Vehicle Driving Patterns and Measurement Methods for Energy and Emissions Assessment

Occasional Paper

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BUREAU OF TRANSPORT ECONOMICS

VEHICLE DRIVING PATTERNS AND MEASUREMENT METHODS FOR ENERGY AND EMISSIONS ASSESSMENT

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FOREWORD

While the benefits of mobility and accessibility afforded by the motor car have long been appreciated, the corresponding costs, especially as a result of exhaust emissions, are the subject of increasing concern at the present time.

Urban air quality management is concerned with comparing two kinds of costs: those arising out of increased levels of air pollution and those involved in implementing an abatement program. This report is concerned with these latter costs insofar as it investigates the relationship between regulatory instruments (ADR27A for example) and their practical effects on emission generation by Australian cars.

There are a number of planning, technical and regulatory problems that may be addressed through the medium of driving pattern analysis and driving cycle development. The planning analyst would like to be able to devise statistically useful abstractions of various combinations of vehicles and driving patterns. Vehicle manufacturers need a predictable, long term basis for design, tooling and marketing. They would be rightly concerned if regulations did not employ a fixed and clearly defined driving cycle such as embodied in ADR27A. Finally, regulatory authorities are concerned that driving cycles should be reliable predictors of in-service emissions. There is obvious need for different approaches to driving pattern analysis catering to the range of relevant applications.

In this report, the author indicates that we may be able to resolve these differences. He proposes that compliance testing of typical cars should be extended to generate continuous traces of emissions throughout the normal test sequence. In theory at least, the instantaneous emissions associated with a specific set of driving conditions can constitute a data base suitable for a wide variety of policy development purposes, including the synthesis of driving cycles for specific applications. If this can be done in practice, and the author points out a number of unresolved difficulties, one result should be to enhance the usefulness of the ADR27A driving cycle and thus ensure its retention as a regulatory test procedure.

The BTE does not necessarily accept these findings, but I believe that they will contribute in a positive way to the discussion now taking place on air quality management and the related question of vehicle fuel efficiency.

The report was prepared by Dr H.C. Watson, Senior Lecturer in Mechanical Engineering in the University of Melbourne, and was supervised and edited by Mr L. Lawlor of the Transport Engineering Branch.

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SUMMARY

This report has been prepared against a background of increasing interest in the methods used to measure motor vehicle emissions and fuel consumption from a national point of view. While the measurement of emissions to meet legislated standards has been carried out overseas for several decades, concern for fuel consumption measurement is much more recent.

The report takes as a starting point the present commitment by regulatory authorities to emission control by means of 'driving cycles'. A driving cycle is a profile of vehicle speed over time that represents a typical driving pattern. Clearly, there is a variety of driving cycles, each reflecting a unique combination of vehicles and driving conditions.

The report proposes a comprehensive approach to driving pattern analysis for emissions and fuel consumption measurement purposes in which driving cycles - while having applications for specific purposes - are seen to be limited in their ability to readily represent the wide degree of variability inherent in general driving conditions.

Two issues concerning emissions and fuel consumption measurement require clarification, and which involve discussion of driving cycles, are as follows:

- How should national driving patterns be converted into test procedures for measurement purposes, given the wide variations in:
  - road networks in various geographical areas of a country
  - traffic conditions with time of day
  - usage of motor vehicles.

- Is a single test procedure (driving cycle) satisfactory for the measurement of both emissions and fuel consumption in

the context of national standards, given the variability mentioned above.

The problems involved in the current approach of using a single driving cycle for regulatory and other purposes can be seen from the following contrasting examples:

- An analysis of the effects of linked traffic signals points to a driving cycle that reflects the change in driving conditions along a specific stretch of road. Since the driving conditions would not be typical of the region as a whole, the driving cycle thus derived would reflect specific <u>local</u> characteristics.

- On the other hand, an evaluation of regional changes to air quality, arising out of changed vehicle design (or marketing) strategies, dictates the need for a driving cycle that reveals the gross changes to <u>regional</u> fleet emissions over a period of five years.

The research embodied in this report addresses these issues and problems. The report outlines a methodology which will enable driving patterns to be measured on a national level and converted into a form suitable for the measurement of emissions and fuel consumption. The methodology will permit these measurements to be made in a way that would take into account the disaggregated criteria mentioned above, with application to a variety of policy development purposes.

The report indicates that while a fixed driving cycle is desirable for regulatory purposes and for industry acceptability, value would be obtained from a joint analysis of driving patterns and engine performance data, in the context of measuring emissions and fuel consumption.

The type of analysis recommended in this report represents an original approach to the problem of dealing with the variation in driving patterns across the nation. The report outlines a work program which would attempt to make use of the current Australian driving cycle (ADR27A) in the process of developing this approach.

Overall, the report advocates the retention of the ADR27A cycle, if possible, as the basis of developing improved test procedures, in view of the large commitment by industry to the cycle.

CHAPTER 1 - INTRODUCTION

BACKGROUND

To active workers in the field of automotive energy and pollution control, it is clear that there is no universal panacea to the problems of reducing fuel consumption and vehicle emissions. The most beneficial solutions to the problems will arise out of a concerted effort to optimise all aspects of both the design of vehicles and their usage.

Much effort has been expended, particularly in the U.S.A., in controlling the design of the motor vehicle by Federal government legislation. Only at the time of the Arab oil embargo were usage restrictions employed (through both quantity supply and nationwide speed limits). It has been recognised by many groups including the OECD that a rational approach to emissions control and the impending liquid fuel energy problem must come from a wide range of social and engineering efforts including urban planning, traffic engineering, car pooling, greater efforts to encourage the use of public transport and so on.

In providing incentives (through legislation, fiscal measures or publicity campaigns), it is important to balance the need for decisions which quickly achieve desired objectives with the long life of motor vehicles in Australia (about 14 years).

To ensure that changes are correctly directed, monitoring of present emissions, fuel consumption performance and current usage patterns of existing vehicles is required. Together with accurate forecasting mechanisms this will ensure that changes are made in directions which produce the best return for effort in terms of cost and energy.

There is evidence (U.S. EPA (1978))[1] that measures currently employed in controlling vehicle fuel consumption do not meet with customer satisfaction in that the test procedures forecast fuel consumption better than that achieved in customer use. "On road, in-use fuel economy is approximately 1 mi/USgl (7%) lower[2] than EPA city test results and 4 mi/USgl (16%) lower than the EPA highway test results." Further, the shortfall for small sub-compact cars was reported to be 19% in highway driving. BETTONY AND CANTWELL (1978) report that changes in fleet fuel consumption over a period of time are not in agreement with calculations based on US EPA data. These differences have severe implications for the US in terms of its ability to meet its projected oil savings by 1985 through motor vehicle fuel consumption legislation.

In addition, vehicle simulation studies by WATSON and MILKINS (1977) supported by experimental evidence of JUNEJA (1978) show that choice of vehicle design variables, particularly axle ratios, gear ratios and shift points, can influence fuel consumption in a way which is advantageous in one driving condition (for example urban driving) and deleterious in another (highway driving). Therefore, it is important to encourage the design of vehicles in a direction which optimises fuel consumption in conditions for which most fuel is used in consumer application. In Australia this implies that passenger cars should be optimised for urban rather than non-urban usage.

It is also important to ensure that the test methods employed in monitoring vehicle fuel consumption and emissions closely resemble in-use conditions. Current procedures do not do so. Some major defects in the ADR27A test procedure are:

- the inertia (weight) adjustments of the dynamometer only account for weight savings if the weight is reduced across the specified test inertia boundaries (in 113 and 227 kg increments).

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(1) References are found in alphabetical order at the end of the report.

(2) It is important to note that lower fuel economy corresponds to worse (higher) fuel consumption.

Thus in-use fuel and emissions reduction achieved through weight reduction are not recognised when weight is reduced within a given weight category.

- road load is set at regulated values according to vehicle weight, which does not allow for aerodynamic drag variations between vehicle designs.

- the driving cycle has unrepresentatively low maximum accelerations and its velocity distribution is different from those found in Sydney and Melbourne (KENT and RULE (1977) and WATSON and MILKINS (1976)). It represents the influence of Los Angeles speed limits, freeways and driving habits of the late 1960's rather than current Australian conditions.

In examining the issues involved in measuring Australian vehicle fuel consumption and emissions, the ADR27A and other US procedures already adopted in Australia have not been rejected out-of-hand. Rather, it is argued that research should be conducted to attempt to relate ADR27A emissions and fuel consumption measurements more closely to actual Australian conditions. Should this not be possible then new procedures must be developed.

This report is not alone in re-evaluating existing test methods. VOLKSWAGEN (1977) have conducted a thorough investigation into the repeatability, reproducibility and representiveness of the U.S. and ECE test methods. Their effort has been largely directed towards improving the engineering precision of the test method, without attempting to account for the impacts which will occur in vehicle use through changes in vehicle design, driving habits and roadways as energy becomes more scarce and costly in the future.

PURPOSE OF THE REPORT

The purpose of the methodology proposed in this report is to permit the accurate estimation of vehicle fuel consumption and emissions sources[1] for prescribed geographic regions.

These methods would thus assist in monitoring the effects of the following matters:

- Government regulations on motor vehicle emissions (ADR27A)
- industry initiatives designed to improve the fuel/emission performance of motor vehicles
- changes in vehicle design parameters which affect fuel consumption caused by changes in consumer preference for motor vehicles

Some typical applications might include the following tasks:

- forecast future demand for motor fuel
- permit development of fuel consumption testing regulations for vehicles
- educate the public on driving habits, vehicle fuel consumption, real costs of driving, etc.
- provide line source emissions descriptions for calculation of ambient air quality
- forecast when new air pollution control measures would be required
- calculate benefits from road improvement schemes, from traffic signal schemes to new freeways
- aid economic studies of regional planning.

An example of the part which the methodology developed in this report could play in the process of motor vehicle emission control is illustrated in Figure 1.1. This shows how mobile emissions sources could be adjusted to meet prescribed air quality standards. However, much effort is still needed to develop precision in the modelling of the atmospheric dispersion and

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(1) "Emissions source" is defined as the rate of emissions of pollutants per unit time in a given region.

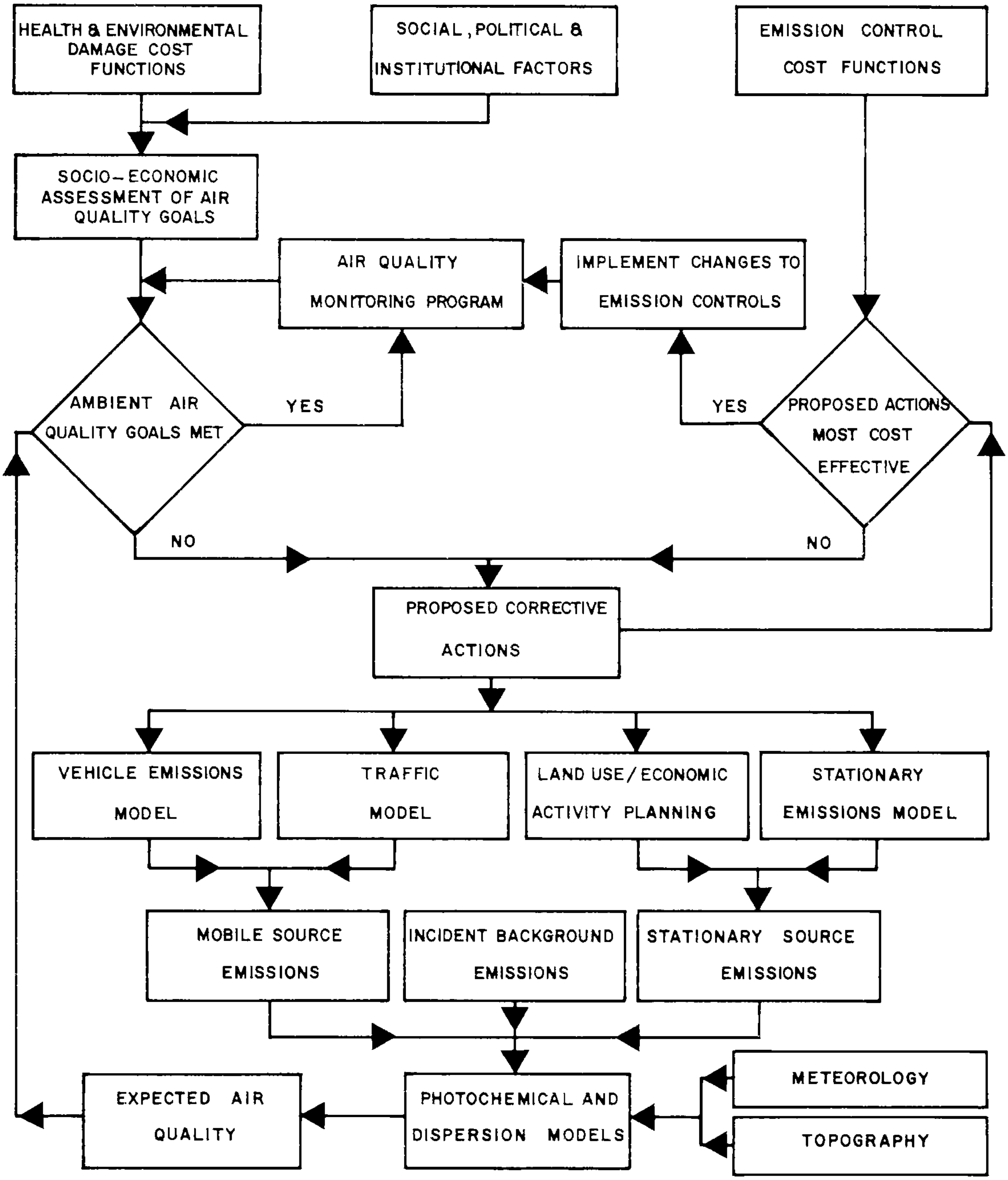

FIGURE 1·1

FRAMEWORK FOR DEVELOPING A STRATEGY TO MEET REGIONAL AIR QUALITY GOALS reaction of pollutants in Australian cities. In the mean time it is possible but rather unsatisfactory to substitute a simple, linear rollback model(1).

The block diagram raises an important issue discussed further in the body of the report: if air quality standards are written around worst or second worst incidence of pollutant levels, then the emissions source might need to reflect the corresponding traffic density and driving patterns.

LAYOUT OF THE REPORT

Methods for estimating vehicle emissions sources and fuel consumption are examined in Chapter 2.

An idealised approach is first presented and then contrasted with a more practical approach. The importance of the driver and driving pattern(2) in affecting emissions source and fuel usage is discussed. The opposing constraints on driving patterns, expressed as driving(3) cycles for test procedures, are presented: the conflict between the need to reflect regional differences in roads and usage, and the desirability of international uniformity; the need for short test times and yet the requirement to cover the wide range of in-use driving conditions.

In Chapter 3, the problems of driving cycle weighting, introduced in Chapter 2 are examined in more detail. The value of explicit weighting is exposed, despite the computational problems it involves. The computational method is examined further in Chapter

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(1) A linear rollback model implies that an X% reduction in emissions will result in an equal X% improvement in ambient air quality.
(2) A driving pattern may be considered as a probability function which summarises the velocity and acceleration attained by all vehicles driven along a specific route during a particular time period.
(3) A driving cycle is defined as a prescribed velocity-time relationship intended to represent typical driving conditions.

4. Modal, transient and engine mapping emissions models and corresponding data reduction methods are examined. Evidence of the relative merit of each approach is presented.

In Chapter 5, driving pattern measurement methods are analysed. A more detailed analysis is presented in the Appendices. Modal and self-weighting driving cycles are contrasted.

Examination of the emissions data reduction methods and traffic pattern analysis leads, in Chapter 6 to recommendations on methods for implementing a unified approach to emissions source and fuel consumption estimation. Many of the recommendations identify areas which need further investigation.

CHAPTER 2 - AN EXAMINATION OF ENERGY USE AND EMISSIONS SOURCE ESTIMATION METHODS

INTRODUCTION

In this section, an ideal method for calculating the energy use and emissions source (EU/ES) from motor vehicles is set out as a datum for comparison with alternative methods, including those currently employed and proposals for new methods.

The simple driving pattern and its inability to weight the influence of many factors which affect EU/ES is described. These factors range from variations in drivers' attitudes to the influence of hot versus cold starts and the non-linearities in the relevant weighting factors.

THE IDEALISED SOLUTION

An ideal solution of the calculation of energy use or emissions source EU/ES is summarised in Figure 2.1.

The purpose for which the calculation is made will define the geographical region and the time interval over which EU/ES is to be evaluated. Figure 2.1 indicates that with region and time period defined, the calculation can be performed from knowledge of the operation of all vehicle engines in the region.

It is suggested that the combined frequency distribution of engine torque and speed (steady state data), plus their time derivatives (transient data), may be sufficient for most calculations. This implies that the sequence in which engine operation occurs may not significantly affect EU/ES. There is increasing evidence that this is true (JUNEJA et al (1978), WATSON and GOLDSWORTHY (1978)) for fuel consumption and gaseous emissions. Indeed there are indications that the loss of the transient information (derivatives of speed and torque) may cause errors of 5-10%.

PROBLEM — CALCULATION OF ENERGY USE OR EMISSIONS SOURCE (EU/ES) FROM MOTOR VEHICLES

SPECIFICATION

REGION	TIME
GEOGRAPHIC AREA FOR WHICH EU/ES REQUIRED	PERIOD OVER WHICH EU/ES TO BE CALCULATED
e.g. . City Street	e.g. . Per Second
. Sq. km of City	. morning peak hours
. Nationwide	. daily
	. annual

SOLUTION REQUIREMENTS — FOR REGION SPECIFIED, TEMPORAL FREQUENCY DISTRIBUTIONS DESCRIBING PARAMETERS PERTINENT TO VEHICLE ENGINE OPERATION:

* FOR EVERY VEHICLE, MULTI-DIMENSIONAL MATRIX DESCRIBING FREQUENCY OF
  - engine operation
    - primary factors
      speed + derivative) coupled
      torque + derivative)
    - secondary factors
      engine temperature
      choke actuation
      + other factors
  - ambient conditions
    - temperature, pressure, humidity
* PATH DESCRIPTORS FOR SEQUENCE IN WHICH EACH SPEED AND TORQUE COMBINATION OCCURS (WHEN SEQUENCE DEPENDENT)
* DATA DESCRIBING EU/ES IN TERMS OF ABOVE PARAMETERS
* CALCULATION OF EU/ES FOR EACH VEHICLE
* SUMMATION FOR ALL VEHICLES

FIGURE 2·1

AN IDEALIZED SOLUTION FOR EMISSIONS SOURCE AND ENERGY USE CALCULATIONS FOR MOTOR VEHICLES

However, for particulate emissions, especially lead for which "hang up"[(1)] is possible in the engine and exhaust system, the sequence dependence of engine operation must be retained (WATSON 1977)), although it must be admitted that the prediction of lead emissions, even on an empirical basis, is still in its infancy (SUMAL (1975)).

In the case of lead it is then imperative that the torque-speed and secondary variables be specified in their sequence of occurrence. Indeed all EU/ES could be handled in this way, replacing the need for frequency distributions.

The purpose of introducing these complex and esoteric concepts is that they have relevance to the application of driving cycle EU/ES results, as will be shown in Chapter 4.

The next phase of the analysis is to obtain the EU/ES data for every power plant for the wide range of transient, steady state and ambient operating conditions found in the field. It is likely that instrumenting every vehicle with fuel flow and emissions monitors would be a cheaper solution. Nonetheless, in this hypothetical analysis, the next step is to combine the usage matrix information and data bank to calculate EU/ES for each vehicle, and sum as appropriate for the region.

THE PRACTICAL SOLUTION

The pragmatic approach to the practical solution of the above problem has been to replace the frequency distributions and path sequences describing the engine operating history by a vehicle driving pattern (driving cycle). This step clearly introduces imprecision into the calculation. The loss of precision arises from the following factors:

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(1) "Hang up" refers to retention of particulate lead in exhaust systems during low speed driving, some of which may be emitted under acceleration conditions.

- not all vehicles have the same performance capability
- not all drivers have the same driving aspirations (the heavy and the light foot driver)
- different geographical regions have different road network shapes
- sampling procedures are subject to error and imprecise weighting for route types.

No serious attempt appears to have been made to quantify the effects of the driving pattern simplification. Some recognition of the variability of patterns between regions is allowed for in emissions factors (e.g. U.S. EPA, AP-42 (1975), IVERACH (1975)) in allowance for average speed variations between regions. Figure 2.2 illustrates BULACH'S (1977) estimation of the emissions variation along a Melbourne route for an average vehicle, compared to its ADR27A cycle emissions. Clearly emissions differences of several hundred per cent can occur from the cycle values. The author has shown (WATSON, MILKINS and BULACH (1976)) that average speed may be a sufficient descriptor for HC and CO, with up to 10% error, but not for NOx and fuel consumption (WATSON 1977)). One must be mindful that even when average speed is a sufficient descriptor for pollutants, the relationship of emissions with speed is non-linear, so that unweighted averaging of speeds in a region will not yield the correct emissions rates from the emissions - speed function for that region(1). The importance of non-linear weighting will be discussed further in Chapter 3.

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(1) For example, BULACH (1977) gives the emission rates of pre-control vehicles as

$$\text{CO gm/km} = \frac{1134.2}{\bar{v}\ \text{km/h}} + 5.86$$

If in one street the up and down streams of traffic have average speeds of 20 and 40 km/h, the net emission rate per vehicle in each stream will be 48.4 gm/km, whereas the expression gives 43.7 gm/km at the mean speed of 30 km/h.

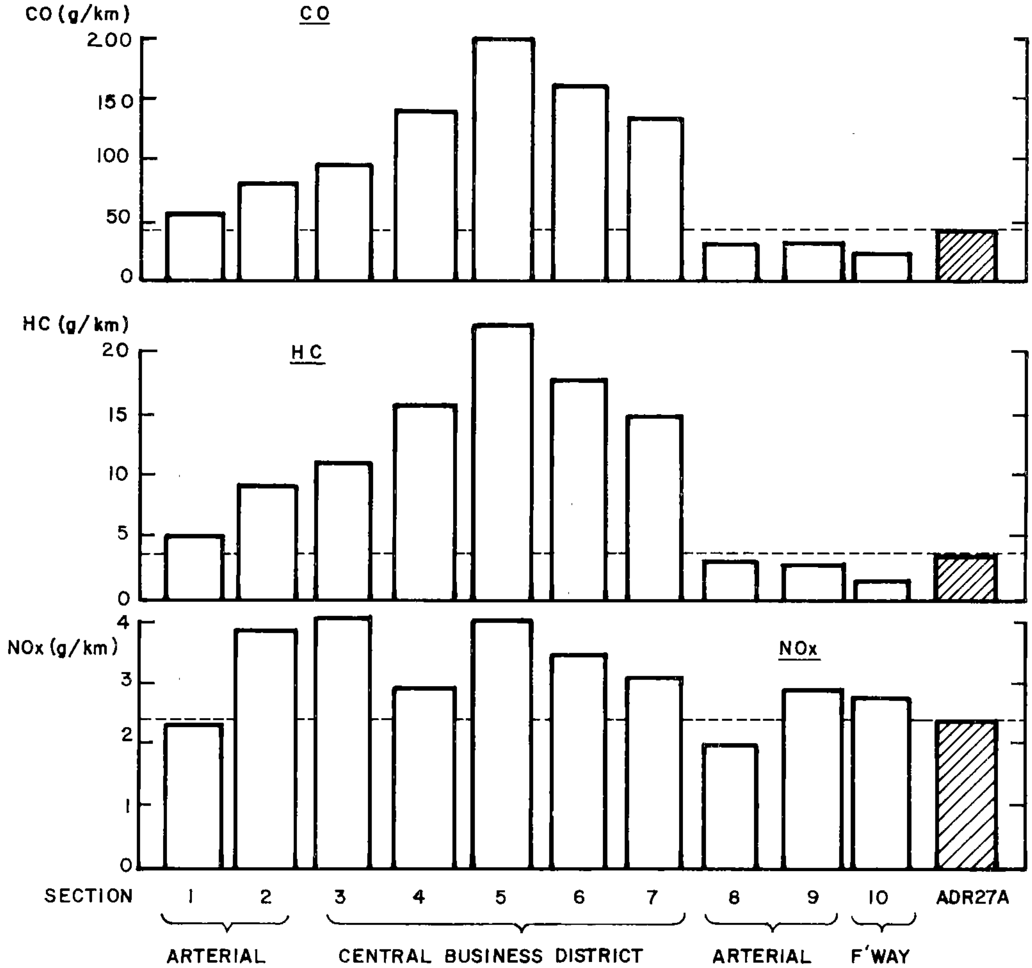

FIGURE 2.2

COMPARISON OF MELBOURNE EMISSIONS WITH ADR 27A

NOTE: Emissions averaged over 10 runs for average mass vehicle (1400 kg) along a Melbourne route

Source: Bulach (1977)

The answer will depend upon the application. Precision will be important in the calculation of absolute values, e.g. nationwide average fuel consumption of cars and station wagons. Where relative answers are required, precision of absolute values may be less important. For example, in applying emissions source calculations to models for atmospheric air quality projections, a sensitivity analysis of the likely magnitude of errors in the estimation of mobile emissions sources is advisable before embarking on elaborate source description embodying detailed driving pattern studies. GOODIN et al (1976) indicates the need for such studies. DEMERJIAN (1975) indicates a need to improve present techniques.

DRIVERS AND DRIVING PATTERNS

Before examining further the limitations of driving cycles, an awareness of the inputs to the driver, affecting the way in which he/she drives, is useful in a qualitative assignment of priorities of importance of the inputs. This will aid judgment on which inputs should be retained and have influence on the development of the driving pattern. Figure 2.3 summarises the driver/vehicle/driving-pattern interactions.

There appear to be two distinct regimes of operation for motor vehicles on roads:

- saturated (or near-saturated) flow
- relatively free flow

In saturated or congested traffic, drivers, except those at the head of platoons of vehicles, are constrained by the proximity (lack of headway) of other vehicles, and although the flow of the platoon is restricted by the most cumbersome vehicle (truck or bus for example), the impacts of intersections, traffic signals and pedestrian activity are of greater importance. Thus the vehicle's performance capability and the driver's mental and physical state are of lesser importance.

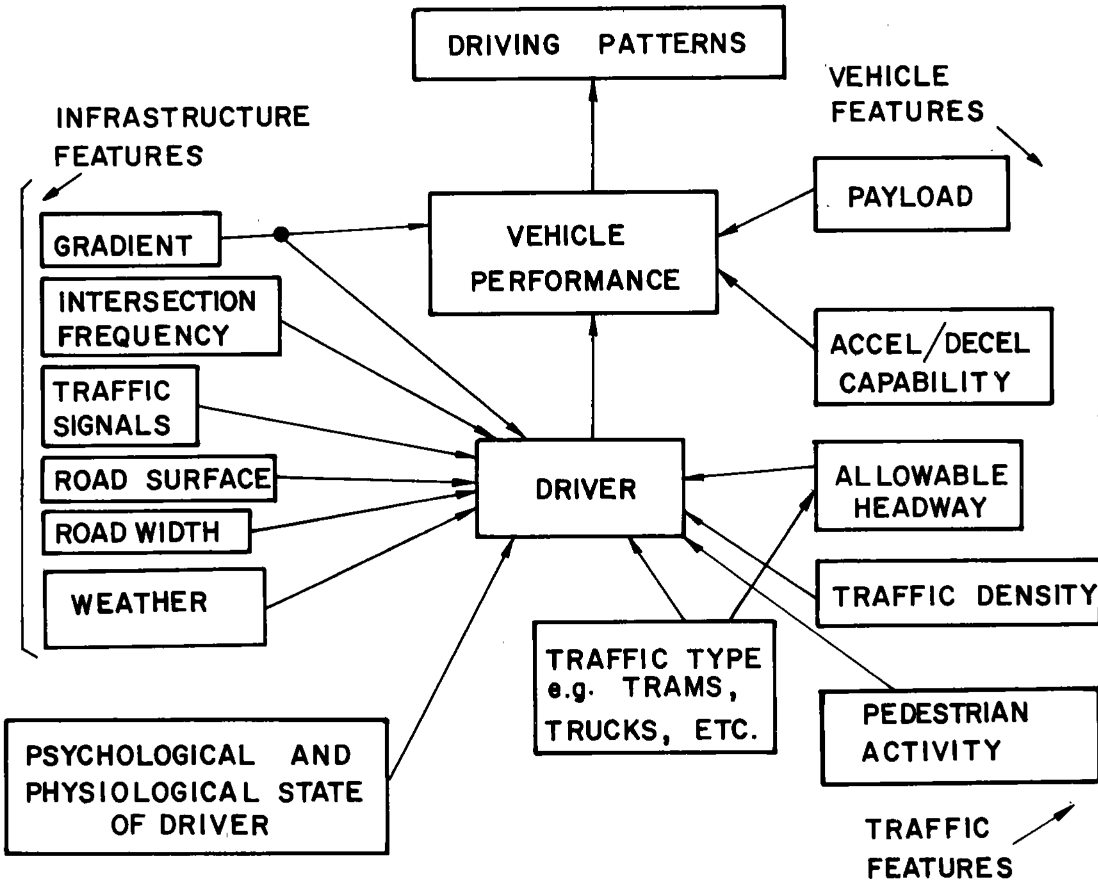

FIGURE 2·3

FACTORS AFFECTING DRIVING PATTERNS

In the relatively free flow situation, the vehicle's performance capability and the driver's attitude are likely to be of greater importance. Gradient is also of more importance in this situation since vehicle speeds and engine load factors will be higher. In these circumstances, some corrective weighting would ideally be necessary, accounting for the end application of the driving pattern. For example, PELENSKY (1970) shows that the extra fuel used on the up gradient is not exactly compensated for in reduced fuel consumption on the down gradient. There is a net increase in fuel consumption. A more dramatic but similar type of trend is anticipated for NOx emissions, but no published data exist. Similarly the random distribution of "heavy" and "light foot" drivers is likely to yield a net increase in fuel consumption over the mean driving pattern (or driver), whilst a net reduction in HC emissions might result.

A subjective ranking of the importance of the input variables to driving patterns is now suggested:

Saturated Traffic	Free Flow
Traffic density	Signals activity
Signals activity	Intersection frequency
Intersection frequency	Vehicle capability
Weather	Driver attitude
Pedestrian activity	Payload
Payload	Traffic density
Driver attitude	Weather
Vehicle capability	Gradient
Gradient	Pedestrian activity
Road surface	Road surface

To be of on-going value, the driving pattern should adjust to accommodate changes in infrastructure and vehicle performance capabilities, which must happen with an increasing rate of change in the near future. Fuel consumption improvement strategies include measures ranging from sequence control of signals to reduced vehicle power-weight ratios, (WATSON and GOLDSWORTHY (1978)), both of which will have effects on driving patterns.

considerations. Two examples are presented as illustrations of this need:

- In calculating regional source inventories of vehicle emissions for air quality forecasting, account should be taken of the variation in driving pattern from region to region, including variations in acceleration rates as well as variations in vehicle speeds, as indicated earlier in this Chapter, and also in the next sub-section.

- Alternatively this regional evaluation could be performed by a classification of traffic patterns according to road types within the region. Such classifications frequently include highways (expressway, expressway-business route, rural highway), non-highway (suburban arterial, unpaved rural etc.). Refer to JOHNSON et al (1975) or SCOTT RESEARCH LABS (1971a). Results of EU/ES could then be appropriately weighted according to vehicle density along each road type in each region.

Such methodology is employed in the U.S. where fuel consumption measured according to the U.D.D.S. and Highway cycles (Refer to Appendix A) are weighted 0.55 and 0.45 respectively.

<u>Patterns for each pollutant and for fuel consumption</u>

In Chapter 2 it was idealistically proposed that the frequency distributions of engine operation for each vehicle be used for emissions and fuel consumption calculation. It has been shown by BULACH (1977) that it is probable that these calculations can be performed equally well from the vehicle driving pattern frequency distribution to be discussed in more detail in Chapter 4.

Research at Melbourne University, LOUGHNAN and WALLS (1973), JAGO and KENNEDY (1977) and WATSON and MILKINS (1976) and at the University of Sydney, KENT and RULE (1977) demonstrate that current driving cycles inadequately represent actual city driving. Apart from improperly weighting velocity distributions, their acceleration distributions are particularly restricted as illustrated in Figure 2.4. This finding is not restricted to Australian driving conditions. In a survey of driving patterns in European cities, VOLKSWAGEN (1977) shows that in one city about 20% of accels[(1)] were in excess of 2 m/s^2 at speeds between 20 and 40 km/h. In the U.S., SCOTT LABS (1971a) indicate that at 16 km/h, 30% of accels were greater than 1.5 m/s^2 and 10% of accels were greater than this value at 32 km/h.

The restriction arises in the inability of many of the Clayton chassis dynamometers, used almost universally for emissions testing in the U.S.A., to maintain acceleration rates greater than 1.5 m/s^2 because of their small (203 mm) diameter polished steel rollers. This dynamometer limitation has resulted in the tail of the accel/decel distribution being "forced" into less than 1.5 m/s^2 values in the U.D.D.S. (ADR27A) cycle. No NOx evaluation was reported as the consequence of forcing the LA-4 cycle to the U.D.D.S. accelerations, as described in Appendix A.

However, a consequence of this can be inferred from WATSON, MILKINS and BULACH (1974), where it is shown that for correct weighting of accelerations for NOx calculation, the mean NOx weighted acceleration rate must be considerably higher than the mean acceleration rate as shown in Figure 2.5. No such upward weighting of accelerations was reported in the description of the development of the U.D.D.S., (KRUSE and HULS (1973)). Indeed had such weighting taken place, undoubtedly some interactive effect on HC and CO emissions would occur.

The need for appropriate weighting of accels is indicated in the development of fuel economy cycles in which higher than the arithmetic mean, but less than maximum, city accels are used in the SAE simulation cycle, SAE (1975). Further discussion and fuel

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(1) An "accel" is an abbreviation for acceleration.

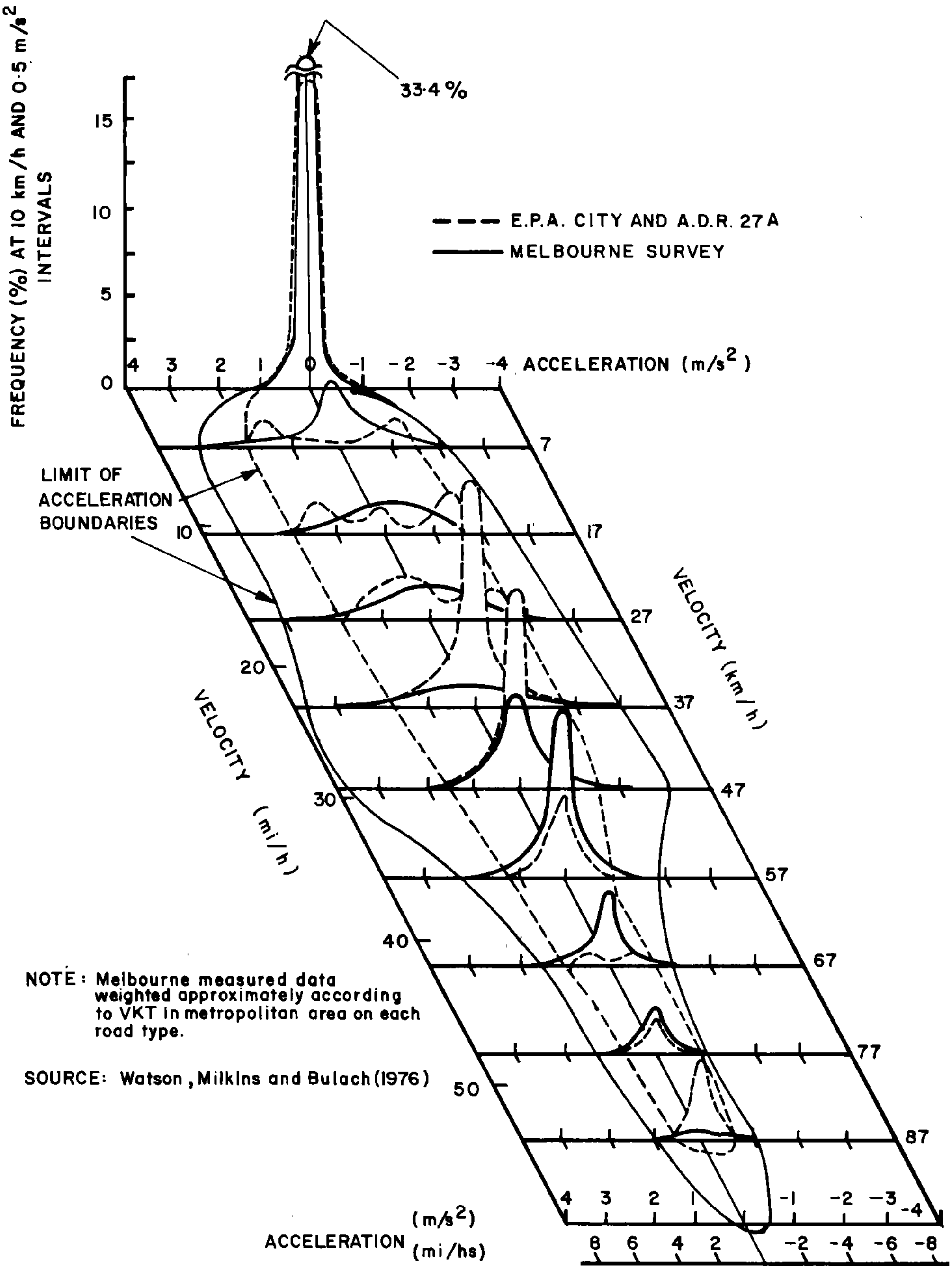

FIGURE 2·4

COMPARISON BETWEEN MELBOURNE DRIVING AND ADR 27A CYCLE PRESENTED AS BI-VARIATE FREQUENCY DISTRIBUTIONS

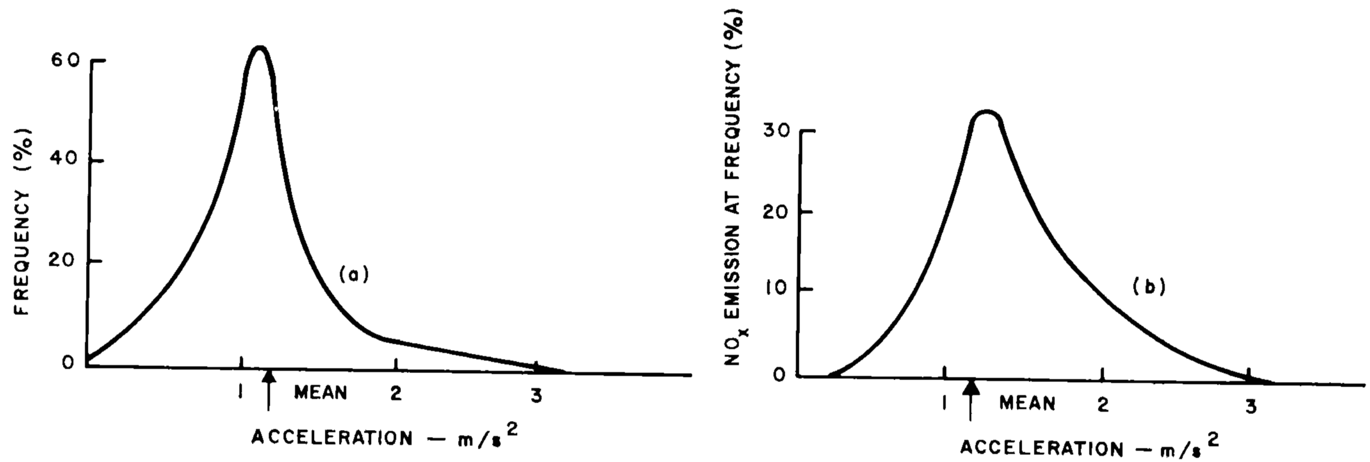

FIGURE 2·5

DISTRIBUTION OF ACCELERATION RATES AND CORRESPONDING NO_x EMISSIONS WEIGHTED BY FREQUENCY, SWANSTON STREET MELBOURNE

SOURCE : Watson (1974)

economy predictions from the cycle, in excellent agreement with customer experience, are summarised in Appendix B.

These arguments lead to the conclusion that once the full and "correctly" weighted spectrum of on-road acceleration and velocities is used, a different cycle is required for each pollutant (HC, CO and NOx) and for fuel consumption.

Time of day effects on driving patterns

The most significant effect of changes in patterns between peak and off-peak traffic conditions is on average speed. Figure 2.6 from SATS (1971) data shows that there is about a 6 km/h shift in the median value of average speed of Sydney traffic between the a.m. peak and the 24 hour average. HAMILTON (1976) has calculated that about 35% of all urban vehicle kilometres are travelled in peak hours. This large proportion of travel carried out when speeds are lowest requires appropriate weighting in the development of driving cycles, since at low speeds, relatively more fuel is used and more emissions produced than at higher speeds.

Other Factors

Trip length and trip frequency are two factors which directly influence EU/ES since they affect the proportion of the time during which an engine is running cold or hot. Engine load factor variation has an effect on warm-up time. Emissions of oxides of nitrogen tend to increase with increasing engine temperature, while hydrocarbons, carbon monoxide and fuel consumption rates all reduce with increasing temperature. The variation of trip frequency and trip length within a sample of urban motor vehicles has been investigated in a recent study conducted by the Bureau of Transport Economics (BTE 1978).

Figure 2.7 shows the frequency distribution of trip lengths in America and the cold start effect on fuel consumption (AUSTIN and HELLMAN (1975)). Similar trends are known for CO and HC emissions.

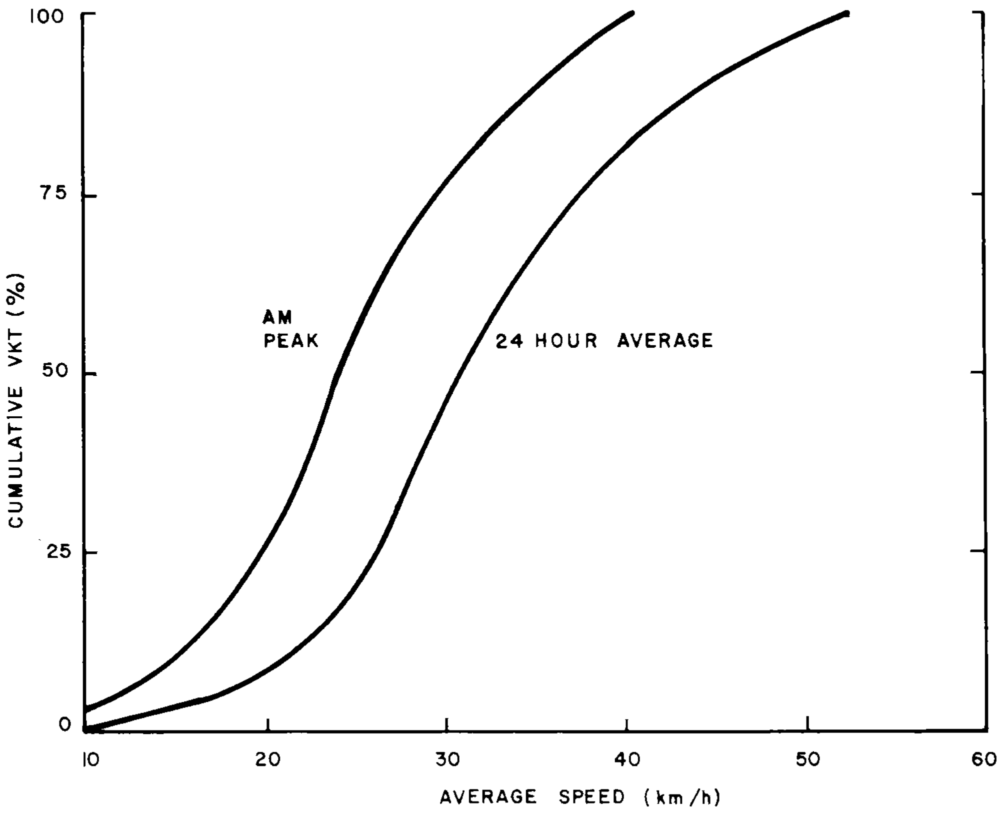

FIGURE 2·6

CUMULATIVE VKT VARIATION WITH AVERAGE TRAFFIC SPEED

SOURCE : Sydney Area Transportation Study (1971)

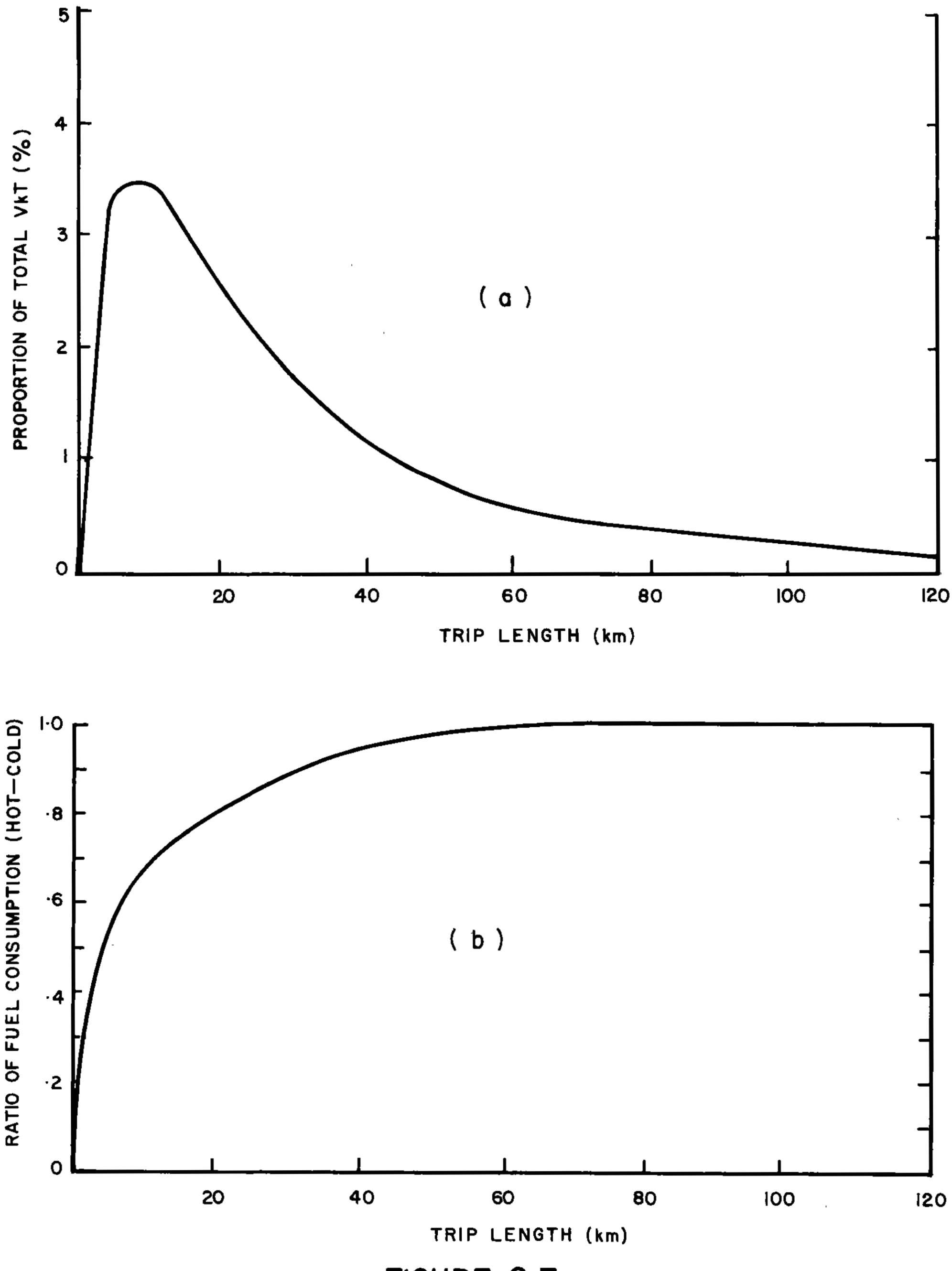

FIGURE 2·7

VKT AND FUEL CONSUMPTION AS FUNCTIONS OF TRIP LENGTH

SOURCE : Austin and Hellman (1975)

Typical values of emissions rates over the U.S. 1975 C-H test procedure show that 54% of the HC, 51% of the CO and 27% of the NOx are produced within the first 25% (distance) of the cycle (VOLKSWAGEN (1977)).

Weather is also known to be a traffic pattern determining parameter, as are other variables such as special functions causing traffic flow restrictions, e.g. parades and street meetings, or road works.

While air pollution is not a problem in wet weather, all other things being equal, such weather can cause serious traffic congestion and consequently increased emissions and fuel consumption. Thus the disruptive effects of traffic restrictions may be an important consideration in evaluating the "worst case" emissions source.

CHAPTER 3 - CYCLE WEIGHTING FACTORS

THE WEIGHTING REQUIRED

The need to apply various weighting factors to driving cycles has been developed in the previous section. The qualitative evidence is that several factors need to be applied. Whether these factors should be applied to results from cycle measurements of EU/ES or should be applied within the structure of the cycle warrants discussion. Until quantitative evidence is developed, most expediently by modelling, on the sensitivity of EU/ES to weighting factors, it is difficult to recommend the optimum strategy. Undoubtedly, practicality must remain a dominant constraint.

The parameters that need weighting, from region to region in which EU/ES are required, as developed in the last section of the previous Chapter, are summarised below:

1. variation in VKT according to each road type(1). (How road types should be classified for driving pattern purposes is yet to be determined).

2. variation in response to each pollutant, e.g. HC, CO or NOx, or for fuel consumption, if the driving pattern is restricted in acceleration or velocity compared to the on-street condition(2).

3. diurnal variation in traffic patterns.

4. engine operating conditions, weighted in terms of trip length and trip frequency, for example.

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(1) This ignores any variation in VKT which may occur between vehicle types. It is probable that greatest sensitivity to this parameter will occur when the region is small, e.g. at the city block level.

(2) It is likely that weighting will also need to be varied with the severity of emission control, since emission control is concentrated in that region of velocity and accel present in currently employed driving patterns.

5. occurrence of traffic disruption, planned or uncontrolled.

6. weighting for other factors including gradient, ambient temperature and pressure effects.

IMPLICIT VERSUS EXPLICIT WEIGHTING

Implicit weighting occurs when a cycle is structured so that some of the weighting parameters are built into the velocity-time history by reiterating a particular segment, or selecting segments from a number of different routes, or by adjusting the cycle time or distance.

Explicit weighting describes the application of a numerical weighting factor to an EU/ES result.

Current driving cycles in the U.S. are structured with both implicit and explicit weighting. For example, the U.D.D.S. cycle (as explained in Appendix A) was implicitly weighted when it was shortened from the 19.3 km of the original LA-4 cycle to 12 km, to match the average trip length in the Los Angeles Basin. It later became clear from a nationwide traffic pattern study that on average only one trip in 4.7 was made with a "cold" engine. Thus the first cold transient phase of 505s, the remaining stabilised phase of 767s and a repeated hot transient phase of 505s were individually weighted (0.43, 1 and 0.57 respectively) in the 1975 FTP-CH test to account for the proportions of cold/hot running. This latter adjustment is an example of explicit weighting.

Each weighting parameter mentioned above may be applied, in the case of explicit weighting, by a weighting factor selected from range of possible factors. An implicitly weighted cycle, on the other hand, has to be arranged to correspond to only one set of weighting factors, one of which corresponds to each weighting parameter.

Thus a large number of implicitly weighted cycles might be required if EU/ES are to be determined for a range of driving patterns and operating conditions that can occur, for example, within a city or a nation.

Explicit weighting can be applied to a single cycle, provided the weighting coefficients are defined. Further, the weighting coefficients can be applied to elements, segments or phases of the driving pattern thus providing considerable flexibility, albeit at the expense of complexity. Thus, for example, changes to driving patterns through freeway construction, computer controlled traffic signals or other factors that can change with time can be allowed for, including the "worst case" consideration of disrupted traffic flow, by re-weighting one set of measurements made over a single driving cycle.

To investigate how this last, and versatile, approach might be employed, the EU/ES functional relationship with the driving cycle is now described.

CHAPTER 4 - EMISSIONS AND FUEL CONSUMPTION DRIVING PATTERN RELATIONS

THE GENERAL METHODS

The method generally employed in modelling the relationship between EU/ES and driving patterns is summarised in Figure 4.1. It can be seen that the modelling method, as applied to either modal or transient analysis, is simply a data reduction technique to yield coefficients by regression for an appropriate function. This function may be then applied to a new driving pattern (or the original to test the modelling error) to calculate emissions and thence fuel consumption[1].

A second and more fundamental approach is shown in Figure 4.2 in which emissions are calculated from bench tests and a vehicle/ transmission model.

SOME ALTERNATIVE METHODS

Modal models[2]

The author WATSON (1973a), (1973b) developed the first Australian modal emissions model, based on the 7 mode 1968 U.S. FTP driving cycle (Refer to Appendix A). Later KINSELMAN (1974) presented a more extensive modal model based on the 37 mode SDS cycle described in Appendix B. Similar modal analysis has been initiated by KENT and RULE (1977). A critique of the modal models is presented in the Appendix, and their apparent limitations have been discussed elsewhere (WATSON, MILKINS and BULACH (1976)).

---

(1) Fuel consumption is not measured directly but from a consideration of exhaust products of combustion. Thus the measurement of fuel consumption must typically be preceded by a measurement of exhaust emissions.

(2) The modal approach involves the conversion of the driving pattern, expressed in terms of velocity and time, into a series of modes, viz., acceleration, cruise, deceleration and idle.

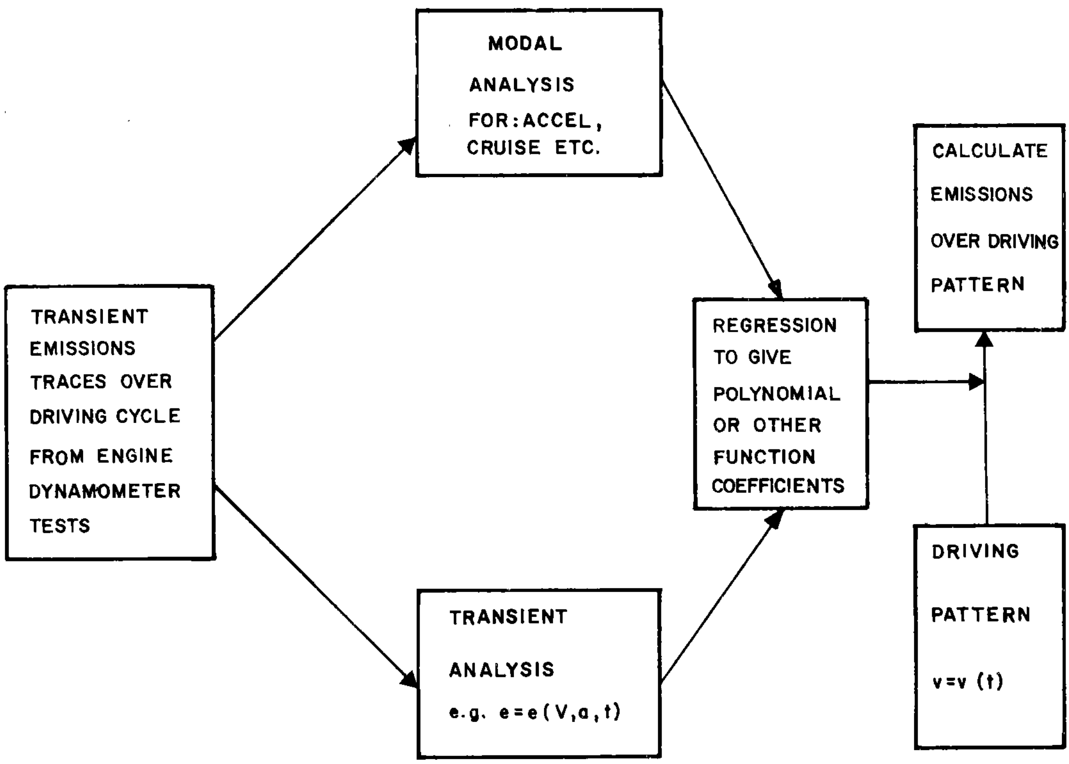

FIGURE 4.1

EMISSIONS CALCULATION FROM EMISSIONS MODELS

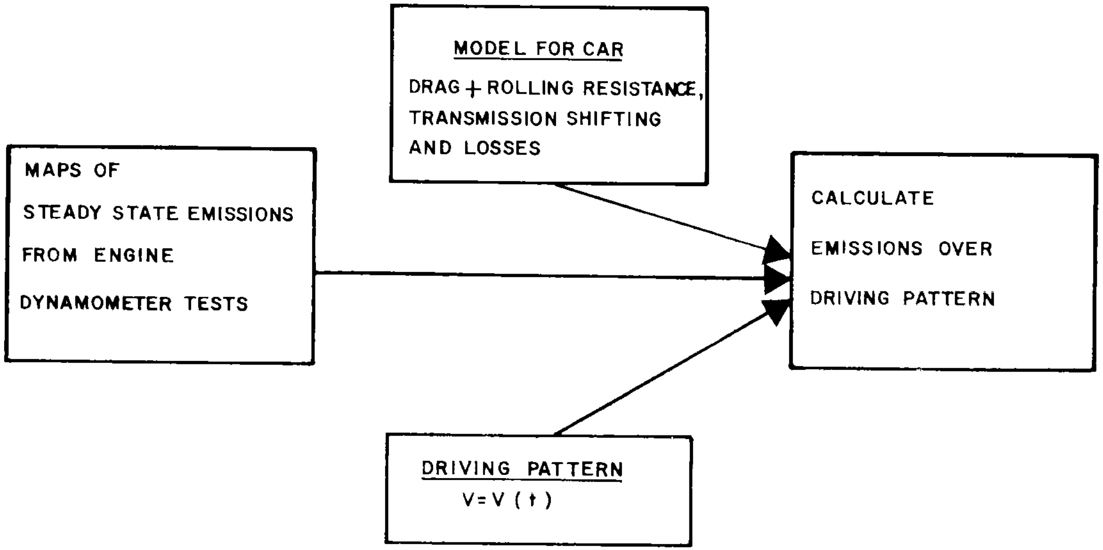

FIGURE 4.2

EMISSIONS CALCULATION FROM ENGINE DYNAMOMETER MEASUREMENTS

Transient models[1]

Recently BULACH (1977) has developed and evaluated a transient model based on continuous emissions traces from the ADR27A driving pattern.

In summary, this method expresses the emissions rate for any species "i" for a given engine as:

$$e_i = e_i\ (v,a,t)$$

where v is the instantaneous velocity
a is the instantaneous acceleration
t is the time from the start of the vehicle engine.

The time dependence may approximately be lumped into a "cold" and a "hot" component to allow for the change in emissions as the engine warms. Thus the expression may be replaced by expressions with the subscript "t" = "h" (hot) or "c" (cold). That is:

$$e_i = e_{it}\ (v,a)$$

Note that this equation is now time and sequence independent.

Using data from 6 cars in the 1.6 to 3.3 litre engine capacity range, BULACH obtained multiple correlation coefficients ranging from 0.6 to 0.9 for the regression[2] of HC, CO and NOx emissions against velocity and acceleration measured continuously (second by

---

(1) The transient approach requires that each second-by-second value of velocity is a driving pattern is taken into consideration.
(2) Highest order of the 16 significant coefficients in the polynomial expression was: a^3v^5.

second) over the ADR27A cycle. It is probable that the correlation could significantly be improved by the elimination of the variable phase lag in the CVS test procedure[(1)].

Although not included in Bulach's evaluation, fuel consumption can be included since this can be obtained by appropriate summation of HC, CO and CO_2 emissions, and the fuel-to-products reaction equation.

Steady state engine mapping models

The sequence independence of emissions and fuel consumption implied in the above expression is substantiated further by the fact that both EU/ES can be calculated from steady state (constant speed) maps of emissions and specific fuel consumption on torque-speed axes. The methodology has been described by WATSON and GOLDSWORTHY (1978). Results of application of the method are to be found in JUNEJA et al (1978), WATSON and MILKINS (1977) and WATERS (1972). In effect this method permits calculation of EU/ES from the engine operation standpoint; the vehicle speed and acceleration serving to describe the engine torque and speed and thence emissions rates and fuel flow.

PREDICTIVE ABILITY

The predictive ability of these models is now summarised in Table 4.1 to give some credibility to the methodology. In the examples selected it should be noted that none of the results are closed loop tests, involving the prediction of EU/ES from which the data was derived. Evidently, most comparisons relate to predictions of measured results over a cycle different from that yielding model

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(1) The residence time of the exhaust gas in the trunking between the car's exhaust pipe and the fresh air dilution Tee is a function of the trunking volume and engine mode of operation (accel flow rate may be 20 times idle flow rate). This should be minimised by moving the mixing Tee to the exhaust pipe.

TABLE 4.1 - SUMMARY OF MODAL, TRANSIENT AND ENGINE MAPPING MODELS' PREDICTIVE ABILITY

Model	Reference for Model Reference for Data prediction if different	Cycle from which model input obtained Cycle for which prediction made	No. of Cars	Result	HC (g/km)	CO (g/km)	NOx (g/km)	FC (l/100km)
Modal	KINSELMAN (1974)	SDS (2)	1020	Measured	4.24	46.5	2.36	
		Short FTP		Predicted	3.67	44.2	2.99	
				Error (%)	-13	-6	27	
Modal	WATSON (1973a)	US70FTP	20	Measured	3.7	56	1.9	
	COMVE (1974)	ADR27	420	Predicted	3.3	60	1.7	
				Error (%)	-11	7	-10	
Modal	KENT and	SDS	4 (1)	Measured	1.28	13.3	1.72	16.7
	RULE (1977)	ADR27A		Predicted	1.32	13.7	2.21	20.2
				Error (%)	3	3	28	21
Transient	BULACH (1977)	ADR27A	6	Measured	3.4	40	2.1	
	MOWLE (1977)	ADR27A	37	Predicted	4.1	40	2.4	
				Error (%)	20	0	14	
Engine Map	WATSON & MILKINS (1976)	-	3	Measured				13.06
	MOWLE (1977)	ADR27A	37	Predicted				12.2
				Error (%)				-6.7
Engine Map	JUNEJA (1978)	-	1 (1)	Measured	14.5	34.6	2.1	16.8
		1975 FTP		Predicted	17.9	32.2	2.0	16.4
				Error (%)	-18	-7	-4	-2

(1) Indicates same cars used for cycle/engine measurement.
(2) Surveillance Driving Schedule.

coefficients. In 3 of the examples, the error contains the additional errors associated with measurement of a different vehicle population from that used to calibrate the models.

WATSON and GOLDSWORTHY (1978) showed that the engine map model approach permitted reliable prediction of the response of fuel consumption to changing vehicle design variables. An example of JUNEJA'S (1978) predictions using the mapping method for EU/ES compared to measurement is shown in Figure 4.3.

SIGNIFICANCE OF THE MAPPING AND TRANSIENT METHODS

Steady State Mapping Method

The measurement of EU/ES on the engine dynamometer and application to calculating EU/ES has significant advantages:

- It removes the need for chassis dynamometer measurement of driving cycles and the associated errors due to:

  : the limitations of the driver in his ability to follow the driving cycle. VOLKSWAGEN (1977) estimate the driver to contribute ±10% variation to measurements

  : the effects of the inadequacies of the chassis dynamometer variously estimated between ±5% to ±30% (U.S. EPA (1977)).

- It enables allowance to be made for all combinations of vehicle variables in production, e.g. axle ratios, body styles, transmissions, air conditioning, etc. and their influence on EU/ES. In contrast, the existing certification procedures involve the selection of only some combinations of options.

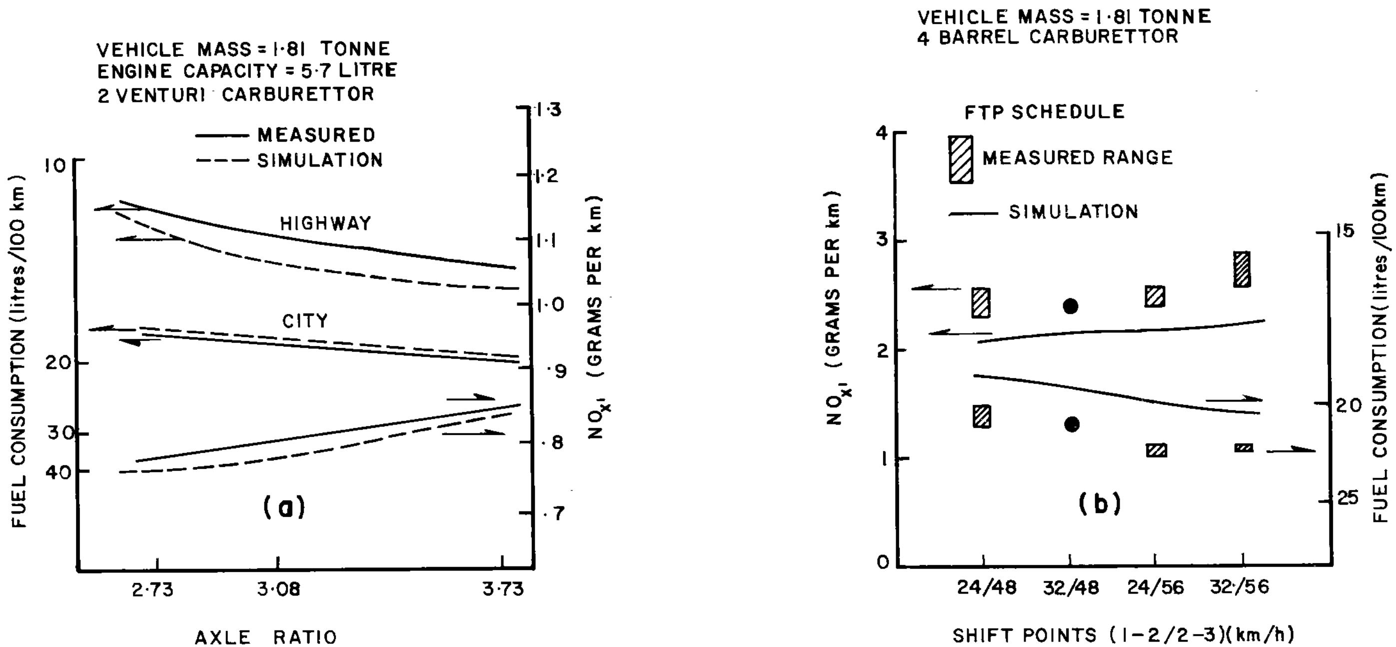

FIGURE 4·3

EFFECTS OF VARIATION OF REAR AXLE RATIOS AND GEAR SHIFT SPEEDS ON EMISSIONS AND FUEL CONSUMPTION

SOURCE :- JUNEJA (1978)

- It permits the input of the whole range of engine operation on EU/ES to be monitored and not just the limited spectrum used in current driving cycles.

- The method lends itself well to calculating emissions over any prescribed driving pattern, and might be adapted to calculation from bivariate frequency distributions.

This method is not without disadvantages, both technical and non-technical:

- There is some loss of EU/ES data with steady state engine mapping, since the transient (changing speed or load) information is not obtained. Likely overall errors for this loss appear to be about 5-10%.

- Mode must be sequenced correctly to allow for gear shifting.

- The method requires highly complex calculation procedures involving the calibration of component inputs, e.g., transmission efficiencies, drag factors, etc.

Transient method

Although the transient method requires further validation, its significant advantages in the analysis and recalculation of emissions for different driving patterns are that:

- Rather than trying to follow a driving cycle closely, the driver need only cover the full range of velocity and acceleration within the cycle.

- It eliminates the influence of driver errors in chassis dynamometer measurements of EU/ES since the EU/ES are related to the actually driven velocity and accel and not the prescribed value in the cycle.

- The functions for EU/ES, being mode sequence independent (refer to the previous section), unlike the modal models, permit calculation of EU/ES over prescribed cycles or velocity and acceleration probability density functions of the type shown in Figure 2.4.

- The method lends itself to calculation of EU/ES on a regional basis: city element, city wide or nationwide.

- It lends itself to the inclusion of traffic pattern variation: e.g., effects of new roads, time of day, and traffic engineering changes.

Implementation of the method requires consideration of the following matters:

- Not all emissions measurement facilities have digital data acquisition systems capable of recording instantaneous EU/ES, or access to the regression programs for data reduction.

- The results have particular vehicle component effects implicitly within them, since the EU/ES data must be obtained for a particular vehicle inertia, axle ratio, etc.

- The method is highly computational.

OVERALL APPRAISAL OF THE EU/ES DATA REDUCTION METHODS

The application of emissions maps for engines coupled to a vehicle simulation model offers the greatest versatility in that EU/ES and their sensitivity to changes in vehicle design variables or to traffic patterns can be evaluated. The method has the strong disadvantage of requiring a mode sequenced driving pattern or a means of replicating gear shift points observed in on-road driving if the velocity and acceleration probability density function is used. In contrast, in the transient model and modal models, the frequency of use of alternative gear combinations at a given speed and acceleration has already been accounted for in the measurement process.

Qualitatively, the modal model must suffer from integrating the whole emissions in a mode with inadequate knowledge of the weighting required to correctly assign the mode. That is, in the application of the model to a new driving pattern one may require, for example, to calculate instantaneous emissions at say 30 km/h, 1 m/s^2, and shall apply the time mean emissions of the 0-60 km/h, 1 m/s^2 accel mode to predict this. Since the emissions rate tends to be a rapidly rising function with speed at constant acceleration, the mean emissions will correspond to instantaneous emissions at a higher speed than 30 km/h, perhaps 45 km/h.

Quantitatively, the NOx (most acceleration rate sensitive) emission predictions of the modal models in Table 4.1 are seen to have large errors (+27 and 28%). The author's own modal model has less (-10%), possibly because the modal integration was carried out on exhaust concentration rather than mass emissions, as done by KINSELMAN (1974) and KENT and RULE (1977).

These qualitative and quantitative arguments lead to the conclusion that modal models should be ideally applied to modal driving patterns. However, the reduction of driving patterns to modes inevitably involves unacceptable subjectivity by the analyst in defining mode end points(1), and is not easy to do computationally, since "real" driving mode end points are not as discrete as in, for example, the Surveillance Driving Schedule.

The transient model has the greatest potential for using current chassis dynamometer emissions measuring techniques. It permits:

. use of standard dynamometer cycles for emissions measurement

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(1) Mode end points are the points which mark the changes between modes, i.e., between accel, cruise, decel and idle.

- the prediction of emissions rates over other driving cycles
- the prediction of emissions for the bivariate frequency distribution of acceleration and velocity,
- easy weighting for changes in traffic patterns and vehicle emissions control for the calculation of regional EU/ES.

The concept hinges on the emissions rate being sequence independent. This would appear to be justified providing long period changes such as engine warm up are accounted for.

The engine mapping method offers considerable flexibility and accuracy, but involves new concepts, not yet accepted in light duty vehicle emissions test procedures[1]. It involves a quite different approach to EU/ES measurement from that currently used in Australia.

CONCLUSION

The author believes that the transient modelling method of forecasting traffic pattern emissions and fuel consumption should be implemented to deal with EU/ES in the future, since it offers the best promise of precision and applicability to currently employed measurement techniques. However, the modal modelling approach may be utilised if some loss of precision can be tolerated.

The engine mapping technique coupled with vehicle/transmission models appears to offer great promise in predictive ability and versatility, but suffers from extremely complex data requirements.

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(1) U.S. heavy duty vehicle emissions standards prescribe engine bench tests for emissions.

CHAPTER 5 - AN ANALYSIS OF EXISTING DRIVING PATTERN REDUCTION METHODS

INTRODUCTION

In this section the suitability of existing driving pattern measurement techniques is examined for applying the emissions and fuel consumption measurement methods, discussed in the previous chapter.

The detailed discussion of the literature on measurements of driving patterns and the development of driving cycles is discussed in some detail in the Appendices. Appendix A deals with legislated cycles and their application to emissions and fuel consumption measurement. Appendix B describes special purpose, non-legislated cycles.

In reviewing this literature, the desired features of explicit weighting will be borne in mind. In Chapter 3 the need to account for the following variables in EU/ES estimation was discussed:

- region to region variations in driving patterns including road type variations
- weighting for variations in emissions response if the selected driving pattern is abridged from reality (e.g., reduction in maximum acceleration rates)
- proportions of trips with cold/hot starts
- the possible need for forecasting worst case situations
- weighting for time of day and other effects such as ambient conditions of temperature and pressure.

However, it will be shown that in the majority of methods already developed, implicit weighting has been preferred.

MODAL ANALYSIS METHODS

Much of the early Californian effort in driving pattern measurement was directed towards the classification of patterns by modes, that is, the proportion of travel time and the frequency of occurrence of the cruise, acceleration, deceleration and idle modes of vehicle operation as described in Appendix A. A similar approach was employed in European and Japanese research also described in Appendix A. In all this research, each mode (except idle) was classified into subsets.

"Straight-line" (constant acceleration, cruise and deceleration) driving cycles were developed which contained the major features of the measured patterns. Explicit weighting factors were used to:

- allow for the proportion of exhaust gas flow in each mode (assumed to be the same proportions for all vehicles) to convert exhaust gas concentration measurements to equivalent of g/mi (or g/km) emissions.

- allow for the frequency of occurrence of each mode.

The test method involved measuring the instantaneous emissions concentrations throughout each mode and finding the time mean values prior to weighting.

The complexity of this method and the lack of allowance for exhaust flow variations between large and small vehicles led to a search for "self-weighting" methods.

SELF-WEIGHTING METHODS

The resultant self weighting (implicit) cycles are the U.S. U.D.D.S. cycle, the Japanese 10 and 11 mode cycles and the European ECE-15 cycle. In the U.S. and Japanese test methods, controlled exhaust dilution with ambient air followed by constant volume sampling is employed, whereas in the European method all the exhaust is collected in a "big bag". The European and Japanese cycles retain straight line features, whereas the U.S. cycle is a modification of the speed-time trace of a single trip around a downtown Los Angeles route, LA-4.

In the development of the U.S. cycle, the need to represent morning peak hour traffic conditions, as the major source of photo-chemical smog precursors, was recognised. It was also thought desirable to apply in the process cycle development weighting proportional to city-wide vehicle density[(1)] in each driving condition. In the absence of any method to do this, it was decided that a cycle representing a typical home-to-work trip would suffice. Further, as discussed earlier, the cycle acceleration and deceleration rates had to be restricted because of the acceleration limitations of the Clayton chassis dynamometer employed to simulate vehicle drag and inertia.

A more detailed description of the cycles is found in Appendix A.

CRITICISM OF THE CYCLES

At the outset of the development of the Californian (7-mode) cycle, the need was seen to weight the cycle according to modal frequency and to hot and cold engine operation (by explicit weighting factors applied to iterations of the cycle).

The U.S. 1972 FTP had achieved the goal of a single measurement for each pollutant to yield cycle measurements of each emission. However, it became obvious that cold start conditions were unduly implicitly weighted in the cycle, and the revised procedure, 1975 FTP, involves cycle iteration and explicit weighting factors.

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(1) Vehicle density is defined as vehicles/hour along various road types.

With the advent of the need to regulate fuel consumption in the U.S., the Highway cycle was introduced, and explicit weighting factors were applied to this and to the urban (1975 FTP) cycle.

However, the fuel consumption projections by this method have led to considerable consumer dissatisfaction, since the fuel consumption estimates are better (higher in mi/U.S.g) than actually achieved in consumer use (U.S. EPA (1978)). It is suggested that there may need to be a further review of the fuel economy weighting factors.

Indeed, this need emphasises the proposition, previously argued, that explicit factors are to be preferred since they permit adjustments to be made to weighting factors as driving patterns change, as vehicle technology changes (to lower power-weight vehicles), and as traffic engineering measures affect driving conditions.

COMPARISON SUMMARY OF EXISTING DRIVING PATTERNS

In Figure 2.4 we saw that there were important differences between the U.S. driving cycle (ADR27A) and actual Australian driving as described by the velocity and acceleration probability density function. However, since both vehicle and road designs have many features in common throughout the world, it is not surprising to find that there are some unifying features of driving patterns.

Average speed is the most important descriptor of the driving pattern. Figure 5.1 shows that both halt frequency and delay (or idle) time are dependent on average speed for a wide range of observations in Australian and U.S. conditions, and dynamometer driving cycles.

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(1) Idle time is calculated as a proportion of trip time.

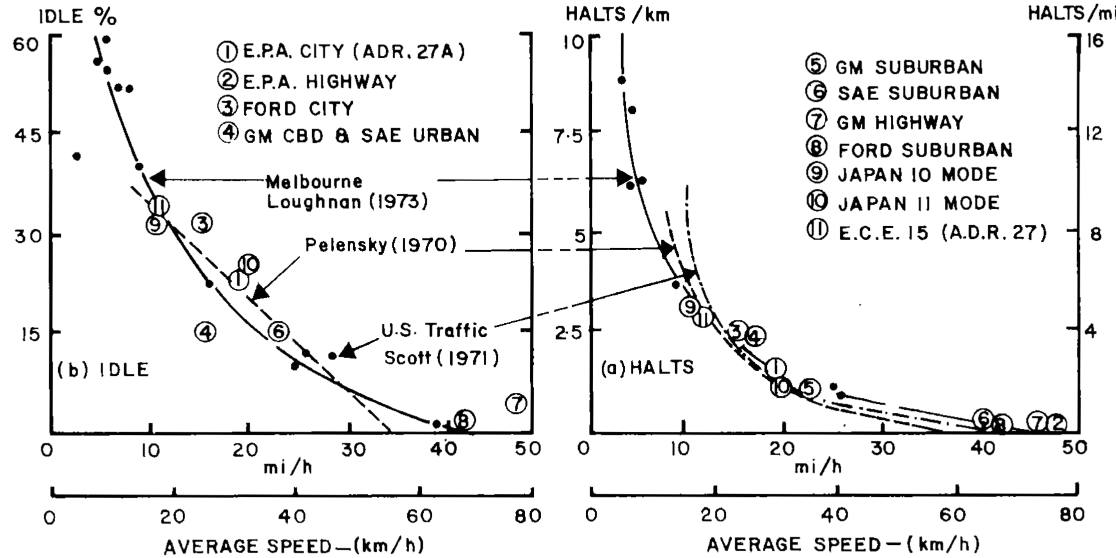

FIGURE 5·1

EFFECT OF AVERAGE SPEED OF TRAFFIC ON STOPPING FREQUENCY (Halt/km) AND IDLE OR DELAY TIME.

SOURCE : Hamilton and Watson (1977)

It is, therefore, not surprising that average speed has a predominant influence on HC and CO emissions (correlation coefficients of R = 0.99), and to a lesser extent on fuel consumption (FC), as seen in Figures 5.2 and 5.3. However, there is only a poor correlation existing between NOx and average speed (R = 0.5), as shown in Figure 5.4.

Table 5.1 provides a detailed comparison of many descriptors of driving cycles and measured on-road patterns in Europe and Australia. It should be noted that the European data represent a 24 hour average, whereas the Sydney and Melbourne data are for peak hours only.

It appears that the ADR27A cycle has an average speed representative of 24 hour driving in Australian conditions (refer Figure 2.6) rather than peak hour conditions when oxidant precursor emissions will be generated. The mean and maximum accelerations of the cycle are considerably less than those observed in Sydney and Melbourne traffic and one can expect that the cycle predicts lower NOx emissions than actually occur[1]. (HC and CO emissions will also be lower because of the average speed influence). For definitive statements a more thorough analysis is required which can only be made if the recommendations of this report are implemented.

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(1) Refer to Figure 2.2.

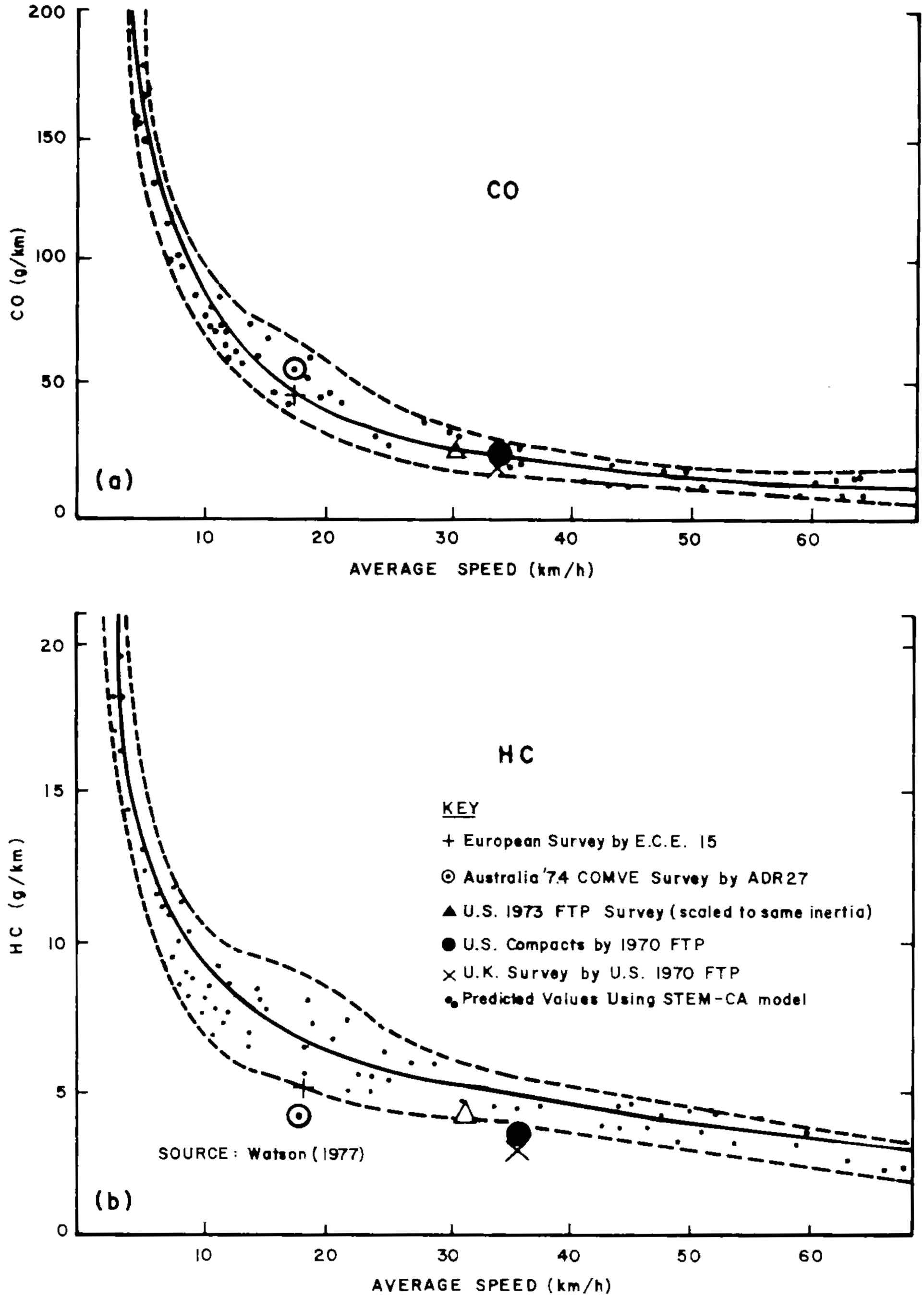

FIGURE 5·2

VARIATION OF HC AND CO EMISSIONS WITH AVERAGE SPEED ALONG A MELBOURNE ROUTE

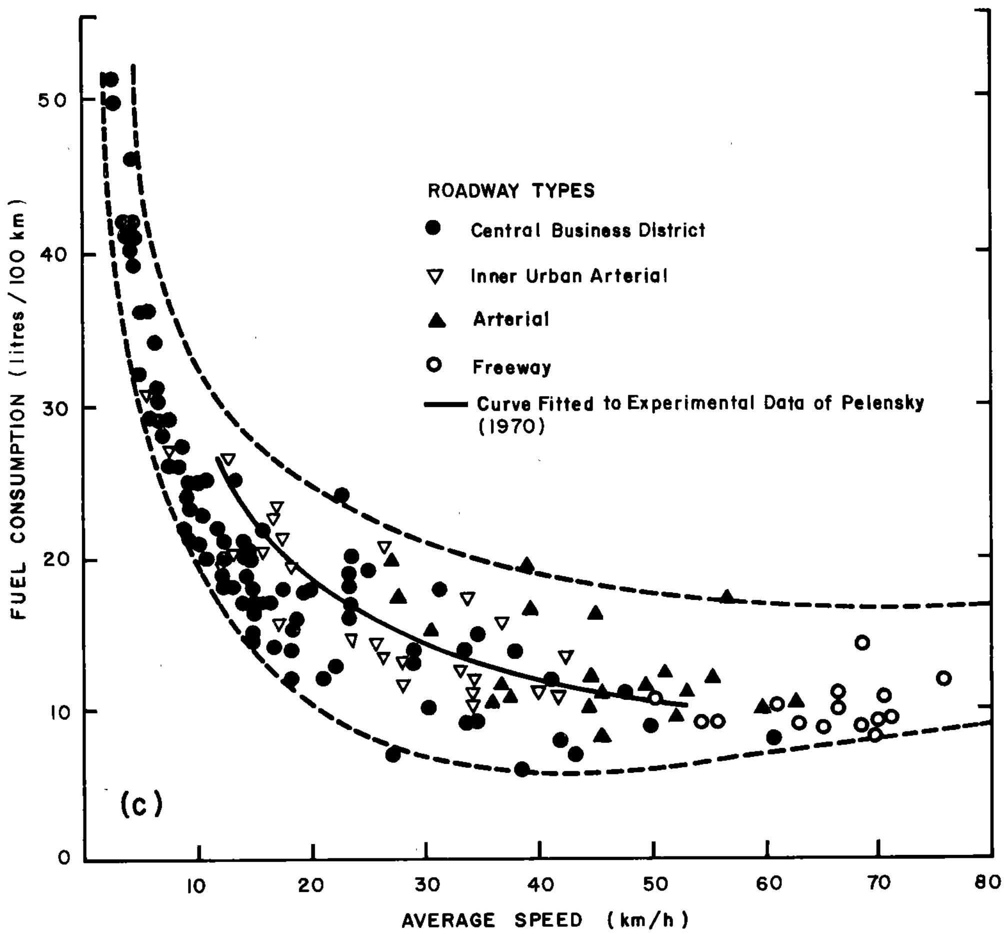

FIGURE 5·3

VARIATION OF FUEL CONSUMPTION WITH AVERAGE SPEED ALONG A MELBOURNE ROUTE

SOURCE : Watson (1977)

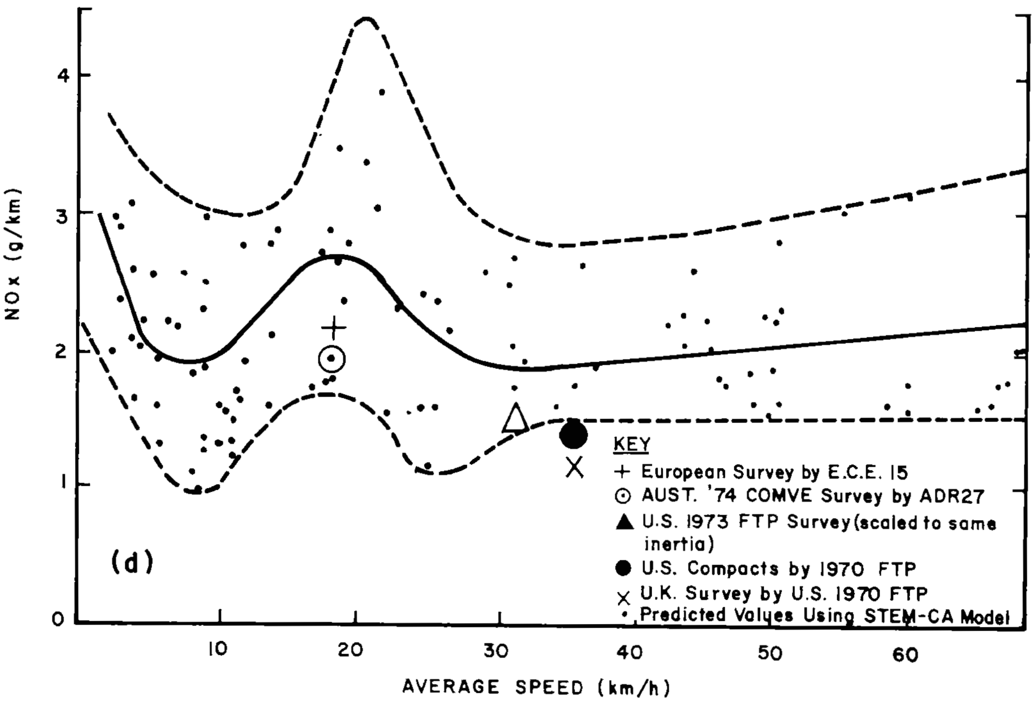

FIGURE 5·4

VARIATION OF NOx EMISSIONS WITH AVERAGE SPEED ALONG A MELBOURNE ROUTE

SOURCE : Watson (1977)

TABLE 5.1 - DRIVING PATTERN COMPARISON TABLE

	Total Length (km)	Driving Time (s)	Average Speed (km/h)	Max Speed (km/h)	Max/Mean Accel (m/s^2)	Max/Mean Decel (m/s^2)	Cruise Time (%)	Accel Time (%)	Decel Time (%)	Idle Time (%)	Stops per km (No)
ADR27 (ECE15)	4.05	780*	18.7	50	1.07 0.64	0.91 0.71	31.4	20.6	19	29	2.96
JAP.10 MODE	0.74	135*	17.7	40	0.82 0.63	1.11 0.62	26.5	21.9	25.6	26	2.72
JAP.11 MODE	3.79	476*	28.7	60	0.69 0.52	0.66 0.58	17.6	29.5	31.9	21	1.05
CALIF. 7 MODE	9.50	959*	35.6	80.5	0.67 0.64	0.76 0.65	21.1	30.3	34.0	14.6	0.74
ADR27A (US 73)	12.07	1372	31.6	91.2	1.47 0.58	1.47 0.69	20.9**	34.0	28.6	17.3	1.42
US1975 F.T.P.C-H	17.85	1878	34.1	91.2	1.47 0.59	1.47 0.70	20.5**	33.7	28.5	17.4	1.24
HIWAY CYCLE	16.48	765	77.6	96.3	1.42 n.a.	1.47 n.a.	n.a.**	n.a.	n.a.	0.78	0.06
MELB[a]	6.18 per run	942	23.6	98.6	3.6 0.74	4.1 0.68	11.9**	26.2	28.4	33.4	3.2
EUROPE[b]	-	-	30.6	115	>2.+ 0.72	>2.+ 0.72	11.9**	35.6	35.2	17.3	2.27
SYDNEY[c]	5.92	637	33.5	81	2.7 0.78	3.3 0.76	12.9	34.0	34.6	18.4	1.34

\+ under some driving conditions 50% of accels and decls >2. m/s^2.
* excludes any warm up time allowed.
** definition of allowable cruise accelerations, $-.1<a<.1$ m/s^2.
***later revised $\bar{v}$ = 27 but details not available.

(a) WATSON & GOLDSWORTHY (1978).
(b) VOLKSWAGEN (1977).
(c) RULE, ALLEN & KENT (1976)

CHAPTER 6 - RECOMMENDATIONS

GENERAL

Based on the emissions and fuel consumption calculation methods discussed previously, it is now possible to define what driving pattern data would be best suited to these methods so that EU/ES may be predicted on a regional basis. The discussion is restricted to passenger vehicles in the first instance in order to develop the approach before applying it to other vehicles.

Firstly an optimum strategy is presented with indications for the possible time phasing of components, given sufficient resources to enable all phases of investigation to be accomplished. Should the resources available be limited, an alternative approach is proposed requiring less effort and sophistication in some areas. It is recognised that it would be less precise than the preferred strategy, and may even prove to be quite impracticable. However, because of its simplicity it may prove to be more acceptable to those who find a highly computational approach untenable.

The recommendations are discussed below.

DRIVING PATTERN ANALYSIS

Data Collection

The traffic data collection task is to survey a sufficiently large quantity of roads. To reduce the size of the task, it should be noted that:

- About 50% of the VKT are travelled on about 7% of Australian roads (HAMILTON, 1977).

- Grouping similar road types into categories will further reduce the amount of data to be collected.

In traffic surveys, roads have been categorized according to simple designations (freeway, arterial, etc) (RULE et al. (1976)) or more complex ones including adjacent land use, e.g. residential and surface type. (JOHNSON et al (1975)).

In attempting to categorise roads for EU/ES purposes, it is suggested that the following factors be accounted for:

1. Vehicle density
2. Road lanes in use
3. Intersection frequency with/without signals
4. Average Speed
5. Idle time
6. Halt frequency
7. Smoothness of flow criteria, e.g. $V_{rms}/\bar{v}$
8. Route interferences, e.g. Trams
9. Road surface type
10. Road type, e.g. freeway, arterial, etc.
11. Adjacent land use, e.g. residential, industrial, etc

Additional features which may be worthy of assessment in the analysis include:

12. Position of sampling car in platoon
13. Power-weight ratio of vehicle being followed
14. Age of driver in vehicle being followed

Many of the above parameters may prove to be redundant in the proposed correlation studies with route patterns. However, if they are not observed they cannot be shown to be redundant.

It is suggested that an instrumented car and recording equipment be used to measure the traffic pattern, using the chase car technique[1] in a wide range of urban and country driving conditions. The vehicle data continuously recorded should include:

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(1) Refer JOHNSON et al (1975).

- vehicle speed, with sufficient sampling rate to obtain acceleration rates accurately by differentiation, (4 samples/second would suffice)
- gear shift position
- engine manifold vacuum
- fuel consumption rate

(gear shift position, engine manifold vacuum and fuel consumption rate: for later dynamometer validation)

Some of the pattern dependent features listed in 1 through 14 above may also be recorded continuously, or on a sampling basis.

Route Pattern Characterization

Determination of parameters which sufficiently describe the driving pattern, as has been shown in Chapter 2, is an ill defined science. The requirement is to define the emissions source and the fuel consumption with "sufficient" accuracy. If absolute values of EU/ES are needed, more precision is required in characterisation than if relative values are the goal. Thus this recommendation for characterisation involves subjective judgement based on the author's experience.

It is recommended that routes be classified according to their joint velocity and acceleration probability density function (VAPDF).[(1)] BULACH, 1977, in preliminary work, has shown that the VAPDF may be described by as few as 7 coefficients in appropriate polynomial expressions to predict emissions with less than 10% error[(2)]. Some of these coefficients represent readily discernable characteristics of the route such as average speed and idle time.

Further research is required to determine if the remaining coefficients can be related to the route descriptors 1 to 14 above.

To obtain the VAPDF with a sufficient number of data points to perform correlation tests with route descriptors, a sample along

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(1) Figure 2.4 illustrates such a function.
(2) The complementary emissions input method is presented in the next section.

all routes of about 7000s or about 2 hours duration is required. Route length must be restricted to the equivalent of about 10-15 mins travel to enable reliable values of vehicle density to be obtained. Thus if the "moving observer method"(1) is employed, then about 10 passes along each route appear to be necessary. As the data bank increases it may prove possible to reduce the data input requirements.

Assembly of Route Descriptors to Obtain Source Inventories

When the VAPDF's have been correlated with the route descriptors, the descriptors should be assembled for all routes in the region(s) to be analysed. Sensitivity analyses should be employed as to the precision required; for example, low traffic density roads may be assigned common values.

A suggested temporal breakdown of the route descriptors is:

- am peak
- day off-peak
- pm peak
- night off-peak

Special allowances will be required to handle weekday/weekend, traffic diversion special functions, and other problems delineated in Chapter 3.

VEHICLE EMISSIONS INPUT

The Initial Requirements

To finally employ the VAPDF approach to traffic patterns, vehicle emissions inventories are needed in the mode independent form, i.e. co-efficients for the transient model described in the second section of Chapter 4.

(1) Cars in the opposing traffic stream are counted from the chase car.

Since the combined VAPDF-transient emissions model approach has only undergone preliminary testing, vehicle emissions inventories for a cross section of the vehicle population are required, in conjunction with driving pattern data. Recent model vehicles should be well represented, because:

- these travel more VKT than older vehicles, and thus the average vehicle emissions coefficients should be VKT weighted.
- by the time the results of the research are applied, current model vehicles will have become older and early model vehicles will have disappeared.

The Representative Driving Cycle for EU/ES input

It would be most rational to construct a driving cycle containing the widest range of VAPDF operating conditions encountered in the traffic pattern survey. A number of short cold cycles (3x5 or 3x10 mins) and a hot cycle (say 30 mins) can easily be constructed by randomly selecting segments (idle to idle components) from all the VAPDF input data, so that the random selection has a VAPDF the same as the overall (weighted or un-weighted) VAPDF for the region. This procedure is most important as it forms the link between the mass of recorded driving pattern data and the relatively simple expression of this data in the form of a driving cycle.

It is likely that such an approach would have technical limitations and implementation problems:

- The problem of obtaining high acceleration rates (greater than $1.5 m/s^2$) without wheel spin on present emissions chassis dynamometers, (this may be overcome, perhaps by increasing the load on the driving wheels if this does not unduly increase tyre rolling resistance and tyre operating temperatures).

- The likely difficulty of many vehicles (with low power/weight ratio) not attaining the maximum accel rates specified on the VAPDF.

- The need to conduct traffic surveys and to construct the test cycle before the emissions survey could begin.

Hence it is proposed to use the ADR27A cycle as the basis for the emissions monitoring cycle and the CVS analysis system. This necessitates a correlation study on a small sample of vehicles to demonstrate that extrapolation (particularly to higher accel rates) of emissions rates, implicit in regression to the mode-independent transient model formulation $e = e_t(v,a)$, retains acceptable precision. The correlation study will involve the additional experimental measurements of emissions at acceleration rates higher than those defined in ADR27A, using a more appropriate dynamometer (with 0.5m rolls) or the tyre loading technique suggested above.

In addition to the ADR27A cycle, some further tests at constant steady speed driving are warranted, say 30s driving at each of 20, 40, 60, 80, 100 and 120 km/h, since low speed and high speed steady driving are infrequently found in ADR27A. Further, in order to obtain "hot transient" conditions it is recommended that the first 505s of the cycle be repeated, i.e. use the 1975 U.S. FTP C-H cycle.

However, if it is proven that the ADR27A cannot adequately be adapted to obtaining representative emissions functions by means of reasonable correlations, then a new test cycle will need to be developed, using the driving cycle synthesis technique proposed above.

The On-going Emissions Input

In order to provide a bank of emissions data for application of this or any other methodology, it is essential that a continuing survey of in-use vehicle emissions and fuel consumption be conducted. Until the ADR27A cycle is found wanting it should be retained, preferably extended as indicated above.

While this survey(1) work is conducted it is quite practicable to record the continuous transients emissions, using low cost(2) passive recording equipment for future data reduction by either transient or modal analysis on a large computer. The loss in vehicle throughput rate due to the extra data acquisition is deemed to be small, and insignificant compared to the value of the extra information obtained.

MODAL ANALYSES AND THEIR APPLICATION TO REGULATORY CONTROL

Modal Analyses

It must be recognised that the proposal to reduce emissions data by transient methods (mentioned earlier in this Chapter) is a relatively new approach. It is possible that on large scale application the regression correlation coefficients may not be sufficiently high to justify the present confidence in the method; or if in the future, the advent of catalyst or thermal reactor emissions control systems introduce mode sequence dependence for emissions thought to be absent in current vehicles, then it may be essential to reduce the vehicle emissions data by the modal method.

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(1) For example the proposed DOT Sydney survey of motor vehicles for emissions measurement could form the initial component of this work.
(2) A suitable 2 x 4 channel FM cassette system would cost less than $5000.

Currently for example, one motor company breaks the ADR27A cycle into 80 discrete modes, as an aid to its emissions development program. Thus emissions measured on a continuous basis could be allocated to each driving mode and reduced by regression methods to a modal emissions model. Then, either the modal emissions could be applied to the traffic VAPDF as for transient emissions,(1) or, a new modal analysis technique and route characterisation method could be developed to apply the modal emissions data. This may involve synthesising driving cycles by random selection of segments from the overall route data to obtain a VAPDF of similar form (i.e. 1st, 2nd, etc. moments) to the original VAPDF, as indicated earlier in the previous section.

Regulatory procedures using modal analyses

The foregoing recommendations imply the use of computational methods for obtaining estimates of emissions (and hence fuel consumption) for defined geographic regions.

It is probable that such a methodology could not be written into a regulation which could account for the variation over time of driving patterns, and thus of emissions weighting factors.

However, it is undoubtedly necessary that regulatory procedures should reflect as closely as is practicable the in-use operating conditions of the vehicle(2). Moreover, it will be recalled that one of the purposes of the above methods is to test how well regulations perform in practice.

Investigation is recommended of an option possible with the CVS analysis method: explicit weighting of the modes of the ADR27A cycle (or preferably 1975 U.S. FTP C-H). For fuel consumption

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(1) This strategy was not rated highly in the fourth section of Chapter 4.

(2) Otherwise the emissions changes achieved in reality will not be in accord with those achieved in the regulated driving cycle. That implies that deliberate or accidental cycle "beating" may occur because of the limited scope or implicit weighting of engine operating modes in the cycle.

measurement, inclusion of the Highway cycle in the weighting formula may require use of modal breakdown.

This can be achieved by continuous emissions analysis and integration to yield segmental breakdown of emissions for weighting; or experimentally, by collecting preferentially gas from selected phases of the cycle for subsequent weighting. The weighting factors and the phase selection would need to be selected to align with:

- the observed frequency of driving modes from the traffic pattern survey (when weighted according to VKT, etc).

- possible "juggling" to align the numbers thus produced with those predicted by the computational method for estimating regional EU/ES from emission controlled cars.

This recommendation would appear to be a solution to the problem experienced in the U.S. of customer dissatisfaction with present fuel consumption calculation procedure.

Early investigation of the applicability and acceptability of such a method is advised, before any regulatory procedures for fuel consumption measurement are adopted in Australia.

DATA COLLECTION FOR WEIGHTING FACTORS

As identified in Chapter 2, the calculation of EU/ES requires data in addition to traffic patterns and emissions. The data required include:

- statistics of vehicle population by type, e.g. engine family, transmission, weight (inertia) for each model year
- vehicle densities along roads and their temporal variations
- trip lengths and trip frequency (which determine the proportions of cold/hot starts)

- mean values and statistical variations of ambient temperature and pressure
- road gradient variations.

SENSITIVITY ANALYSES

Sensitivity analyses should form a continuing part of the evaluation of the research into traffic patterns and vehicle emissions. At the commencement, or as soon as possible, thereafter, tests should be made on the merit of including additional factors in the model thus ensuring the inclusion of only those features in the calculation method for which the end results are sensitive.

Sensitivity tests for the inclusion or rejection of data and weighting factors should be performed on both median and "worst case" emissions or fuel consumption calculations.

SUMMARY

The recommendations discussed above are summarised in terms of three major task areas, as follows:

<u>Driving Patterns</u>

- Measure a wide range of driving patterns in urban and country areas.

- Develop a means of relating driving patterns to simple, and preferably readily available characteristics or descriptors of roads.

- Assemble an inventory of these descriptors and weighting factors and thus obtain a classification of driving patterns for nationwide or regional analysis.

Emissions measurements

- For a small group of vehicles verify the suitability of the ADR27A cycle (preferably slightly modified to U.S. 1975 FTP) as a suitable reference cycle for transient emissions measurement.(1)

- If ADR27A proves to be inadequate, develop a new test cycle.

- Carry out a survey of in-use vehicle emissions to obtain a continually updated inventory of the transient emissions of the vehicle population over the selected test cycle.

Calculations

- Reduce the transient emissions data to that for the population "average" vehicle on a year by year basis.

- If the transient analysis method proves unacceptable, reduce the emissions to modal values for application in a modal emissions model.

- Develop from the data gathered an explicit weighting procedure (by selective segment bag analysis - experimentally or modal emissions analysis - computationally) for fuel economy regulatory purposes or as a crude substitute for the previous calculation steps.

Implementation of these recommendations would permit the calculation of the data required for the wide range tasks introduced at the outset of this report.

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(1) The cycle has acceleration and velocity values known to be exceeded in Australian driving conditions; but there are many reasons for retaining the cycle.

CHAPTER 7 - CONCLUSIONS

It has been demonstrated in this report that procedures for the measurement of emissions and fuel consumption cannot be separated from the analysis of vehicle driving patterns. These aspects are both integral components of the procedure for estimating fuel consumption and emissions generated by vehicles of various categories (passenger vehicles, trucks etc.) in specific geographic regions (ranging from individual streets to the entire nation) at prescribed times (ranging from peak hour through to annual averages).

To achieve such flexibility in the estimation procedure, it has been argued that the process of measuring emissions and fuel consumption should be completely separated from the weighting procedure required to account for the variation in actual driving patterns on Australian roads.

The current Australian driving cycle for emission testing, (ADR27A), which is based on the U.S. 1972 Federal Test Procedure, is seen to be unsatisfactory in that being implicitly weighted, it is difficult to adjust to account for either variations in driving patterns over time or for differences in driving patterns between the U.S. (where the cycle was developed) and Australia.

Recent U.S. test procedures (as from 1975) attempt to overcome this problem by applying explicit weights to a modified version of the 1972 (implicitly weighted) test procedure. This is intended to account for differences in engine performance caused by the fact that sometimes engines are started from cold, while at other times they are started when they are warmer. However, this is only a partial improvement since the implicitly weighted content of the cycle still cannot be readily adjusted.

The report demonstrates that emissions and fuel consumption may be measured more appropriately from an analysis of data collected on driving patterns which take into account all the variation due to road type, time of day and usage patterns across a regional or nation, together with data on the emissions and fuel consumption performance of motor vehicle engines representative of the vehicle fleet. This would provide a disaggregated basis for emissions and fuel consumption measurement which would permit the testing of alternative policies and strategies.

The driving cycle is seen to be an output from this analysis process which is convenient and useful for regulatory purposes, but which may have drawbacks, depending on its design.

The current ADR27A driving cycle should be tested for its suitability as the basis of the proposed measurement process because of the considerable experience already gained by industry with the cycle. The cycle would be utilised as a means of obtaining emissions and fuel consumption data from the moderate range of velocity and acceleration values contained in the cycle. It remains to be seen whether the limitation on acceleration/deceleration inherent in ADR27A would seriously jeopardise its usefulness in this regard. Retention of the cycle, however, has the advantage of permitting comparison of data already measured with future test information.

The recommended measurement procedure involves the combined measurement of emissions (on a second-by-second basis over a representative range of velocity and acceleration) and typical driving patterns. This would be followed by regression analysis of these emissions rates which would provide coefficients for polynomial expressions for emissions in terms of instantaneous velocity and acceleration for each vehicle in a sample of the vehicle population. These coefficients would be weighted to account for the proportions of each type of vehicle within the total vehicle fleet, distance travelled and other factors known to affect the emissions source (rate of emissions) in the regions considered. The appropriately weighted summation of the coefficients would yield the emissions values for the population average vehicle for each region and/or time period of interest. Fuel consumption values would be obtained in the usual way by analysis of the emissions data.

Should this preferred procedure prove unworkable or unacceptable, other possibly less accurate methods have been proposed. The use of these other methods would not provide the highly desirable flexibility of the recommended method.

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NOTE - re Appendices

A variety of units of measurement have been quoted in the source material used in these Appendices. Because of the problems of converting some of the data to metric, it has been decided to publish the Appendices with a mixture of metric and non-metric units.

APPENDIX A

DEVELOPMENT OF LEGISLATED DRIVING CYCLES

INTRODUCTION

This appendix is devoted to cycles which have become part of legislated emission and fuel consumption control procedures. It includes, where known, the methodology employed in the development of driving cycles, and a brief summary of the test methods as well as the cycle descriptions. Other, non-legislated cycles, are dealt with in Appendix B.

Firstly, American cycles are described, beginning with the development of the Californian 7 mode cycle, which later became the U.S. 1968 FTP (Federal Test Procedure). The change to the Los Angeles 4 (LA-4) cycle and its development to the U.D.D.S. (Urban Dynamometer Driving Schedule) cycle employed in the 1972 FTP and slightly modified for the 1975 FTP is then described. This cycle is also that used in ADR27A. The final U.S. procedure presented is the Highway cycle, also embodied in the Australian Standard AS-2077.

Secondly, the development of the ECE 15 cycle (embodied in the Australian 1974 test method ADR27) is described, and is followed by a description of Japanese cycles in the final section.

AMERICAN DRIVING CYCLE DEVELOPMENT

1950 Los Angeles County survey

This survey was undertaken in 1950, using a single vehicle along a single route. The times in the four driving modes were recorded manually, using stop watches. Complete details are not available, but TEAGUE et al (1957) summarise the findings in Table A.1.

TABLE A.1 - 1950 LOS ANGELES SURVEY

Mode	Proportion of Time (%)
Idle	18
Acceleration	18
Deceleration	18
Cruise	46
	100

1956-57 Los Angeles survey

This survey followed the identification by HAGEN-SMIT (1952) that Los Angeles "smog" was motor vehicle caused. The survey was carried out under the auspices of the Automobile Manufacturers Association, Vehicle Combustion Products sub-committee. In the traffic pattern data collection they employed a range of vehicles, experimental methods and test routes.

Seven cars were employed consisting of (then) popular models encompassing V8 and 6 cylinder engines and manual and automatic transmissions.

The experimental equipment consisted of 3 types:

1. Manifold vacuum sensor for classifying engine operation into rapid acceleration, moderate acceleration, cruising, idle, mild deceleration and rapid deceleration.

2. Counters for totalising time in ten increments of car speed, fuel consumed in each speed increment, time in each manifold vacuum condition and time of positive and negative acceleration.

3. Continuous Car Speed Measurement using a fifth wheel driven speed transducer and strip chart recorders.

Further details may be found in TEAGUE et al (1957) and STONEX K.A. (1957).

The former reference notes that "continuous speed measurements are to be considered more descriptive (than methods 1 and 2) of the automobile traffic in Los Angeles".

Nearly 60 runs were made on arterial, residential, freeway and business district routes. The results of the survey are summarised in Table A.2. The route IA is a derivative of the 1950 survey route.

A conclusion from this work worthy of special mention is the driver-to-driver variation in behaviour described in the final right hand column in Table A.2.

The outcome of analysis of the continuous speed-time traces and the data contained in Table A.2 was a recommended cycle which should contain proportions of time identified as in Table A.3. This table also details the corresponding proportion of total exhaust gas flow, as reported by HASS (1960). Note the relative importance of the accel modes.

U.S. 1968 (FTP) 7-mode cycle

This work culminated in the promulgation of the 7-mode cycle, (the original cycle proposed had 16 modes embodying the 11 operating conditions as defined in Table A.3). To obtain the 7-mode cycle, depicted in Figure A.1, the cruise modes were reduced to two at 30 and 15 mi/h, and the 0-25 accel was extended to 0-30 mi/h accel and the 0-60 and 15-30 accels replaced by a 15-50 accel. The 50-20 and 30-0 decels were combined. Weighting factors were applied to allow for two factors:

- frequency of mode of operation in urban traffic over 24 hours
- exhaust volume produced in that mode.

TABLE A.2 - COMPARISON OF LOS ANGELES ROUTES

Mode/Speed	Proportions of (average) time spent in each mode (%) (1)					Driver Diff. Mean Dev. From Mean (%)
	Route IA	Arterial road	Residential road	Freeway	Business district	
Total Acceleration	19.0	12.3	15.6	12.5	16.7	±3.8
Road Load	37.3	51.7	35.5	56.6	33.4	±5.7
Idle	19.4	11.3	20.6	12.7	29.8	±1.3
Mild Deceleration	9.0	8.3	14.0	9.6	11.7	±0.9
Rapid Deceleration	15.4	16.7	13.8	8.6	8.2	±2.8
Total (2)	100	100	100	100	100	
Average Speed, mi/h	22.3	24.6	16.4	29.6	13.2	±0.5
Number of Test Runs:						
Automatic Trans.	9	18	1	1	2	
Manual Trans (No)	16	3	2	5	3	

(1) Averages weighted for vehicle transmission type. These were figured on basis of Registration proportions of make, year and transmission type in Los Angeles County as published by Air Pollution Control District (February 15, 1956); 28% automatic, 72% manual transmissions.

(2) The totals do not exactly equal 100.0 due to rounding of intermediate data.

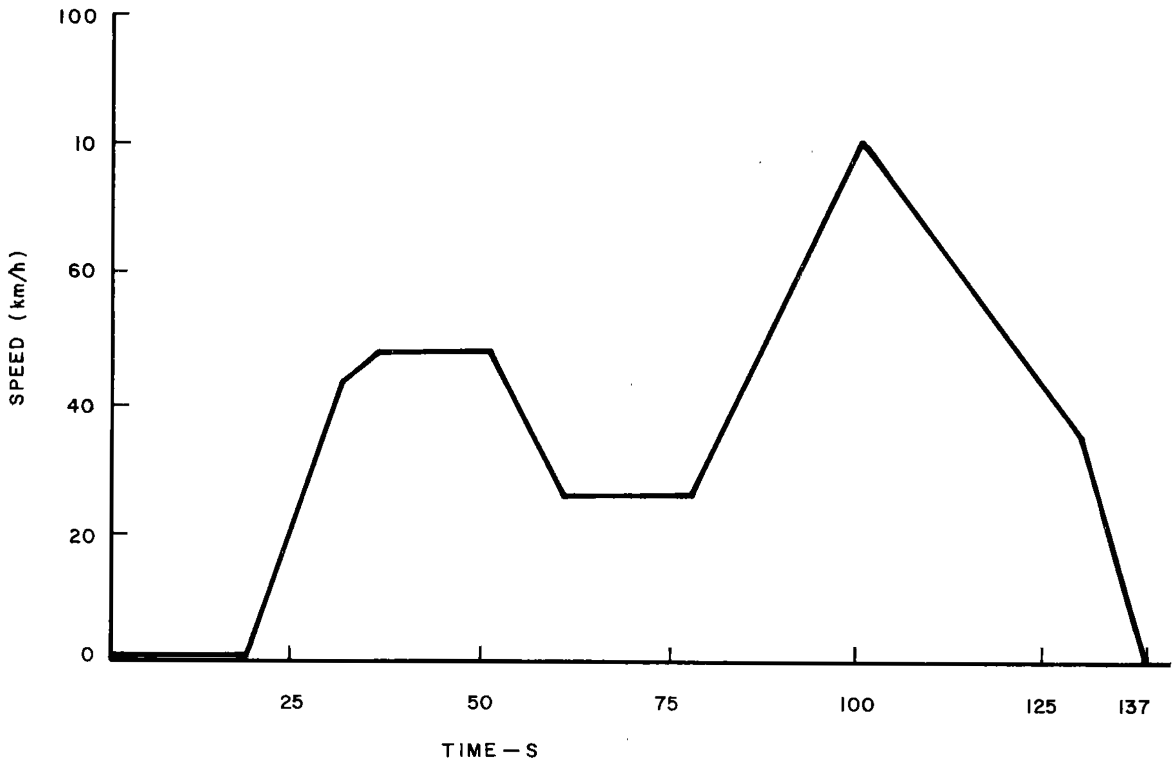

FIGURE A·1
CALIFORNIA TEST PROCEDURE FROM MODEL YEAR 1968 EMBODIED IN 1968 FEDERAL TEST PROCEDURE

Conditions:

1. Cold start (12h preconditioning min.)
2. Schedule is to be repeated 7 times
3. Continuous sampling
4. Continuous analysis and computation of data
5. Different weighting factors for each mode
6. Calculation of exhaust gas volume

Notes:

a) Influence of individual modes on the total result can be determined
b) Exhaust gas volume is determined by calculation
c) Data collection and calculation is rather extensive
d) Theoretically developed driving schedule.

Source: Fed. Register Vol 33, No. 105
Calif. Exhaust Emission Standards

TABLE A.3 - PROPOSED 1960 LOS ANGELES DRIVING CYCLE

Condition	Rate of Speed Change (mi/hs)	Proportion of Total Time (%)	Proportion of Total Sample Volume (%)
Idle	-	15.0	4.2
Cruise			
20 mi/h	-	6.9	5.0
30 mi/h	-	5.7	6.1
40 mi/h	-	2.7	4.2
50 mi/h	-	0.7	1.5
Acceleration			
0-60 mi/h	3.0	1.1	5.9
0-25 mi/h	2.2	10.6	18.5
15-30 mi/h	1.2	25.0	45.5
Deceleration			
50-20 mi/h	1.2	10.2	2.9
30-15 mi/h	1.4	11.8	3.3
30- 0 mi/h	2.5	10.3	2.9
		100.0	100.0

These factors were derived from Table A.3 and are indicated in Table A.4.

TABLE A.4 - 7-MODE CYCLE WEIGHTING FACTORS APPLIED TO EMISSIONS CONCENTRATIONS

Mode	Speed (mi/h)	Weighting Factor
1	Idle	0.042
2	0-30	0.244
3	30	0.118
4	30-15	0.062
5	15	0.050
6	15-30	0.455
7	50-20	0.029

In application the cycle was repeated (iterated) 7 times, starting with a cold engine. The "cold" cycles (1-4) were weighted by 0.35 and the "hot" cycles (6 and 7) by 0.65 and the results summed. Cycle 5 was discarded.

The Californian 7-mode cycle was adopted as the U.S. nationwide cycle and called the 1968 U.S. Federal Test Procedure.

Further Cycle Development

The need to weight emissions concentrations averaged over each driving mode of the 7 mode cycle, and the lack of any allowance for total exhaust volume variation between vehicles (especially as affected by vehicle weight) led to further research for a new cycle.

HASS et al (1966) reported that the objectives were:

- The cycle should be closed, repetitive and self weighting; that is the entire exhaust volume generated from a cycle will represent a time-volume weighted composite of the individual modes.

- The cycle should be as short as possible consistent with encompassing the "correct" speed operating modes, and contain a minimum number of modes.

- The cycle should match the reference road operation in terms of pollutant concentrations, exhaust volume and average speed.

An additional and important decision was also taken that the new cycle should represent morning peak-hour travel[1] in contrast with the 7-mode cycle which had been designed to represent 24 hour average conditions.

Peak hour trips were studied within a 12 mile radius of the vehicle pollution laboratory in Los Angeles. The duration of engine operating conditions over these trips was accumulated in 19 manifold depression engine speed categories. Then a 12 mile route

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(1) Although the importance of the early morning primary pollutant contribution to photo-chemical smog was not understood at this time.

was found which produced a very similar engine mode pattern during off-peak hours (the LA-4 route). Next a synthetic[(1)] driving cycle was established, the XC15 test cycle, which contained 18 operating modes and gave the same proportions of engine operating conditions. The average speed of this cycle was 22.7 mi/h and was of 4 minutes duration.

The XC15 cycle was shown to yield proportionally (to exhaust flow) sampled and total bag emissions of HC, CO and NOx which correlated well with those measured by proportional sampling over the LA-4 road route, thus achieving the objectives set out above.

1972 FTP Cycle (UDDS)

However, this synthetic XC15 cycle was abandoned in favour of a "real" cycle based on a speed-time tape from a vehicle actually driven on the LA-4 route (KRUSE and HULS (1973)). Since the route was 12 miles long, and the average trip length in Los Angeles was known to be 7.5 miles, segments of the 12 mile cycle were discarded to reduce the trip length to 7.5 miles. An attempt was made to preserve the proportionate time in each operating mode, so that average speed, proportion of idle time and so on remained unaltered. This paring process removed much of the low speed driving iterations to compensate for the freeway driving reductions as can be seen in Figure A.2.

The cycle was further modified by reducing maximum accel and decel rates to 3.3 mi/hs to avoid exceeding the design capability of the (203mm diameter roller) dynamometer.

This modified cycle, displayed in Figure A.3, became the Urban Dynomometer Driving Schedule (U.D.D.S.) embodied in U.S. 1972 FTP, refer FEDERAL REGISTER (1970-72) and later adopted as ADR27A, refer AUSTRALIAN DEPARTMENT OF TRANSPORT (1974).

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(1) The cycle was synthetic in that the accels and decels were "straight line", constant rate values.

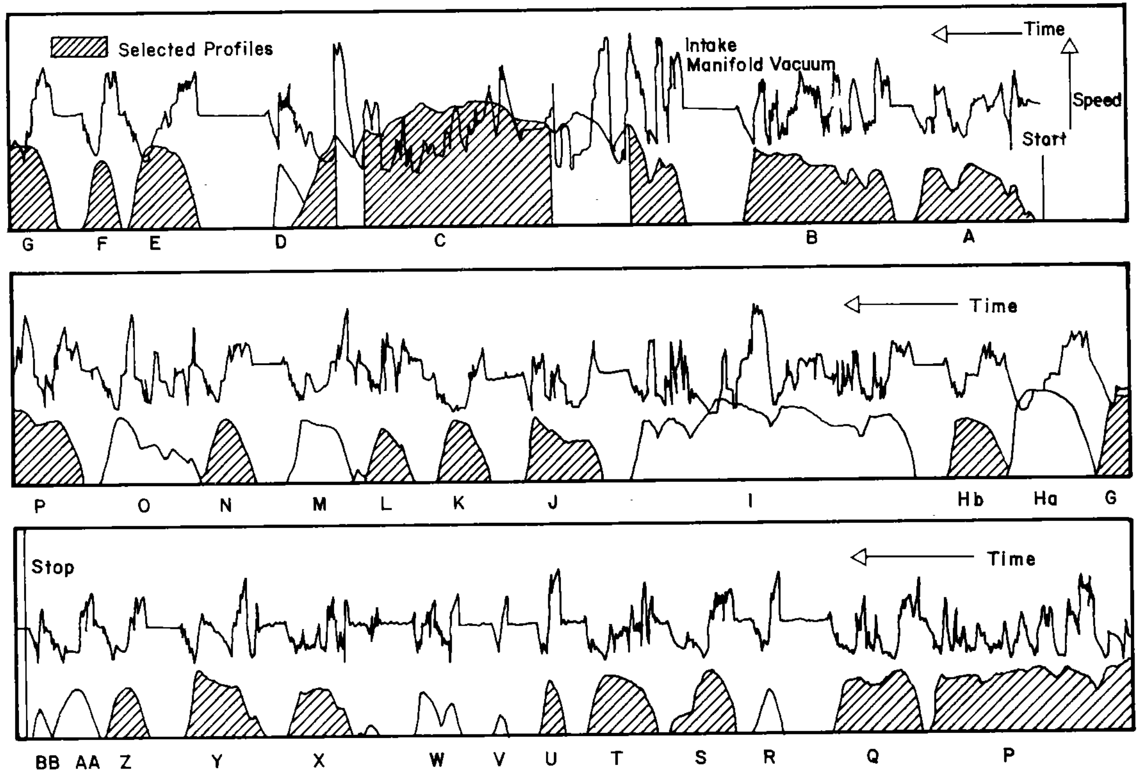
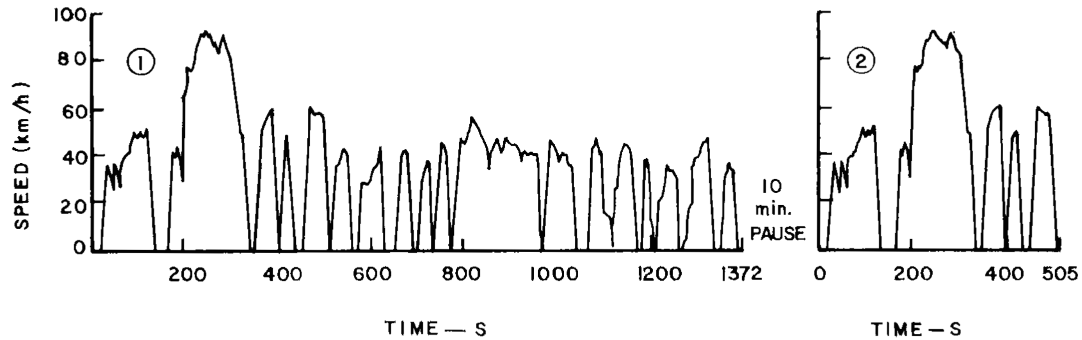


FIGURE A.2

PROFILES SELECTED FROM LA-4 TRIP TO REDUCE CYCLE DISTANCE TO APPROX. 12 km.

NOTE :— Elimination of slow speed, congested traffic segments R, V, W, etc. to compensate for inclusion of much of freeway section C.

SOURCE : Kruse and Huls (1973)



US-TEST 1972

ADDITIONAL DRIVING CYCLE WHICH TOGETHER WITH US-TEST 1972 COMPRISES US-TEST 1975 (COLD-HOT FEDERAL TEST PROCEDURE)

FIGURE A.3

US—TEST 1975 FROM MODEL YEAR 1975

NOTE : US—Test 1972 comprises U.S. E.P.A. Urban (City) Driving Cycle (equivalent to ADR 27A and AS 2077 (City))

SOURCE : (1) Federal Register Vol. 35, No. 219

(2) Federal Register Vol. 36, No. 124, June 28, 1973 and Vol. 41, No. 164, August 23, 1976

FIGURE A.3: US-TEST 1972

Conditions:

1. Cold start (12h preconditioning min.)
2. Schedule not repeated
3. Continuous sampling of diluted exhaust into one bag
4. Integral analysis
5. Determination of the diluted exhaust gas volume
6. Determination of evaporative emissions

Notes:

a) Integral analysis, no modal data evaluation
b) Test duration: 23 minutes
c) Exhaust gas volume is determined
d) Actual driving cycle obtained in Los Angeles is the basis
e) Total distance 12.1 km.

Source: Volkswagen (1977)

FIGURE A.3: US-TEST 1975

Conditions:

1. Cold start (12h preconditioning min.)
2. After 1372 sec. 10 min.
   soak with engine turned off restart and hot start driving schedule first 505 sec.
3. 3-bag sampling:
   first bag 0 ... 505 s, second bag 506 ... 1372 s.
   third bag 0 ... 505 s/2nd start (three phases of schedule)
4. Integral analysis of the three bag samples
5. Calculation of results by applying given weighting factors for the three phases
6. Determination of diluted exhaust gas volume
7. Determination of evaporative emissions.

Notes:

a) See under US-72 "Notes a,c,d"
b) Test duration: 41 minutes
c) Analysis of extreme low concentrations
d) Total distance (US-1972 and US-1975) 17.9 km.

Source: Volkswagen (1977)

The emissions rates over the modified cycle were shown to correlate well, R = .77, .94 and .99, for HC, CO and CO_2 respectively with emissions of 5 vehicles over the complete LA-4 cycle. Significantly no correlation or explanation for the absence of NOx data is reported. It can be expected that NOx emissions would have had a less satisfactory correlation, because of the sensitivity of NOx emissions to changes in acceleration rates (discussed in Chapter 2) in contrast to HC, CO and CO_2 rates which are essentially average speed dependent and which remained unaltered between LA-4 and U.D.D.S.

The U.D.D.S. cycle is a cold start cycle driven once only. In the modification for the 1975 U.S. FTP the first 505s is repeated at the end of the 1372s cycle, after a 10 minute soak.

This change was motivated by two factors:

- The Cape-10 project results, refer SCOTT (1971), indicated that the average vehicle, in the 5 cities traffic pattern survey, made 4.7 starts per day and therefore there was need for more "hot" weighting to the emissions cycle,

- the morning peak hour traffic was not the sole contributor to the smog problem, but also later-in-the-day emissions participate in the photo-chemical reaction.

Yet recently DIMITRIADES (1977) states that "the effect of fresh precursor influx into the reacting system (simulating the morning peak input) has not been determined".

U.S. Highway Cycle

The Highway (non-urban) cycle was developed (AUSTIN et al. 1974) as the counterpart of the 1972 FTP which related to urban driving conditions. It was designed to:

- reflect driving on a variety of non-urban roads

- be self-weighting (i.e., have the correct proportion of travel on each road type)
- be of a length equal to the average trip in a non-urban area
- preserve the non steady-state nature of real world driving
- have an average speed and number of stops per mile equal to that experienced in non-urban driving

The characteristics of U.S. non-urban roads are listed in Table A.5.

TABLE A.5 - ANALYSIS OF U.S. NON-URBAN ROAD TYPES

Road Type	Total Non-urban Road Length (%)	Non-urban VMT (%)
Principal arterial	3.7	39.5
Minor arterial	5.5	22.4
Collector	22.4	23.9
Local	68.4	14.2
Total	100.0	100.0

A test vehicle[(1)] was driven over 1050 miles of non-urban road in the Michigan-Ohio-Indiana area to generate the speed-versus-time traces that were used to construct the composite non-urban cycle. The principal arterial mileage used to develop the cycle was taken from driving done only in Ohio where the official speed limit had been 55 mi/h for several months. Three different drivers were used during the data collection phase. Drivers were instructed to flow along with traffic, that is, to pass as many cars as passed them. An observer was present on each trip to monitor the equipment and to make notes pertaining to the speed-time trace generated by the vehicle.

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(1) The test vehicle was a 1971 model Ford Ranchwagon with 429 CID-4V engine, 3-speed automatic transmission and a 2.75 ratio rear axle.

To facilitate the analysis of the charts, they were identified according to route number and were reviewed and verified by the route observers. They identified route segments according to type of road, determined which segments represented urban driving (those having a population above 5000) and deleted the urban segments. Data reduction consisted of tabulating route speeds at 15 s intervals to determine the maximum, minimum, and average segment speeds. Total segment time, distance, number of stops, and number of major speed deviations per mile for each segment were calculated. A speed deviation was defined as an excursion greater than ±5 mi/h from a line connecting end-point velocities on 1.5 minute intervals of the entire segment. These data, presented in Table A.6, were compiled from all of the charts and the average (target) characteristics were determined for each road type.

TABLE A.6 - OBSERVED CHARACTERISTICS OF U.S. NON-URBAN DRIVING

Road Type	Average Speed (mi/h)	Stops/ mile	Speed Deviations/ mile
Principal arterial (A)	57.16	0.0100	0.070
Minor arterial (B)	49.42	0.0575	0.439
Collector (C)	45.80	0.1260	0.484
Local (D)	39.79	0.2360	0.598
Composite	49.43*	0.0800	0.327

$$\text{*Composite speed} = \frac{1}{\left(\frac{0.395}{V_A}^{(1)} + \frac{0.224}{V_B} + \frac{0.239}{V_C} + \frac{0.142}{V_D}\right)}$$

(1) Proportions used in calculation are from Table A.5.

The next step in the cycle construction process was to locate segments of the actual speed-time traces that would approximate these average characteristics and would produce a composite cycle roughly 9.9 miles long. This meant, for example, that a section of strip chart from operation on a minor arterial had to be located having an average speed of 49.42 mi/h, containing 0.0575 stops and 0.439 speed deviations/mile, and measuring 2.22 miles in length.

Segments of the strip charts that came close to meeting the criteria shown in Table A.6 were then checked for their compatibility with each other. It was necessary to arrange the various segments in such a way that the vehicle speed profile at the end of one segment would match the vehicle speed profile at the beginning of the next segment. The composite cycle, composed of four segements taken from the strip charts, is shown in Figure A.4.

Two seconds of idle occur at the beginning and the end of the cycle to account for the portion of idle operation that analysis of the strip charts indicated would be experienced in this length of non-urban driving. Data is not available in the source document on the time duration of the segments corresponding to each road type.

The final step in the cycle development process was to run the cycle on a chassis dynamometer. Several organisations that tested the non-urban driving cycle reported that the initial acceleration and final deceleration rates were high enough to sometimes cause belt slippage on dynamometers with belt-driven inertia weights. Calculations show that the rates were about 4.9 mi/hs. To facilitate running the non-urban cycle on belt-driven dynamometers without causing abnormal slippage and wear, the first 10 s and the last 20 s of the cycle were modified slightly to reduce the acceleration and deceleration to less than 3.3 mi/hs. These modifications are stated to have no significant effect on the fuel economy a vehicle will achieve driving the cycle, probably because of the short duration over which the cycle was modified compared to the total duration.

Table A.7 shows the characteristics of the final version of the non-urban cycle compared to the target characteristics. The values in parentheses are the target characteristics determined from the analysis of the strip charts for all 1050 miles of test car operation.

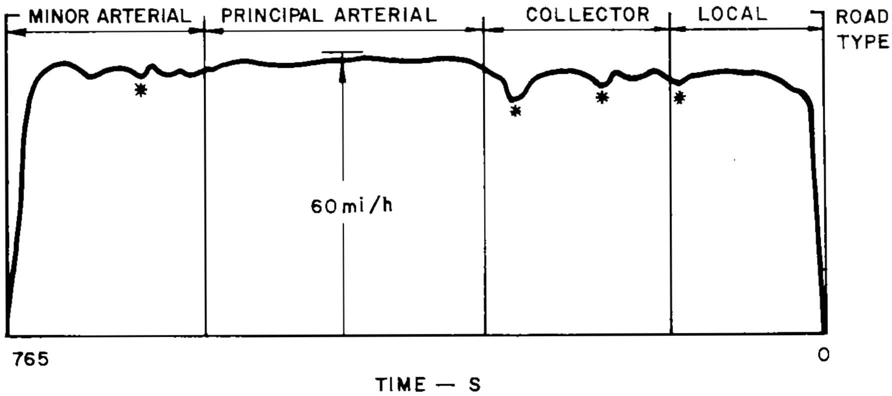

FIGURE A·4

US-EPA HIGHWAY TEST PROCEDURE

NOTE : Procedure is identical to AS 2077 (Highway Cycle)
✱ Indicates the locations of speed deviations (see text)

SOURCE : Austin, Hellman and Paulsell (1974)

TABLE A.7 - U.S. NON-URBAN DRIVING CYCLE CHARACTERISTICS SHOWING TARGET AND ACTUAL VALUES

Road Type	Average Speed (mi/h)		Speed Deviation/ Mile		Stops/Mile		Length (Miles)	
Principal arterial	(57.2)[1]	56.1	(0.070)	0	(0.0100)	One stop for entire cycle	(3.91)	3.96
Minor arterial	(49.4)	48.2	(0.439)	0.397	(0.0575)		(2.22)	2.52
Collector	(45.8)	43.8	(0.484)	0.952	(0.1260)		(2.37)	2.10
Local	(39.8)	40.7	(0.598)	0.617	(0.2360)		(1.41)	1.62
Composite	(49.4)	48.2	(0.327)	0.391	(0.08)	.098	(9.9)	10.2

(1) Numbers in parentheses indicate the target values.

EUROPEAN TEST CYCLES

The French have been almost entirely responsible for the development of the European test cycle. CHAPOUX and DELPEYROUX (1966) report the early development of a cycle to simulate Paris driving. Two routes, a north-south (8.4 km) and east-west (11.25 km) were selected in Paris, and continuous traces of engine speed, engine manifold depression, brake usage, and gear selection were recorded in two vehicles driven over the routes. Analysis of the resulting traces yielded data similar to that obtained in the Los Angeles research of TEAGUE et al (1957) and the construction by U.T.A.C. of a 11 mode cycle which contained model times as indicated in Table A.8 and further detailed in Table A.9 with appropriate weighting factors for continuous emissions analysis as per U.S. 7 mode cycle methods.

TABLE A.8 - COMPARISON BETWEEN PARIS DRIVING, U.T.A.C. AND ECE 15 CYCLES

Mode	Proportion of time in driving mode (%)		
	Paris	U.T.A.C. cycle	ECE 15
Accel	32	15.6	20.6
Cruise	13	52	29
Decel	22	13.4	19
Idle	33	19	31.4

TABLE A.9 - U.T.A.C. CYCLE AND WEIGHTING FACTORS FOR EMISSIONS TESTING

Mode	Speed (km/h)	Weighting factor
1	Idle	.073
2	0-20	.331
3	20	.064
4	20-40	.362
5	40	.033
6	40-25	.071
7	25	0
8	25-60	.052
9	60	.011
10	60-25	.003
11	25-0	0

Under the auspices of the E.C.E., GRPA[1] carried out studies of driving patterns in 10 European cities, according to SWEDISH M.O.T. (1971), and recommended modification of the U.T.A.C. cycle to that shown in Figure A.5. This cycle was legislated under ECE 15 regulations and was adopted as ADR27 for testing certification vehicles for the period 1974 to June 1976. The concept of modal weighting in the U.T.A.C cycle was abandoned in favour of collection of all the exhaust gas from the cycle, iterated 4 times, in a big bag. The vehicle was cold started for this test after an appropriate soak period.

JAPANESE TEST CYCLES

The 1969 Japanese test cycle consisted of a simple accel, cruise, decel and idle cycle iterated 7 times with increasing cruise speed increments of 10 km/h to 70 km/h and thus varying cycle time, since constant accel and decel rates were maintained.

In 1973 the previous cycle was abandoned, JAPAN (1973), and replaced by the 10 mode cycle. This was a hot start cycle and was intended to simulate Tokyo driving. In 1975 the 11 mode cold start cycle was added to the legislated test procedure.

The low speed 10-mode cycle is typical of urban transient conditions (SIMANAITIS (1977)) with very low maximum speed (40 km/h) whereas the cold start cycle is more typical of suburban driving.

The 10 and 11 mode cycles are shown in Figures A.6 and A.7.

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(1) Groupe des Rapporteurs sur la Pollution Atmospherique.

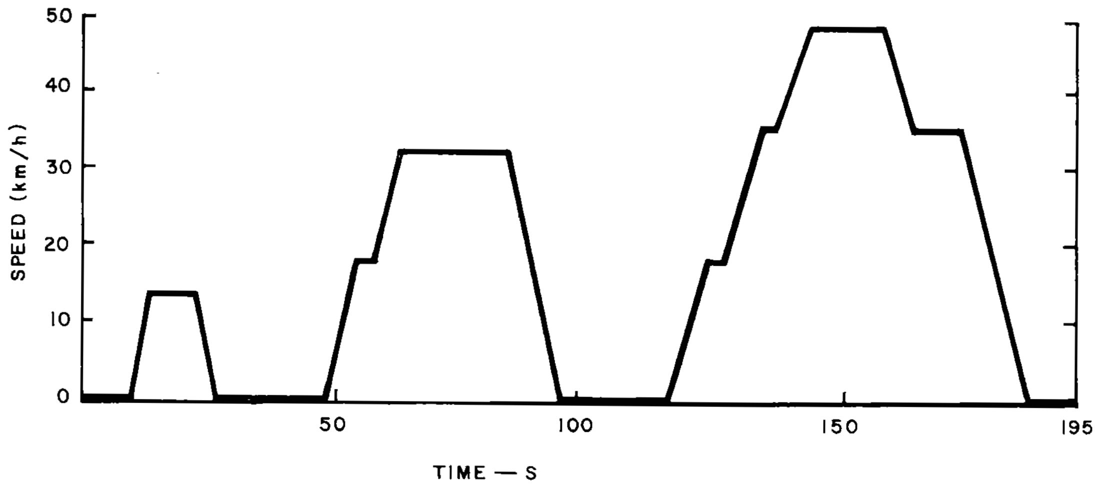


FIGURE: A·5

EUROPEAN TEST FROM MODEL YEAR 1970 (ECE 15)

Conditions:

1. Cold start (6h preconditioning min.)
2. The three phases are repeated four times
3. Continuous sampling of total exhaust volume into one bag
4. Integral analysis
5. No modal break down of results
6. Exhaust gas volume is determined directly

Notes:

a) Determination of NOx is dubious
b) Test duration: 13 minutes
c) Cranking phase is excluded
d) Theoretically developed driving scheme
e) Total distance 4.1 km.

Source (diagram) : Official Journal of the European Communications No L 76 1 Council Directive May 1974 (74/290 EWG)

Source : (Conditions and Notes) Volkswagen (1977)

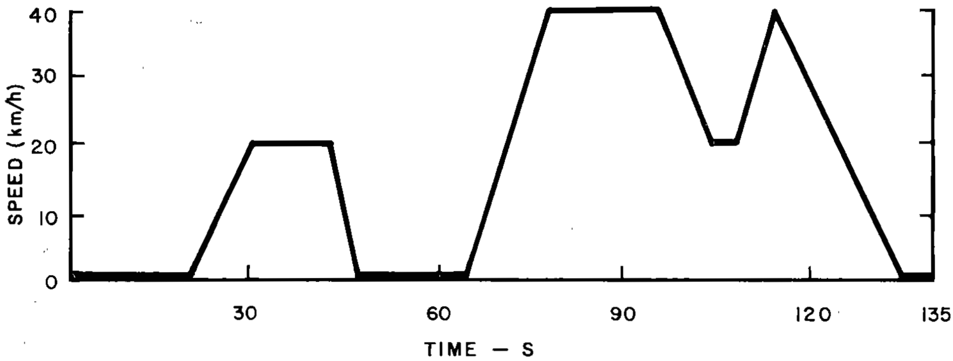


FIGURE A-6

JAPAN –TEST FROM APRIL 1, 1973 (10 Mode–Cycle)

Conditions:

1. Hot start (stabilized)
2. Driving schedule six times repeated (one pre-cycle)
3. Continuous sampling of diluted sample into bag
4. Integral analysis
5. No modal breakdown of results possible
6. Determination of exhaust gas volume
7. Determination of evaporative emissions

Notes:

a) Integral analysis comparable to US 72 test
b) Test duration: 14 minutes
c) Determination of volume analog US 72 test
d) Theoretically developed driving schedule
e) Test is driven as hot start
f) Total distance 4.0 km.

Source: Volkswagen (1977)

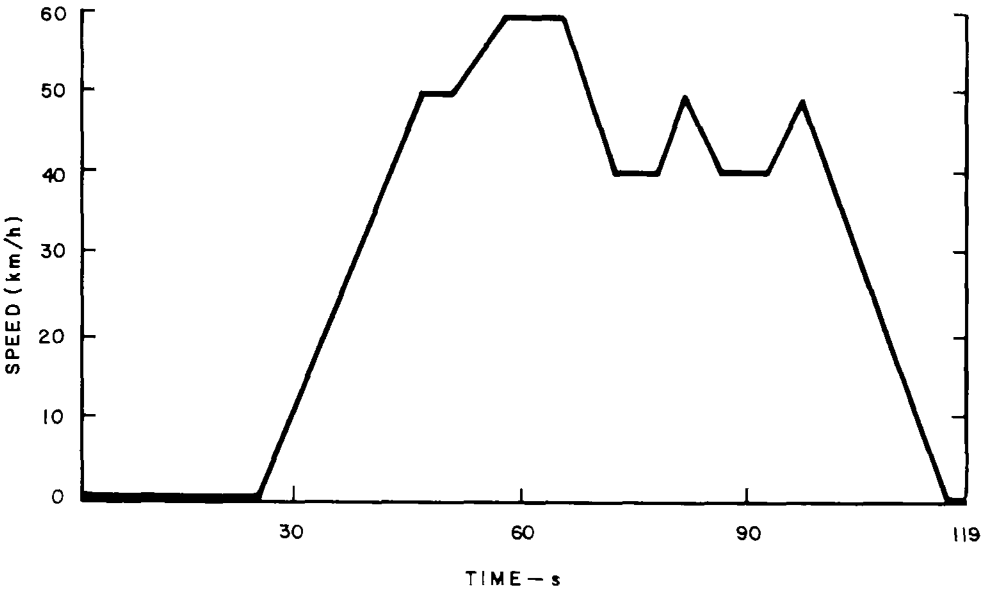


FIGURE A·7

JAPAN—TEST FROM APRIL 1, 1976 (11 Mode—Cycle)

Conditions:

1. Cold start
2. Driving cycle is 4 times repeated
3. Continuous sampling of diluted gas sample into one bag
4. Integral analysis
5. No modal breakdown of results
6. Determination of exhaust gas volume
7. Determination of evaporative emissions

Notes:

In general this test agrees with the 10 mode test.
Exceptions are:

a) Cold start
b) Increased power demand on engine
c) Total distance 4.1 km.

Source: Volkswagen (1977)

APPENDIX B

SPECIAL PURPOSE DRIVING CYCLES

INTRODUCTION

This section describes some special purpose cycles: cycles designed for the measurement of pollutants in worst case situations, or for a specific parameter, e.g. fuel consumption or sulphate emission.

Firstly, the modal emissions cycle, the S.D.S. cycle is presented. Next the development and function of the S.A.E. fuel economy procedure is outlined. Short cycles for in-field use or end-of-line testing are followed by a specialised cycle for sulphate emissions studies. Finally, the recent German proposal for a new emissions cycle is examined.

THE SURVEILLANCE DRIVING SCHEDULE

In 1971, the Surveillance Driving Schedule (SDS) was developed by the U.S. E.P.A. to measure vehicle emissions over a variety of steady state and transient driving conditions, refer to CALSPAN (1974). The acceleration and deceleration modes represented in SDS consist of all possible combinations of the following five speeds: 0, 15, 30, 45 and 60 mi/h. The average acceleration or deceleration rate observed for each mode in the Los Angeles basin is used during the operation of 20 of the 26 transient modes. The remaining 6 transients are repeated using accel rates higher (average accel 2.4 mi/hs, 1.07 m/s^2) or lower (1.305 mi/hs, 0.58 m/s^2) and similarly average decel rates higher (-3.0 mi/hs, -1.34 m/s^2) and lower (-1.25 mi/hs, -0.56 m/s^2) to determine the effect of accel/decel rates on emissions. These accelerations and decelerations were chosen to represent the full range of accelerations and decelerations observed in the CAPE-10 project (SCOTT (1971a)).

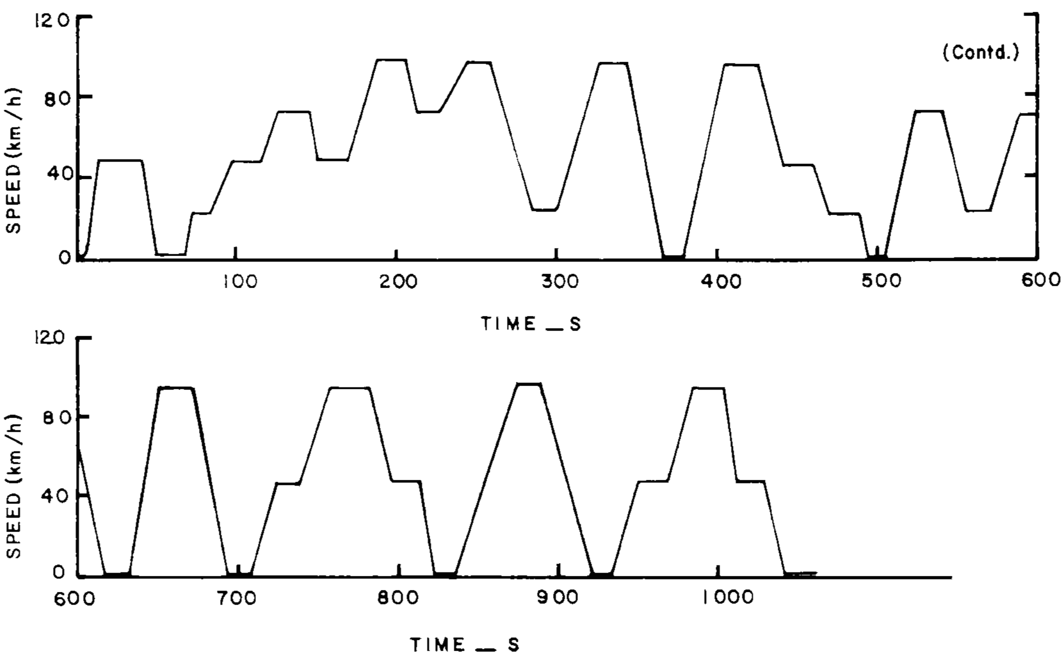


FIGURE B.1

SURVEILLANCE DRIVING SCHEDULE (SDS) CYCLE USED FOR MODAL EMISSIONS ANALYSIS

SOURCE : KINSELMAN (1974)

The cycle has been specially plotted for this report in Figure B.1. The standard accel/decel combinations are from time 0 through 618s. The special accel/decel combinations constitute the remaining component of the cycle to 1054s total.

The joint velocity and acceleration probability density function cycle is compared with Australian driving in Figure B.2.

Application of the modal emissions data permit the specification of coefficients in a mathematical model. These coefficients describe, when applied in an appropriate expression, the prediction of:

- emissions rates at steady speeds,
- fleet average emissions rates, given the appropriate weighting (for population,VKT etc.) of the coefficients and their summation.

It will be noted that emission rates for acceleration are calculated as deviations from the steady state for individual vehicles.

The model worked satisfactorily for HC and CO (prediction errors less than 20%), but errors for NOx predictions were large, as much as 40-60%, and this, in this author's opinion, arose not in the experimental data and associated errors with the experimental methods, but rather in the way in which the emissions rate integral was lumped to describe the per mode emissions. BULACH (1977) (page 158) has shown that regression of instantaneous rather than modal emissions can lead to good NOx predictions (maximum error 20%) and it was shown that poor correlation (R = .76) exists between modal model predictions over a transient cycle, compared to the use of a modal model applied to a modal cycle (R = .91). Best prediction is achieved when a transient model is applied to a transient cycle.

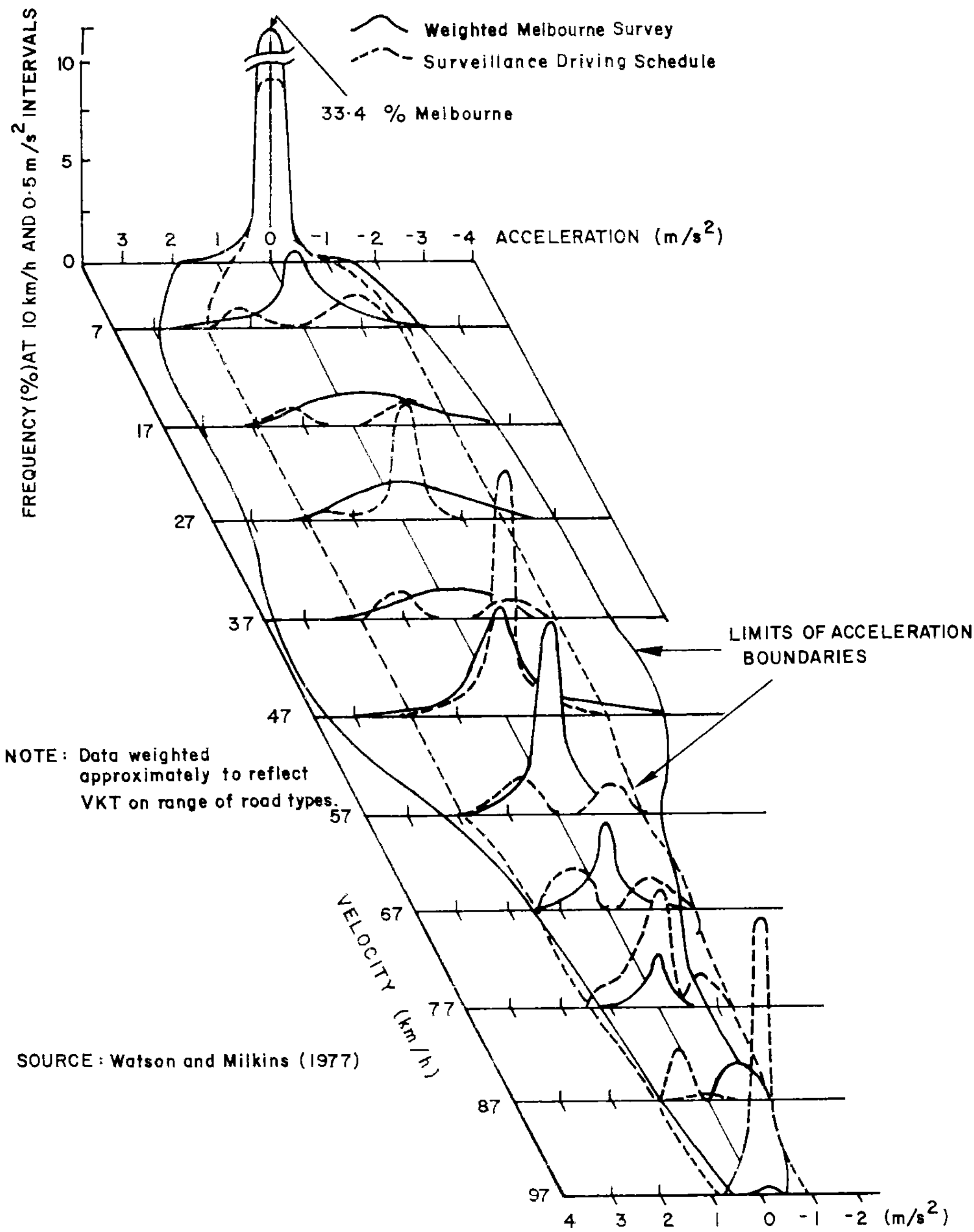


FIGURE B·2

COMPARISON BETWEEN JOINT VELOCITY-AND-ACCELERATION FREQUENCY DISTRIBUTIONS OF SURVEILLANCE DRIVING SCHEDULE AND OBSERVED MELBOURNE DRIVING

SAE FUEL ECONOMY CYCLES

The SAE fuel economy cycles were adapted from those of various U.S. auto manufacturers. The object was to establish a road/test track fuel economy procedure with secondary efforts being applied to the development of a laboratory dynamometer procedure. The primary result is now established in SAE Fuel Economy Measurement - Road Test Procedure J-1082. Further details may be found in SAE (1975).

Details of the selected cycles are summarised in Table B.1 and the cycles are depicted in Figure B.3.

It is an important feature (although not specifically emphasised by the authors) that the accel rates are generally higher than those observed in U.S. driving, as shown in Figure B.4. Because of the rapid increase of fuel consumption with acceleration rate, it would be necessary to weight the higher accels more than the lower ones in the calculation of fuel consumption.

The ability of these procedures to predict the fuel economy of 4 vehicles (with special fuel consumption instrumentation) in normal consumer use in two U.S. states is shown in Figure B.5.

One must conclude on this evidence that the SAE cycles have appropriately weighted modes for fuel consumption measurement of American vehicles, and because of the range of average speeds covered in the four cycles (26, 68, 81 and 113 km/h) they lend themselves to further weighting for application to national EU/ES calculations.

Enquiry with SAE (U.S.) for information with progress on the dynamometer cycles could yield more useful information.

TABLE B.1 - SAE TEST TRACK FUEL ECONOMY CYCLES

Cycle (Source Company)	Av. Speed (km/h)	Distance (km)	Stops/ Km (No)	Idle Time (%)	Accel Rate (m/s^2)	Decel Rate (m/s^2)	Road Load Speed (km/h)
Urban							
(G.M.)	25.6	3.22	2.49	13.3	1.78 (1)	-1.53, -1.84	24.1, 32.2 40.2, 48.3
Suburban							
(Ford)	67.6	8.37	0.25	1.4	.92,1.53, 2.15	-1.53, -3.07	64.4, 80.5 96.6
Interstate (50	80.5	7.56	0	0	0.31	-0.31	80.5
(Chrysler) (70	112.6	7.56	0	0	0.31	-0.31	112.6

(1) Initial rate, subsequently constant throttle position maintained.

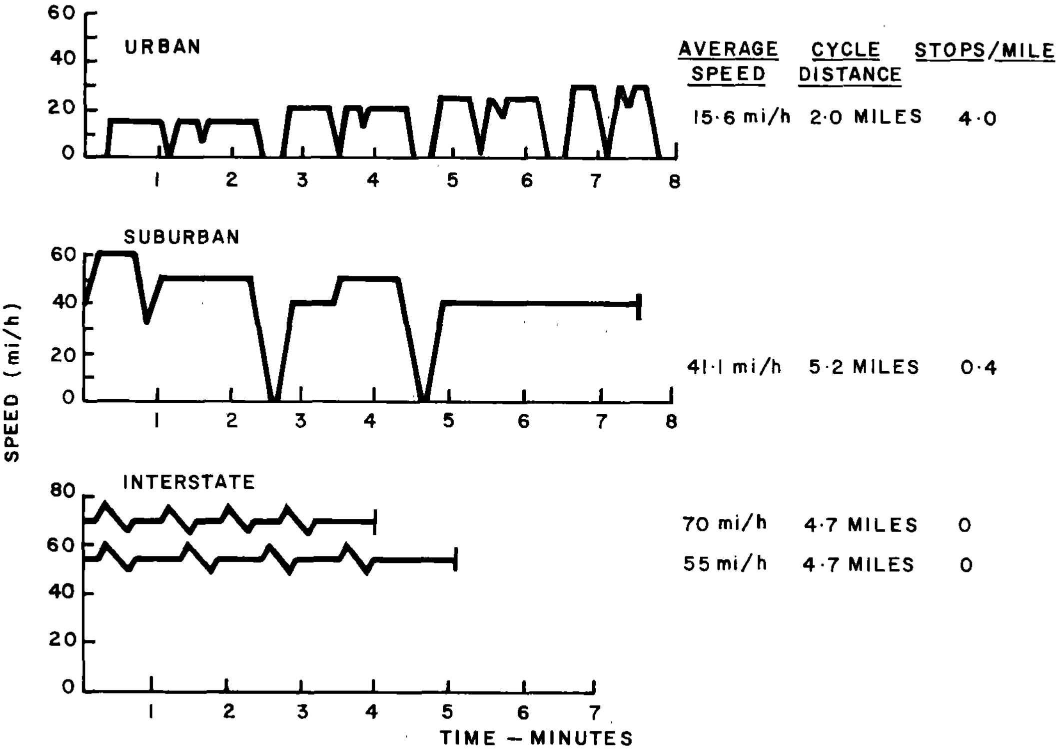


FIGURE B.3

S.A.E. FUEL ECONOMY CYCLES FOR ON-ROAD USE

SOURCE: S.A.E (1975)

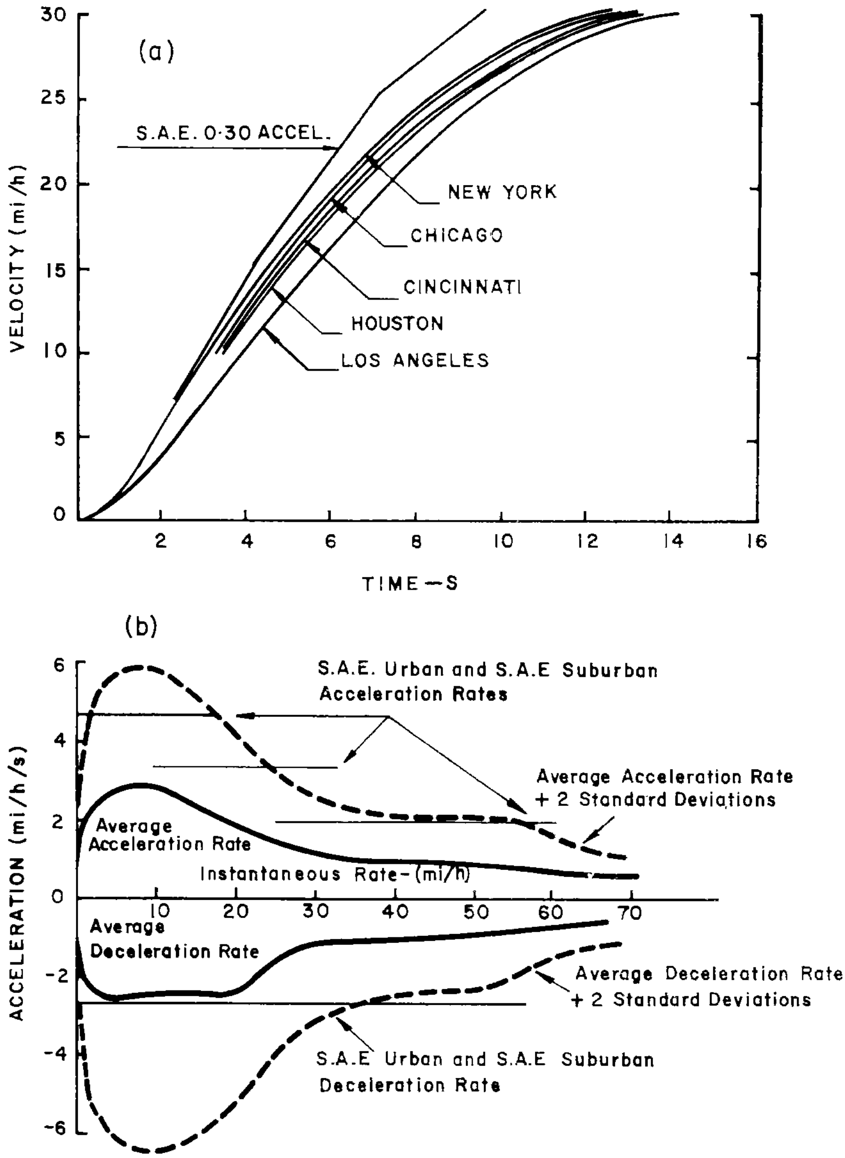


FIGURE B·4
COMPARISON OF ACCELERATION: S.A.E FUEL ECONOMY CYCLE AND U.S. 5 CITY SURVEY

SOURCE: S.A.E. (1975)

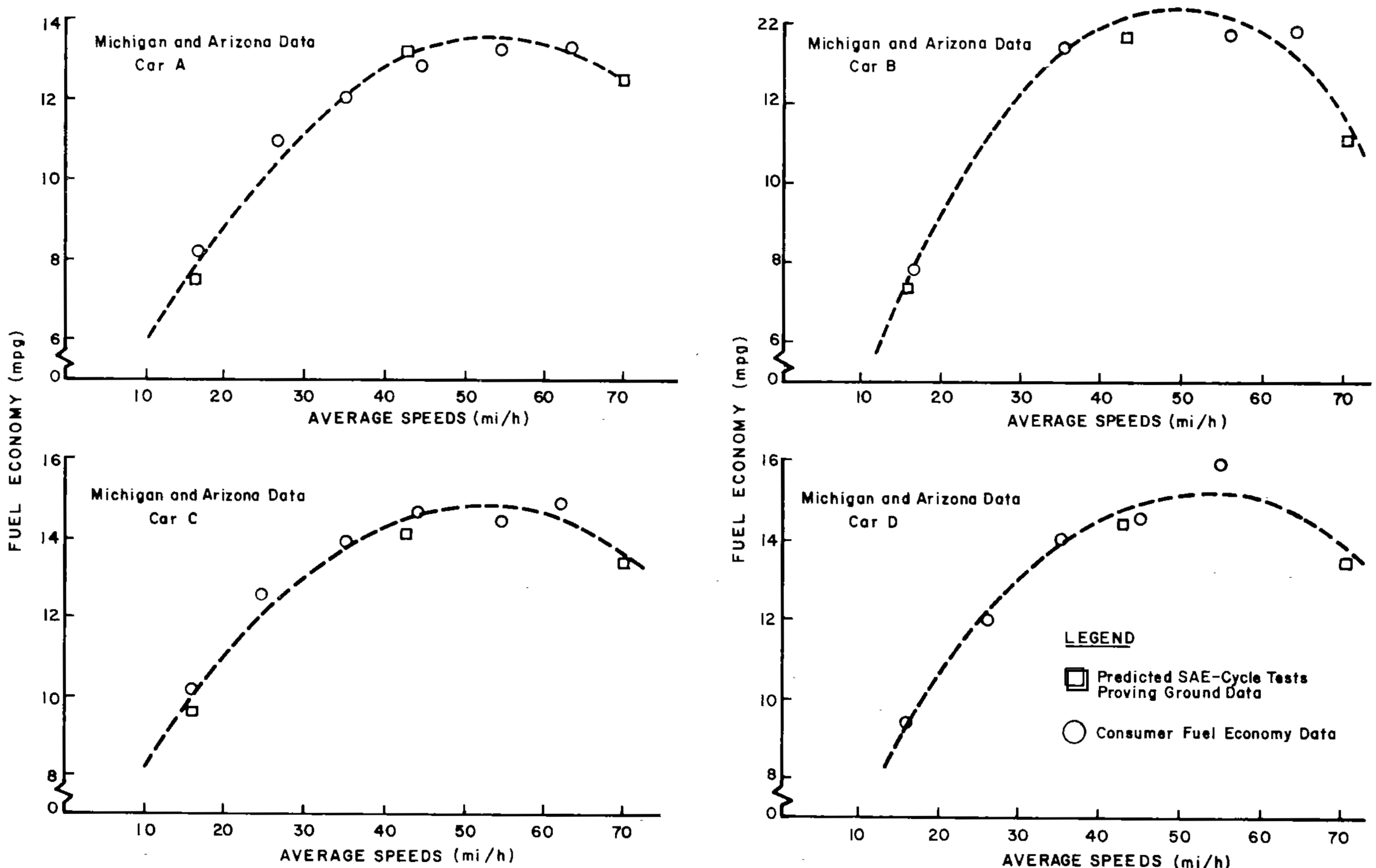


FIGURE B·5

COMPARISON BETWEEN FUEL CONSUMPTION MEASURED IN CONSUMERS CARS AND S.A.E. CYCLE PREDICTIONS

SOURCE: S.A.E. (1975)

CYCLES FOR INSPECTION TESTS

A number of short tests have been developed or proposed in the U.S. for end of (production) line testing or for in service monitoring of emissions, using C.V.S. (constant volume sampling) analysis techniques and chassis dynamometers with inertia and aerodynamic drag simulation (Reference VOLKSWAGEN (1977)).

Figure B.6(a) shows the Federal Short Cycle for end-of-line testing. Figure B.6(b) is the ACID test cycle consisting of one each of Accel, Cruise, Idle and Decel. This cycle is also known as the FAKRA cycle used for evaluating the performance of electric cars, (Reference ALTENDORF et al (1978)). In Figure B.6(c) the New York and New Jersey State cycles, used in their emissions maintenance programs are depicted. These are part of a "go", "no-go" test to determine if remedial maintenance is required for emissions control restoration on in-use cars.

PROPOSED FEDERAL SULPHATE (SULFATE) EMISSION CYCLE

Under certain operating conditions, exhaust catalysts are capable of storing sulphur oxides as aluminium sulphate which they release later on. It is therefore necessary to stabilise the vehicle and condition the catalyst prior to emission measurement.

The appropriate E.P.A. cycle proposed for this purpose is shown in Figure B.7 and extracted is from KLINGENBERG (1977). This then is an example of a special purpose cycle designed specifically to simulate a "worst case" situation.

VOLKSWAGEN CYCLE

An analysis by VOLKSWAGEN (1977) of current test procedures, and comparison with driving patterns in European cities using the bivariate frequency distribution display method (see WATSON and MILKINS (1976)), led to a number of definitive conclusions about test methods. Amongst these was that the U.S. 1972 FTP could be

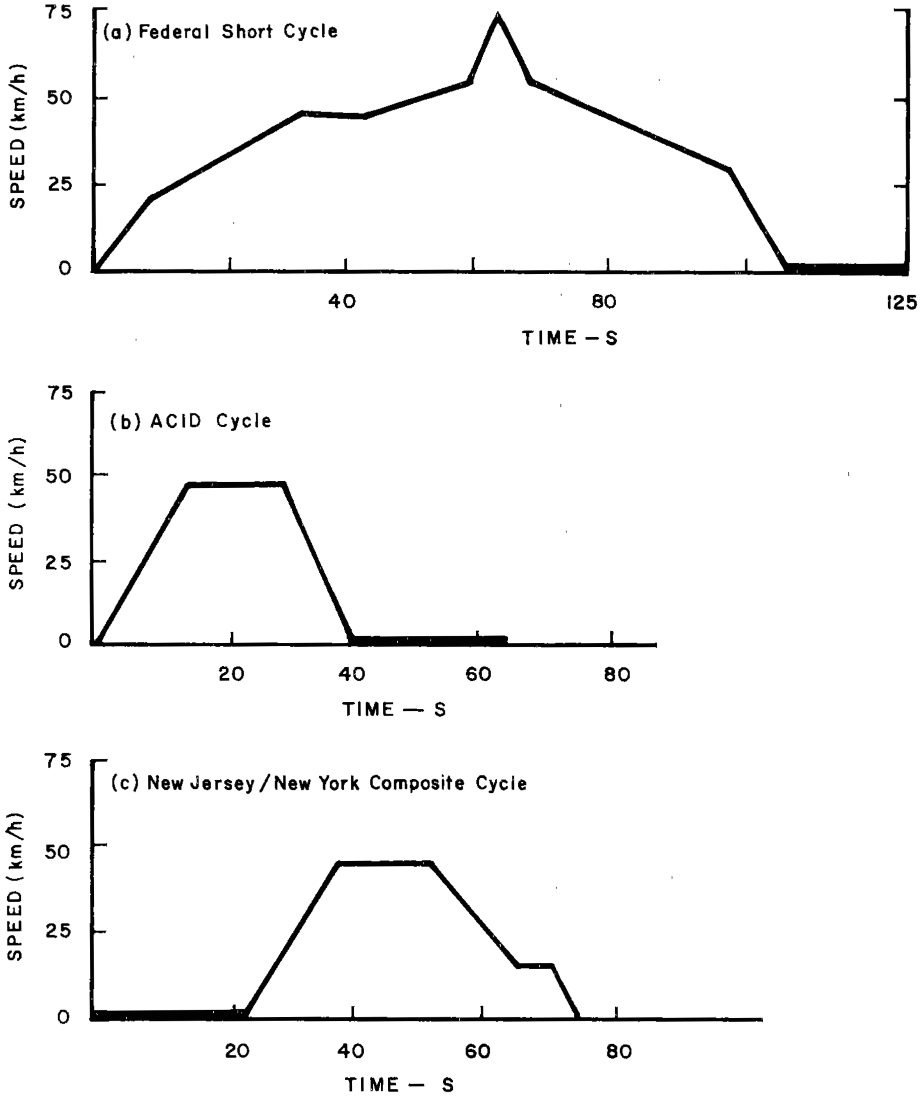
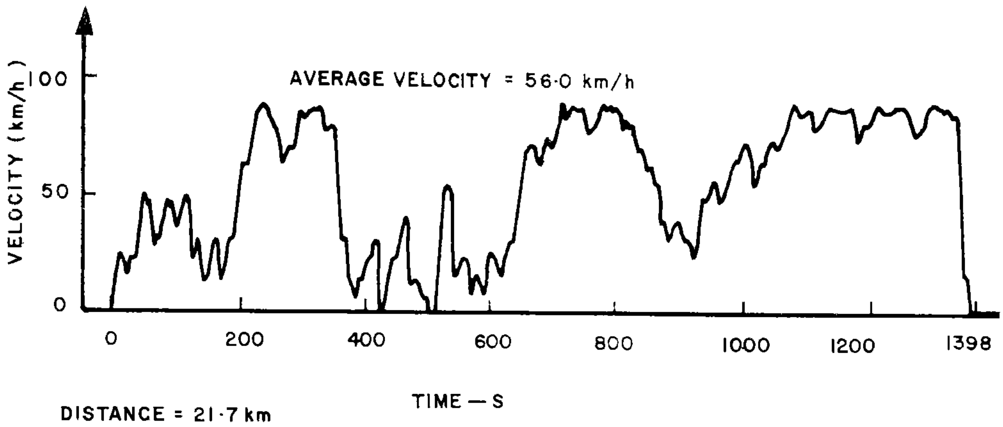


FIGURE B·6

SHORT CYCLES FOR INSPECTION TESTS USING CVS SYSTEM

SOURCE: Volkswagen (1977)



DISTANCE = 21·7 km

FIGURE B·7

DRIVING SCHEDULE FOR SULPHATE EMISSION TEST

SOURCE : Klingenberg (1977)

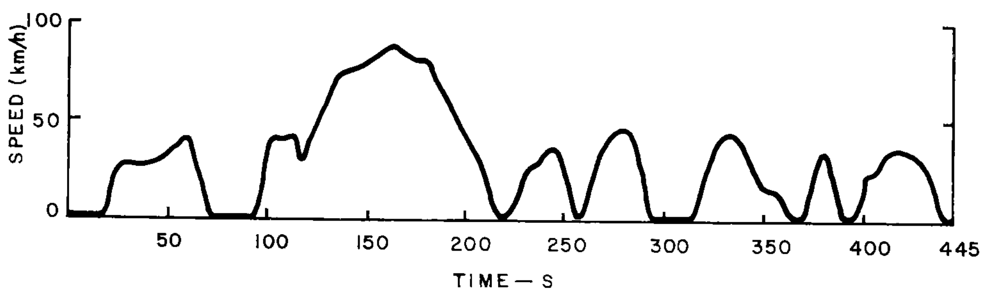


FIGURE B·8

DRIVING CYCLE PROPOSED BY VOLKSWAGEN COMPOSED OF RESEQUENCED PHASES (OR SEGMENTS) OF U.S. 1972 FPT

NOTE: Cycle repeated once
Total duration 890 s.
Total test distance 7·35 km

SOURCE : Volkswagen (1977)

reduced to about 445s and 3.67 km by selection of phases (idle to idle) in the following sequence; number 7, 2, 9, 12, 14 and 15. This proposal is now before the International Standards Organisation Committee on motor vehicle emission test methods. The cycle is iterated twice (cold start plus hot start) and is shown in Figure B.8.

OTHER CYCLES

The foregoing is not a complete review of existing driving cycles. There exists within the automotive industry an extensive range of driving cycles used for proving ground evaluation of vehicles. SAE (1975) provides data of the type given in Table B.1 for these cycles and basic information (average speed, halt frequency, etc.) is to be found in HAMILTON and WATSON (1976).