100	0.901	0.949	1.000	1.054	1.113

ANNEX D

PARAMETER ESTIMATION

DATA SOURCES

In considering the values of parameters for use in estimating electric car performance, due account must be taken of the design and manufacturing processes involved in contemporary car production. In addition, the characteristics of electrical equipment likely to be incorporated in electric car design must be estimated. In this Annex, information gathered from a variety of sources is amalgamated to form the basis for the parametric analyses described in the report.

It was found that there was an almost complete lack of consistent information on weights and dimensions of conventional cars in Australia. Accordingly, a limited study was undertaken, using information available from road tests[1] and manufacturers' published figures.

Statistics on new automobile registrations in Australia in 1972[2] indicated that 167 identifiable models were available, representing vehicles marketed under 53 separate brand names. However, 35 of the 167 models represented 90 per cent of all new registrations in that year. Due to difficulty in obtaining consistent data on some models, 31 models were examined (representing 81 per cent of the 1972 new automobile registrations). The study generally used 1972 data, except in a few cases where 1973 information was more readily available. The errors involved in this substitution are minor.

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(1) Predominantly from the NRMA journal Open Road.

(2) Motor Vehicle Registrations 1972, op. cit.

Characteristics of electrical traction equipment were obtained by a literature search and use was made of regression analysis in determining likely parametric values. A similar approach was adopted in estimating values of coefficients for aerodynamic drag and rolling resistance.

VEHICLE WEIGHT

Many possibilities are available to car manufacturers in regard to materials and techniques for vehicle construction. However, in spite of attempts to introduce construction techniques involving light alloys and plastics, the distribution of weight between major components of cars appears to be relatively fixed. The rationale adopted in estimating electric vehicle weight was to:

(a) Identify components of a conventional car which would have the same <u>actual</u> weight in an electric vehicle of similar size.

(b) Identify components which would have similar <u>relative</u> weights in comparably-sized electric and conventional vehicles.

(c) Eliminate components made redundant by electric traction.

(d) Add extra components required for electric traction.

The most readily available source of information on component weights relative to total vehicle weight in conventional cars is research performed by Hoffmann[1]

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(1) G.A. Hoffman:

<u>Automobiles - Today and Tomorrow</u>, Rand Memorandum RM-2922-TF, November 1962.

'The Electric Automobile', <u>Scientific American,</u> October 1966.

'Hybrid Power Systems for Vehicles', presented at U S Department of Health, Education and Welfare Symposium <u>Power Systems for Electric Vehicles</u>, April 1967.

in the 1960's. Figure D.1 shows an estimated weight distribution for American cars, taken from the most recent of the papers cited. These proportions tally well with limited Australian information obtained by BTE. This is not surprising when it is considered that two-thirds of the cars currently marketed in Australia are manufactured by organisations of direct United States origin.

It was found that the length of a conventional car is an excellent descriptor of its other physical characteristics, largely due to the relatively fixed design of current vehicle shapes. On analysis of the weights of the sample of automobiles previously mentioned, it was found that weight as a function of length was well described by the expression shown in Figure D.2. The weight of a conventional car of length equivalent to that of a proposed electric vehicle may therefore be predicted by the expression:

$$\ln W = -2.38737 + 0.56338\ L \qquad (D.1)$$

where **W** is the conventional automobile weight (tonnes),
L is the vehicle length (metres), and
ln denotes a natural logarithm.

The electrical equipment included in an electric vehicle may be considered as comprised of motors, control equipment and batteries. Estimates of weights of such equipment obtained from the literature survey were particularly varied, and a similar approach to that used in estimating conventional vehicle weights was adopted. Ultimately, a reasonably adequate set of information on this equipment was assembled, and is shown in Table D.1.

In the case of motor weight versus power, data on a sample of eleven traction motors were used. Details of the motors are given in Table D.1. The weights and powers of these motors are shown in Figure D.3, together with a

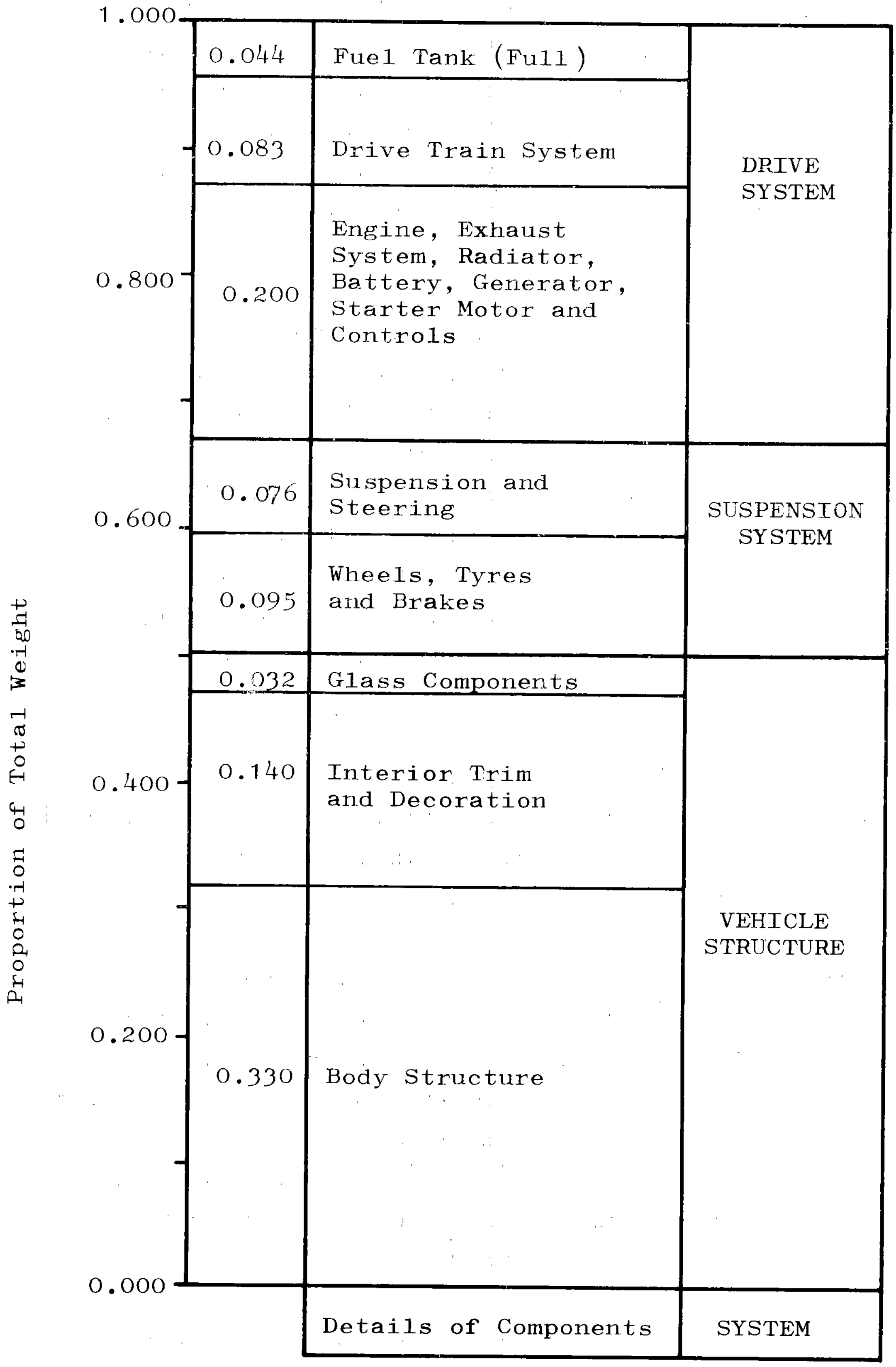

FIGURE D.1 - CONVENTIONAL CAR WEIGHT STRUCTURE

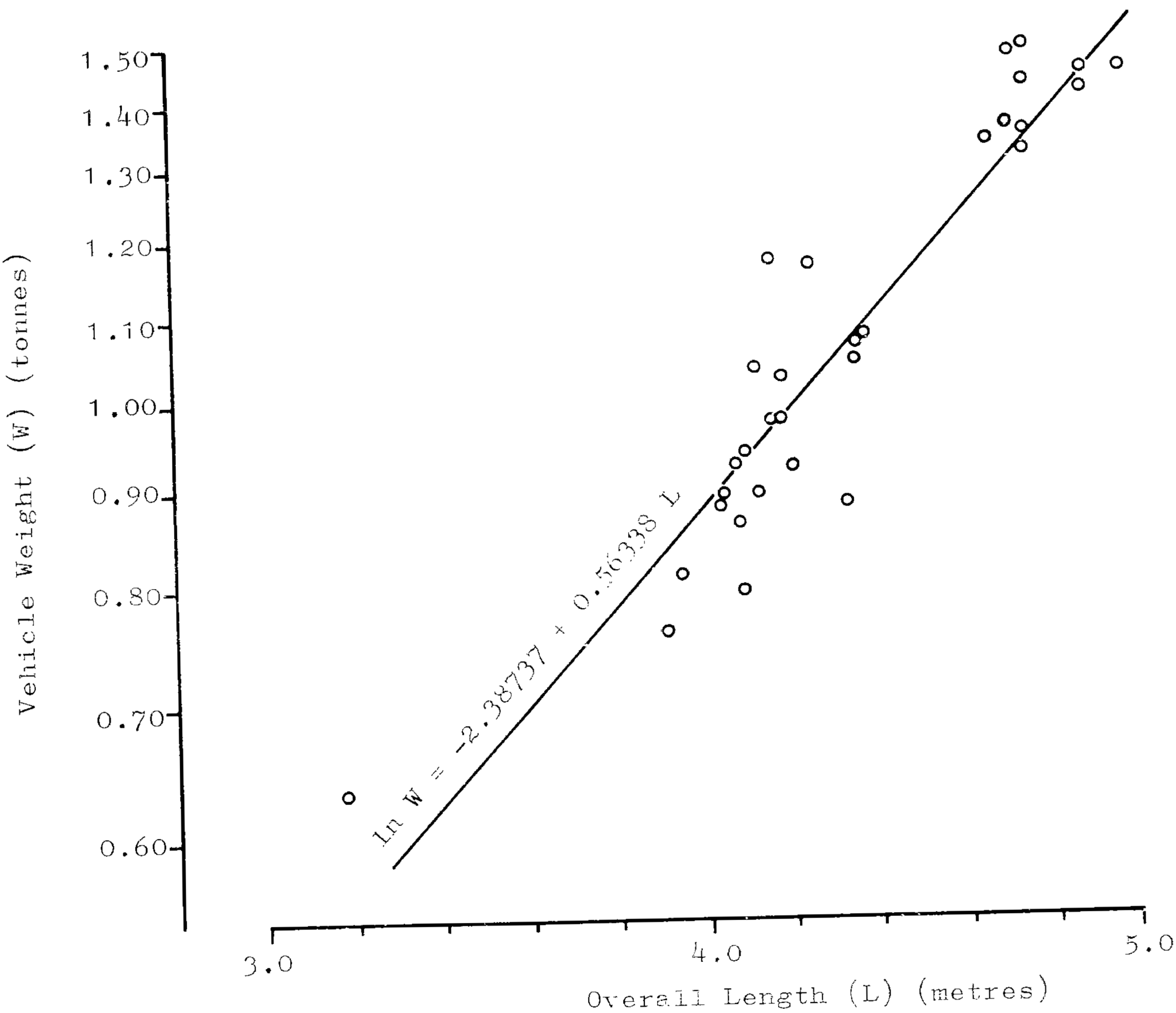

FIGURE D.2 - WEIGHT vs LENGTH FOR 1972-73 AUTOMOBILES

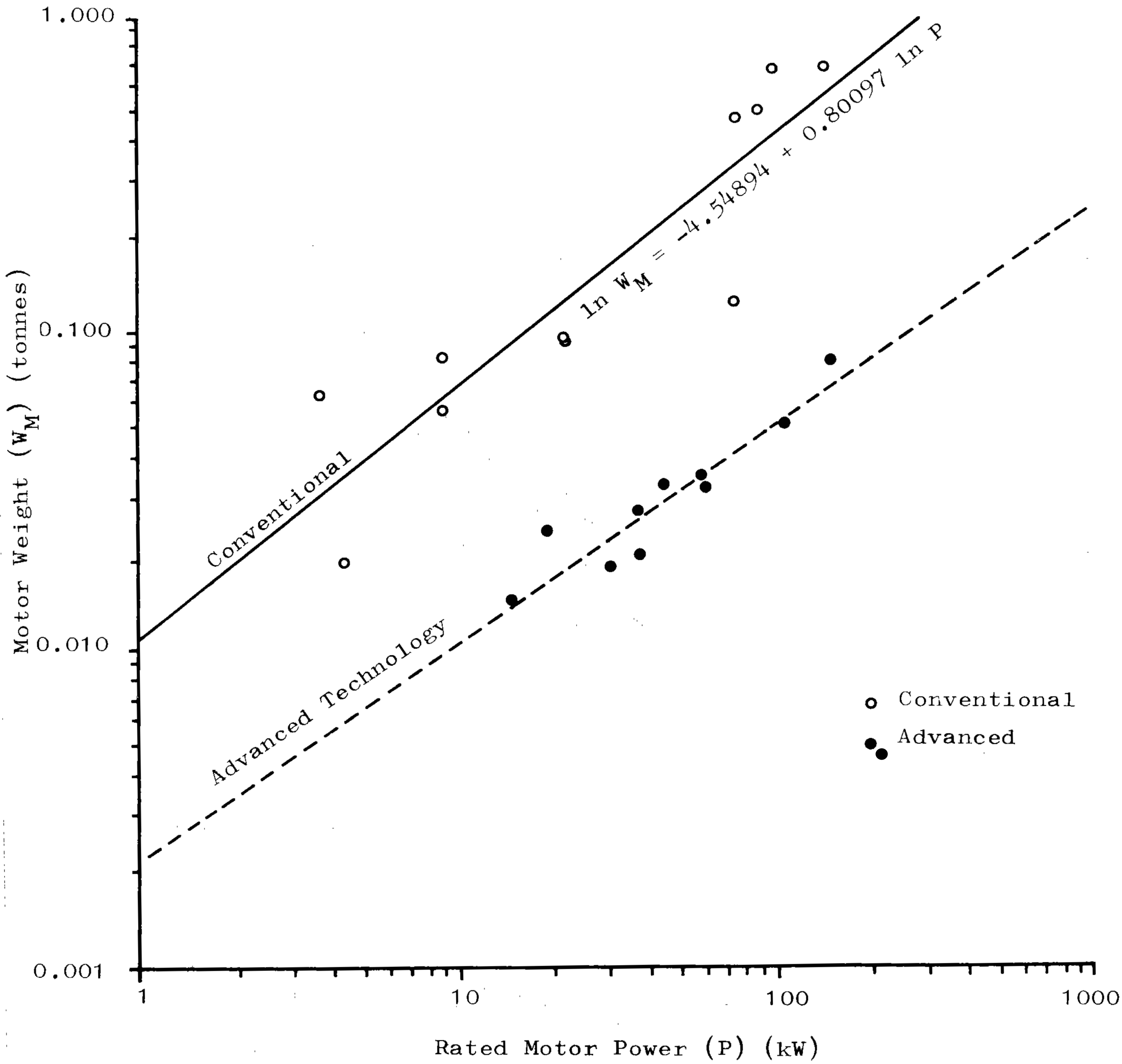

FIGURE D.3 - TRACTION MOTOR WEIGHT vs RATED POWER

TABLE D.1 - TYPICAL WEIGHTS FOR ELECTRIC TRACTION EQUIPMENT

Case	Rated motor power (kW)	Motor weight (kg)	Control system weight (kg)	Battery capacity (kWh)*	Battery weight (kg)	Comments
1	3.7	64	-	-	-	Motor estimate[a]
2	4.5	19	-	15.0	317	Research vehicle[a]
3	9.0	57	-	27.6**	844	CDA Phase III vehicle[b]
4	9.0	82	50	7.3**	376	Mini-traveller vehicle[c]
5	22.0	95	85	10.6	361	Automobile[d]
6	22.0	95	93	25.9	900	Small truck[d]
7	75.0	122	-	-	-	Electrovair II vehicle[e]
8	75.0	470	215	94.5	3500	Electric bus[d]
9	90.0	510	215	100.8	3500	Electric bus[d]
10	100.0	680	-	-	-	Railway power unit[f]
11	145.0	660	-	-	-	Railway power unit[f]
12	-	-	-	5.0	182	Scamp vehicle[c]
13	-	-	-	96.2**	3557	Bus Battery[g]

* 5-hour discharge rate. ** Converted to 5-hour discharge rate equivalent.

Sources:

(a) Flinders University Electric Research Vehicle, op. cit.

(b) R.L. Burns, 'The Possible Impact of Electric Vehicles', presented at Australian Lead Development Symposium on Electric Vehicles - Current Developments and the Future, September 1972.

(c) M. Barak, 'European Developments of Power Sources for Electric Vehicles', presented at US Dept of Health, Education and Welfare Symposium on Power Systems for Electric Vehicles, April 1967.

(d) G. Baumann, Propulsion Systems for Electric Vehicles, Bosch Technische Berichte, December 1971.

(e) Electric Vehicle Research, op. cit.

(f) Manufacturers' data sheets.

(g) B. Smith, The Unplug-and-Drive Buses, British Information Service (Feature), July 1972.

regression line representing weight variation with power for motors manufactured under typical current production techniques. Also shown is a set of data (and the associated regression line) for advanced-technology rotating electric machinery (predominantly aircraft generators) used in Hoffmann's[1] analysis of hybrid vehicles. These devices have power/weight ratios approximately five times as great as the conventional equipment, and may represent the likely upper limit for electric vehicle motors. However, in this analysis, motor weight characteristics for the conventional devices described are used, and are represented by the equation:

$$\ln W_M = -4.54894 + 0.80097 \ln P \qquad \text{(D.2)}$$

where W_M is the motor weight (tonnes) and

P is the rated motor power (kW).

Since most vehicles considered in this analysis would be equipped for regenerative braking, it is quite likely that they would be fitted with electronic control equipment. This equipment is considerably more efficient than resistive control, and is likely to be less expensive, in production quantities, than other systems which permit regeneration (e.g. hydraulic transmissions). Although a large amount of information is available on the merits and demerits of electronic control for traction motors (particularly in the railway field), information on weights and associated characteristics is particularly scarce. From the point of view of equipment in the power range applicable to electric road vehicles, only five relevant sets of information were revealed and these values, together with the associated regression line, are shown in Figure D.4. While considerable reservations must be held about the use of limited data of this type, the weight of control equipment appears to be a function of rated motor power in the following terms:

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(1) G.A. Hoffmann, Hybrid Power Systems, op. cit.

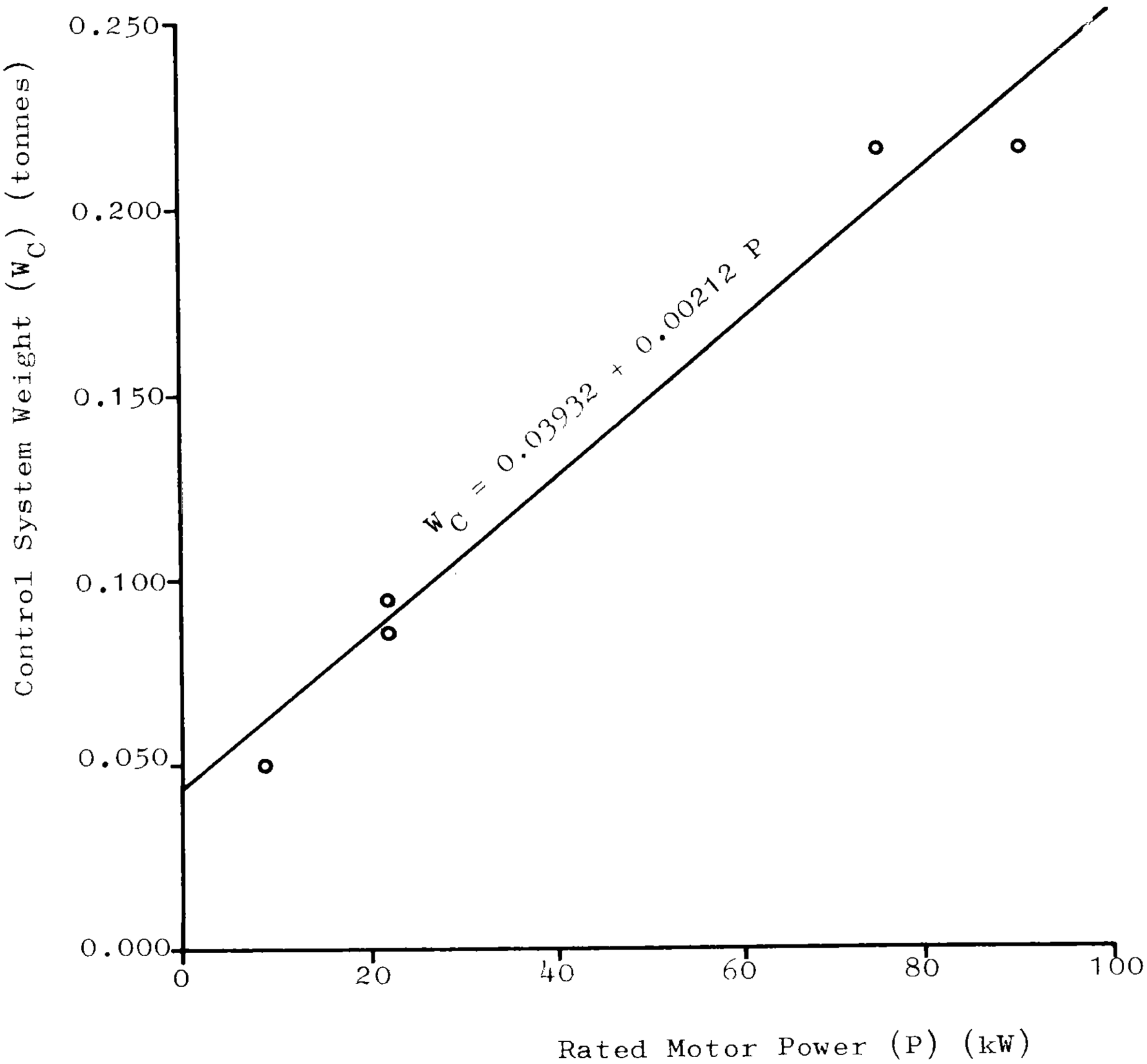

FIGURE D.4 - CONTROL SYSTEM WEIGHT vs RATED POWER

$$W_C = 0.03932 + 0.00212\ P \qquad (D.3)$$

where W_C is the control equipment weight (tonnes) and P is the rated motor power (kW).

In considering the weight of lead-acid batteries required to achieve specific energy capacities, another problem is introduced. The capacity of a particular battery system varies with the rate at which it is discharged (with higher discharge rates resulting in lowered capacity, and vice versa). Accordingly, battery capacity is normally designated at a particular discharge rate (the rate corresponding to discharge in 5 hours is frequently, although by no means universally, used for this purpose). Of the nine sets of data on battery weights in Table D.1, only six actually related to a 5-hour discharge rate. However, the remainder were converted to this rate by using a standard table of capacity versus discharge rate for lead-acid traction batteries(1). The results are plotted on Figure D.5, together with two regression lines. One of these relates to all nine batteries considered, while the second relates to a limited set of data for batteries below 30 kWh capacity. The latter is considered to be more appropriate for lead-acid batteries of the types likely to be fitted to electric cars, and was obtained by eliminating cases 8, 9 and 13 in Table D.1. The resulting regression line is represented by the following expression:

$$W_B = 0.04740 + 0.02949\ C \qquad (D.4)$$

where W_B is the battery weight (tonnes) and C is the battery capacity (kWh) at a 5-hour discharge rate.

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(1) The Electric Industrial Truck, Australian Lead Development Association, August 1972.

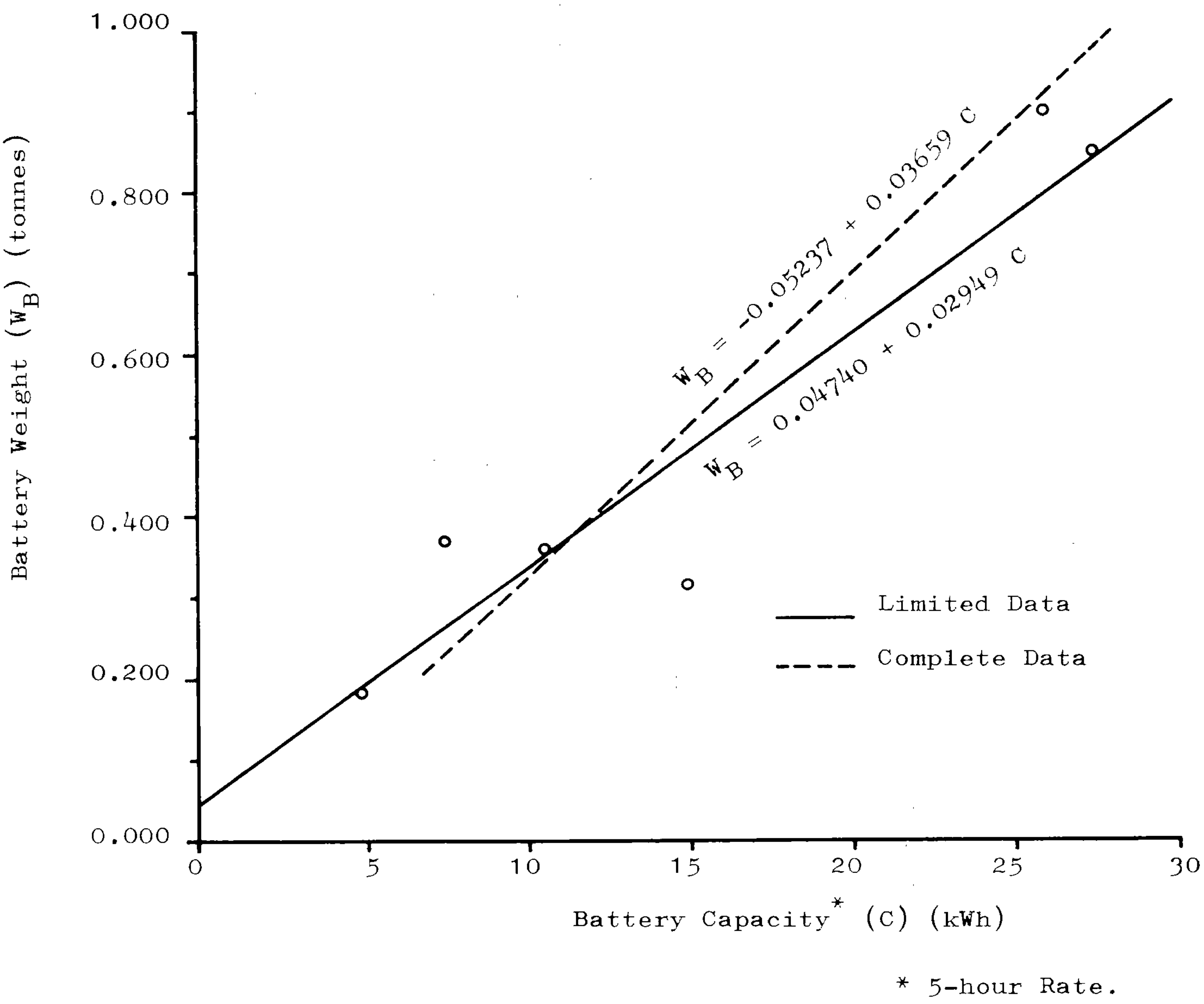

FIGURE D.5 - BATTERY WEIGHT vs CAPACITY

At this stage, it is possible to estimate the weight of an electric vehicle of given size, power and battery capacity. The first step is to consider the component weight distribution for conventional cars (Figure D.1) and to determine the changes in this distribution for an electric car of comparable size. This procedure is carried out in Table D.2, with W the weight of a conventional car of a particular size, and W' the weight of an electric vehicle of comparable size. It will be noted that glass and trim components have been allocated the same actual weights as in comparable conventional cars, since it is considered that these relate to vehicle size, not weight. On the other hand, structural components are considered as fractions of the total electric vehicle weight, since they are clearly dependent on this in their ability to support loads and perform similar functions.

If the weights of motors, control equipment and batteries are now included, the total weight of an electric vehicle of given parameters may now be estimated in the following way:

$$W' = 0.510\ W' + 0.172\ W + W_M + W_C + W_B \qquad (D.5)$$

$$\text{or } W' = 0.351\ W + 2.041\ (W_M + W_C + W_B) \qquad (D.6)$$

If the values derived for W, W_M, W_C and W_B in equations (D.1) to (D.4) are substituted in equation (D.6), the following expression for the total weight of an electric vehicle is obtained:

TABLE D.2 - CHANGES TO COMPONENT WEIGHT DISTRIBUTION

Components	Weight in conventional car	Factors in alteration	Weight in electric car
Body structure	0.330W	Improved distribution of component weights, lower overhead weights (doors,etc.)	0.300W'
Interior trim and decoration	0.140W		0.140W
Glass components	0.032W		0.032W
Wheels, tyres and brakes	0.095W	Regenerative braking and improved weight distribution	0.090W'
Suspension and steering	0.076W	Improved weight distribution	0.070W'
Engine and ancillaries	0.200W	Eliminated	-
Drive train system	0.083W	Reduced complexity, elimination of sections	0.050W'
Fuel tank	0.044W	Eliminated	-

NOTE : W is the weight of a conventional car;
W' is the weight of an electric car of equivalent size.

$$W' = a_0 + a_1 P + a_2 C + a_3 \exp(a_4 + a_5 L) + a_6 \exp(a_7 + a_8 \ln P) \qquad (D.7)$$

where $a_0 = 0.17700$

$a_1 = 0.00433$

$a_2 = 0.06019$

$a_3 = 0.35100$

$a_4 = -2.38737$

$a_5 = 0.56338$

$a_6 = 2.04100$

$a_7 = -4.54894$

$a_8 = 0.80097$

W' is expressed in tonnes,

P is expressed in kW,

C is expressed in kWh, and

L is expressed in metres.

Values of electric vehicle weight as a function of length, estimated on the basis of equation (D.7), are shown for various values of power and battery capacity in Figure D.6.

FRONTAL AREA

The presented frontal area of an automobile is clearly dependent on its styling and shape. In general, the frontal area may be expressed in the following terms:

$$A = c\,w\,h \qquad (D.8)$$

where A is the frontal area,

c is a factor depending on the cross-sectional shape of the vehicle,

w is the overall width, and

h is the overall height.

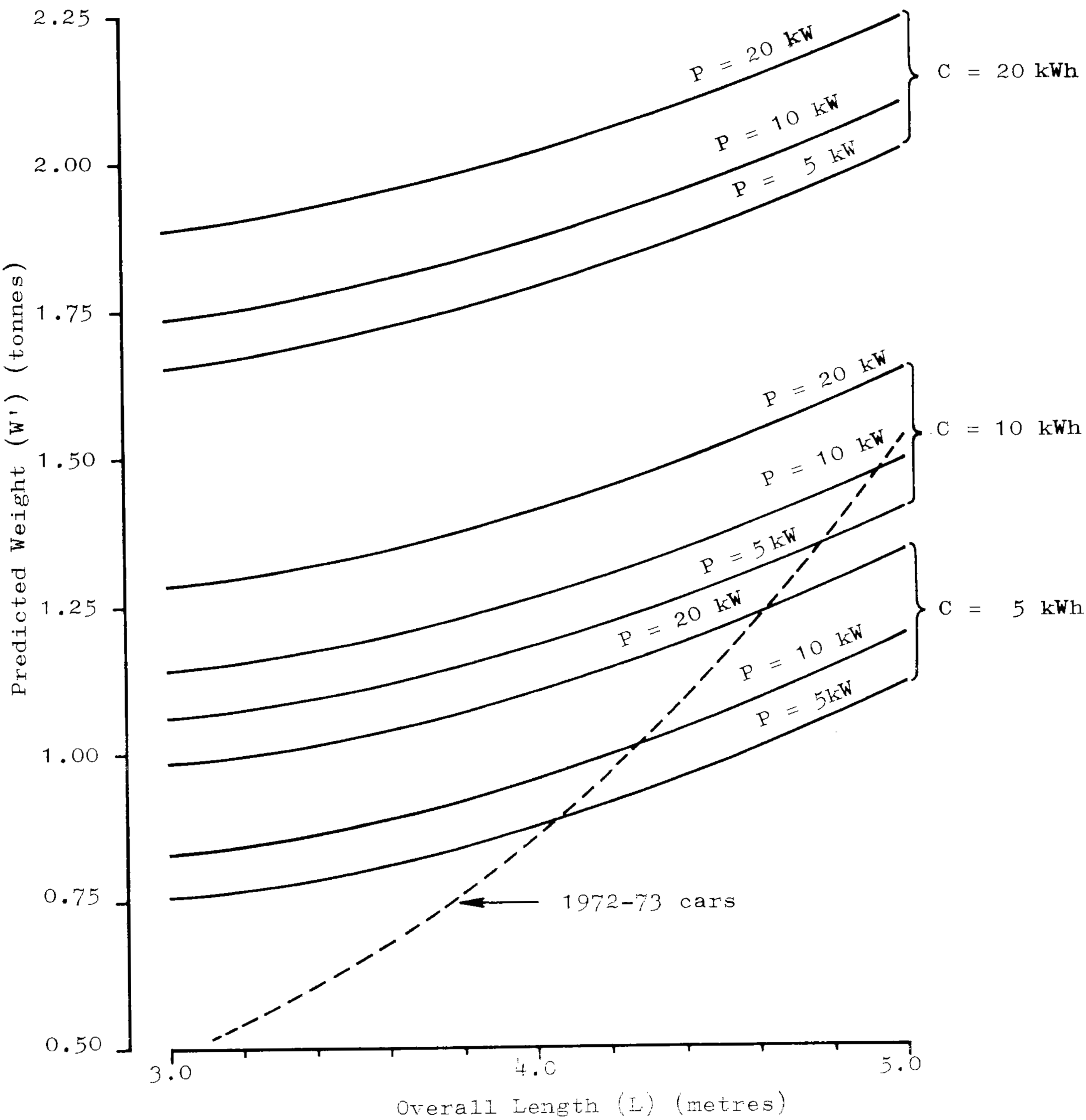

FIGURE D.6 - PREDICTED WEIGHT OF ELECTRIC CARS

The widths and heights of 1972-73 automobiles as functions of length are shown in Figures D.7 and D.8, respectively, together with the associated regression lines. This information may be used to estimate the proportions of potential electric vehicles, assuming that these vehicles will follow the styling characteristics of present automobile shapes. Limited examination of the shapes of current automobiles indicated that 0.90 was an appropriate value for c. This information was then amalgamated to provide the following predictive expression for frontal area:

$$A = 0.15562 + 0.41050\ L + 0.00784\ L^2 \qquad (D.9)$$

where A is expressed in m^2 and
L is expressed in metres.

Variation of frontal area with vehicle length, according to equation (D.9), is shown in Figure D.9. From the shape of the curve, it is obvious that the second-order term in equation (D.9) may be neglected.

POWER-SPEED VARIATION

Variation of available power with speed is very closely allied to motor design, and therefore will vary significantly from case to case. The most favoured configuration for current traction motors is the series-wound system, in which the motor field is wired in series with the armature. This type of motor has an essentially flat power-speed characteristic, with a slight rise at middle-range speeds. Specific electric vehicles considered in this report use such a power-speed variation as a reasonable representation of likely characteristics.

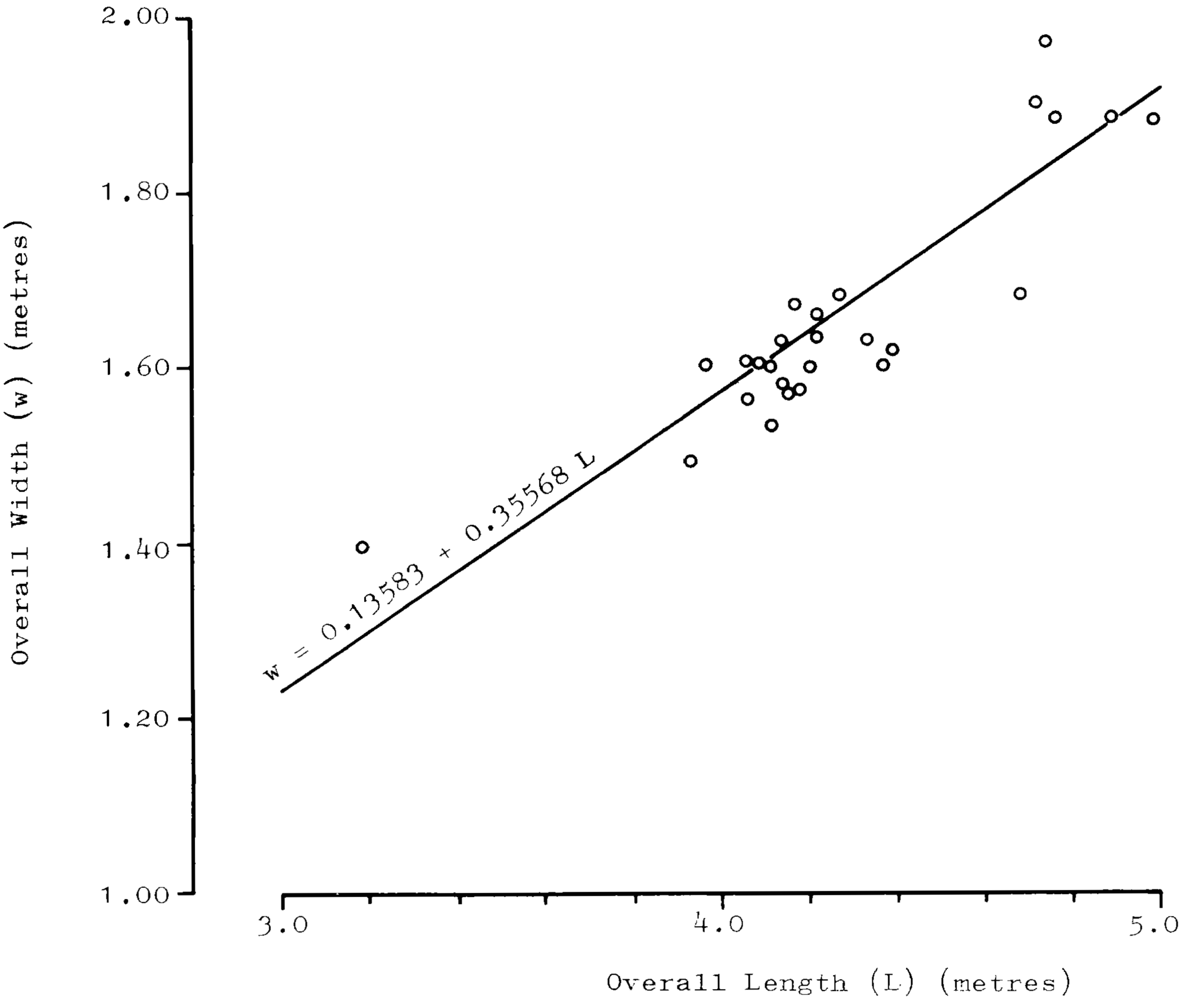

FIGURE D.7 - WIDTH vs LENGTH FOR 1972-73 CARS

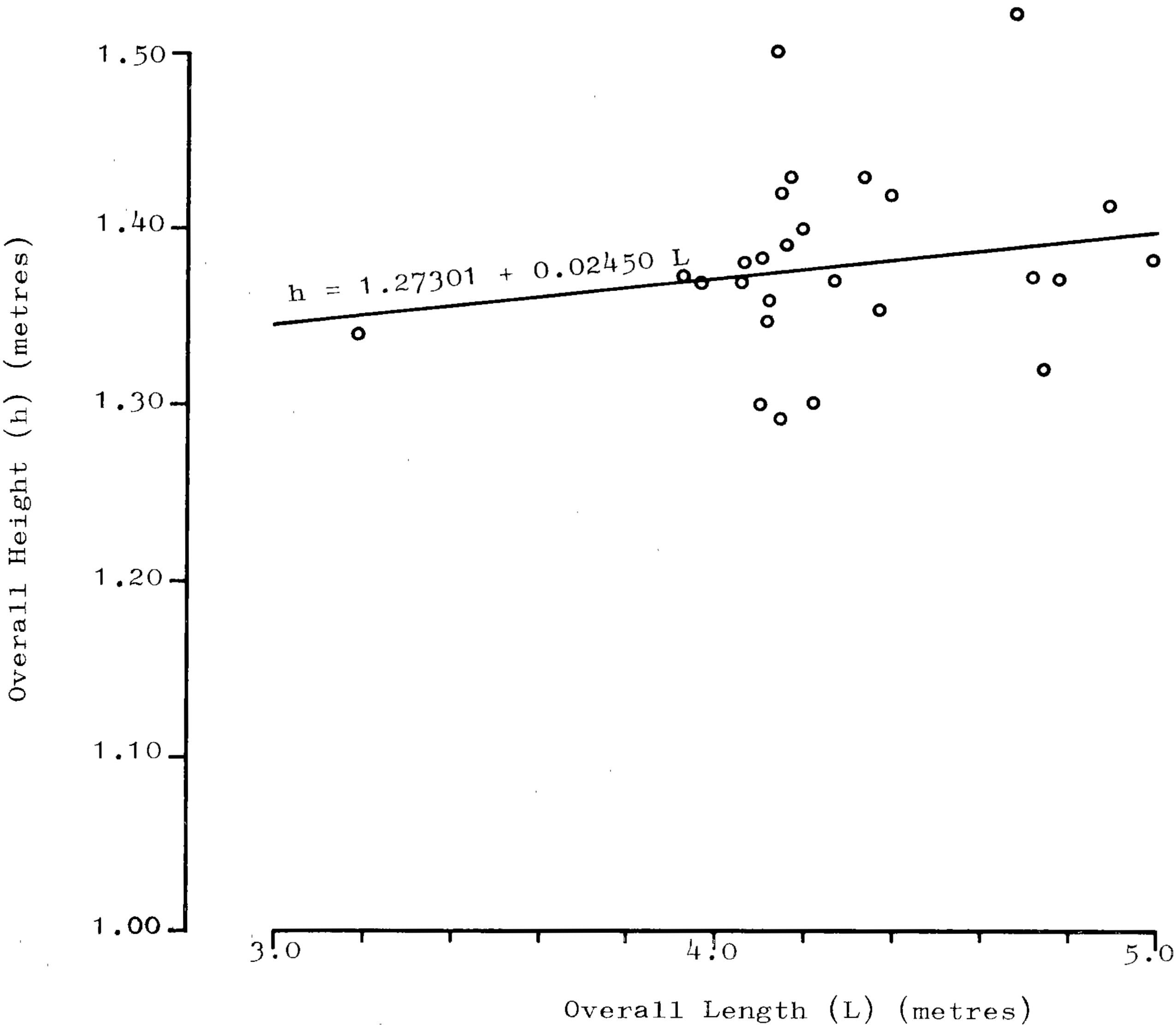

FIGURE D.8 - HEIGHT vs LENGTH FOR 1972-73 CARS

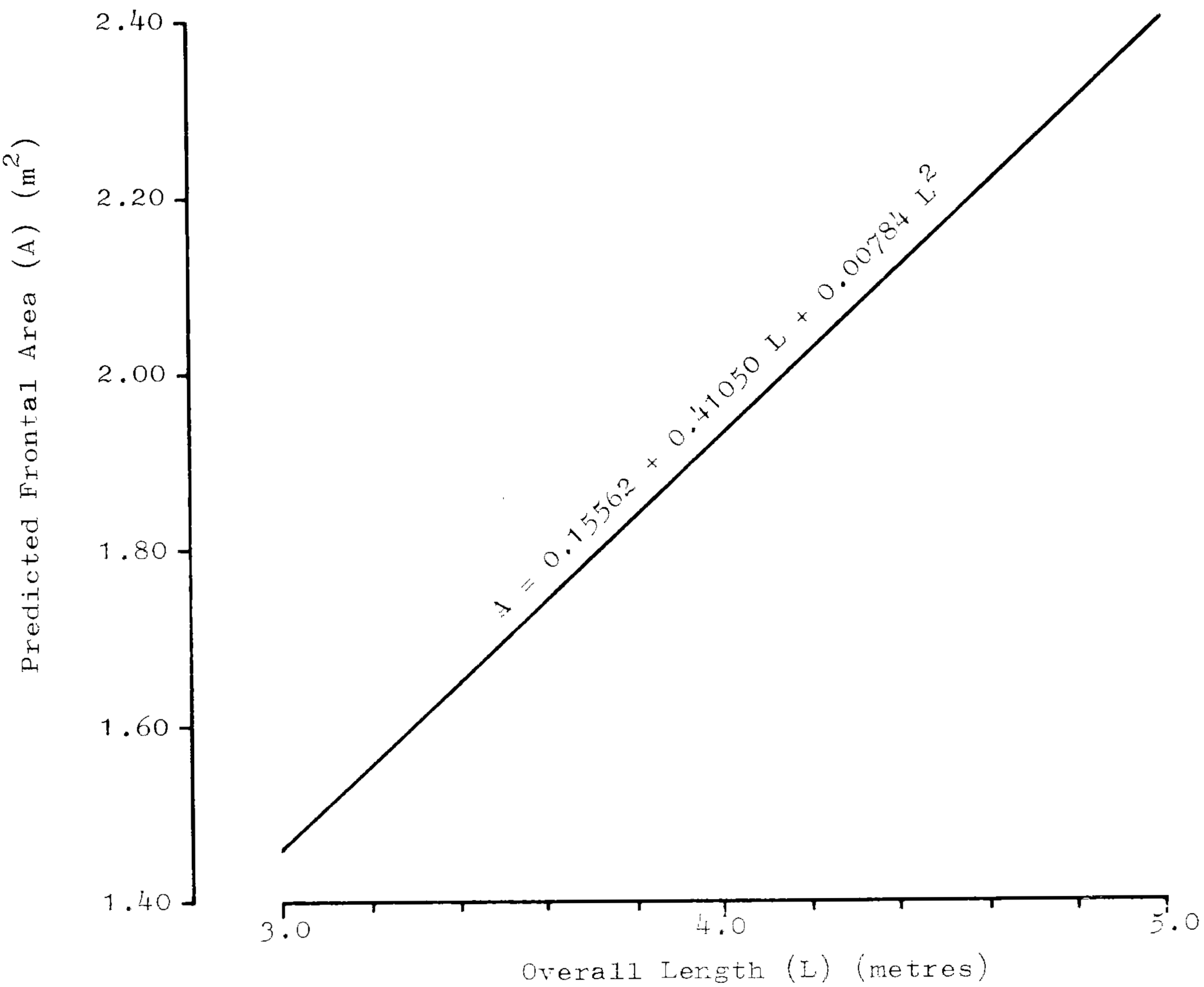

FIGURE D.9 - PREDICTED VEHICLE FRONTAL AREA

A further feature of power variation is that advanced control systems tend to cloud the distinction between classical motor types. In effect, the motors used are stepping devices only, and the characteristics of the system are determined by the nature and characteristics of the control system. Use of such control systems can result in a traction system which can be particularly well-tailored to the individual requirements of the vehicle.

CONSTANT-FORCE LIMITING SPEED

For motor systems with essentially flat power-speed characteristics, the force available to drive the vehicle is, roughly, inversely proportional to vehicle speed. Thus, the theoretical driving force available at very low speeds approaches infinity. However, the driving force is limited at low speeds by the electric current which the motor can sustain. Although the physical reasons for this limitation and the means by which it may be overcome are complex, the apparent nature of the phenomenon is explained by considering a constant-force regime, which prevails up to a certain limiting speed. In effect, this method constrains the vehicle to a largely constant acceleration capability at low speeds (modified slightly by air drag and rolling resistance variations).

While various values of the limiting speed for the constant-force regime are used or implied in the literature, the actual value used is largely a matter of design, and 10 km/h is regarded as an acceptable estimate in this Report.

POWER OVERLOAD FACTOR

The values of motor power used in predicting the weight of battery vehicles were based on rated continuous power levels for specific motors. While such values of motor power are good descriptors of the weight of both motors and control systems, they do not reflect the situation encountered when motors are used to propel electric vehicles. The continuous rating system is more appropriate to industrial applications than to automotive purposes, since motors used in industrial environments may be required to operate continuously for months (or even years). In automotive applications, full power is unlikely to be sustained for more than an hour at a time (this is particularly so for battery vehicles, in which battery capacity would effectively inhibit attempts at sustaining high power levels). Accordingly, motors used in automotive applications may be operated for comparatively short times at power levels considerably in excess of their rated power outputs. Thus, twice the rated power (or even higher) may be available for acceleration, while the motor may be operated at perhaps 50 per cent above its rated output for times of the order of one hour.

These characteristics are incorporated into the power overload factor, which is applied to the rated motor power at particular speeds to obtain the power actually available. The value of this factor is not well documented, and changes according to driving conditions (cruise, acceleration, etc.) as noted above. A figure of 1.75 has been used in this analysis as a reasonable representation of the overload which could be achieved, without damage, under a wide range of driving conditions.

CONVERSION EFFICIENCY

In this case, the conversion efficiency considered is effectively a system efficiency (i.e. the fraction of power supplied by the battery which is actually available at the wheels). This overall efficiency is comprised of the individual efficiencies of several vehicle components, but predominantly of the control system, motor and transmission. While each of these three components may be designed to be highly (perhaps 80-90 per cent) efficient, the resultant overall efficiency is the product of the efficiencies of all three, and is not nearly so impressive. While several sources of information on individual component efficiencies are available, similar information on total system efficiency is less prevalent. Under present conditions, it appears that overall efficiencies in the region of 60 per cent should be attainable without undue effort. Accordingly this figure is used as representing possible near-term design capabilities.

Variation of efficiency with speed is not specifically considered, since available information on practical values of efficiency is so limited that postulation of a variation would be extremely suspect.

AERODYNAMIC DRAG COEFFICIENT

The major problem is assessing values of aerodynamic drag coefficients for cars is that, until very recently, considerations of aerodynamic efficiency have been largely suppressed by styling requirements (except, perhaps, for vehicles with unusually high speed capabilities). The result is that the drag coefficient values available cover a surprisingly wide range. There is an a priori case for postulating that the potential drag coefficient for large cars is somewhat larger than that for small ones (on the basis that skin friction is an important consideration at the speeds involved), but even this possibility is not universally borne out in practice. However, with the importance of reduced aerodynamic drag in improving battery vehicle performance, it is expected that any serious attempts to design such vehicles would take due account of the importance of reductions in this parameter.

The order of magnitude of automobile drag coefficients is relatively simple to establish. Several sources of such information were consulted, although in some cases the values presented were necessarily converted from empirical formulae to provide drag coefficients compatible with the drag expression used in Appendix I. A standard engineering handbook(1) indicated that values might range from 0.34 (for a moderately streamlined vehicle) to 0.52 (for a more upright and angular vehicle). There was evidence of a slight decrease in drag coefficient with increases of speed within the normal car speed range (particularly for highly streamlined shapes). On the other hand, a value of 0.97 was indicated for an experimental vehicle without doors or side windows(2). Vansant(3) indicated a value of 0.47 (after appropriate conversion), while the drag expressions used by Ayres and McKenna(4) suggested values of 0.43 for a Volkswagen car, and 0.63 for large US cars. A value of 0.45 has been used in estimating the performance of small 'city cars'(5).

On the basis of these figures, it is suggested that basic values of 0.45 and 0.55 would be fairly easily attainable for small (3-metre) and large (5-metre) battery vehicles, respectively. Since such drag coefficients would be produced by relatively streamlined shapes, there is likely to be some decrease in drag coefficient as speed increases. The estimating equation for the aerodynamic drag coefficient is, therefore, as follows:

$$C_D = 0.30000 + 0.05000L - 0.00025V \qquad (D.10)$$

where C_D is the aerodynamic drag coefficient,

L is the vehicle length (metres), and

V is the vehicle speed (km/h).

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(1) T. Baumeister (Editor), Marks' Standard Handbook for Mechanical Engineers, 1967.

(2) Flinders University Research Vehicle, op. cit.

(3) G.A. Vansant, 'The Mechanical Design of Electric Automobiles', presented at US Dept of Health, Education and Welfare Symposium on Power Systems for Electric Vehicles, April 1967.

(4) Ayres and McKenna, Alternatives to the Internal Combustion Engine, op. cit.

(5) Cars for Cities, op. cit.

Values derived from equation (D.10) are plotted on Figure D.10.

ROLLING RESISTANCE COEFFICIENT

Rolling resistance coefficients express the resistance to vehicle motion caused by tyre motion on the road surface. The primary information on this topic was derived from Ayres and McKenna[1], and the appropriate values of rolling resistance coefficient as a function of speed (for different tyre materials) are shown in Figure D.11. It should be noted that rolling resistance is a function of tyre inflation pressure, and that reductions of up to 30 per cent may be expected by suitable selection of tyre pressures. However, this possibility bears on suspension design and other features of the vehicle, and the rolling resistance coefficient used in this paper is representative of the lower limit for rayon tyres. Values of the rolling resistance coefficient for different values of speed are given in the following table:

Vehicle speed (km/h)	Rolling Resistance Coefficient (N/kg)
0	0.109
10	0.110
20	0.112
30	0.115
40	0.118
50	0.122
60	0.126
70	0.131
80	0.137
90	0.142
100	0.149
110	0.158
120	0.168

(1) Ayres and McKenna, Alternatives to the Internal Engine , op. cit.

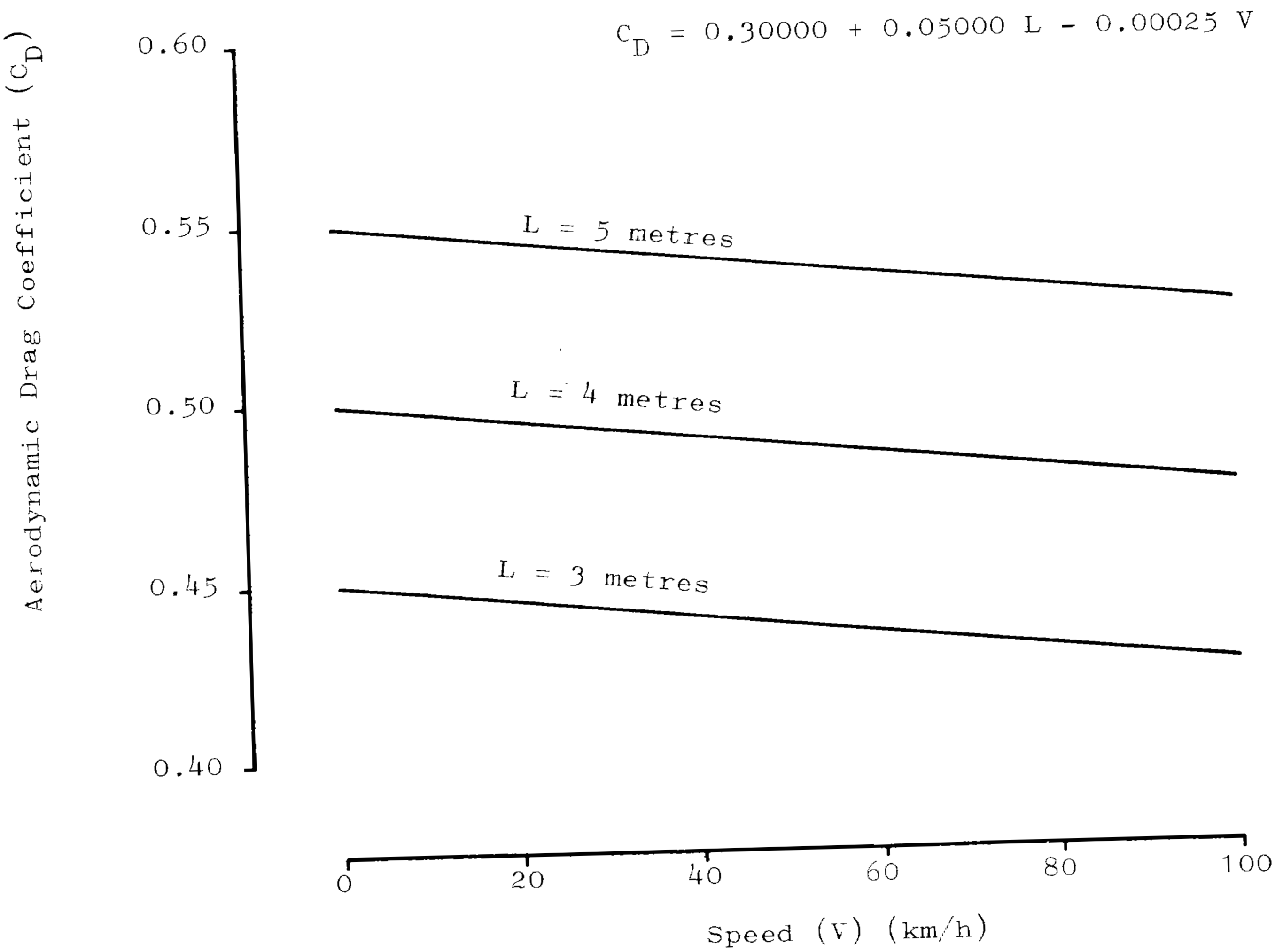
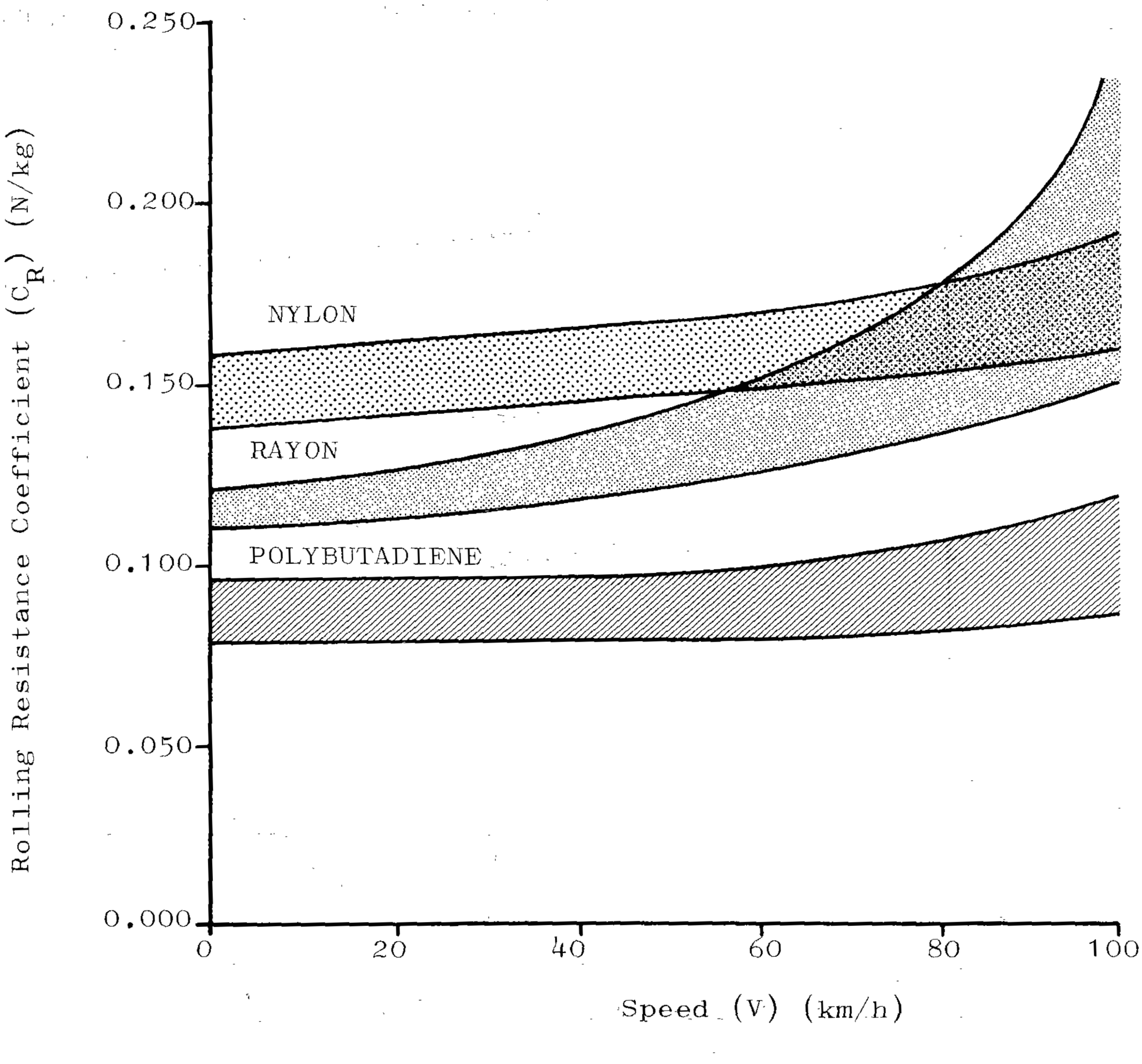


FIGURE D.10 - AERODYNAMIC DRAG COEFFICIENT



<u>FIGURE D.11 - ROLLING RESISTANCE COEFFICIENT</u>

While these values are higher than those which might be obtained by using advanced tyre materials, they are considered representative of values which should be attained in near-term potential electric vehicles.

CAPACITY-POWER VARIATION

Several sources of information on the variation of lead-acid traction battery capacity with power were examined, and one has already been cited[1]. In this particular case of parameter variation, some difficulty is involved in choosing the independent and dependent variables, since there is an interactive effect between the parameters involved. The method ultimately chosen was to estimate the variation of capacity (relative to 5-hour capacity) with the time period over which the battery is discharged. Although battery weights were estimated on the basis of a particular set of characteristics, a more detailed examination of available data was made in the case of capacity variation. Ultimately, the information presented by Douglas[2] was chosen as representative of characteristics likely to be obtained in practice. The variation provided by this information is represented by the following expression:

$$\ln r_C = -0.39808 + 0.24734 \ln t \qquad (D.11)$$

where r_C is the ratio of battery capacity the 5-hour capacity and
t is the discharge time (hours).

It should be noted that equation (D.11) is not derived by regression analysis, but is, in fact, a suitable expression which adequately fits the observed data. Selection of an appropriate expression in this way was necessary to meet the requirements of an exact fit at one point. The form of this variation is shown in Figure D.12.

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(1) The Electric Industrial Truck, op. cit.

(2) D.L. Douglas, 'Lead-Acid Batteries and Electric Vehicles', presented at US Dept of Health, Education and Welfare Symposium on Power Systems for Electric Vehicles, April 1967.

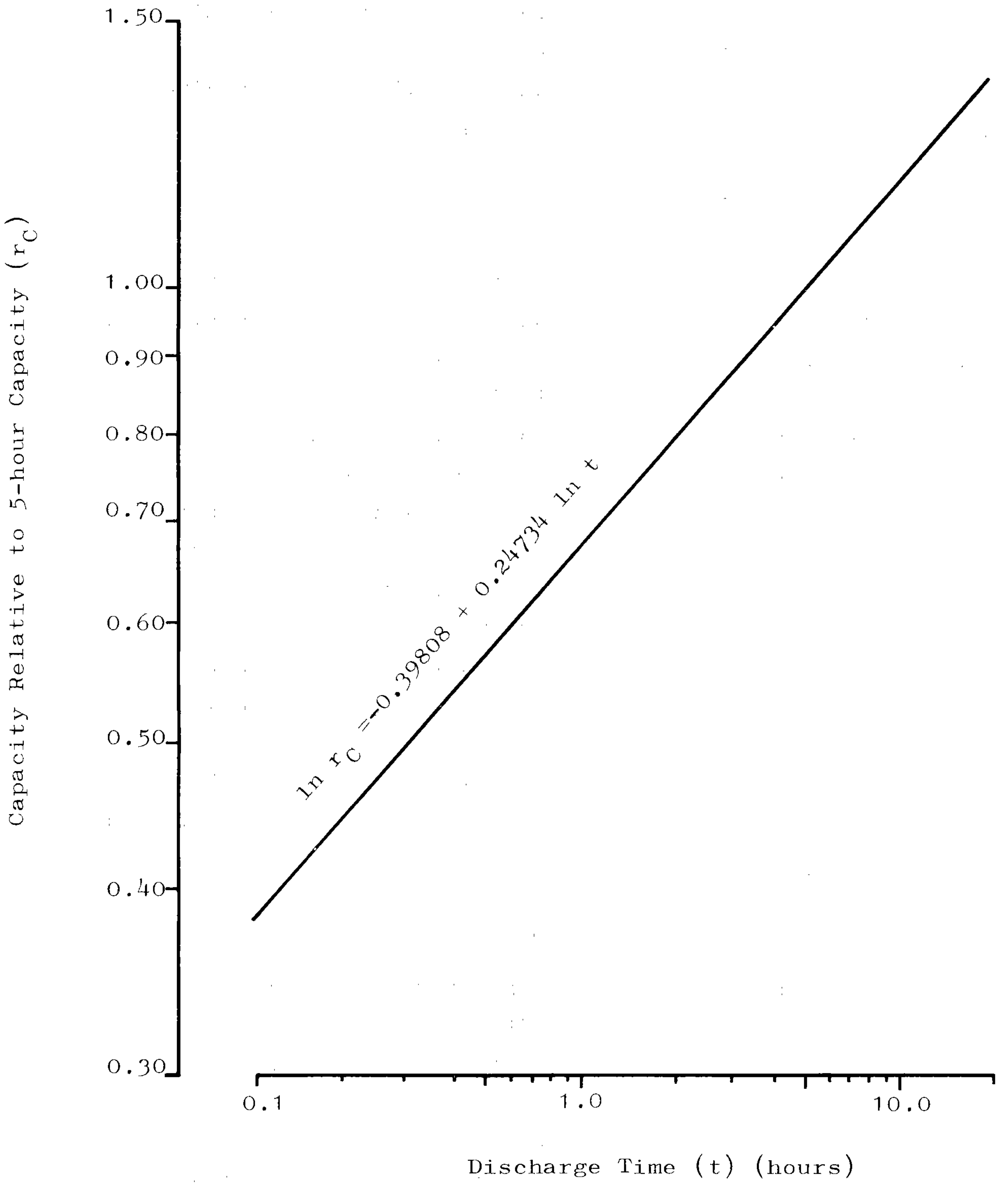

FIGURE D. 12 - LEAD-ACID BATTERY CAPACITY/POWER VARIATION

ANNEX E

PERFORMANCE ANALYSIS RESULTS

The model described in Annex A was used to obtain estimates of the likely performance of a range of electric cars. The bulk of the current Australian car market consists of cars between 3 and 5 metres in length(1), although specific low-volume sales are recorded for vehicles outside this range. Accordingly, estimates were derived for three possible electric car sizes:

- a 3-metre car, representing the smaller cars currently sold in Australia;
- a 4-metre car, which is comparable in size to most four-cylinder current models; and
- a 5-metre car, similar in size to the popular six-cylinder cars currently on the market.

The basic physical characteristics of these three cars were determined in accordance with the estimation procedures outlined in Annex D. Of necessity, a number of judgements had to be made regarding other characteristics of the cars (such as the sizes of motors and batteries), but the resultant vehicle specifications are consistent with those of a limited number of overseas experimental vehicles whose characteristics are known. On the other hand, every effort was made to ensure that the characteristics of the cars are realistic, and that they are representative of cars, powered by lead-acid batteries, which might be manufactured in considerable quantities by 1980.

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(1) A distribution of new car registrations by length, for a large sample of 1972 Australian models, is given in Figure 2.4.

The basic characteristics of the three cars are summarised in Table E.1. It is assumed that each car carries two passengers and a small amount of luggage. Maximum rated power is assumed to occur at 60 km/h in all cases, dropping to 90 per cent of the maximum value at 120 km/h. The remainder of the power-speed variation is established by setting a notional zero-speed value of 80 per cent of the maximum rated power. Conversion efficiencies, aerodynamic drag coefficients and rolling resistance coefficients are postulated on the basis of the values given in Annex D. Variations of battery capacities with power drawn from the batteries are determined from equation (D.11).

TABLE E.1 - SPECIFIC BATTERY CAR CHARACTERISTICS

	Overall car length		
	3-metre	4-metre	5-metre
Unladen weight (tonnes)	0.983	1.711	2.680
Passengers (2) and luggage (tonnes)	0.154	0.154	0.154
Total running weight (tonnes)	1.137	1.865	2.834
Overall width (metres)	1.20	1.56	1.91
Overall height (metres)	1.35	1.37	1.40
Estimated frontal area (m^2)	1.46	1.92	2.40
Nominal (5-hour) battery capacity (kWh)	7.5	15.0	25.0
Rated motor power (kW)	10	20	30
Operational altitude (metres)	0	0	0

For each car, results of the performance analysis are presented graphically in six parts:

(a) Variations of conversion efficiency, aerodynamic drag coefficient and rolling resistance coefficient with speed.

(b) Complete power-speed variation.

(c) Battery capacity-power variation.

(d) Variation of drive force, aerodynamic drag force and total retarding force with speed (for level roads).

(e) Acceleration capabilities under full power for five specified grade values (ranging from a down-slope of 1:50 to a climb of 1:10).

(f) Range-speed characteristics for the same grade values.

The results for the 3-metre car are presented in Figures E.1 to E.6, those for the 4-metre car in Figures E.7 to E.12 and the 5-metre car results in Figures E.13 to E.18.

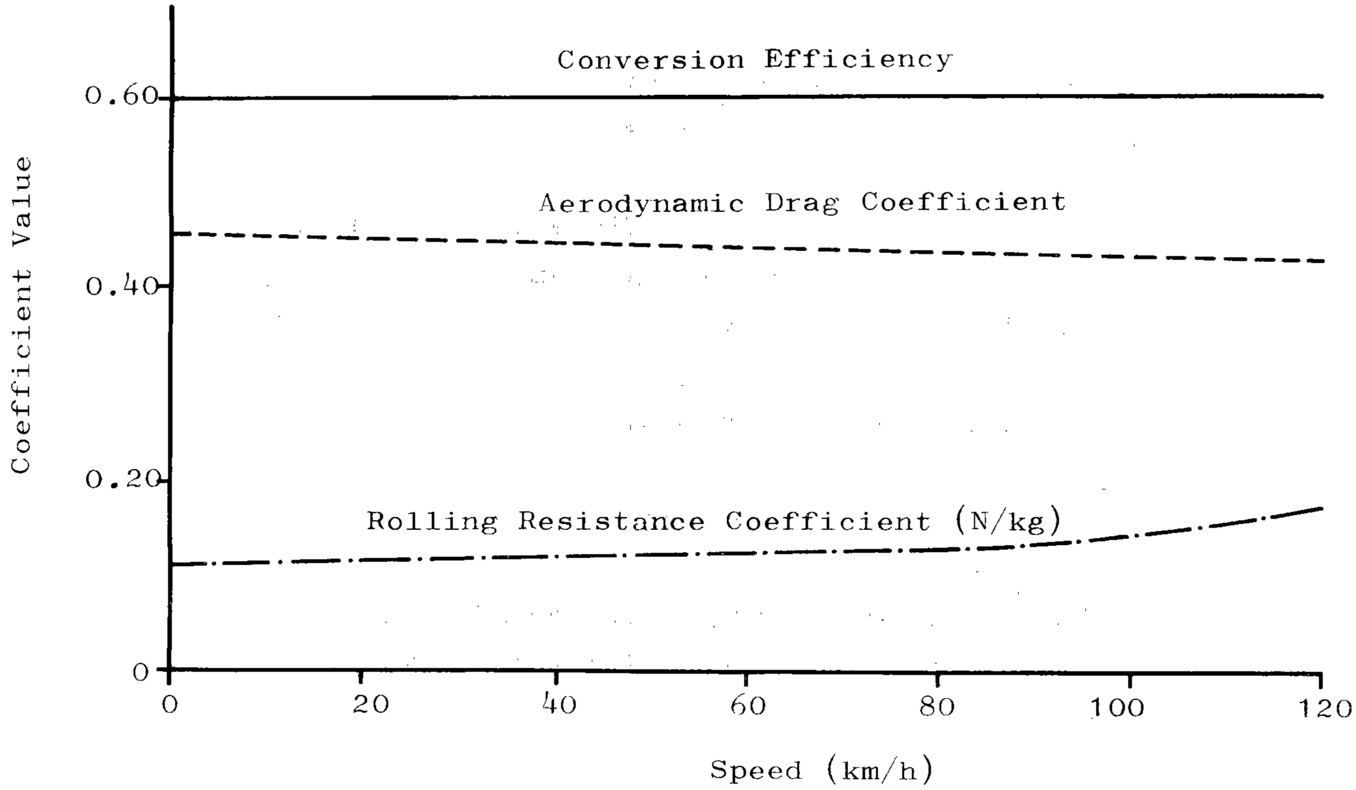

FIGURE E.1 - COEFFICIENT VARIATIONS, 3-METRE CAR

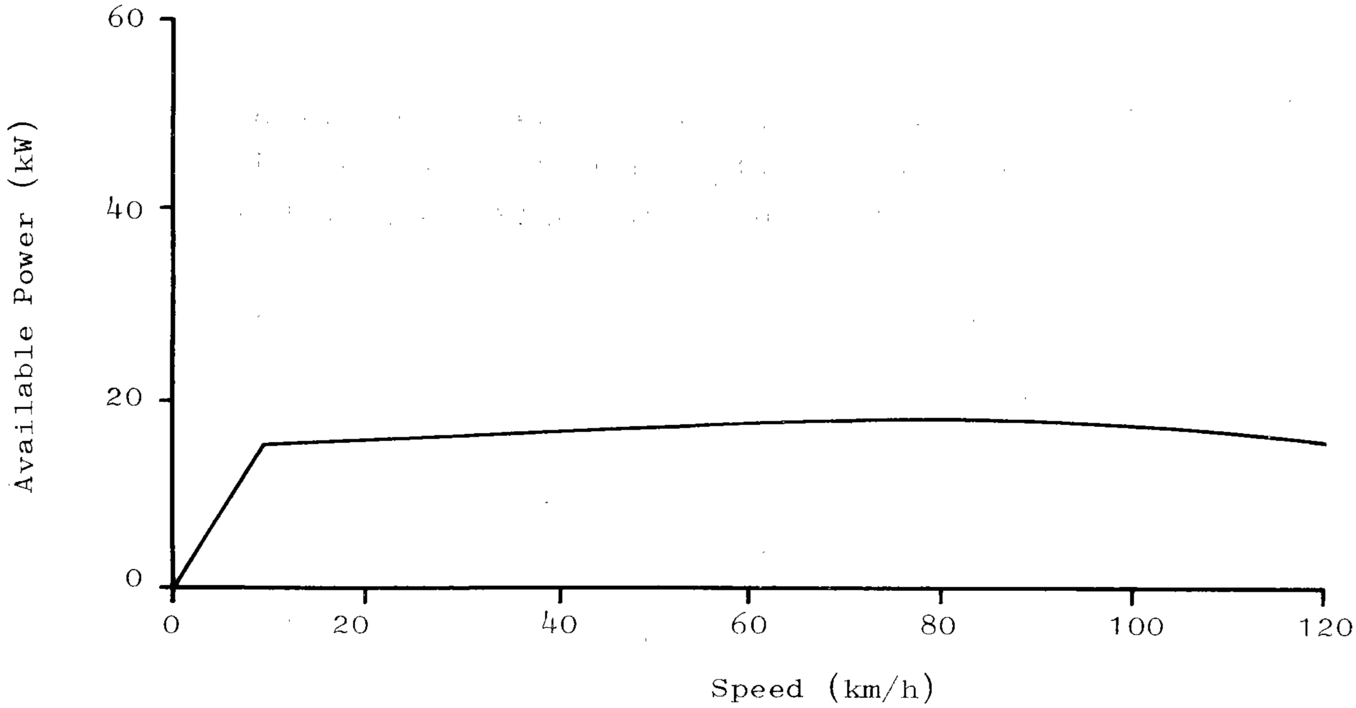

FIGURE E.2 - POWER-SPEED VARIATION, 3-METRE CAR

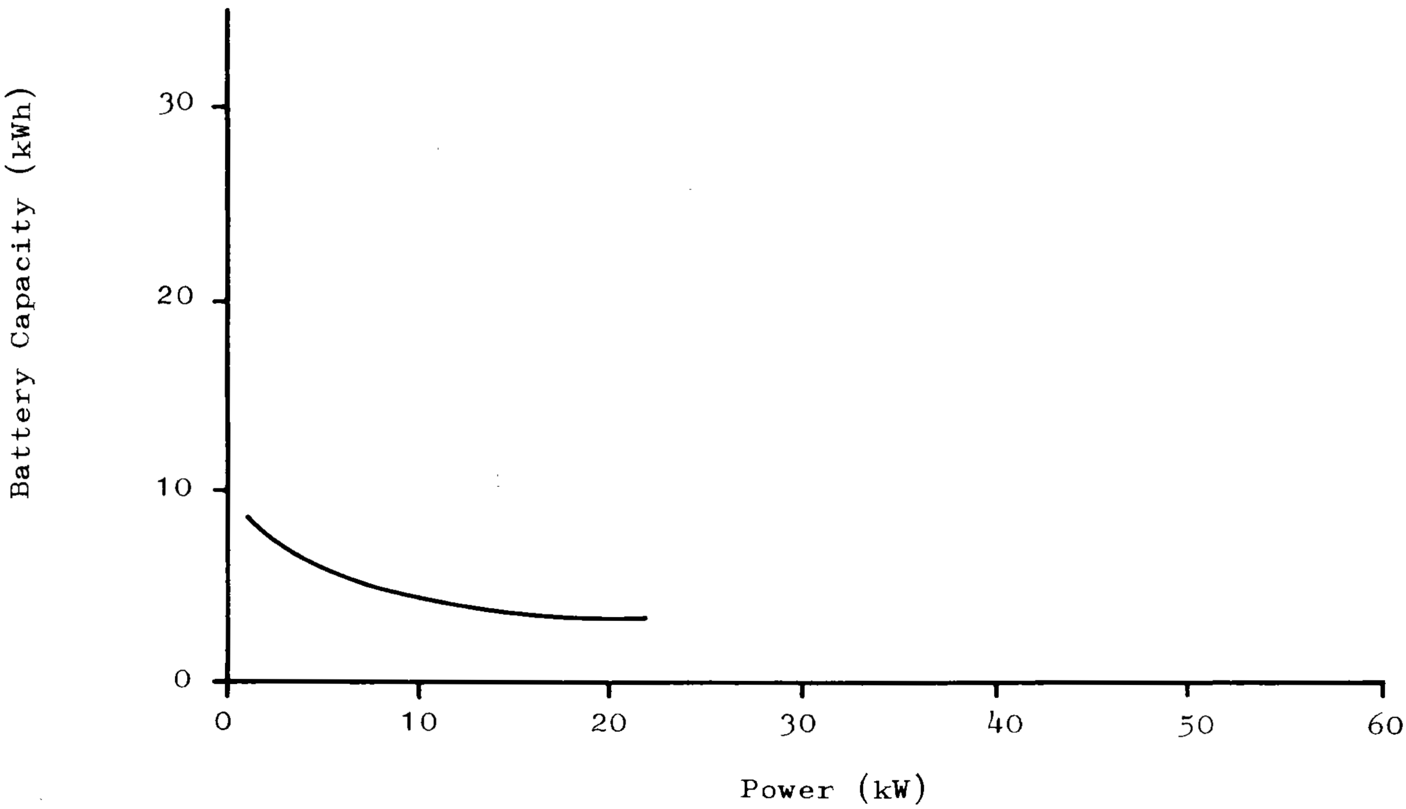

FIGURE E.3 - CAPACITY-POWER VARIATION, 3-METRE CAR

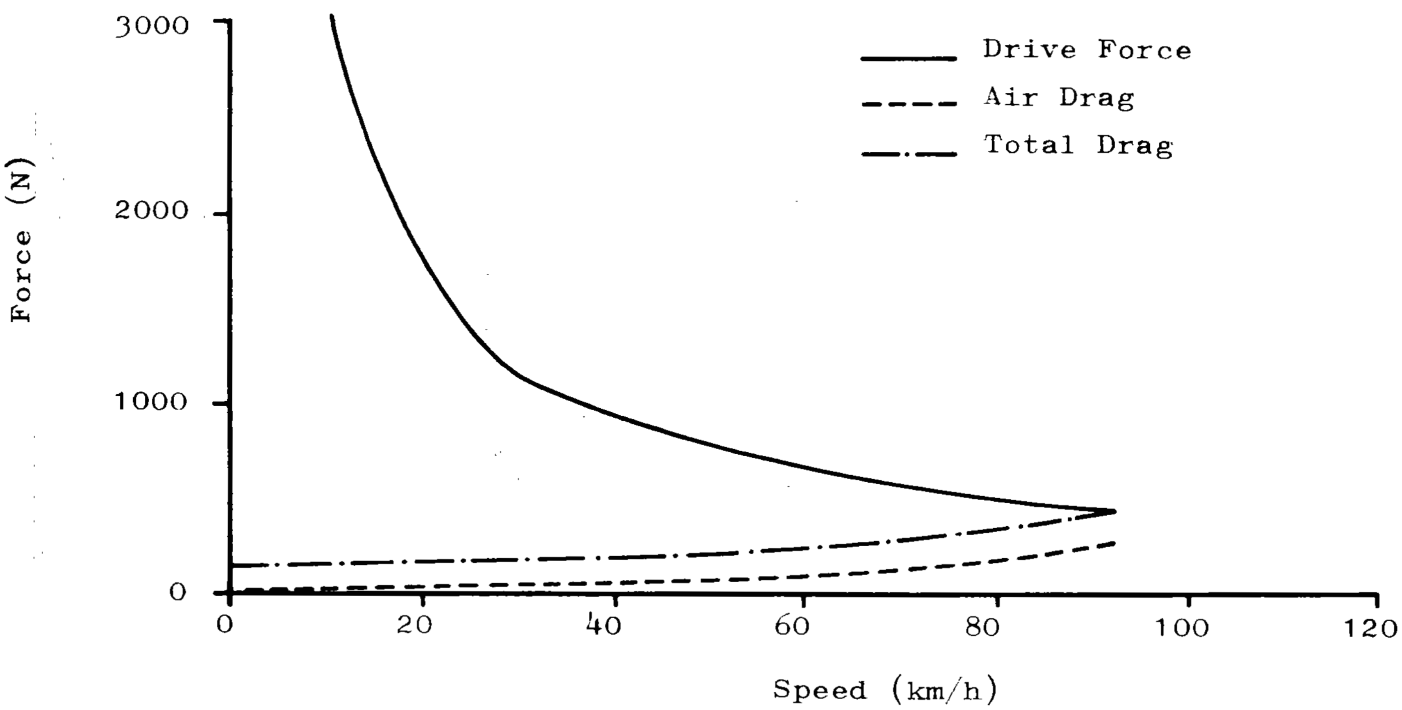

FIGURE E.4 - FORCES VARIATION, 3-METRE CAR

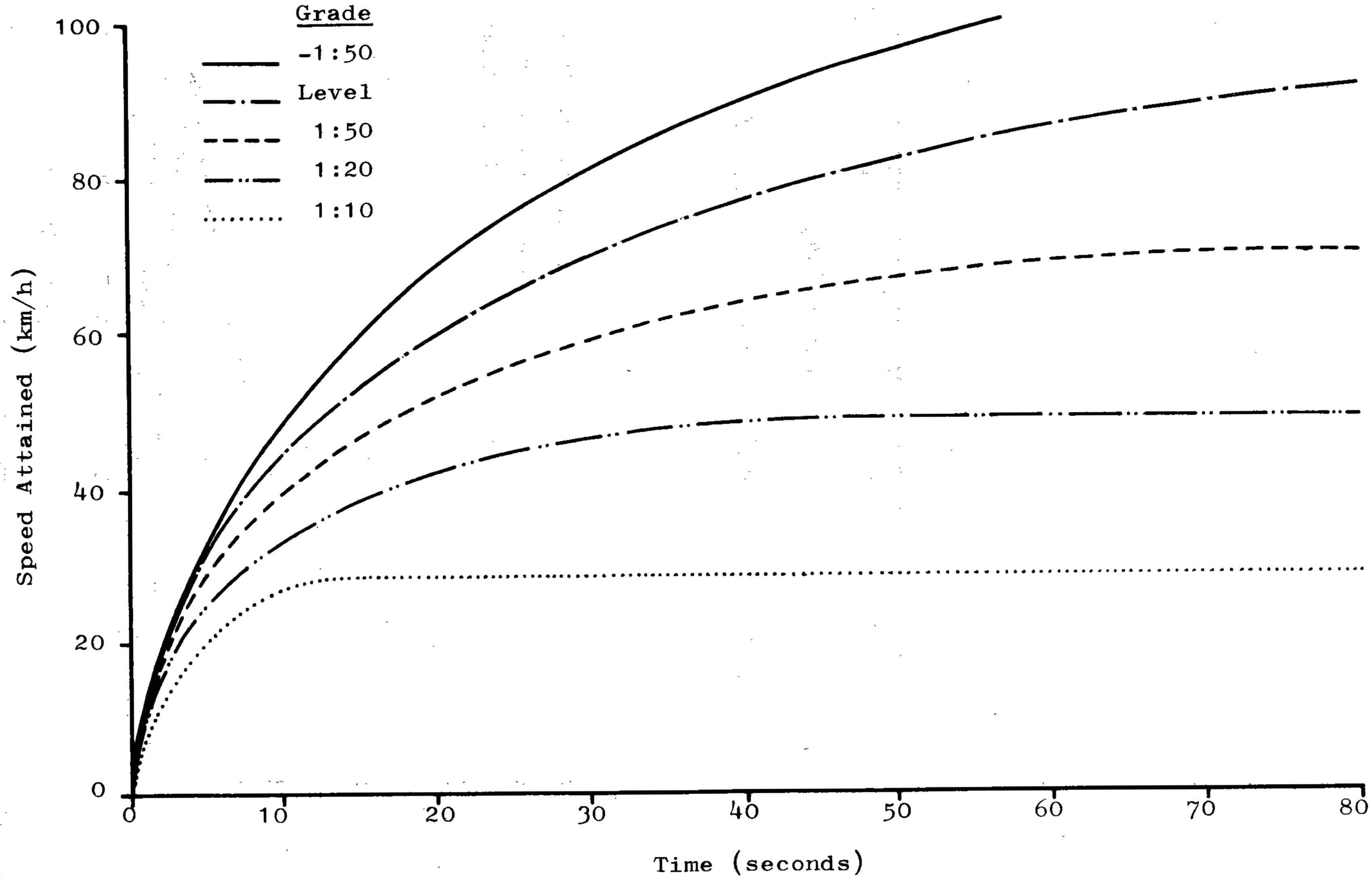

FIGURE E.5 - ACCELERATION CAPABILITIES, 3-METRE CAR

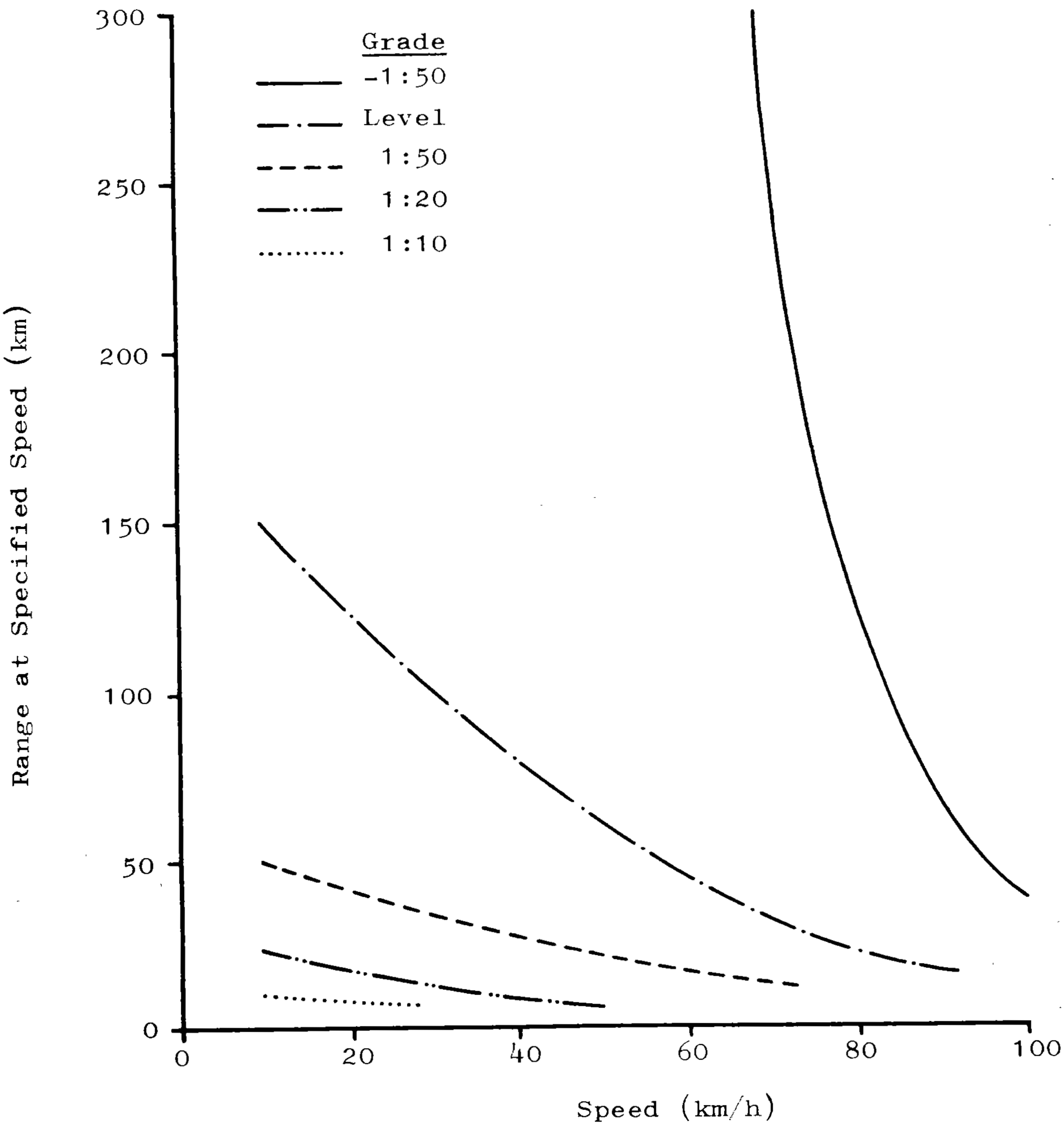

FIGURE E.6 - RANGE AT CONSTANT SPEED, 3-METRE CAR

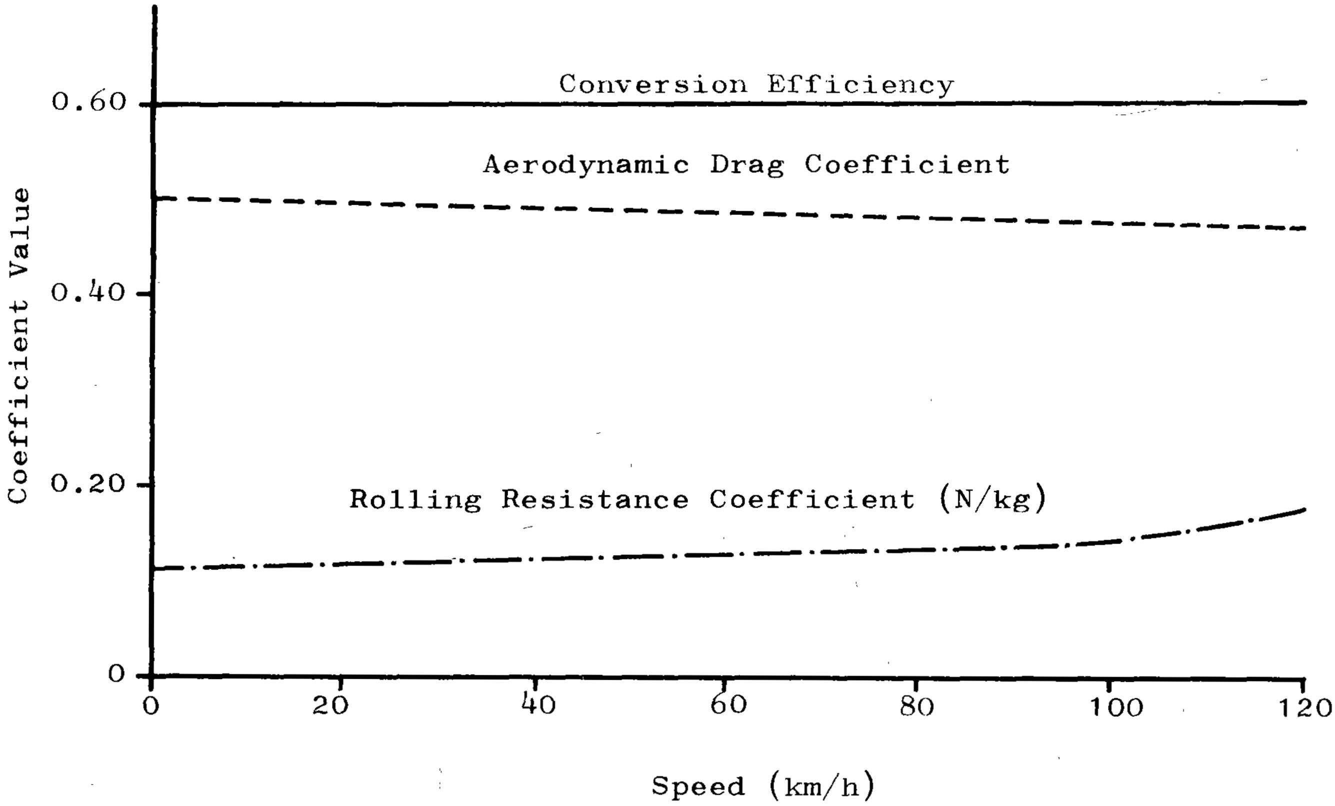

FIGURE E.7 - COEFFICIENT VARIATIONS, 4-METRE CAR

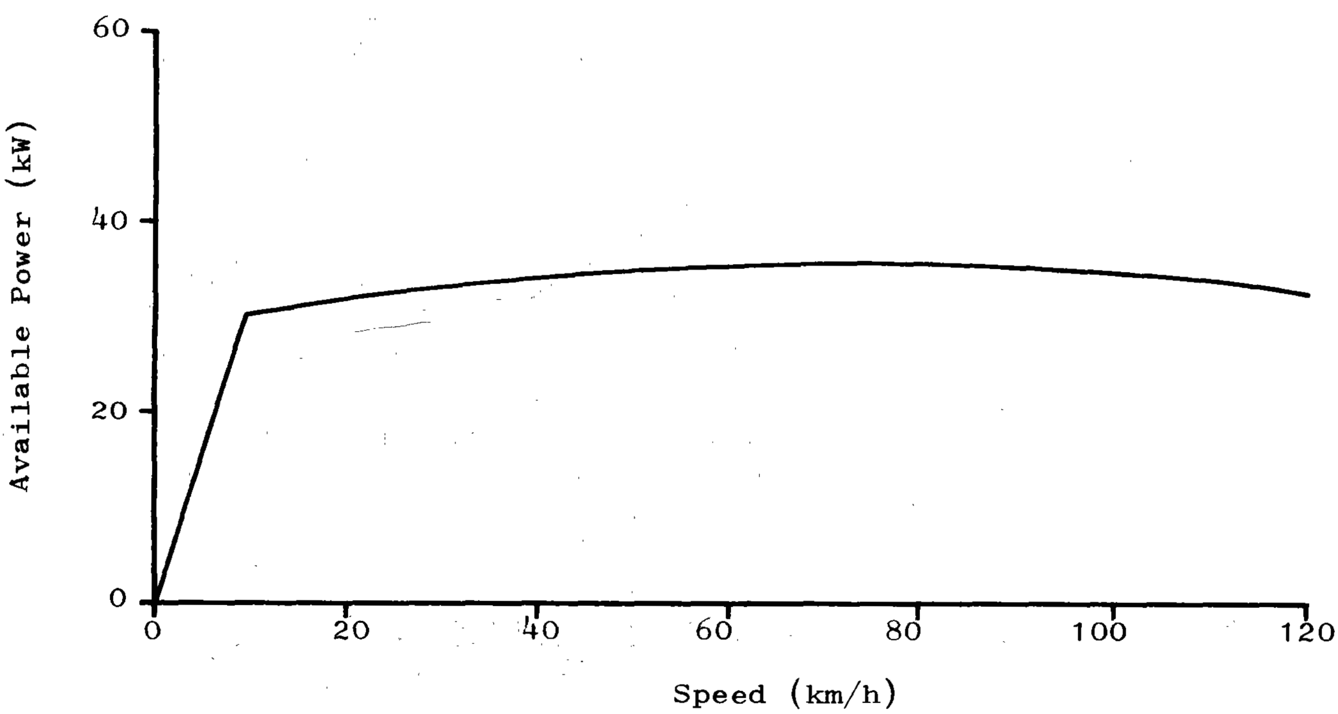

FIGURE E.8 - POWER-SPEED VARIATION, 4-METRE CAR

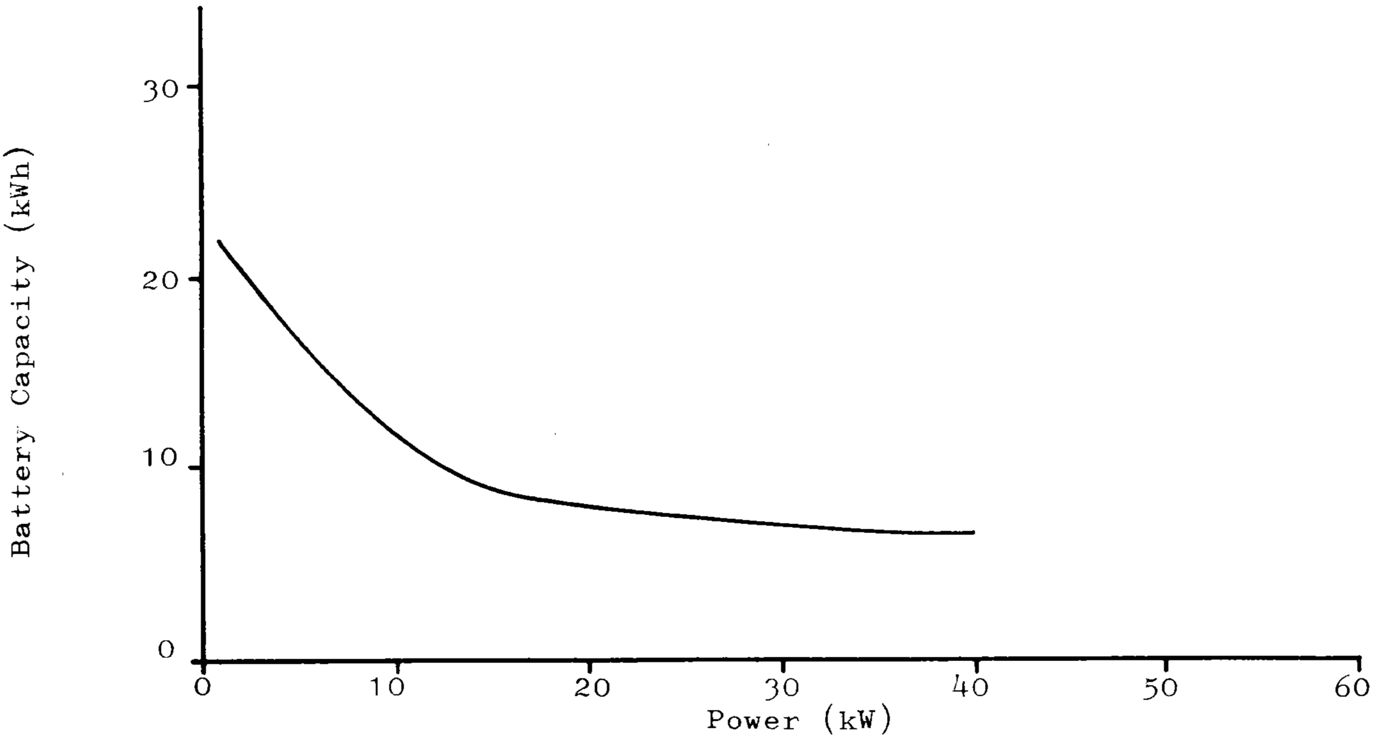

FIGURE E.9 - CAPACITY-POWER VARIATION, 4-METRE CAR

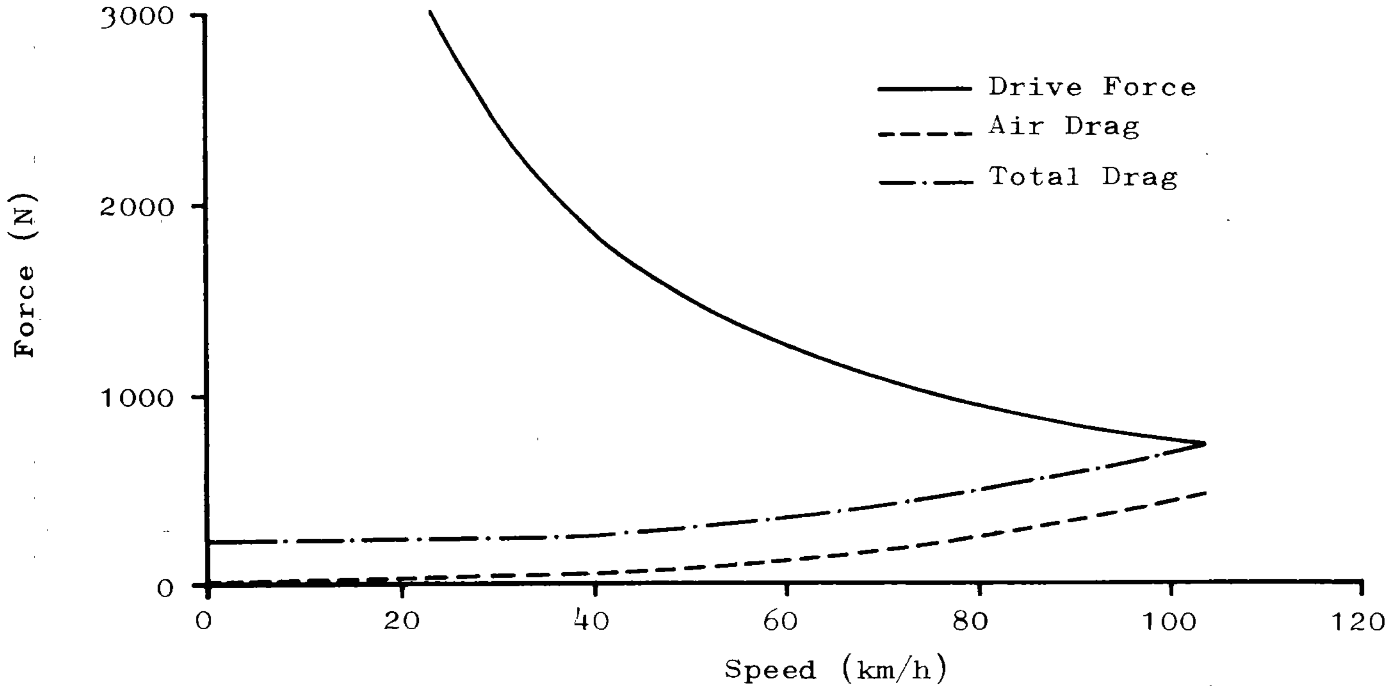

FIGURE E.10 - FORCES VARIATION, 4-METRE CAR

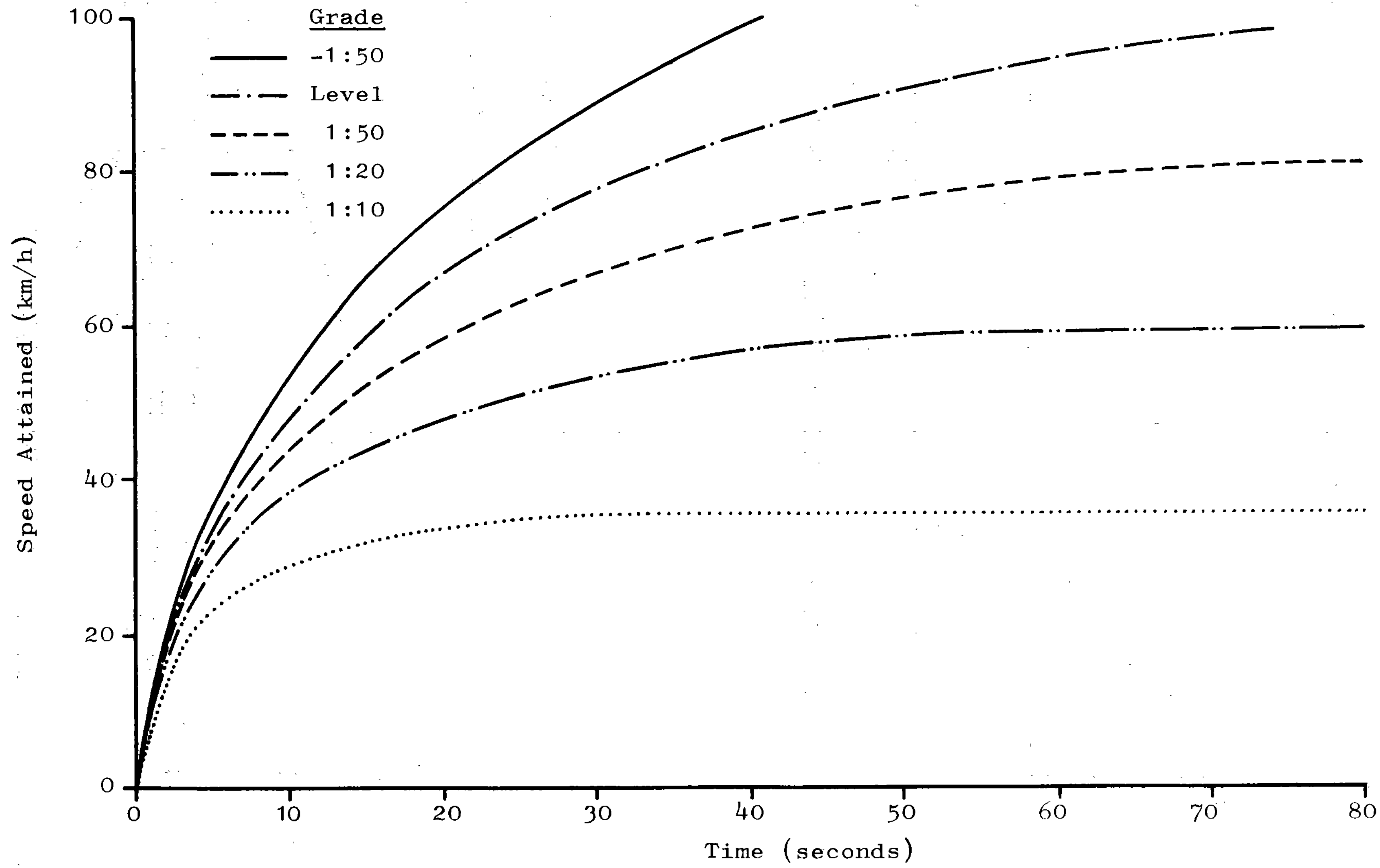

FIGURE E.11- ACCELERATION CAPABILITIES, 4-METRE CAR

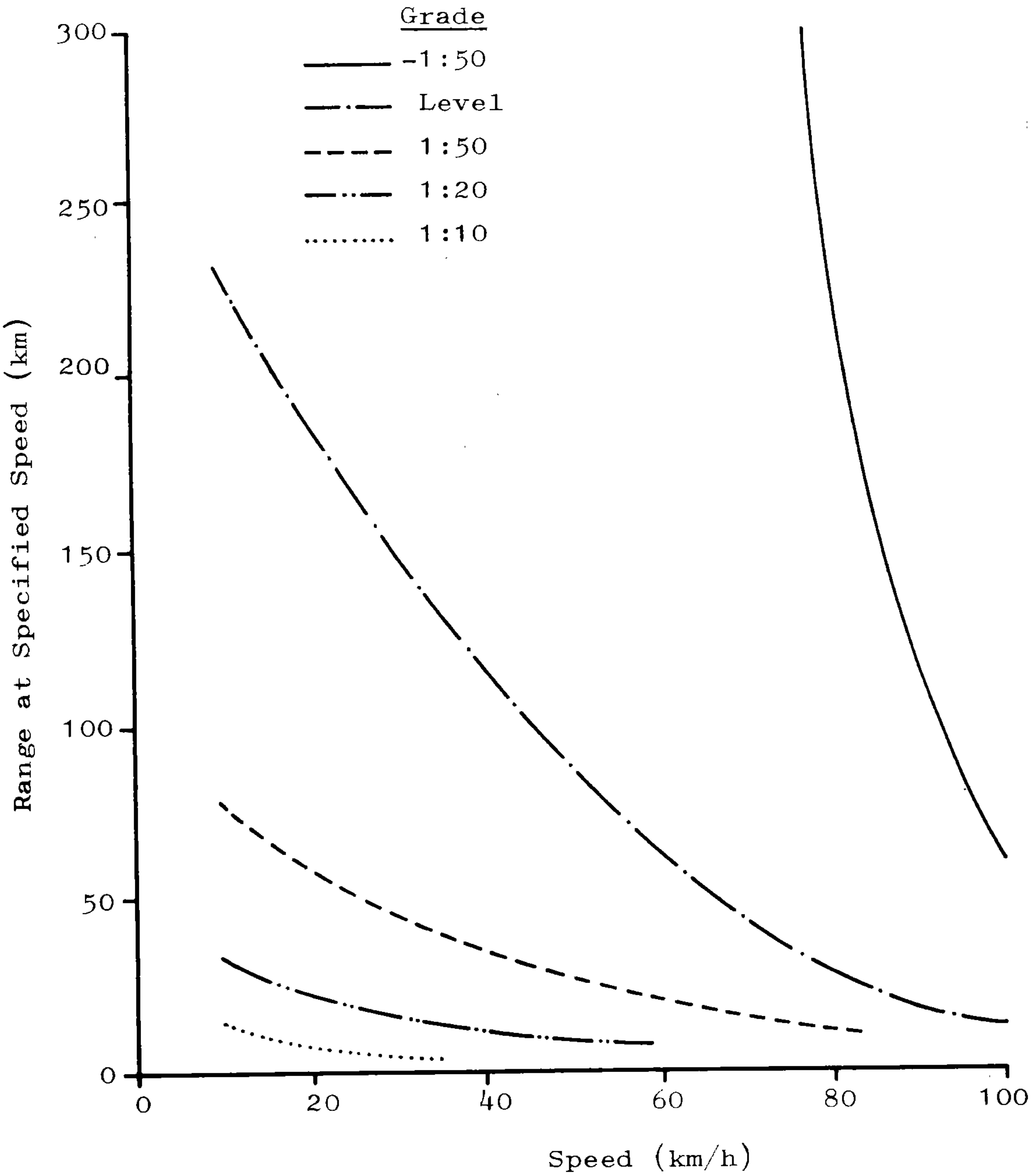

FIGURE E.12 - RANGE AT CONSTANT SPEED, 4-METRE CAR

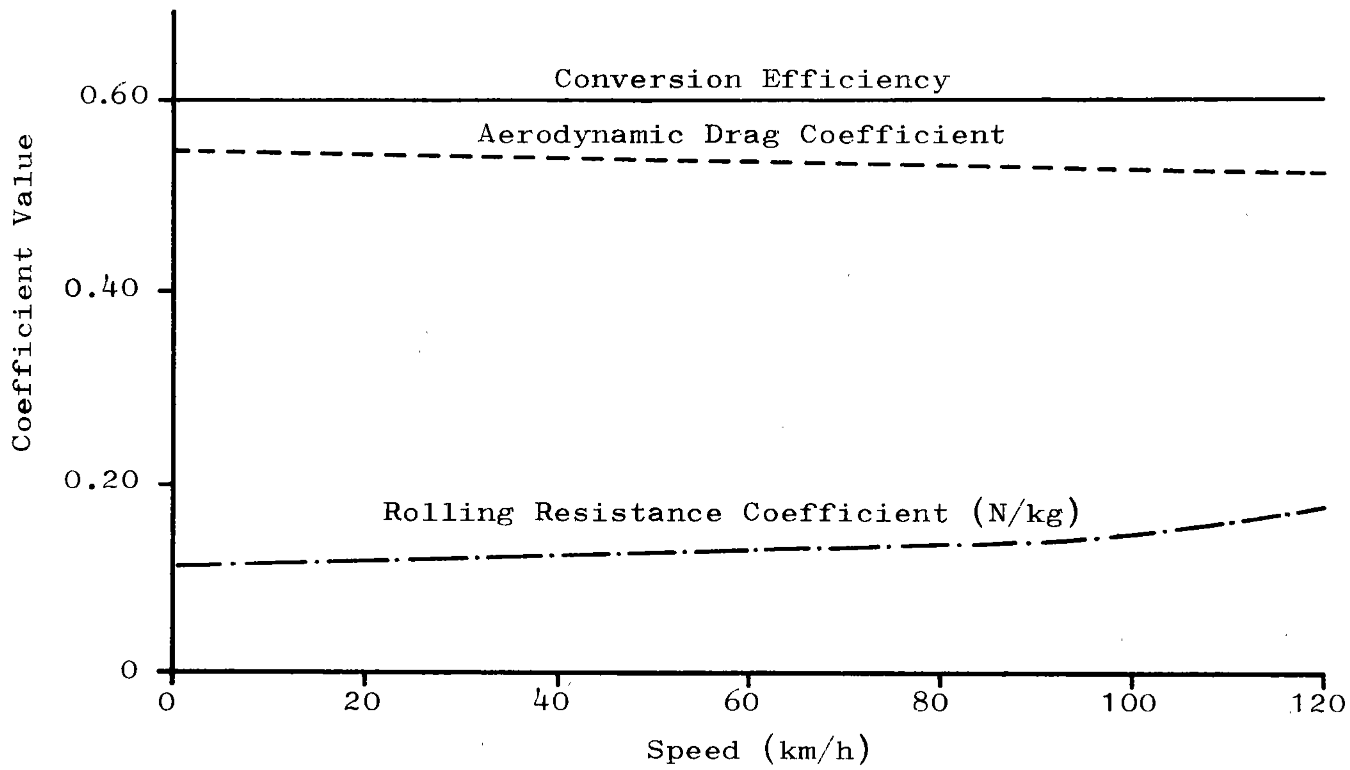

FIGURE E.13 - COEFFICIENT VARIATIONS, 5-METRE CAR

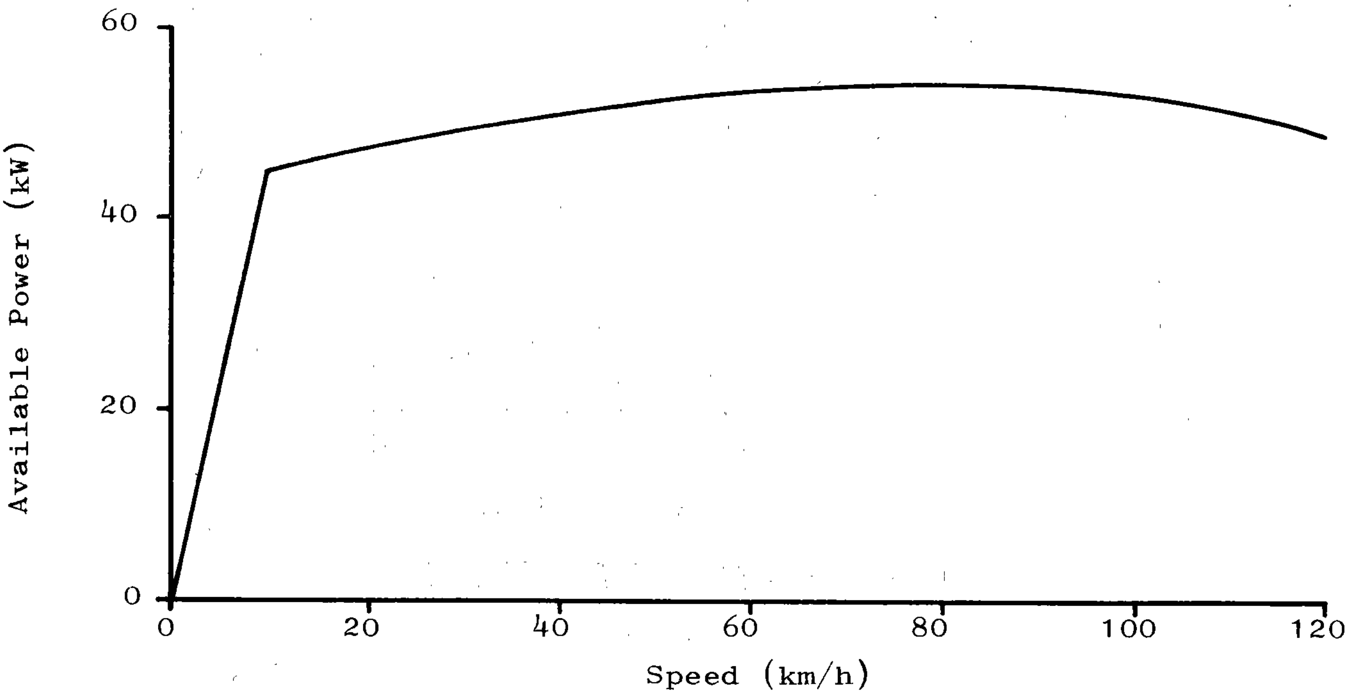

FIGURE E.14 - POWER-SPEED VARIATION, 5-METRE CAR

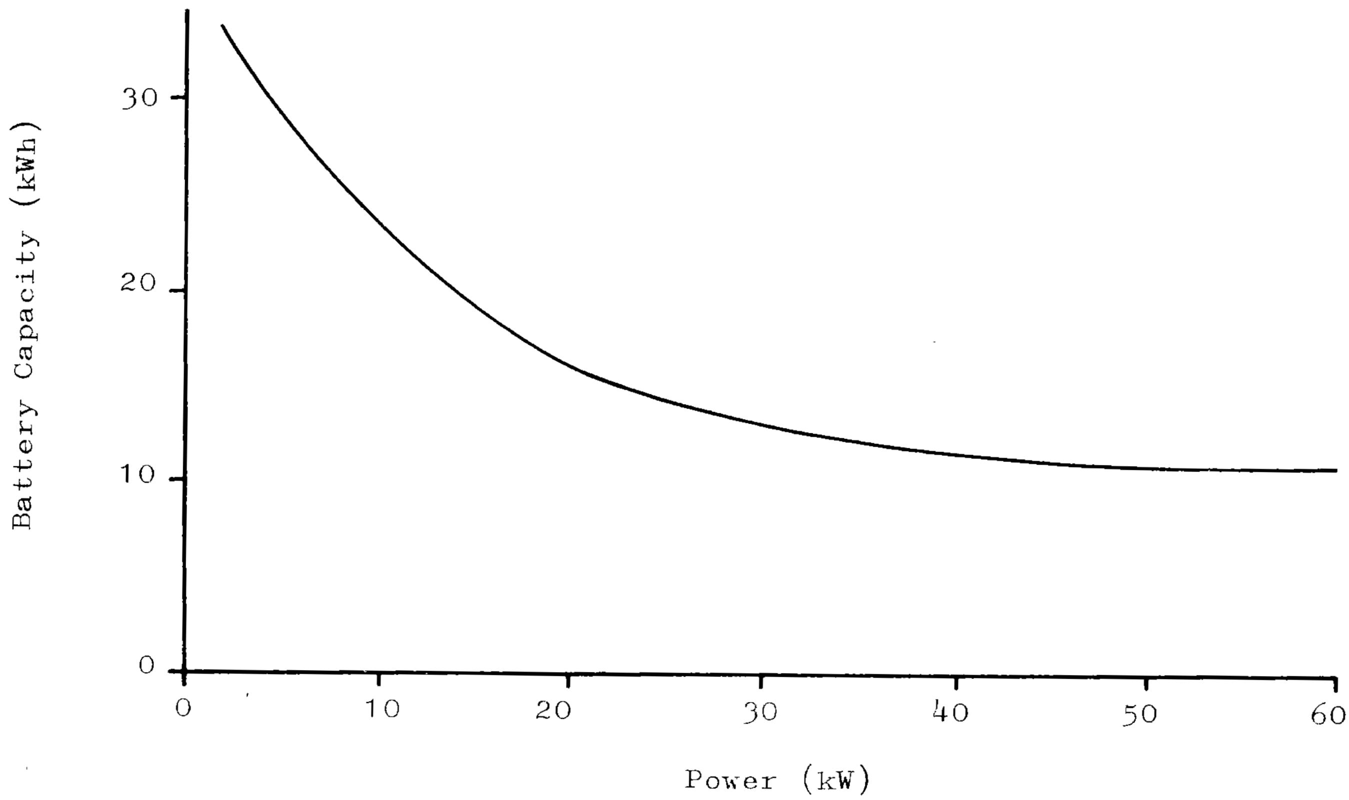

FIGURE E.15 - CAPACITY-POWER VARIATION, 5-METRE CAR

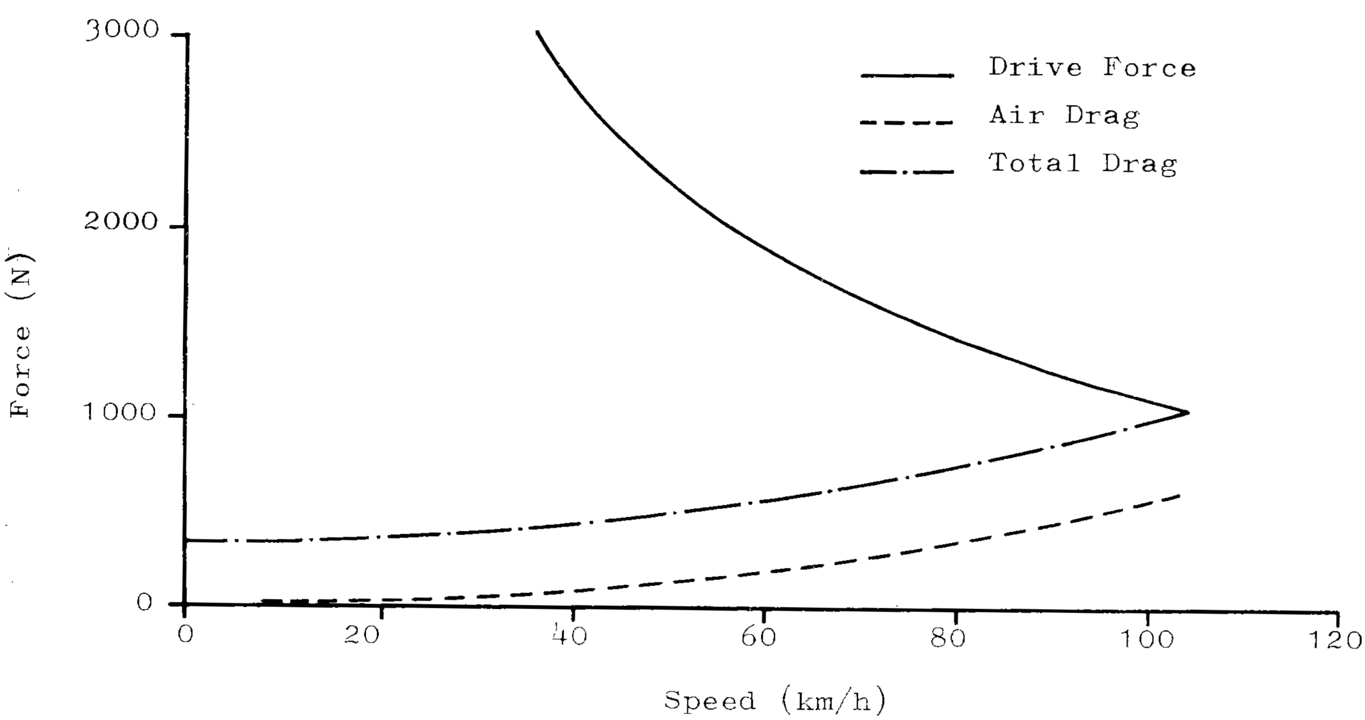

FIGURE E.16 - FORCES VARIATION, 5-METRE CAR

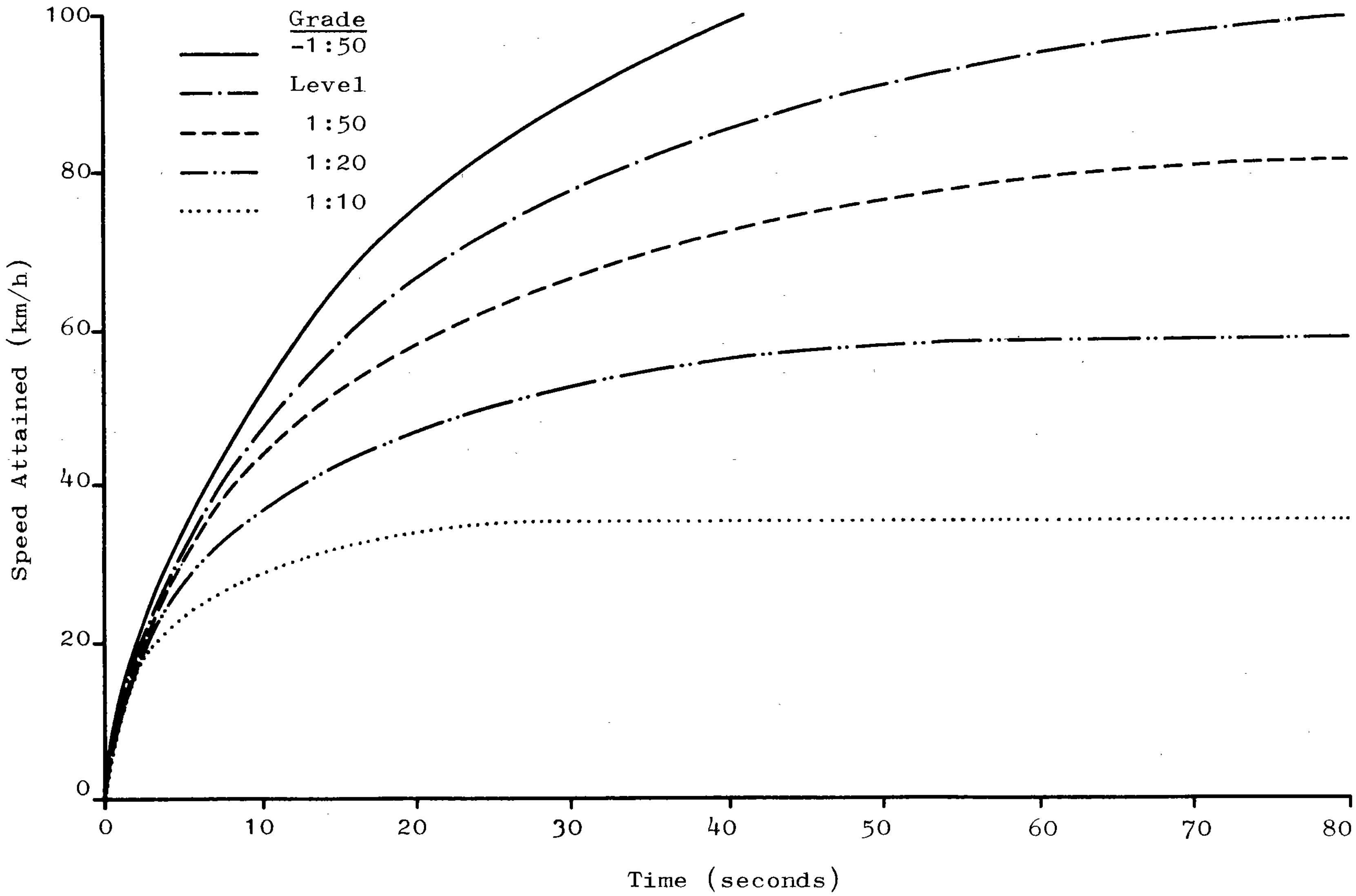

FIGURE E.17 - ACCELERATION CAPABILITIES, 5-METRE CAR

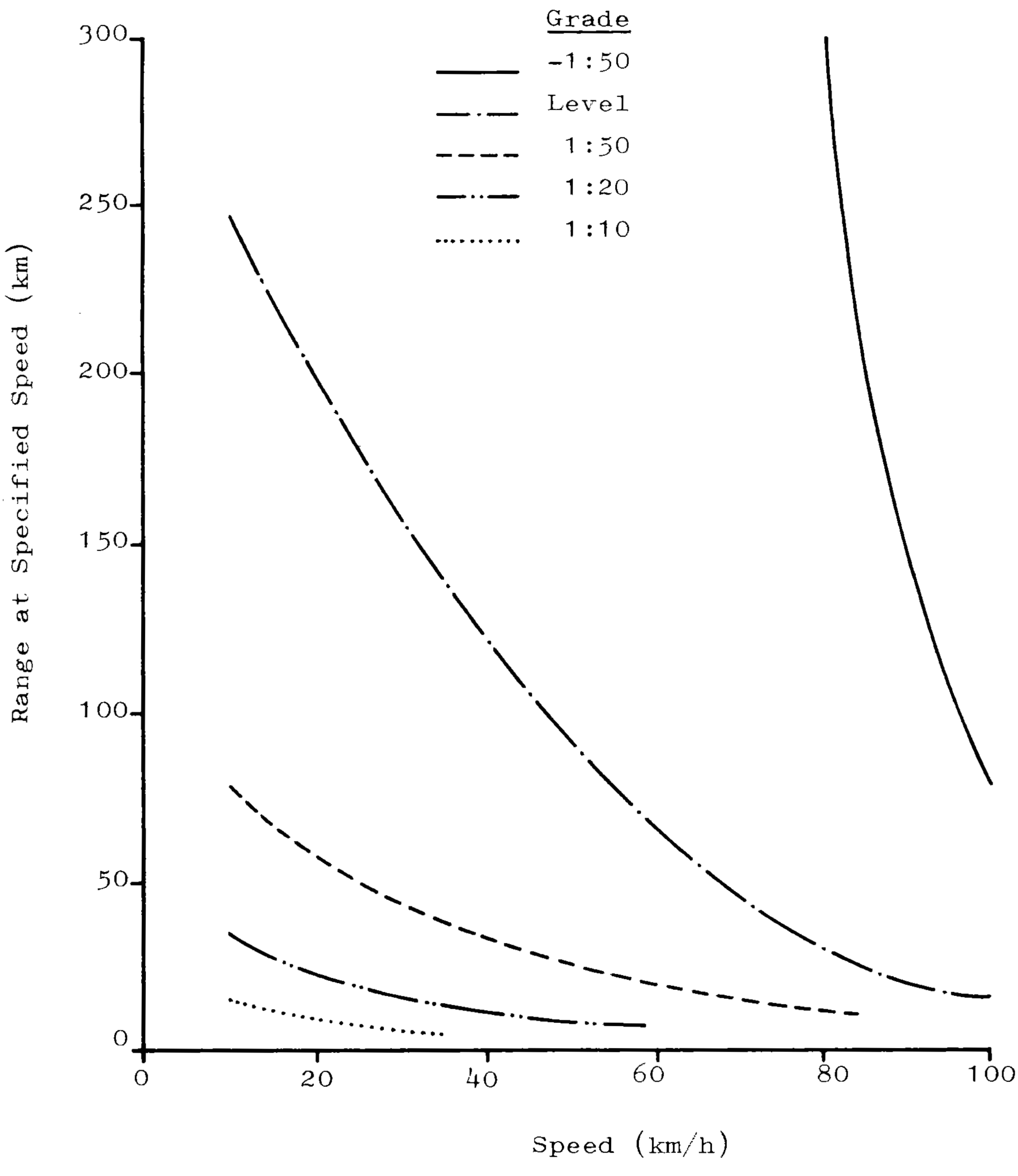

FIGURE E.18 - RANGE AT CONSTANT SPEED, 5-METRE CAR