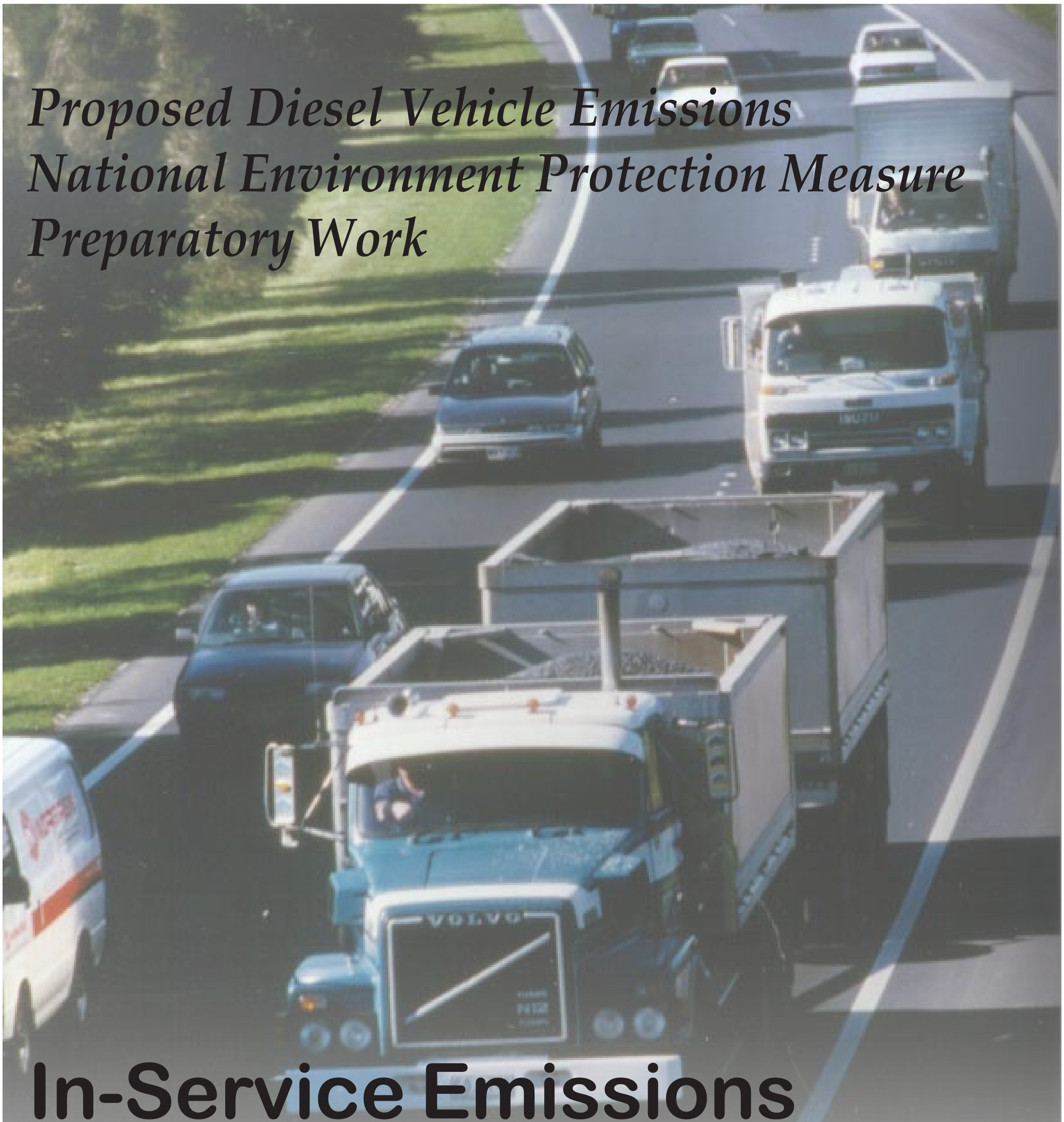

Proposed Diesel Vehicle Emissions National Environment Protection Measure Preparatory Work

In-Service Emissions Performance - Drive Cycles

Volume 1

March 1999

NEPC

NATIONAL ENVIRONMENT PROTECTION COUNCIL

Prepared for the

National Environment Protection Council

by

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ISBN 0 642 32323 2

A suite of projects have been developed during the preparatory work for a proposed Diesel Vehicle Emissions National Environment Protection Measure. These projects are:

> The Australian Diesel Fleet Existing Vehicle Characteristics and the Modelling of Transport Demand, Vehicle Populations and Emissions
>
> In-Service Emissions Performance - Phase 1: Urban Drive Cycle Development
>
> In-Service Emissions Performance - Phase 2: Vehicle Testing
>
> In-Service Certification Correlation Studies
>
> A Review of Dynamometer Correlations, In-Service Emissions and Engine Deterioration
>
> In-Service Emissions Testing – Pilot Study, Fault Identification and Effect of Maintenance

Major funding for these projects has been provided by Environment Australia. The other contributing agencies are the Department of Transport and Regional Services, NSW Roads Traffic Authority and the National Road Transport Commission.

Electronic copies of these documents are available from:

National Environment Protection Council Service Corporation
Level 5, 81 Flinders Street
ADELAIDE SA 5000

Telephone: (08) 8419 1200
Facsimile: (08) 8224 0912

These documents are also available online: http://www.nepc.gov.au

ACKNOWLEDGMENTS

The Project Team acknowledges the considerable support and cooperation given during the project by the following -

- the transport operators who at some inconvenience, willingly made vehicles available to us for installation and removal of data logging systems –

  - Australia Post
  - McPhee Transport
  - Refrigerated Roadways
  - Boral Transport
  - Cleanaway
  - Sydney Buses
  - Westway Bus Company
  - Black and White Couriers & Taxi Trucks

- The Road Transport Forum, the Road Transport Association of NSW and the Bus and Coach Association of NSW for their assistance in organising test vehicles, and in encouraging their members to attend our Focus Group meetings.
- The many representatives of transport companies who attended and provided expert commentary at our Technical Managers Focus Group meeting.
- The members of the Institute of Automotive and Mechanical Engineers who gave their time and provided considerable insight into vehicle maintenance issues, at our Repair and Maintenance Industry Focus Group meeting,
- The testing staff at the EPA's Motor Vehicle Testing Unit who assisted with the tasks associated with installation and removal of data logging equipment.

Thank you!

DEVELOPMENT OF DRIVE CYCLES AND IN-SERVICE SHORT TEST EVALUATION

CONTENTS OF VOLUME I

DEVELOPMENT OF DRIVE CYCLES

IN-SERVICE SHORT TEST EVALUATION

CONTENTS OF VOLUME II

EXECUTIVE SUMMARY

Introduction

This report outlines the work referred to as *Project 2: phase 1 - Drive Cycles,* undertaken by the NSW Environment Protection Authority (EPA) under contract to the National Environment Protection Council (NEPC) Service Corporation. This project is one of three encompassing preparatory work identified by NEPC, to provide information that will assist in development of a National Environment Protection Measure (NEPM) for diesel vehicles. The three Projects are –

- **Project 1:** Diesel Fleet Characteristics.

- **Project 2:** In-Service Emissions Performance
  - Phase 1 - Drive Cycles
  - Phase 2 – Vehicle Testing

- **Project 3:** Fuel Characteristics.

This *Phase 1 Project* involved two main areas of investigation -

- development of 'real world' drive cycle(s).
- selection of 5 In-Service Short Tests for further evaluation during the *Phase 2 Project*.

Note: the *Phase 2 Project* is not included within the scope of the EPA's contract.

Project Team

The Project team consisted of the following core staff, who were able to draw on experience and assistance from other personnel within and outside their organisations -

Project Manager:	Mr Stephen Brown, EPA Motor Vehicle Testing Unit.
Project Officer:	Mr Chris Bryett, EPA Motor Vehicle Testing Unit.
Project Consultant:	Mr Michael Mowle, Independent Consultant.
Testing Officer:	Mr Shaun Hanrahan, EPA Motor Vehicle Testing Unit.
Data Analysts:	Mr John Donnelly, Mr Steve Davies and Mr Ross Sparks, CSIRO Mathematical and Information Sciences (CMIS).

Other organisations, including the Road Transport Forum, the Road Transport Association of NSW, the Bus and Coach Association of NSW, and the Institute of Automotive and Mechanical Engineers, provided expert advice and assistance during the course of the work.

Objectives

The objectives of the project were to:

- develop typical 'urban emissions drive cycles' (UEDCs) for diesel vehicles in Australian cities, and derive 'composite urban emission drive cycles' (CUEDCs) suitable for testing vehicles in order to establish fleet in-service emission performance for inventory purposes.
- identify vehicle-based causes of increased emissions, and short tests potentially suitable for use as in-service diesel vehicle emission inspection/maintenance procedures in Australia.

These objectives have been addressed in the following two separate parts of this report -

- **Part A:** Development of Drive Cycles.
- **Part B:** In-Service Short test Evaluation.

Approach

For logistical reasons and ease of reporting the project was sectioned into two Parts, comprising the two very different and distinct aspects of the project –

- **Part A**: Development of Drive Cycles
- **Part B**: In-service Short Test Evaluation

Interim Reports were prepared at the conclusion of each Part, outlining the methodologies adopted, key findings and recommendations. This Final Report brings together the two Interim Reports and illustrates using ADR category NB as an example, the data analysis process undertaken to develop the CUEDCs.

The specific approaches and investigative techniques employed to meet the two principle objectives are discussed within each Part. However, the following approach to collect up-to-date information and advice, was common to both Parts -

- contact and discussion with experts in government authorities and research organisations during Mr Brown's recent overseas study tour.
- search for and review of relevant literature.
- discussion with local researchers and relevant industry groups.

This approach enabled the Project Team to –

- gain up-to-date awareness of relevant programs in progress overseas through direct contact with their principal researchers and managers.
- obtain valuable overseas and local advice relevant to the carriage of this Project.
- establish a framework within which to focus and optimise limited Project resources.

We consider this approach has increased the quality and scope of information obtained, which will ultimately be of benefit in the *Phase 2 Project* and in other areas of NEPC's Diesel NEPM preparatory work.

Part A - Development of Drive Cycles

The actual on-road driving patterns of 17 vehicles, ranging from off road passenger vehicles to heavy goods vehicles were logged during normal use. Using mathematical analytical tools, the data were analysed according to the characteristics of discrete segments of the vehicles' speed/time traces, referred to as 'microtrips' (defined as a period of rest followed by periods of acceleration, cruise and deceleration until the vehicle is at rest again).

For each vehicle, each microtrip was allocated to a road flow category ('freeway/highway', 'arterial', 'residential/minor' or 'congested'). The most representative microtrips in each road flow category were then combined to form an urban emission drive cycle (UEDC) of approximately 60 minutes duration, for each vehicle/ADR category. These UEDCs are recommended as 'reference' drive cycles.

A CUEDC of approximately 30 minutes duration (and thus more suitable for test purposes) was derived from each UEDC. The data analyses showed no consistent patterns to suggest the CUEDCs could be combined into composite groups covering more than one vehicle/ADR category. These complex CUEDCs are recommended for in-service testing (equipment permitting) for inventory purposes.

A 'straight line' 'simplified CUEDC' was then constructed from each CUEDC, in order to reduce the number and frequency of transients to allow greater ease of testing on less sophisticated (and less costly) chassis dynamometers.

Part B – In-Service Short Test Evaluation

From the literature, and from discussion with overseas agencies and the local transport industry, a number of short tests, and a '7-point inspection' were identified. Of the short tests, 5 are recommended for further evaluation in conjunction with the '7-point inspection' and the '10-second rule', as in-service inspection procedures. These are –

- the free acceleration smoke test – SAE J1667.
- a steady state, loaded mode chassis dynamometer test – the 'D550'.
- a 'full load, 2-speed' chassis dynamometer test, derived from ADR 30.
- a 'lug-down' chassis dynamometer test, as used in Colorado.
- A 'full load acceleration, 80 km/hr cruise', chassis dynamometer test.

Recommendations

Development of Drive Cycles

1. The UEDCs be used as the ‘real world inventory reference cycles’.
2. The CUEDCs be further simplified to ‘stylised test cycles’, prior to testing in Phase 2 of this Project.
3. The following three test cycles then be considered (in order of their technical suitability, practical application, and cost) for use in the Phase 2 Project for determination of the emissions performance of the diesel in-service vehicle fleet -
    (a) The complex CUEDCs.
    (b) The simplified (straight line) CUEDCs.
    (c) The ‘stylised test cycles’.

In-service Short Test Evaluation

It is recommended that during Phase 2 of this Project –

(1) The potential benefits of combining tests and/or using different tests for different ADR categories be considered.

(2) The potential for refinement or modification of the proposed tests to meet equipment and/or vehicle limitations be considered.

(3) The ‘10-second rule’ be considered an on-road enforcement tool (as it is now used), to be complemented by a short test or inspection-based inspection/maintenance procedure.

(4) The ‘7-point inspection’ be considered as a road-side screening tool, as well as an addition to the suggested short tests.

(5) Less emphasis be given to emissions of NOx than to smoke and particulates, in evaluation of the short test procedures.

(6) Smoke opacity be evaluated as a low cost surrogate for particulate emissions during evaluation of those short test procedures that do not specify smoke opacity as the unit of measurement.

(7) The findings of the CARB in-service short test project, when available, be considered as part of the Phase 2 Project.

PART A – DEVELOPMENT OF DRIVE CYCLES

1 INTRODUCTION

The objectives for this work were to develop practical chassis dynamometer-based test cycles that may be used in Phase 2 of this Project (and subsequently) for –

- diesel vehicle emissions inventory development.
- assessment of a range of static and/or dynamometer-based inspection procedures for in-service use.

This Part of the report presents our rationale, and provides detailed descriptions of -

- logging ‘real world’ operating data from a sample of diesel-engined vehicles in Sydney.
- identification of typical urban driving patterns.
- derivation of urban emission drive cycles (UEDCs) for the relevant ADR vehicle categories, covering each of the following road flow categories -
  - ‘highway-freeway’,
  - ‘arterial’,
  - ‘residential/minor’
  - ‘congested’.
- development of composite urban emission drive cycles (CUEDCs).
- development of ‘simplified CUEDCs’.

Throughout the report vehicle ADR category NB has been used as an example to illustrate the process used by CMIS to develop the CUEDCs. It also makes a number of recommendations.

2 PRELIMINARY WORK

2.1 Contact with overseas organisations

During late June and July 1998, our Project Manager Mr Steve Brown undertook an overseas study tour, during which he visited a number of relevant organisations –

- Millbrook Proving Ground Ltd, Bedford, UK, where study included the development of a London Urban Bus driving cycle for in-service emission measurement, and assessment of test facilities and procedures.

- Ministry of Transport, and Department of Environment, London, UK, for discussions on policies, and development of in-service diesel emission standards and test protocols.
- Government Departments of Transport, Energy and Environment, Netherlands, for discussions on strategies to reduce diesel vehicle emissions, including in-service vehicle compliance testing and enforcement procedures.
- TNO Research, Netherlands, for study of diesel testing facilities and procedures, and recent research programs covering driving cycle development, in-service vehicle testing, inspection and maintenance. TNO expressed interest in the Australian Diesel NEPM project and has since formally invited the EPA to participate by providing the drive cycle data produced from this project for inclusion in a 'world driving cycle'.
- University of West Virginia, USA, for discussion of recent developments in in-service heavy-duty diesel testing procedures.
- California Air Resources Board and California Bureau of Automotive Repair, for study of CARB's certification and in-service diesel inspection/maintenance programs including the development of short tests.

The tour yielded considerable information relevant to this Project. In particular –

- The European Parliament is to develop a 'world driving cycle' for diesel-powered vehicles. TNO and the German organisation FIGE have been tasked with this project.
- In each country visited (UK, Netherlands and the US), research organisations were developing 'real world' drive cycles to evaluate the on-road emissions and fuel consumption performance of diesel vehicles.
- While there are many vehicle types, use patterns, road catagories, and driver behaviours, that together could generate an array of representative drive cycles, those research organisations visited believed that the simpler the cycle the better and that representation of more than three road-flow categories was superfluous. This was strongly communicated by Milbrook having completed development of a London bus drive cycle, a garbage truck cycle and a rigid truck cycle. All had just three distinct operating conditions, namely Suburban, Urban and Motorway.
- At West Virginia University a '5 mile' route truck cycle has been developed, wherein the truck is driven on a chassis dynamometer across 5 modes (20, 25, 30, 35 and 40 mph). The vehicle is accelerated rapidly through the gears until the target speed is reached and then driven steadily at that speed. At a specified time (calculated by the computer controlling the dynamometer and drive trace) the vehicle is decelerated under brakes to rest. This is repeated for each speed. The University's researchers have tested over 1000 in-service heavy-duty vehicles and found this cycle to be repeatable, providing a means to compare vehicle emission performance.

2.2 Literature review

The literature was scanned for information that would assist in the carriage of this Project. This was supplemented by trawling the Internet sites of Australian and overseas libraries and research organisations, and by enquiry of overseas contacts. There was much that provided useful background information on development of representative driving cycles, but little that provided specific guidance in this Project.

From the literature, most driving cycle development has been carried out on motor cars.

Andre (1) and Bata (2) provides a useful review of methods used. In general, these have been based upon the collection and statistical analyses of data from large numbers of vehicles/trips in particular city regions. The ability of particular cycles derived in one region to represent driving in another region, is questionable. Also, the degree to which current internationally accepted cycles, for example US FTP and ECE, represent typical driving in any region remains under debate, and as a consequence there have been many proposals to augment these cycles with additional sequences to improve their representativity.

Andre (3, 4) describes methodology used in the EC DRIVE program, a cooperative research program carried out by INRETS (France), TUV Rheinland (Germany) and TRRL (UK) during 1989 to 1995. In this program, 58 privately owned motor cars were equipped with sensors and logged over about one month of normal driving, a total of 73,300 VKT. Analyses of the data was based on statistical analyses of 'kinematic sequences' (the speed time curve between successive stops, including the preceding idle period). This work was particularly influential in setting the methodology for this work.

So far as heavy duty diesel vehicles are concerned, research on driving cycles is relatively recent and immature. However, much work has been done, especially by TNO (Netherlands), West Virginia University (USA) and Millbrook (UK).

Van de Weijer (5, 6) provides valuable background information on the theoretical considerations in driving cycle development for heavy duty vehicles, and describes a methodology based upon statistical analyses of masses of vehicle/trip data in developing region-specific cycles. These methods are in use, and under further development at TNO (7).

West Virginia University (7, 8, 9, 10) have developed transient driving cycles for certain heavy vehicles. They have also designed and built a transportable chassis dynamometer test and exhaust analysis laboratory, on which they are basing work on in-use heavy-duty vehicles.

Millbrook Proving Ground Ltd (11) has set up a chassis dynamometer test facility capable of testing small and large heavy-duty vehicles to complex transient real world driving cycles, under controlled ambient conditions. Driving cycles for various vehicle types have been developed based on monitoring actual vehicles in use, and many testing programs have been carried out or are ongoing. In particular, Millbrook have developed a London Bus Driving cycle and used this in emission control system development.

2.3 Review of Sydney inventory methodologies

The major sources of vehicle and traffic movement data for Sydney are the various publications of the Australian Bureau of Statistics (ABS), the Roads and Traffic Authority of NSW (RTA), and the NSW Department of Transport’s Transport Data Centre (TDC) (previously Transport Study Group). Analyses of these data have been carried out on occasions by the NSW EPA, in support of vehicle emission inventory development.

A major review of the Sydney emissions inventory was carried out by Carnovale et al (12) during 1993 to 1995 as part of the NSW EPA's Metropolitan Air Quality Study (MAQS). For this study, supplementary analysis was undertaken by the TDC, which provided estimates of VKT within 3x3 km grid squares throughout the Sydney Region according to road-flow category ('arterial', 'freeway/highway', 'commercial-arterial', 'commercial-highway', and 'residential/minor'). Carnovale derived estimates of VKT and emission factor, by vehicle category ('passenger', 'light commercial', 'heavy duty' and 'motor cycle') and age profile, for each fuel ('petrol', 'diesel' and 'LPG'), in each road category, in 'free-flow' and 'congested' mode. Vehicle emission inventories for Sydney, for the 1992 calendar year, were then modelled on these estimates.

During 1997/98, the NSW EPA with assistance from the TDC, carried out a further substantial review of the Sydney roads and traffic data. The EPA made subsequent adjustments and refinements to the Sydney inventory model (the Motor Vehicle Emissions Projection System - MVEPS), to better enable its use in development of inputs to motor vehicle emission control policy. The MVEPS development work is unpublished.

The MVEPS (and Carnovale) uses a range of emission factors (based on speed-adjusted engine dynamometer test results compiled in the US EPA’s ‘Mobile 5’ (13)) assumed for different road-flow categories, defined as follows -

Arterial:	Major roads with moderate average speeds (say 20 – 40 km/hr), moderate congestion levels (say 20% idle time) and low proportion of heavy duty vehicles (say less than 7% of total fleet VKT).
Freeway/Highway:	Major roads with relatively high average speeds (say in excess of 40km/hr), and low congestion levels (say less than 5% idle time
Residential/Minor:	Secondary roads with moderate average speeds (say 20 – 40km/hr) and negligible congestion.

3 RATIONALE

3.1 Constraints

The primary constraints for this work are -

- the budget limitations and the time allowed for completion.
- the requirement (implied in the Project Brief and clarified in subsequent correspondence and discussion) that the UEDCs be combined to produce a smaller number of CUEDCs (perhaps even just one) to cover all vehicle-ADR categories.

- the equipment limitations for phase 2 of the Project, stated in the Project Brief - 'Because of limitations of dynamometer and emissions measurement equipment in Australia, the UEDCs and CUEDCs need to be loaded modal type of tests (including steady state) and must not take more than 15 minutes in total dynamometer time to conduct.'
- the requirement (implied in the Project Brief, and clarified in subsequent correspondence and discussion) that the UEDCs and CUEDCs be adaptable to all major Australian City Regions.

3.2 Composite UEDCs

We consider that driving characteristics of various vehicle types within the ADR categories will in some cases be significantly different. Such differences might be expected, for example, when comparing a light vehicle, with a city bus, or a heavy articulated vehicle. In addition, different vehicle categories have different proportions of use over the different road categories. For example, a light vehicle might have higher usage on minor roads, while a city bus will have high usage on commercial roads and a heavy articulated vehicle would have high usage on arterial roads and highways/freeways.

For this work (as shown in section 4.3) we assumed that for the purposes on-road driving data acquisition, the diesel vehicle fleet could be represented in 6 vehicle-ADR categories as follows –

1. Passenger cars (MA), forward control passenger vehicles (MB), and off-road passenger vehicles (MC).
2. Light goods vehicles (NA) and light buses (MD) below 3.5 tonnes GVM.
3. Medium goods vehicles (NB) and light buses (MD) above 3.5 tonnes GVM.
4. Heavy buses (ME)
5. Heavy goods vehicles (NC) below 25 tonnes GVM or GCM.
6. Heavy goods vehicles (NC) greater than 25 tonnes GVM or GCM (designated NCH in this work).

Our proposal was to develop a separate CUEDC for each group of vehicle-ADR categories that could be combined due to their having similar driving characteristics, as might be shown through the analyses of actual on-road driving data.

In the event, statistical analyses of the data did not suggest any such combinations. Therefore, we have derived 6 separate CUEDCs, covering the 6 vehicle-ADR categories shown above.

3.3 Dynamometers and Driving Cycles

The status of developments around the world in chassis dynamometer-based test procedures for heavy-duty diesel vehicles, was reviewed through the literature and through discussion with relevant overseas research organisations. This indicated that much research is in progress aimed at developing practical chassis dynamometer procedures for pollutant inventory development and in-service enforcement, but there are as yet no such procedures that have a high level of acceptance.

It is considered that steady state dynamometer testing, using a series of constant speed and load combinations, cannot replicate on-road driving sufficiently well for reasonable estimation of on-road pollutant emissions. Therefore, most research is targeted to development of procedures using recorded 'real world' (complex transient) driving cycles, or synthetic (simple transient) cycles characterising 'real world' conditions. These cycles incorporate, or characterise, transient (accelerating and decelerating) conditions as well as steady state (cruise) conditions encountered in road driving.

Such cycles require the use of chassis dynamometers capable of simulating vehicle inertia, either directly through coupled inertia wheels, or indirectly through programmed computer control of dynamometer load characteristics.

The majority of heavy-duty chassis dynamometers in Australia were designed for steady-state operation only, that is, to apply loads under steady road-speed conditions for power and torque measurement. They are incapable of simulating inertia, or otherwise applying dynamic load changes necessary to simulate the controlled acceleration/deceleration modes that dominate urban driving and that produce the majority of vehicle pollutants. Therefore, they are unsuitable as tools for credible indication of on-road vehicle emission performance.

There are though, some electrical dynamometers in Australia that are equipped with, or that could be equipped with computer controls, and that could be upgraded to enable simulation of inertia-limited, or load-controlled accelerations. These would then be suitable for operation of simple transient cycles at least to about 150 kW power absorption, which would cover perhaps 80% of the diesel vehicle fleet. There may also be other heavy-duty dynamometers in Australia, capable of upgrade to enable higher powered vehicles to be adequately tested.

We consider test procedures based on simple transient modal test cycles provide the optimum balance between representative emission measurement, and dynamometer capability. Therefore, we have targeted this work to the development of simple transient CUEDCs that characterise on-road driving.

3.4 Adaptation of UEDCs and CUEDCs to other Australian Cities

Characterisation of driving patterns in more than one city region would have been well beyond the budget and time constraints.

Therefore, in this work –

(1) We have attempted to characterise driving patterns for each vehicle type (ADR category), according to the traffic flow conditions that may be expected on different categories of road -

- high traffic speeds and relatively free-flow conditions, which are indicative of (and therefore referred to as) ‘*highway/freeway*’ driving conditions.

- moderate traffic speeds and interrupted flow conditions, which are indicative of '*arterial'* driving conditions.
- moderate road speeds and relatively free-flow conditions, which are indicative of 'residential/minor' driving conditions.
- low traffic speeds and frequent flow interruptions which are indicative of '*congested'* driving conditions.

(2) We have then developed UEDCs and CUEDCs, comprising sequences representative of each road flow category.

Dynamometer testing (in phase 2 of this Project and subsequently), would use the CUEDCs or test cycles, and would yield emission factors for each vehicle category, for each of the four road flow categories. For inventory development in any city or region, these emission factors would then be applied according to the relative VKT on each of the four different road categories in that city or region.

The main underlying assumptions for this methodology, are -

- that vehicles of a given type (ADR category), being driven on a given category of road, will have similar driving patterns whichever the city.
- that differences in overall driving patterns for vehicles of a given type (ADR category), in different cities, relate primarily to the proportions of VKT driven on the different road categories within each city region.
- that credible estimates of relative VKT for each type of vehicle in each road category, exist or can be derived for each city region.
- that gross traffic flow descriptors, such as average speed and percent idle time, can satisfactorily describe traffic flow conditions in each road category.

The first two of these assumptions are given some credence in the literature and were emphasised in discussion with some overseas researchers. In particular, INRETS (France) have derived motor car driving cycles incorporating 'congested urban', 'free-flow urban', 'road' and 'motorway' sequences, and Millbrook (UK) have developed heavy vehicle driving cycles incorporating 'urban', 'suburban' and 'motorway' sequences.

All four of these assumptions underpin methodologies used in the most recent vehicle emission inventories developed for Sydney (13), Melbourne (14), Brisbane (15) and Perth (15).

This approach would seem to have advantages, compared to alternative approaches based upon the development of a number of city-specific driving cycles –

- emission factors developed from tests run to the CUEDCs could be used to compile emission inventories for any city, or any region, for which estimates of the proportion of travel on the different road categories are available.
- new CUEDCs would not need to be developed to take account of changes in road infrastructure, in a city or region, over time.

Against this, must be weighed the extra complication of carrying out four separate analysis sequences during each emission test. We consider this extra complication (and test time) would be small, given the advantages stated above.

3.5 Duration of the Test Cycles

Drive cycles that are too long would add unnecessary costs in vehicle testing. Therefore, we have targeted the development of CUEDCs with minimum duration.

We consider 15 minutes for each CUEDC, as specified in the Project Brief, is too short to provide -

- adequate characterisation of driving and representation of emission performance, for each of the four road flow category sequences.
- sufficient time for exhaust sample collection and measurement of pollutant emissions, in each road flow category sequence.

We propose CUEDCs of approximately 30 minutes duration.

The UEDCs are the representative ‘real world’ driving cycles from which the CUEDCs have been developed. They will have a reference function only. That is, assuming suitable test equipment is or becomes available, they may be used to validate the CUEDCs. They may also be used to derive alternative CUEDCs.

Therefore, we consider the UEDCs should not be unduly limited by the costs of testing, or by currently available test equipment. We propose UEDCs of approximately 60 minutes duration.

A contract variation in this regard, was sought and agreed.

3.6 Linkage with Project 1 – Fleet Characteristics

While not considered a constraint for this work, the linkage with Project 1’s inventory projection model is considered paramount to the success of the *Diesel NEPM Preparatory Work*. In Project 1, the model being developed for all Australian capital cities, is based on the US EPA’s ‘MOBILE 5’ methodology, which uses a relationship between average vehicle speed and emissions. We consider that approach is not inconsistent with the drive cycles developed in this work.

We consider the following process could be adopted to convert the CUEDC ‘real world’ emission factors for each road flow category to an adjusted emission factor based on average speed information obtained from each of the capital cities -

- the average speeds for each road flow and ADR category tabulated within the summary statistics shown in section 5.3.2, could be plotted against the emissions factors (CO, HC, NOx and PM in g/km) determined for each road flow category in the Phase 2 Project.

- the emission factors used for each capital city could be derived from these plots, as those corresponding to the average speeds obtained from road traffic data for each road flow condition.

4 ON-ROAD DATA ACQUISITION

4.1 Approach

Our literature reviews and enquiries of the transport industry uncovered no sources of information that would assist in characterising urban driving sequences for typical diesel vehicles in Australia.

Therefore, our approach relies on the collection and subsequent analyses of actual on-road driving data, collected through direct data logging of sample vehicles in normal use.

The chase-vehicle technique, which has been used in many driving pattern studies particularly for light passenger vehicles, was considered. This technique has inherent difficulties, which may lead to inaccurate representation of the target vehicle's driving characteristics. These difficulties would be accentuated when a vehicle having totally different driving characteristics from the chase-vehicle, is being monitored. Also, there are difficulties in identifying the target vehicle type and load, from a chase situation.

In contrast, the direct data logging method used in this work, yields accurate records of actual vehicle driving patterns, according to identified vehicle characteristics. Also, this method yields information on engine speed and gear selection.

Nevertheless, due to difficulties in sourcing suitable light goods vehicles for data logging, we obtained some data from this category using a chase-vehicle. In this exercise the chase vehicle and target vehicles were all panel vans of similar weight, thus minimising data inaccuracies that would be caused through dissimilar driving characteristics. This is discussed further in section 4.5.7.

4.2 Contact with Transport Organisations

Contact with major fleet operators in Sydney was established through the Road Transport Forum (RTF), the Road Transport Association of NSW, and the NSW Bus and Coach Association, whose assistance is appreciated.

The RTF surveyed member companies to solicit -

- assistance in allowing Project team members access to vehicles used in the Sydney region, for data logging.
- information on actual driving statistics (vehicle types, routes, speeds, loads, etc. against time/distance).

- attendance of their expert representatives at focus group meetings to discuss matters related to this Project.

A number of companies offered, and in the event provided, access to their vehicles. However, suitable information on vehicle/driving characteristics, was not available.

Several companies provided representatives for the focus group meetings, discussed in Part B of this Report.

Other transport operators in Sydney were approached directly, for assistance with access to vehicles for data logging.

4.3 Sample Selection

The Roads and Traffic Authority (RTA) was contacted for information from the vehicle registration data base, on the numbers of Sydney-registered diesel vehicles, by ADR category, vehicle type and gross vehicle mass (GVM). A sample of 17 vehicles, being the maximum number that could be data-logged within the time and budget constraints, was compiled from this data. While this small sample was designed to broadly represent the Sydney diesel vehicle fleet, no attempt was made to obtain statistical validation.

The RTA data, and the vehicle sample are shown in table 1.

Table 1: Number of Sydney-registered diesel vehicles and sample.

Vehicle ADR Category (Gross vehicle mass)		Nr on register	% of total	Target sample
MC – off road passenger vehicles		3506	3.5	2
MD – light omnibus (<5 tonnes)		2408	2.4	-
ME – heavy omnibus (>5 tonnes)		3636	3.6	4
NA – light goods vehicle (<3.5 tonnes)	- panel van	14939	14.8	2
	- rigid truck	28638	28.3	-
	- prime mover	2	0.0	-
	- plant	2114	2.1	-
	- total NA	45693	45.2	2
NB – medium goods vehicle (3.5 – 12 tonnes)	- panel van	96	0.1	
	- rigid truck	22717	22.4	3
	- prime mover	22	0.0	-
	- plant	2677	2.6	-
	- total NB	25512	25.1	3
NC – heavy goods vehicle (12 – 25 tonnes)	- panel van	2	0.0	-
	- rigid truck	10275	10.2	3
	- prime mover	4045	4.0	-
	- plant	1787	1.8	–
	- total NC	16109	15.9	3
NCH – heavy goods vehicle (>25 tonnes)	- rigid truck	1594	1.6	3
	- prime mover	947	0.9	-
	- plant	1787	1.7	-
	- total NCH	4328	4.3	3
	- Total all categories	**101192**	**100.0**	**17**

Notes:

- It was considered that NC category 'heavy goods vehicles' towards the heavy end of the range (especially prime movers having Gross Combination Mass (GCM) above 40 tonnes) would likely have different driving characteristics compared to other 'heavy goods vehicles' at the lower end of the prescribed weight range. Therefore, for the purposes of this work, the NC range has been subdivided as follows –

  NC Heavy goods vehicle 12 – 25 tonnes GVM/GCM
  NCH Heavy goods vehicle >25 tonnes GVM/GCM

- No 'plant' were included in the sample. This category consists mainly of mobile equipment and machinery, whose duty cycles would be dominated by non-road use.
- Rigid trucks and panel vans were considered to have very similar road performance and use patterns. They are frequently derived from similar model and powertrain

configurations and are all categorised as goods vehicles within the ADRs. Therefore, no NA-category rigid trucks were included in the sample.

- MD-category light buses were considered to have similar road performance and use patterns to goods vehicles of similar weight. Therefore, none were included in the sample.
- MA-category passenger cars and MB-category forward control passenger vehicles are almost all petrol powered. Those few powered by diesel vehicles are considered to have similar road performance and use patterns (in urban areas) to MC-category off road passenger vehicles. Therefore, none were included in the sample.

4.4 Vehicle Selection

Those transport operators who had offered assistance, were surveyed for information on the types of vehicles that could be made available for data logging. Vehicles were then selected according to the target sample, to represent a cross section of types, weights, use patterns, and geographical areas of operation within the Sydney Region.

The vehicles were selected according to the following criteria:

- Vehicles were chosen which had near constant normal use patterns as it was felt that these vehicles would represent the highest contributors to diesel vehicle kilometres travelled (VKT) in the metropolitan area. Vehicles in intermittent use were avoided, as insufficient driving data would be collected during the logging period.
- Vehicles were selected to reflect typical use patterns within a metropolitan area for that category of vehicle. For example, in the NCH rigid truck category, a bulk waste collection truck was chosen as this type of vehicle would make up a significant proportion of the vehicles in this category.
- Vehicles were selected, which operated in as many different geographical areas of Sydney as possible where that particular type of vehicle would be expected to operate. For example, in the ME heavy bus category, 4 vehicles were logged in a variety of inner and outer urban areas of Sydney. This was to cover the variations in traffic flow conditions and consequent driving patterns experienced in different suburbs of a major city.
- Selection of vehicles was targeted to those regularly using the major routes typical for that type of vehicle in a metropolitan area. For example, it was considered important to include in the sample, a heavy truck using the arterial roads leading out from the Port Botany area onto the main Hume Highway or Great Western Highways via the busy Inner Western suburbs.

The vehicles selected for data logging are shown in table 2, with their specifications given in table 3.

The geographical operating areas for each vehicle, are shown in figures 1-6.

Table 2: Vehicles selected for data-logging

ADR Category		Vehicle Description	GVM (t) *GCM* (t)	Gears	Use pattern during logging
1	MC Off road Pass vehicle	1997 Mitsubishi Pajero 4WD wagon	2.65	5 sp man	commuting and general transport
2	MC Off road Pass vehicle	1997 Toyota Landcruiser DX 4WD	2.96	5 sp man	commuting and general transport
5	ME Heavy bus	1997 MAN Ansair Orana rigid bus	11.5	3 sp auto	inner urban route bus
9	ME Heavy bus	1997 Scania rigid bus	19.1	3 sp auto	inner urban route bus
10	ME Heavy bus	1998 Mercedes 0405 rigid bus	17.6	4 sp man	outer urban route bus
11	ME Heavy bus	1992 Volvo B10M rigid bus	17.3	4 sp auto	outer urban route bus
3	NA Light goods vehicle	1996 Ford Transit panel van	2.83	4 sp auto	postal delivery
4	NA Light goods vehicle	1997 Ford Transit panel van	2.83	5 sp man	chase vehicle *****
8	NB Medium goods vehicle	1993 Daihatsu Delta rigid flat bed truck	4.45	5 sp man	road category definition ******
6	NB Medium goods vehicle	1990 Ford Trader rigid flat bed truck	4.45	5 sp man	courier truck
7	NB Medium goods vehicle	1996 Isuzu NPR300 rigid pantech truck	6.2	5 sp man	parcel delivery
12	NC Heavy goods vehicle	1998 UD PK235 rigid pantech truck	13.9	6 sp man	bulk parcel delivery
13	NC Heavy goods vehicle	1993 Mitsubishi FM557 MS rigid pantech truck	15.0	10 sp man	bulk parcel delivery
14	NC Heavy goods vehicle	1994 Isuzu FTH 1400 rigid refrigerated truck	20.4	9 sp man	bulk delivery to supermarket
17	NCH Heavy goods vehicle	1996 Inter ACCO 2350 rigid front lift refuse truck	30.0	6 sp auto	industrial waste collection
16	NCH Heavy goods vehicle	1994 Ford L9000 prime mover	23.5 *42.5*	18 sp man	bulk parcel delivery
15	NCH Heavy goods vehicle	1995 Freightliner 11295A prime mover	23.5 *45.0*	18 sp man	bulk quarry products

***** this vehicle was driven by EPA personnel as a "chase vehicle" and used to follow similar panel vans (see section 4.5.7)

****** this vehicle was driven by EPA personnel and used solely to provide a "definition" of driving patterns in the 4 different road categories (see section 4.5.6)

Table 3: Sample vehicle specifications

Veh Id	Vehicle Type	ADR Categ	Year man	Vehicle Manufacturer and Model	Nr axles	Turbo	Odo (km)	Gears	Eng cap (l)	Power (Kw) "@" RPM	TORQUE (NM) "@" RPM	Un'l Mass	GVM/ GCM
1	passenger	MC	1997	Mitsubishi Pajero	2	yes/intercool	100	5M	2.8	92/4000	292/2000	2.055	2.645
2	passenger	MC	1997	Toyota Land Cruiser	2	no	52,000	5M	4.2	96/4000	271/2000	2.187	2.96
3	P'van	NA	1996	Ford Transit (AUTO)	2	yes	35,000	5A	2.5	63/4000	200/2100	1.8	2.8
4	P'van	NA	1997	Ford Transit	2	yes	5,000	5M	2.5	74/4000	224/2100	1.8	2.8
5	Bus	ME	1997	MAN 11-220 HOCL-N/Ansair Orana	2	yes/intercool	45,000	3A	6.9	162/2400	800/1200		11.9
6	Rigid	NB	1990	Ford Trader 79864	2	no	194,000	5M	3.5			2.5	4.495
7	Rigid	NB	1996	Isuzu Npr301	2	no	75,000	5M	4.5	85/3200	291/1600	3.6	6.2
8	Rigid	NB	1993	Daihatsu V119-MWY (Dual Cab)	2	no	53,000	5M	3.7	71/3400	247/2000	2.23	4.495
9	Bus	ME	1997	Scania Euro-II (low floor)	2	yes/intercool	78,000	3A	11.0	180/2000	1000/1100	12.2	19.1
10	Bus	ME	1997	Merc 0405	2	yes	18,000	4A	12.0	220/2200	1245/1250	10	17.6
11	Bus	ME	1992	Volvo B10M	2	yes	407,000	4A	9.6	178/2200	890/1300	13	17.3
12	Rigid	NC	1998	Nissan UD PK235	2	yes/intercool		6M	6.9	173/2800	647/1800	7.15	13.9
13	Rigid	NC	1993	Mitsubishi FM557MS	2	yes	328,000	10M	7.5	157/2800	626/1400	7.4	15
14	Rigid	NC	1994	Isuzu FTH 1400	3	yes	246,000	9M	8.4	163/2550	735/1700	10.86	20.4
15	Prime Mov	NCH	1995	Freightliner 11295A	3	yes/intercool	254,000	18M	12.7	375/2100	2237/1200	7.76	23.5/45
16	Prime Mov	NCH	1994	Ford L9000	3	yes/intercool	53,000	18M	12.7	375/2100	2237/1200	8.58	23.5/42.5
17	Rigid	NCH	1992	International ACCO 2350G	4	yes/ intercool	120,000	6A	10.0	225/1500	709/1500	15.11	30

Vehicle	Destinations
General Transport Mitsubishi Pajero Vehicle 1	Lidcombe, Coogee, Randwick, Chippendale, Abbotsbury, Central Coast, Eastwood, Marrickville, Sefton
General transport Toyota Landcruiser Vehicle 2	Lidcombe, CBD, Randwick, Willoughby, Abbottsbury, Central Coast

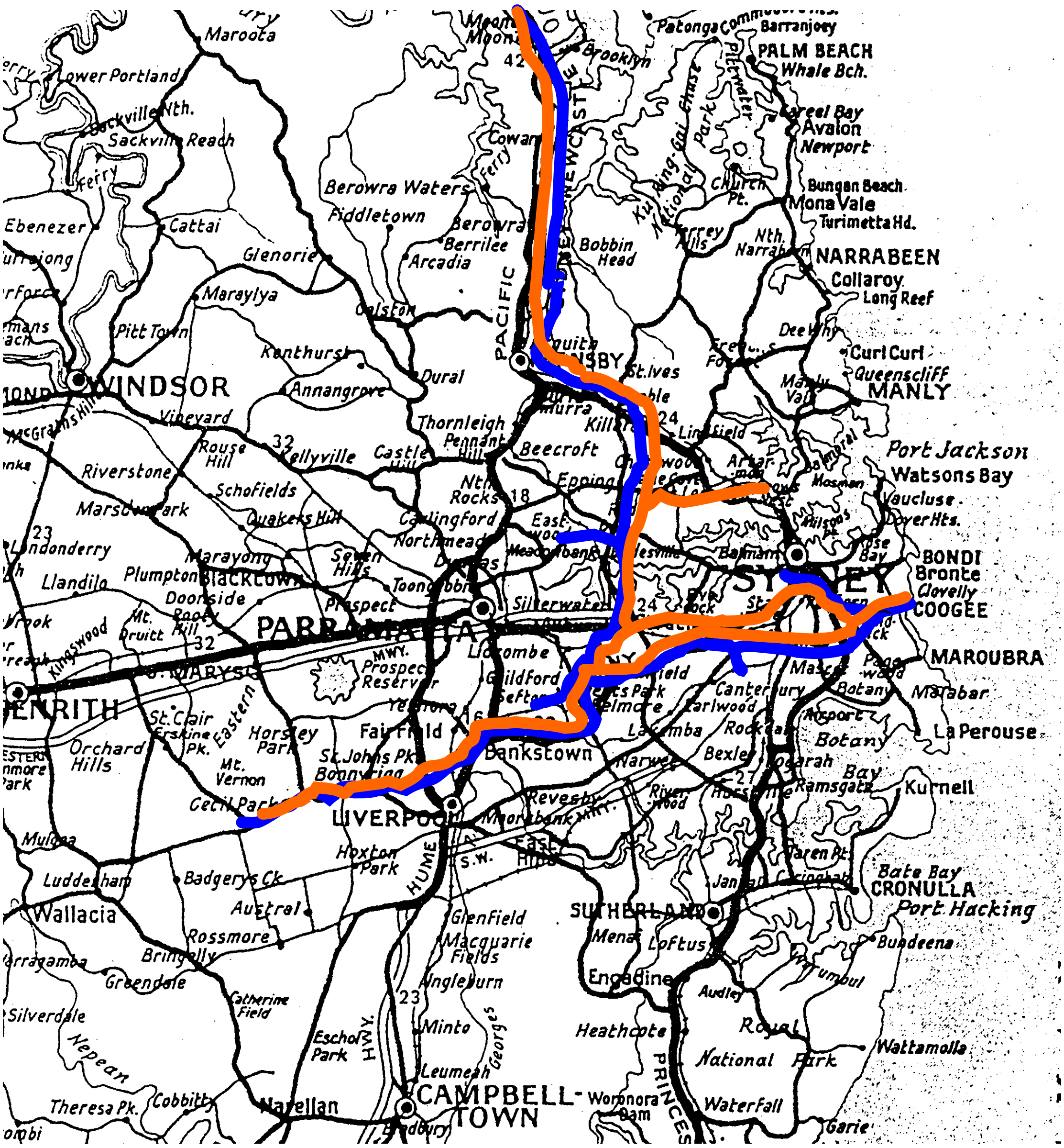


Figure 1: Routes Travelled by MC-category Off Road Passenger Vehicles

Vehicle	Destinations
Postal Delivery Ford Transit Van Vehicle 3	Lidcombe, Lewisham, Ryde, Bankstown, Five Dock, CBD, Smithfield.
Chase vehicle Ford Transit Van Vehicle 4	Alexandria, CBD, Vaucluse

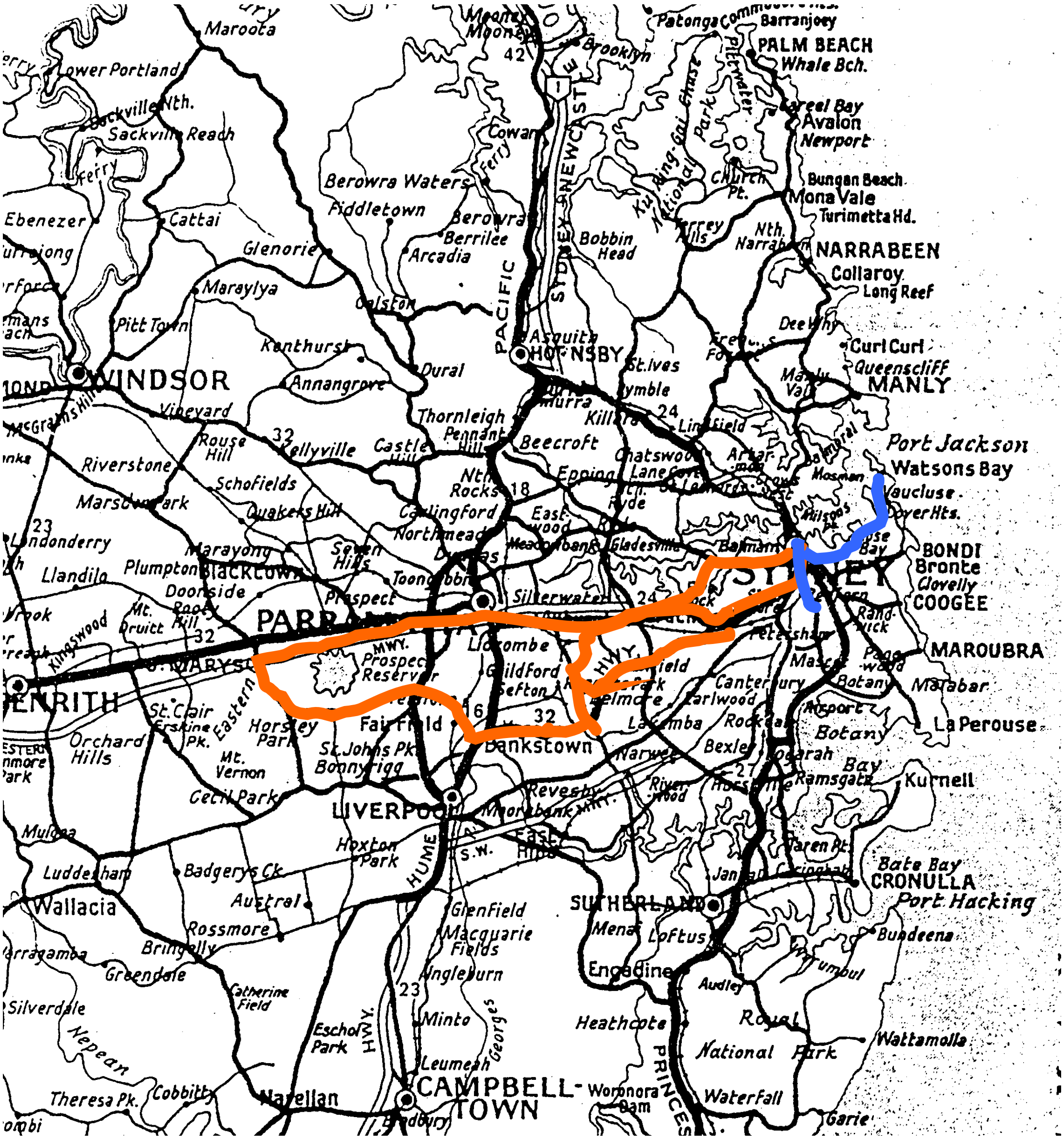


Figure 2: Routes Travelled by NA-category Light Goods Vehicles

Vehicle	Destinations
Courier Ford Trader Vehicle 6	Lidcombe, Silverwater, Chatswood, South Strathfield, Auburn, Emu Plains, Regents Park, Arndell Park, West Ryde
Parcel delivery Isuzu NPR300 Vehicle 7	Homebush, CBD

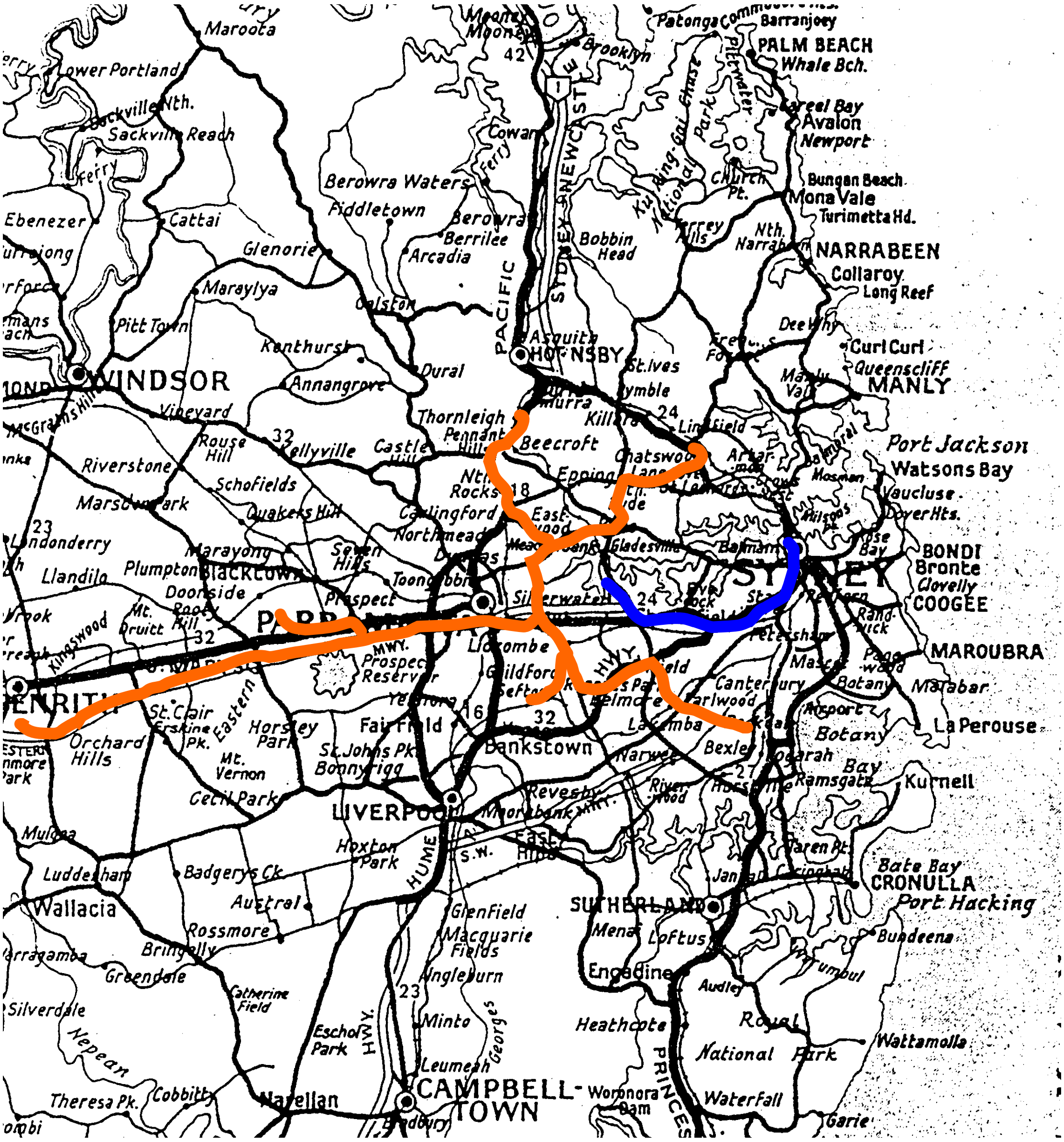


Figure 3: Routes Travelled by NB-category Medium Goods Vehicles

Vehicle	Destinations
Bulk parcel del'y Nissan UD PK235 Vehicle 12	Homebush, Liverpool, Hoxton Park, Smeaton Grange, Camden, Chipping Norton, Milperra, Prestons, Bringelly, Narellan, Picton Bargo
Bulk parcel del'y Mitsubishi FM557MS Vehicle 13	Clyde, Severn Hills, Chatswood, St Leonards, Airport (Mascot)
Bulk supermarket del'y Isuzu FTH 1400 Vehicle 14	Homebush, Parramatta, West Ryde, Berala, Padstow, Coogee, Rockdale, Ryde, Waterloo, Newtown, Brighton, Hornsby, Ermington, CBD

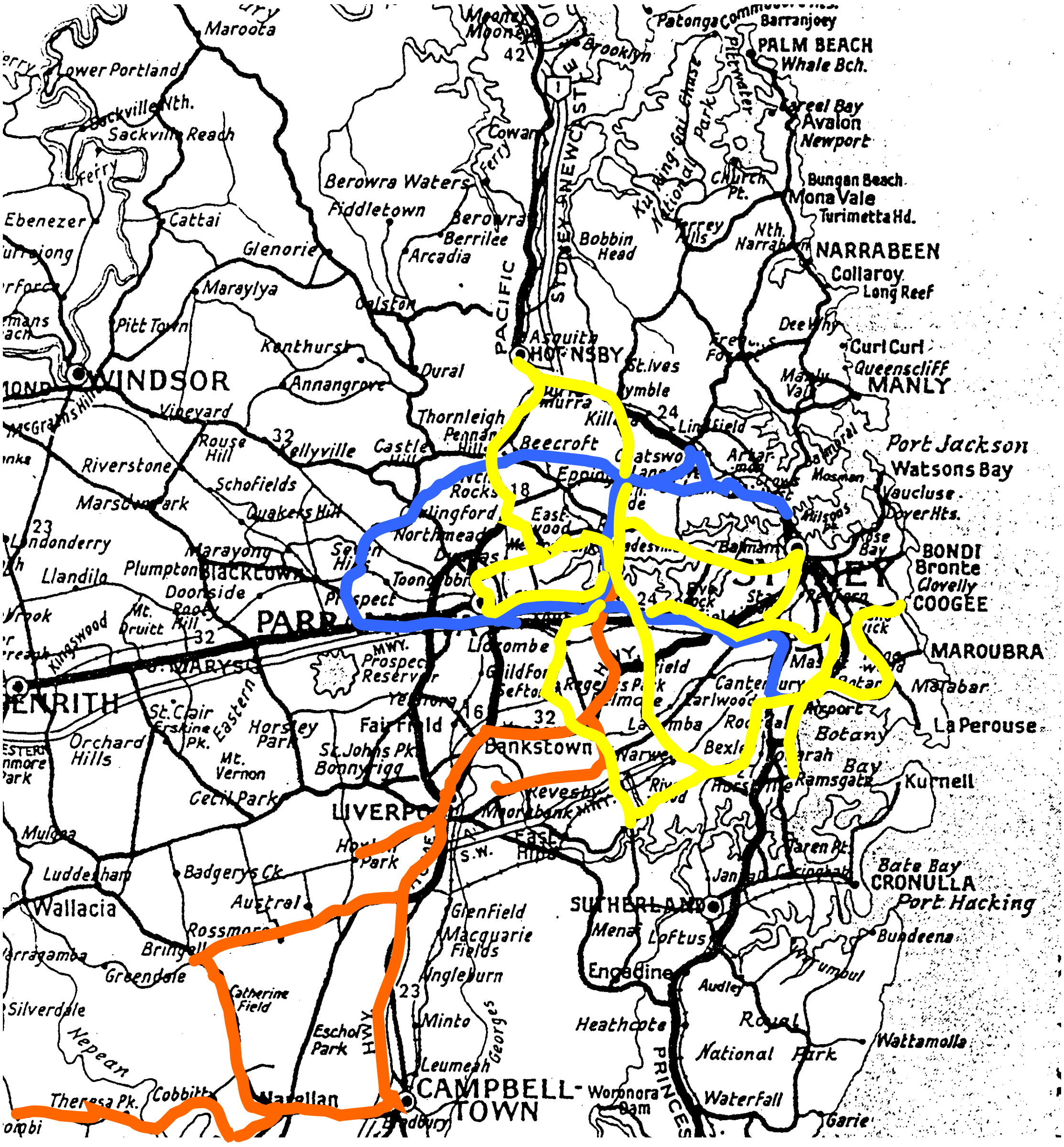


Figure 4: Routes Travelled by NC-category Heavy Goods Vehicles

Vehicle	Destinations
Bulk quarry prods Freightliner Vehicle 15	Emu Plains, St Peters, Prospect, Blacktown, Liverpool, Chipping Norton
Bulk parcel del'y Ford L9000 Vehicle 16	Clyde, Port Botany, Glebe, Darling Harbour
Ind waste collection ACCO 2350G Vehicle 17	Erskine Park, Parramata, Granville, Auburn

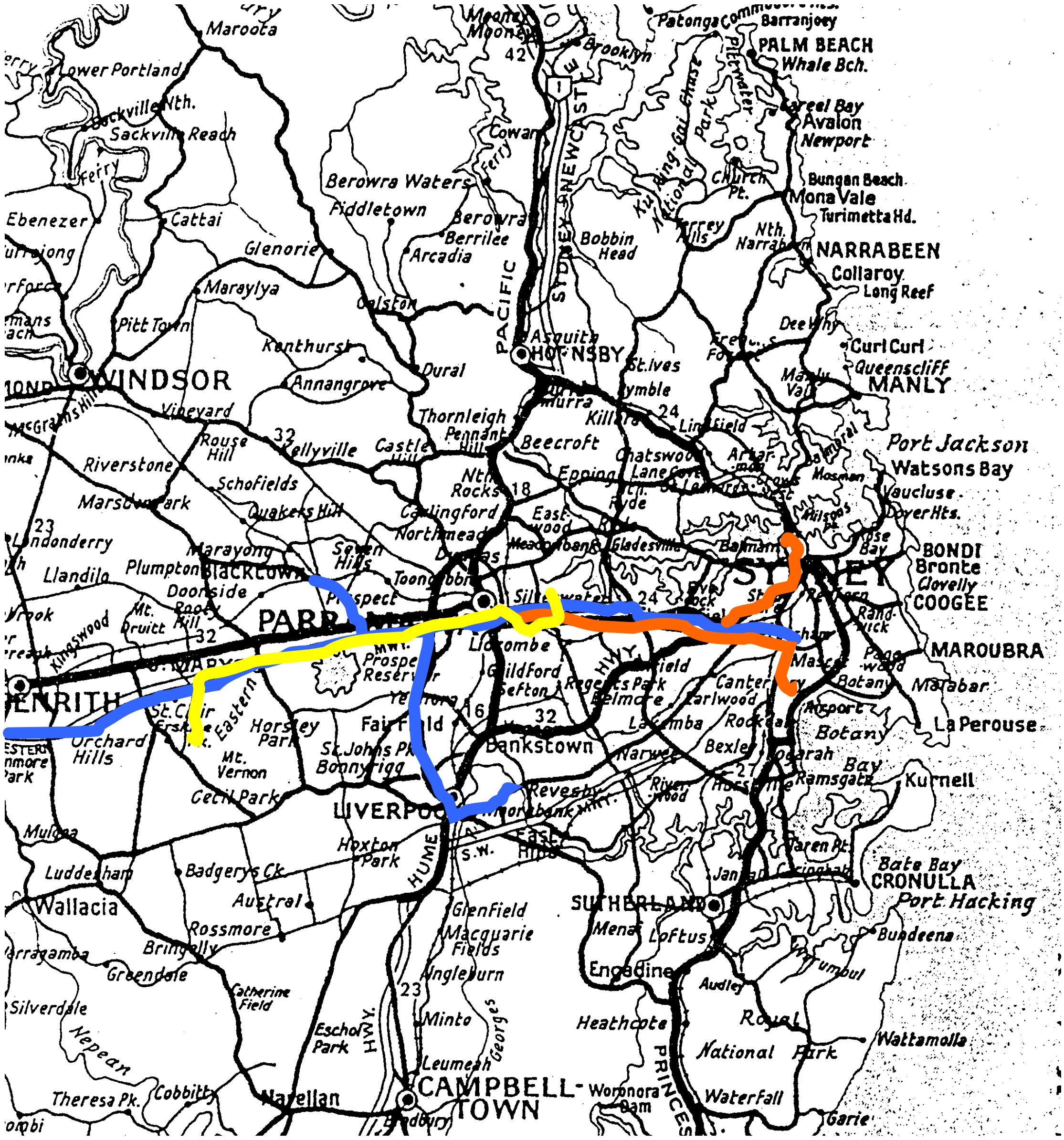


Figure 5: Routes Travelled by NCH-category Heavy Goods Vehicles

Vehicle	Routes
MAN Ansair Vehicle 5	Cremorne, Neutral Bay, Mosman Area
Scania Vehicle 9	CBD – Chatswood, CBD – Epping
Mercedes 0405 Vehicle 10	Bankstown – Liverpool
Volvo B10M Vehicle 11	Blacktown Area

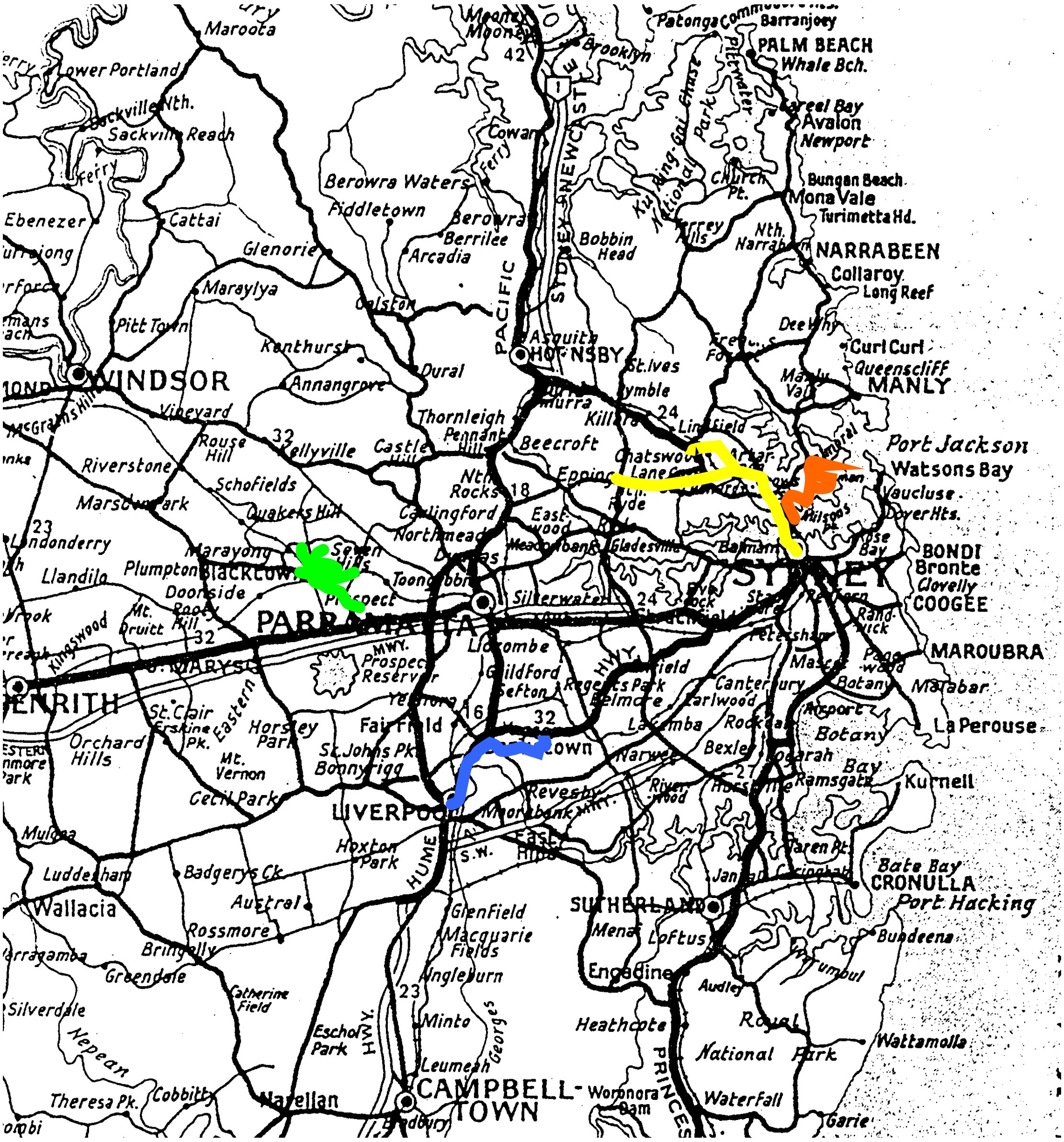


Figure 6: Routes Travelled by ME-category Heavy Buses

4.5 Data Collection

4.5.1 Data-logger

Road speed and engine speed signals were collected from each vehicle during its normal in-service use using a Datataker 605 portable, programmable data-logger, which was mounted inside the driver's cab (see figure 7). The data-logger was programmed to record engine and road speed signals at a sampling interval of 1 second, and to apply user defined calibration coefficients to convert these signals to km/h and rpm, respectively.

The data-logger was set to start recording when the vehicle engine was running, and to stop recording when the engine was switched off. The data-logger had sufficient memory for about 24 hours of data (2-3 days of normal on-road use), and was set to stop recording when the memory was full.

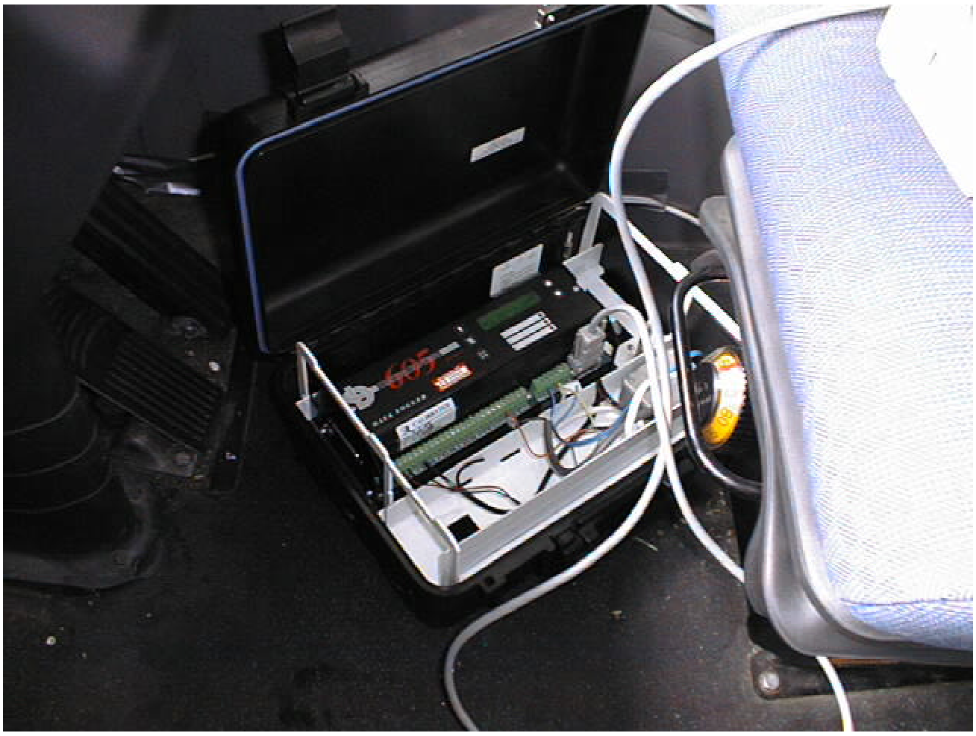


Figure 7: Datataker 605 Data-logger

4.5.2 Road Speed

A light beam tachometer (refer figure 8) providing an analogue output signal voltage, was used to measure road speed for all vehicles except one. The tachometer was mounted under the chassis rails of the vehicle, using a clamping system specially fabricated for the Project. The beam from the tachometer was directed towards strips of reflective tape attached to the vehicle's drive shaft. The tachometer's output signal, which was proportional to road speed, was captured by the data-logger. The arrangement of this system is illustrated in figure 8.

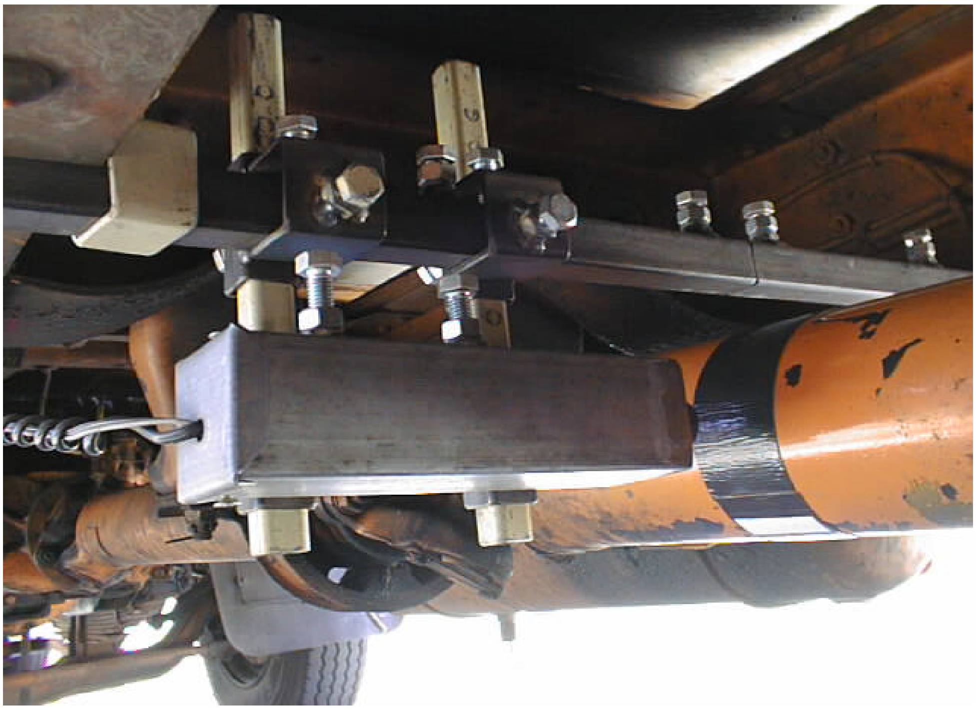


Figure 8: Arrangement of Road Speed Measuring Equipment.

The light beam tachometer was calibrated by driving the vehicle on the road at a range of speeds, and referencing the tachometer output signal against the speed indicated by the vehicle's speedometer. Linear calibration coefficients were then calculated and programmed into the data-logger.

One vehicle (number 17, the waste collection truck), had a high quality speed sensor fitted to drive its speedometer. The sensor's digital output signal was intercepted for capture by the data-logger, and calibrated in the same manner as for the light beam tachometer.

4.5.3 Engine Speed

Engine speed was obtained, where possible, by accessing the signal to the vehicle's dashboard tachometer, and was calibrated against the tachometer readings.

It was not possible to collect engine speed for all vehicles in the sample because -

- 2 vehicles did not have engine speed sensors and tachometers fitted as standard equipment , and therefore did not have speed signals that could be accessed
- on 4 vehicles, electronic incompatibilities made the engine speed signal noisy and/or discontinuous, and therefore unreliable.

In all, 11 of the 17 vehicles had engine speed successfully logged.

4.5.4 Vehicle Details

A record of the vehicle specifications was made on pre-printed data-sheets at the time the data-logging equipment was installed.

Vehicle operators were given a log sheet on which the drivers were asked to fill in details of time, load carried and journey destinations. Operators and drivers were fully briefed on how to fill out these forms, and of their importance to the Project objectives. Other information, such as routes, timetables and duty rosters, was obtained from the operators where available.

Where log sheets were not correctly or completely filled out by the drivers, estimates of the load carried were made based on the operator's assessment of a normal load for that vehicle.

4.5.5 Data Handling

At the end of the logging period, the data were down-loaded from the data-logger onto a portable lap-top computer. The data were then screened for errors using the "excel" spreadsheet program and reviewed by the Project Team's Quality Assurance Officer, before analysis.

4.5.6 Definition of Road Categories

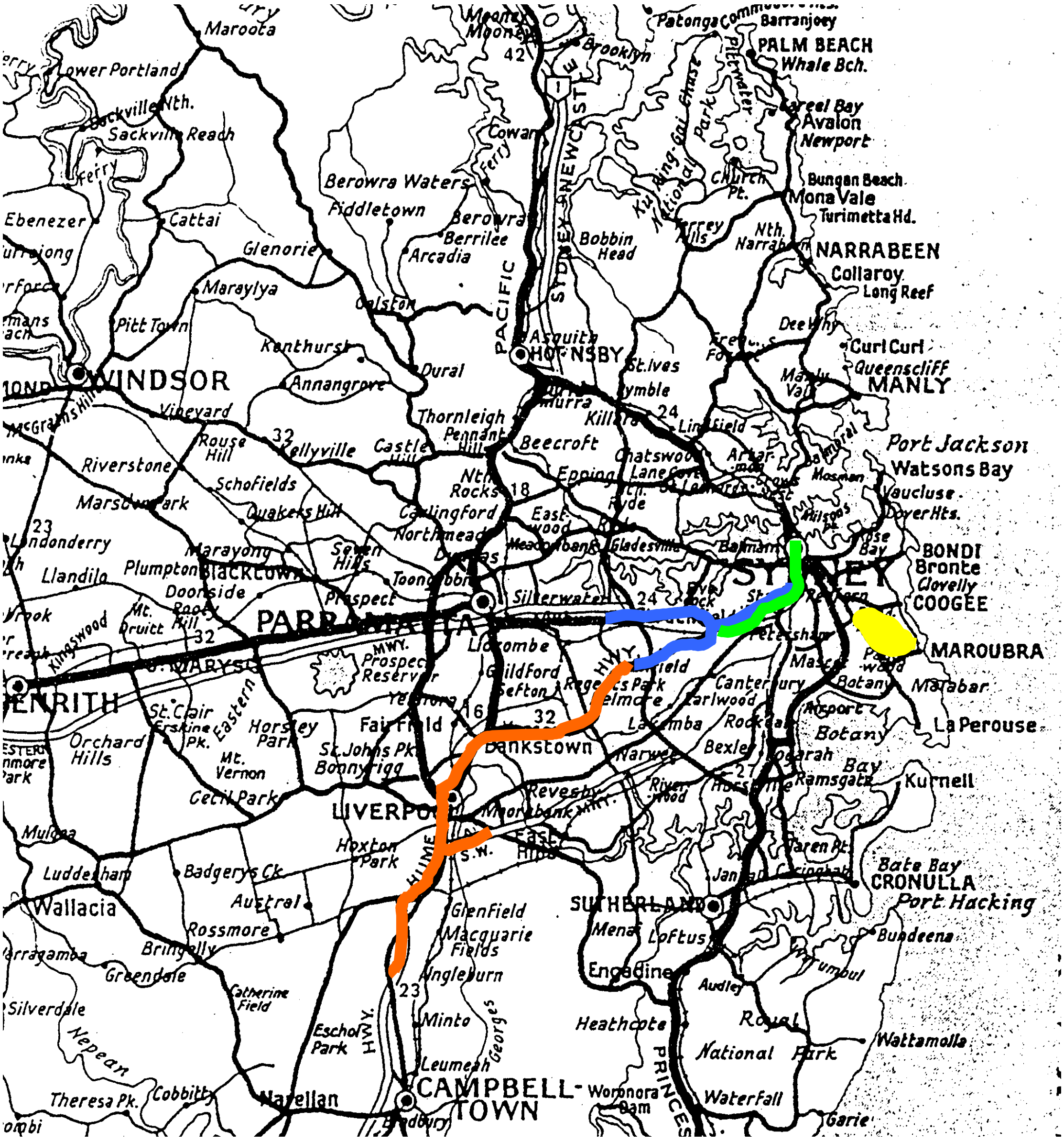
One vehicle was sent out specifically to aid statistical characterisation of the driving sequences, in each of the road trip categories (highway/freeway, arterial, minor/residential and congested). This vehicle (number 8, an EPA-owned Daihatsu Delta 4.45t GVM truck) was equipped with data-logging equipment, and was sent out with an EPA driver to follow a predetermined route comprising discrete, one to two-hour sequences of driving in each of the road categories. The data collected were split into four separate road category files, for characterisation and analyses.

The routes selected are shown in figure 9.

4.5.7 Use of Chase Vehicle

Difficulties were experienced in obtaining more than one light commercial diesel vehicle (GVM <3.5t) for inclusion in the sample. Most operators using vehicles of this size were using either petrol or LPG vehicles; could not guarantee their diesel vehicles would be in regular use during the logging period; or were not prepared to have a vehicle out of service for the time necessary for installation of the logging equipment.

Therefore, data-logging equipment was installed in an available EPA-owned diesel panel van (number 8), which was sent out to follow similar diesel panel vans at random in order to obtain typical route and driving characteristics. In this way, the inherent inaccuracies of the chase-vehicle technique caused by dissimilar chase and target vehicle driving characteristics, was minimised.



Highway/Freeway :

Arterial:

Minor/Residential:

Congested

- Hume Hwy from Greenacre to Liverpool, then M5 to Ingleburn and return to Moorbank (off peak hours)
- Hume Hwy from Strathfield South to Haberfield (off peak hours)
- Parramatta Rd from Glebe to Auburn (off peak hours)
- Randwick/Kingsford/Maroubra suburban streets (off peak hours)
- Sydney Central Business District (off peak hours)
- Parramatta Rd from Haberfield to Ultimo (peak hours)
- City Rd/King St from Ultimo to Newtown (peak hours)

Figure 9: Location of Definitive Road Category Driving Patterns

5 DATA ANALYSES

CSIRO Mathematical and Information sciences (CMIS) provided assistance with analyses of the on-road driving data and derivation of the UEDC's and CUEDC's. This section outlines the methodology used by CMIS to derive these drive cycles and illustrates the development process using ADR category NB as an example. (The full CMIS report is included as Attachment 1).

5.1 Methodology

Representative driving patterns were required for each of four road flow categories ('congested', 'residential/minor', 'arterial' or 'freeway/highway'), from which the UEDCs and CUEDCs could be constructed. Various mathematical techniques were applied to achieve this.

All methodologies were based on the notion of a *microtrip*, which is similar to a "sequence" as defined and used by Andre *et al*. (3).

A *microtrip* is defined as the excursion between two successive time points at which the vehicle was stationary. By convention, a period of rest is at the beginning of a microtrip rather than at the end. Thus a typical microtrip is a period of rest followed by periods of acceleration, cruising, deceleration until the vehicle is at rest again, whereupon the next microtrip starts.

The data logged from each vehicle were segmented into microtrips and following further analysis used to build the UEDCs and CUEDCs.

5.2 Road Flow Classification

Information published by Carnovale *et al* (12) was used to define important predictors of road flow category and the values of their respective cut-points for distinguishing transition between different categories -

Freeway/Highway:	Major roads with relatively high average speeds (say in excess of 40km/hr), and low congestion levels (say less than 5% idle time).
Arterial:	Major roads with moderate average speeds (say 20 – 40 km/hr), and moderate congestion levels (say 20% idle time).
Residential/Minor:	Secondary roads with moderate average speeds (say 20 – 40 km/hr) and negligible congestion.

From this we infered –

Congested:	Any roads where average speeds are limited by traffic congestion to, say, less than 20 km/hr.

These conditions are tabulated as follows –

	Congested	Res/Minor	Arterial	Fwy/Hwy
Average speed	<20	20 - 40	20 – 40	>40
Idle time	0 – 100%	negligible (<5%)	approx 20%	<5%

These descriptors were assumed to be the important predictors of road flow category, and their values above were used as the initial cut-points for distinguishing transition between different categories.

Using these empirical rules we attempted to classify every microtrip for one of the vehicles (Vehicle 12). The table above failed to classify a number of microtrips, as they fell outside the above ranges of idle time and speed. Also, there was a very large number of congested microtrips.

From examination of the microtrips we found –

- categorisation was difficult, since very many microtrips had characteristics of others
- even at high (freeway/highway) average speeds, there were congested elements, and idle times of 15%+
- in many sequences having characteristics of minor roads, there were significant idle periods
- the difference between minor and arterial sequences was difficult to see
- in most obviously congested sequences, % idle time was quite short

Some adjustment to the cut-points was required to categorise all the data and to assign reasonable splits between categories. This included –

- adoption of a definition of congestion, which was arbitrarily assigned as average speed below 15 km/hr, or microtrips of less than 20 seconds duration.
- assignment of 15 km/hr as the minimum average speed for 'freeflow' arterial and minor road sequences.
- removal of the limitation on idle time for freeway/highway trips.

The revised empirical rules are given as follows -

	Congested	Res/Minor	Arterial	Fwy/Hwy
Average speed	< 15 km/hr	15-40 km/hr	15-40 km/hr	> 40 km/hr
Idle time	0-100%	< 10%	> 10%	0-100%

Although the rules are complete (all microtrips were classified), there were some microtrips with excessively long idle periods for which none of the categories seemed appropriate. A new category, *Wait*, was defined to accommodate these microtrips. This category was intended for long periods (> 150 sec) where the vehicle was at rest. Reasons for these periods may include warming the engine or loading and unloading with the engine on.

Aside: all microtrips falling into the *Wait* category were excluded from the determination of UEDCs and CUEDCs, as mass emission levels would be very low and would not significantly impact on inventory calculations. However, summary statistics for these categories were calculated and are reported in section 5.3.

In order to validate the expert rules, a test vehicle (Vehicle 8) was dispatched specifically to be driven in each of the four road flow conditions. Some data for this vehicle were culled to increase the accuracy of the nominal driving conditions.

The empirical expert rules were applied to the microtrips for Vehicle 8 and the results are given in the following classification table:

Nominal Classification	Predicted Classification				Total M'trips
	Congested	Res/Minor	Arterial	Fwy/Hwy	
Congested	56	9	15	0	80
Res/Minor	1	8	2	3	14
Arterial	26	9	25	9	69
Fwy/Hwy	11	1	7	15	34

The row labels indicate 'nominal' road category and the column labels indicate the classified or predicted road flow conditions. So for example, out of the total of 80 microtrips for data collected from road conditions nominated as congested, 56 were classified as 'congested', 9 as 'residential/minor', 15 as 'arterial' and 0 as 'freeway/highway', giving a success rate of 56/80 or approximately 70%.

The overall 'nominal' classification rate was (56+8+25+15)/197 = 53% (or 47% misclassified). The term 'nominal' is used here since, although the general driving conditions of Vehicle 8 were recorded, there may have been short periods of one road condition (congestion say) during driving in other road conditions which were not taken into account. Therefore 53% should be viewed as a minimum overall classification rate.

Misclassifications occur where microtrips have some features pertinent to one category and some features pertinent to another. The method of selecting representative microtrips (as described in section 4) endeavours to select microtrips with features distinct to one road flow condition, and are therefore less likely to be misclassified.

This is a fairly low overall classification rate for many applications. However, for the present application, that of finding the most representative microtrips for each road flow condition, it may be adequate. How robust the choice of representative microtrips is to misclassifications is an important consideration, but the resources of this project were too limited to investigate this question.

Using statistical methods, a classification tree which would best predict road conditions given the set of predicting variables, was generated. A number of statistics of the Vehicle 8 microtrips were supplied as predicting variables. These 13 statistics included duration of microtrips, average speed and number of periods while in each of the four modes idling, cruising, accelerating or decelerating (3 x 4 = 12 variables), as well as the overall average speed. Of these variables, the tree-based classifier chose idle time and average speed as the two most important variables, these being the same variables used by Carnovale. For a tree with four nodes specified the tree-based classifier produced classification rules as follows –

	Congested	Res/Minor	Arterial	Fwy/Hwy
Average speed	< 31 km/hr	31-46 km/hr	31-46 km/hr	> 46 km/hr
Idle time	0-100%	< 20%	> 20%	0-100%

The resulting classifications of each microtrip using the tree-based classifier are as follows –

Nominal Classification	Predicted Classification				Total M'trips
	Congested	Res/Minor	Arterial	Fwy/Hwy	
Congested	**76**	**3**	**1**	**0**	**80**
Res/Minor	**3**	**11**	**0**	**0**	**14**
Arterial	**44**	**12**	**9**	**4**	**69**
Fwy/Hwy	**16**	**2**	**3**	**13**	**34**

That is, the classification rate for congested roads was 76/80 = 95% while the overall classification rate was (76+11+9+13)/197 = 55%, an expected improvement since the classifier was constructed from the same data used for validation.

However, these classification rules had cut-points that were considered unrealistic –

- average speed of 31 km/hr, was felt to be too high for 'congested' conditions, and would cause probable over-representation.
- 20% idle time was felt to be too high a cut-off to adequately distinguish 'arterial' versus 'residential/minor' road flow conditions.

From all of the above, the following cut-points were considered appropriate –

- 45 km/hr for the average speed threshold between 'freeway/highway' and other categories
- 15 km/hr for the average speed threshold between 'congested' road flow and other categories, which would reduce the chance of over-representation of 'congested' flow conditions.
- 15% idle time for the cut-point to distinguish 'residential/minor' and 'arterial' road flow conditions.

Note: the supporting rule considered earlier, that all microtrips less than 20 seconds duration be classified as 'congested' road flow, was now redundant because the average speed was less than 15 km/hr for all such microtrips.

The classification rules used throughout the remainder of the analysis were then –

	Congested	Res/Minor	Arterial	Fwy/Hwy
Average speed	**< 15 km/hr**	**15-45 km/hr**	**15-45 km/hr**	**> 45 km/hr**
Idle time	**0-100%**	**< 15%**	**> 15%**	**0-100%**

This approach is illustrated in the Figures 10 and 11 where the microtrips for Vehicles 12 and 8 are superimposed over the cut points for the different road flow conditions represented by vertical and horizontal lines. For Vehicle 8, (Figure 11) each microtrip is represented by a coloured letter, each letter identifying each nominal (observed) road condition. For example, microtrips for 'congested' road conditions represented by a blue 'C' fall predominantly within the rectangular area of 0 to 15 km/hr. The horizontal line at 15% idle represents a supporting cut-point to separate 'arterial' (above the line) microtrips from 'residential/minor' (below the line) microtrips.

The resulting classifications of each microtrip using the revised empirical classifier are given below –

Nominal Classification	Predicted Classification				Total M'trips
	Congested	Res/Minor	Arterial	Fwy/Hwy	
Congested	56	12	12	0	80
Res/Minor	1	12	1	0	14
Arterial	26	14	24	5	69
Fwy/Hwy	11	3	7	13	34

The classification rate for 'congested' roads was 56/80 = 70%, while the overall classification rate was (56+12+24+13)/197 = 53%. The classification rate for 'residential/minor' was 12/14 = 86%.

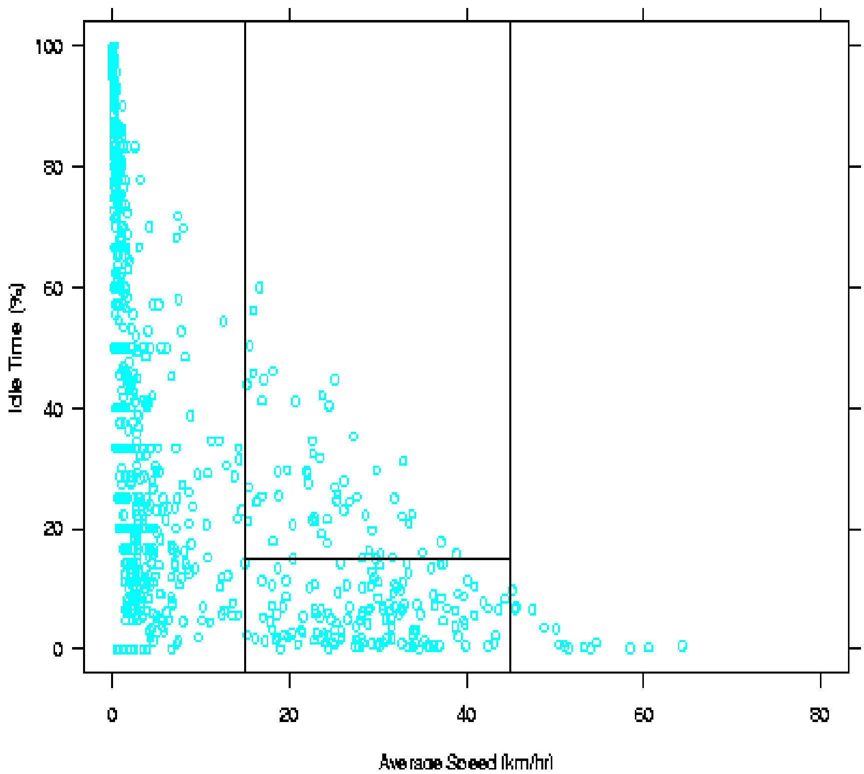


Figure 10: Classification of Vehicle 12 Microtrips

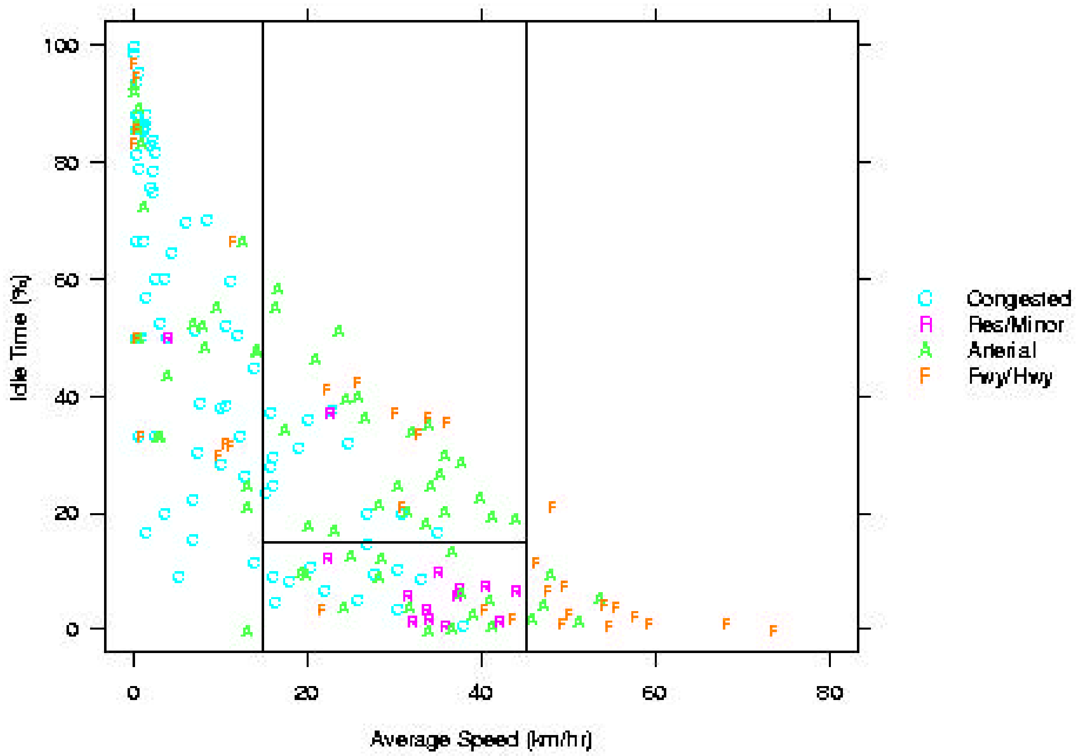


Figure 11: Classification of Vehicle 8 Microtrips

5.3 Microtrip Summary Statistics

Initially, exploratory data analysis tools were used to gain a better understanding of typical urban driving patterns for the vehicles. Graphs of speed versus time were produced and important summary statistics were calculated. Summary statistics for each road condition within each ADR category are presented in the following tables. Statistics for the '*wait*' category defined previously are also given.

5.3.1 Summary statistics of microtrips

The following summary statistics were calculated on microtrips:

- Number of microtrips
- Median microtrip distance (m)
- Median microtrip duration (sec)
- Median microtrip average speed (km/hr)
- Median microtrip idle time (sec)
- Median microtrip idle time (%)
- Median microtrip maximum speed (km/hr)
- Median number of periods of acceleration

A period of acceleration was defined as a period of increasing speed during which the actual acceleration exceeded 2 km/hr/sec some time in the period, not necessarily over the whole period.

For a number of microtrips, especially those classified as Congested, there were no periods of acceleration using this definition. This definition and similar definitions for periods of deceleration and cruising are used for the fitting of piecewise linear segments to the CUEDCs in section 5.5.2.

By way of example, the summary statistics of microtrips for ADR category NB are shown below -

Summary statistics of microtrips for ADR category NB

Statistic	Congested	Res/Minor	Arterial	Fwy/Hwy	Wait
Total nr of microtrips	1130	226	176	77	2
Median microtrip distance (m)	3.3	687.8	681.0	2765.6	0.1
Median microtrip duration (sec)	11	81.5	96.5	202	1694.5
Median microtrip av. Speed (km/hr)	1.3	29.7	26.1	51.1	0
Median microtrip idle time (sec)	4	4	28.5	8	1694.5
Median microtrip idle time (%)	52.9	6.0	27.7	3.7	100
Median microtrip maximum speed (km/hr)	4.6	52.2	60.5	75.1	0.3
Median nr of periods of acceleration	0	2	1	3	0

5.3.2 Summary statistics for each road condition in each ADR category

Summary statistics were calculated for each road condition within each ADR category as follows:

- Distance travelled (km)
- Time spent (hr)
- Average speed (km/hr)
- Idle time (hr)
- Idle time (%)
- Number of periods of acceleration

By way of example, the summary statistics for ADR category NB are shown below –

Summary statistics for ADR category NB

Statistic	Cong'd	Res/Min	Arterial	Fwy/Hwy	Wait	Overall
Distance Travelled (km)	42.4	244.4	156.4	508.6	0	951.8
Time Spent (hr)	7.6	7.1	5.5	7.7	0.9	28.8
Average Speed (km/hr)	5.6	34.4	28.6	66.4	0	33.0
Idle time (hr)	4.3	0.4	1.6	0.3	0.9	7.5
Idle time (%)	55.8	5.8	29.4	3.8	100	26.0
Nr of periods of acceleration	436	640	316	260	0	1652

5.4 Determination of Most Representative Microtrips

For this work, 'representative microtrip' were defined as follows -

"The representative microtrip of a set of microtrips is that microtrip which spends time at speeds and accelerations in similar proportions to the entire set of microtrips."

In mathematical terms, this is the microtrip which minimises the distance between its empirical distribution function (a function of speed and acceleration) and the pooled empirical distribution function (edf) from all microtrips. Many statistics can be determined in terms of the edf. In theory, choosing microtrips with a similar edf to that of the pooled microtrips ensures that the chosen microtrips have similar statistics to the pooled microtrips.

This method, albeit with a minor modification, was used to obtain a number of representative microtrips for each of the four road conditions for each of the vehicles within each ADR category. The modification was to downweight periods spent at rest, as these tended to dominate the choice of microtrip. That is, microtrip selection was almost exclusively decided on length of idle period rather than on other characteristics of the driving sequence.

For each ADR category, representative microtrips for each road flow condition were obtained by pooling the data for the vehicles in each category. Plots of the fifteen most representative microtrips for 'congested' roads and the five most representative microtrips for 'residential/minor', arterial' and 'freeway/highway' road flow conditions, for ADR category NB are presented by way of example in Figures 12 to 15. These plots have been copied from the CMIS report at Attachment 1.

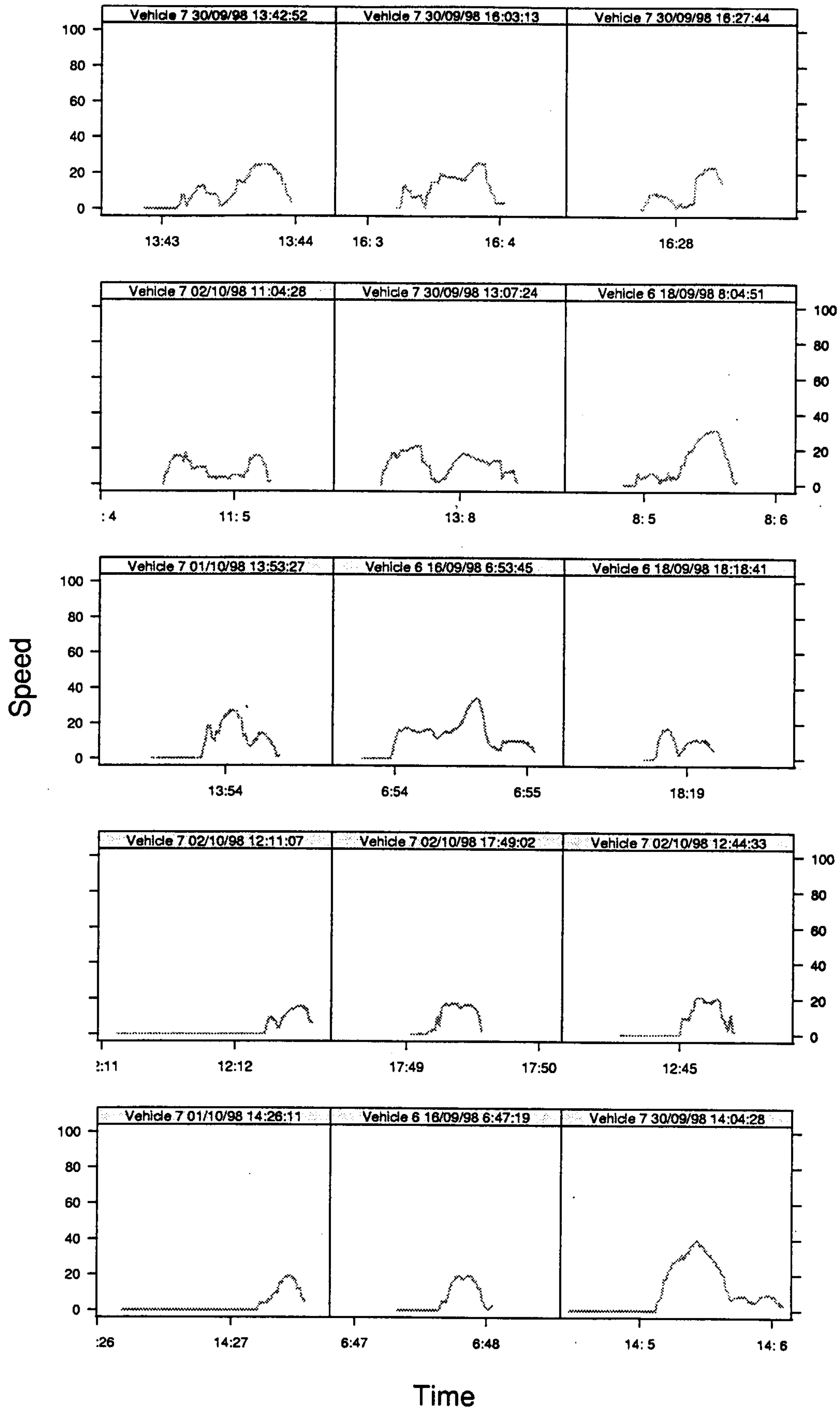


Figure 12: Most Typical Congested Microtrips for ADR category NB

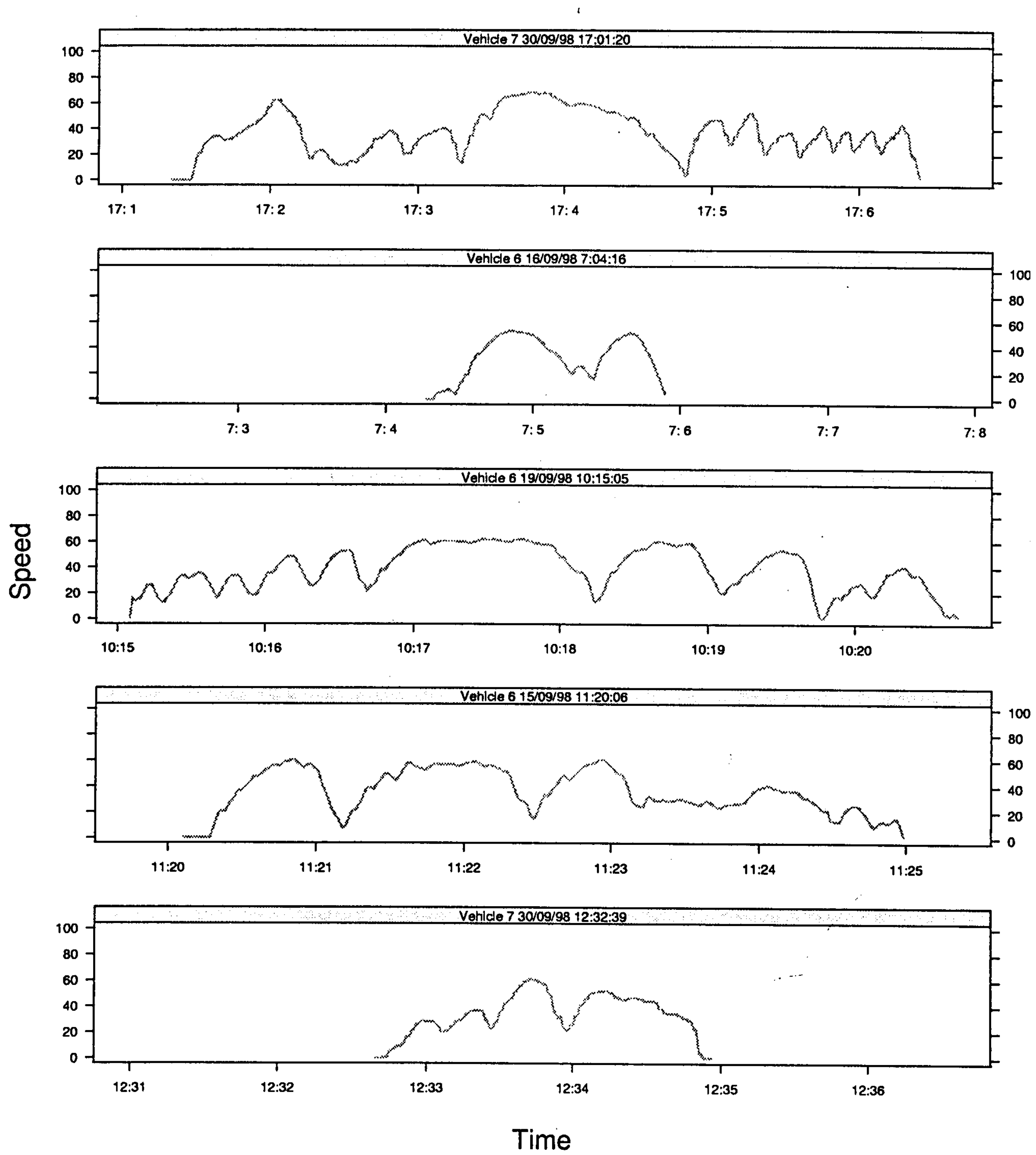


Figure 13: Most Typical Residential/Minor Microtrips for ADR category NB

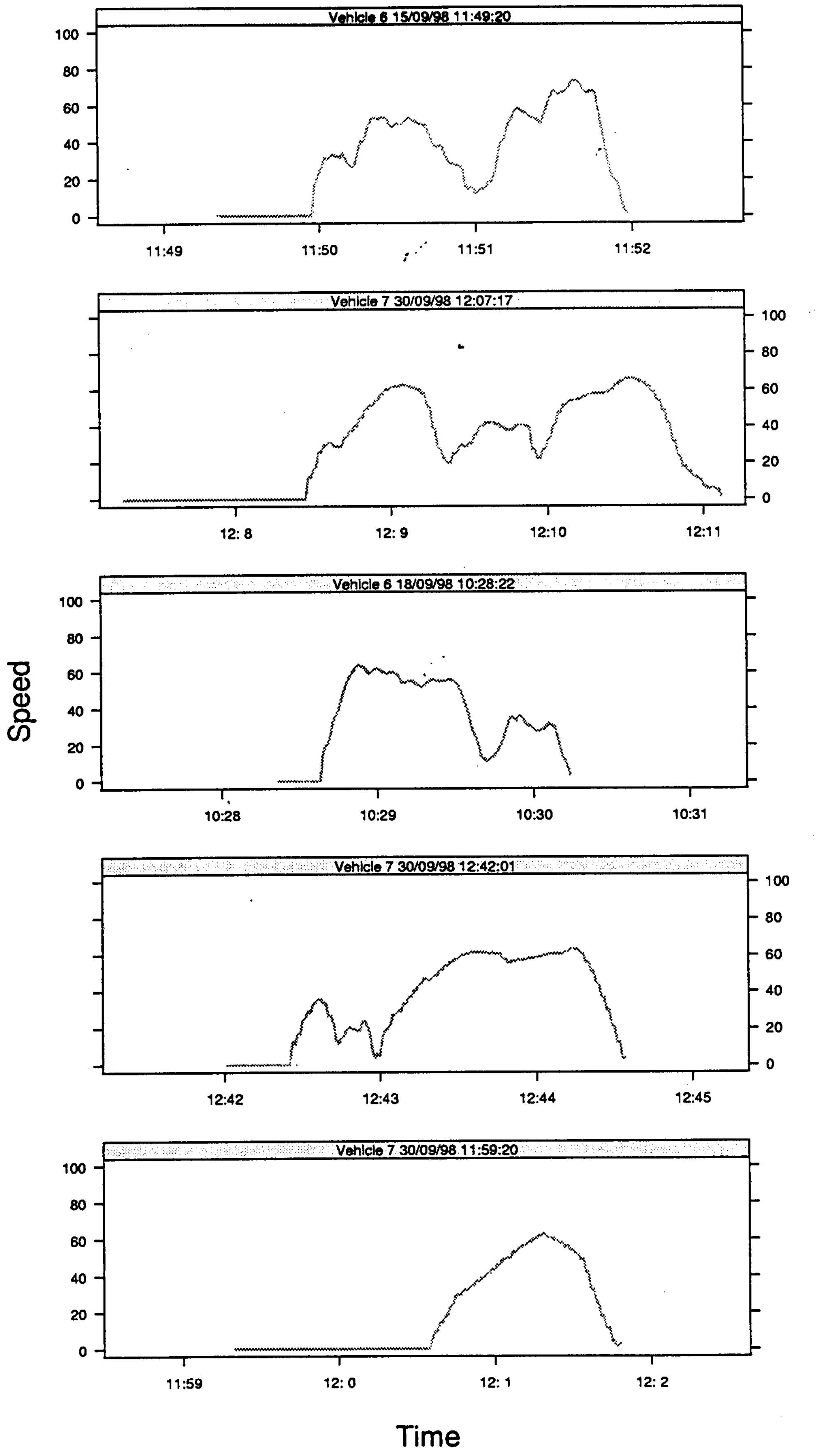


Figure 14: Most Typical Arterial Microtrips for ADR category NB

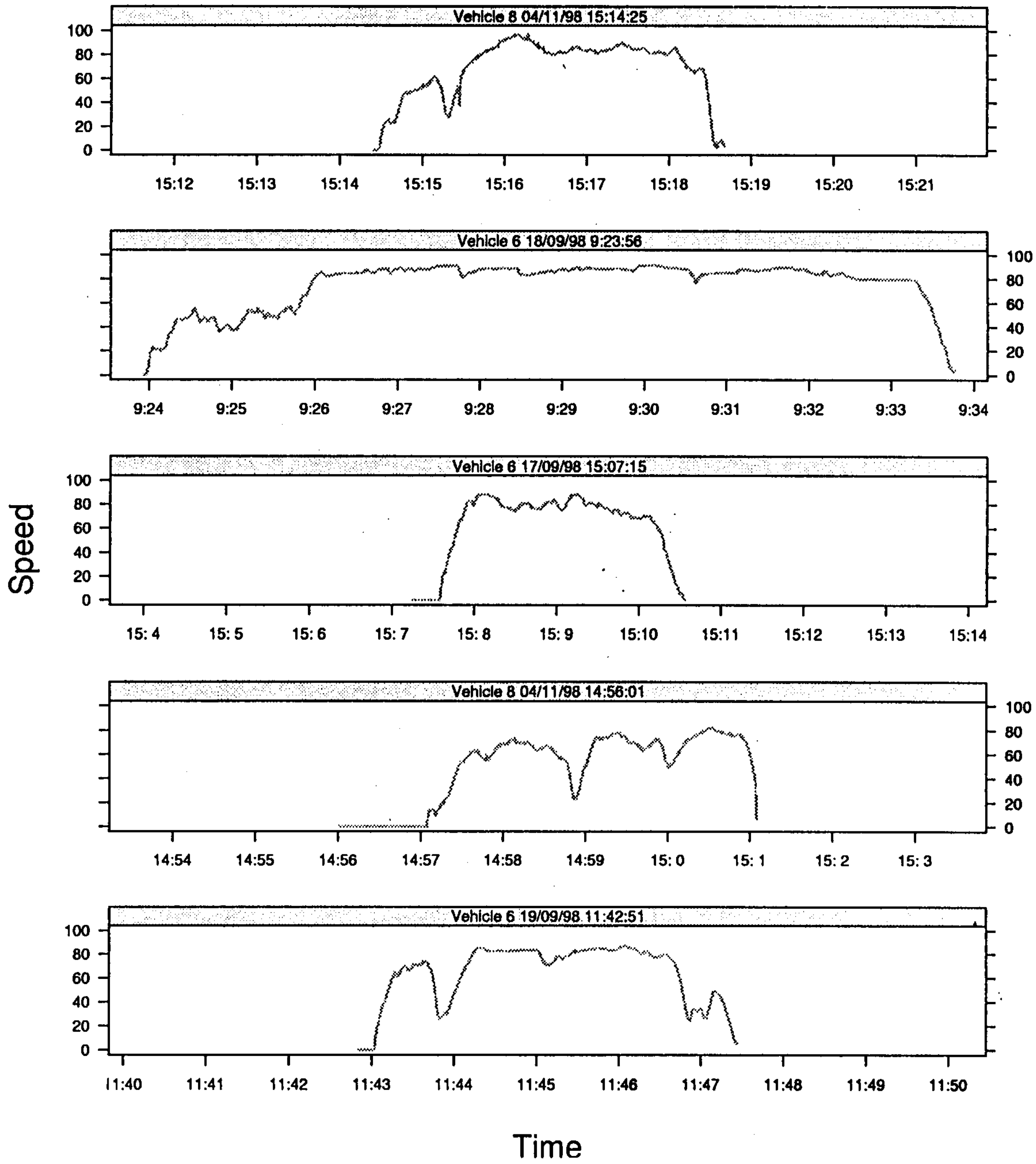


Figure 15: Most Typical Freeway/Highway Microtrips for ADR category NB

5.5 Establishing UEDCS and CUEDCS for ADR Categories

The time durations for the UEDCs, CUEDCs and their constituent road flow category sections, were targeted to allow adequate representation (no of microtrips) of on-road driving, and in the case of the CUEDCs, to allow the minimum sufficient time for emission sampling and analyses during testing. These target time durations were as follows -

	Target Duration (minutes)				
	Congested	Res/Minor	Arterial	Fwy/Hwy	Total
UEDC	6	18	18	18	60
CUEDC	5–6	7–8	6–7	8–9	26–30

5.5.1 UEDCs

For each ADR category, an appropriate number of (in almost all cases) the most representative microtrips that together closely met the target time duration requirements, were selected and added together to form the UEDC.

For example, the UEDC for ADR category NB was formed from the first 7 most representative microtrips for 'congested' flow, the first 4 for 'residential/minor' flow, the first 7 for 'arterial' flow and the first 3 for 'freeway/highway' flow conditions. The four road flow conditions of the UEDC are shown below in figure 16.

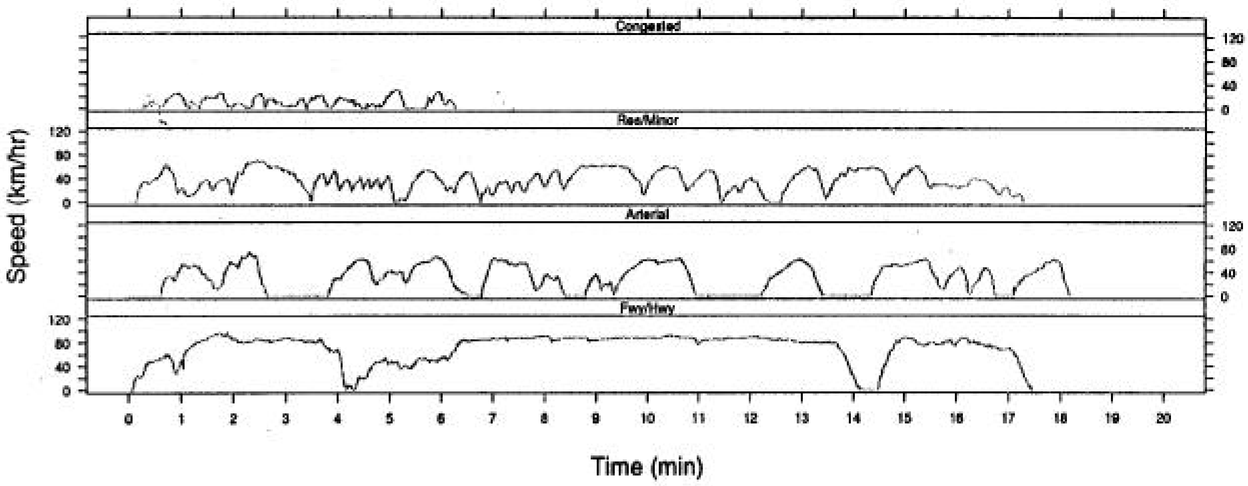


Figure 16: UEDC for ADR Category NB

5.5.2 CUEDCs

Hierarchical Cluster Analysis was used to explore which ADR categories, if any, could be combined to form a CUEDC. The distance measure used in the cluster analyses was the same as that used for identifying representative microtrips. For each road condition, cluster analysis was performed on a 6 x 6 similarity matrix consisting of all pairwise distance measures between the six ADR categories. This distance measure takes into account both acceleration and speed. The results of the cluster analyses are shown in the CMIS report at Attachment 1 (Appendix F) – and indicate no consistent clustering or grouping of subsets of ADR categories across the different road flow conditions. Therefore, separate CUEDCs were established for each ADR category.

By way of example, the resulting CUEDC for ADR category NB is presented in Figure 19. This figure also illustrates a mathematically 'smoothed' cycle (generated by CMIS) is superimposed over the CUEDC.

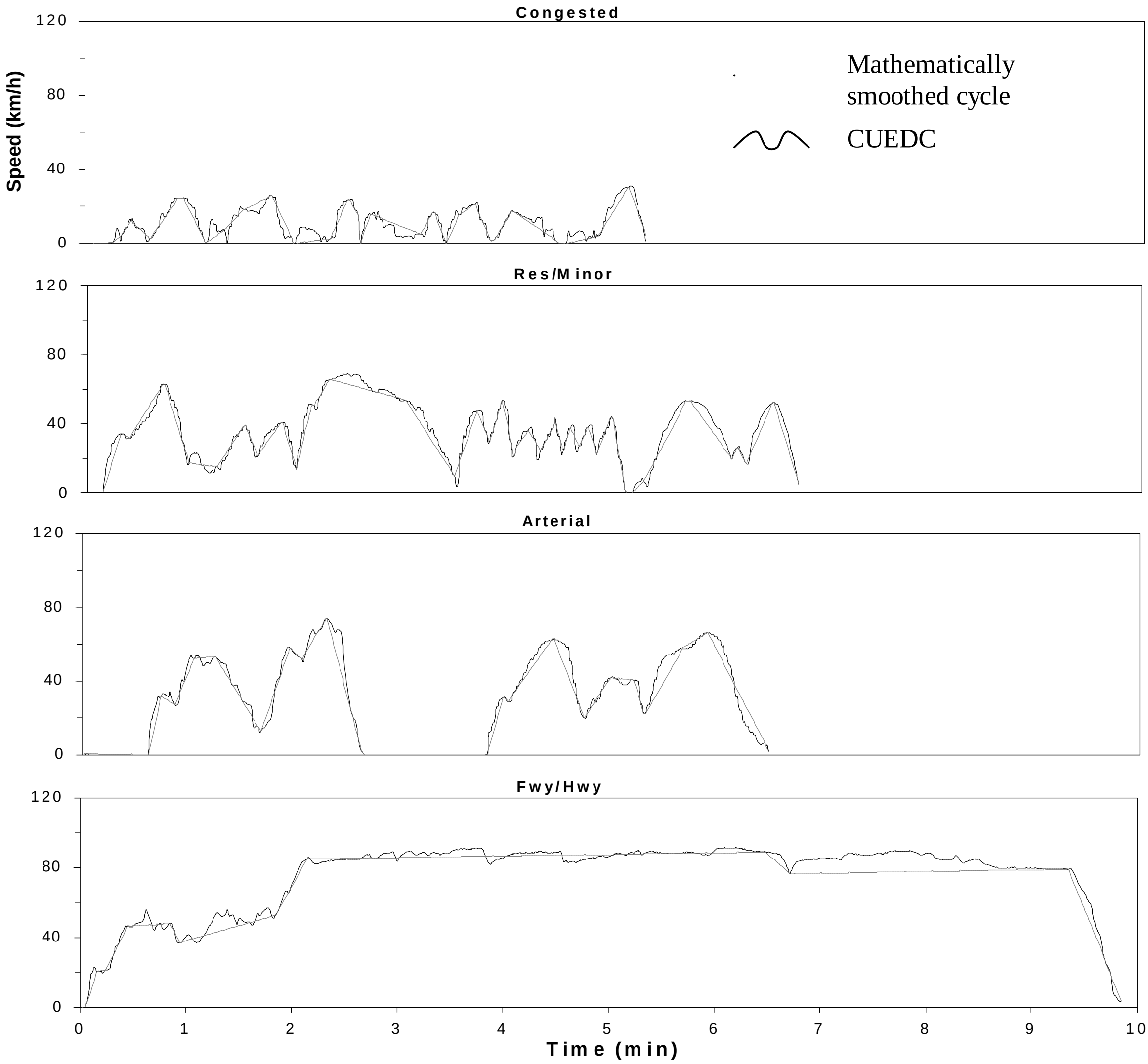


Figure 17: CUEDC for ADR Category NB

6 DEVELOPMENT OF 'SIMPLIFIED CUEDCS'

Simple 'straight line' transient cycles would likely be less demanding of dynamometer testing facilities than the complex CUEDCs given above, and might require less costly upgrading of currently available dynamometers. This would likely be at only small cost to the 'real world' representation of emission test results obtained over the cycle. Therefore, we have attempted to derive simplified CUEDCs.

We were hopeful that usable simple cycles would emerge from CMIS' application of statistical smoothing techniques, to the CUEDCs. However, given the complex nature of the microtrips, budget and time limitations forced this approach to be abandoned in favour of a non-mathematical approach.

Straight lines were manually drawn through each CUEDC, broadly following the major transient and cruise conditions while smoothing out the minor, using the mathematically 'smoothed' CUEDCs as a guide. These straight lines were then adjusted until the cycle's summary statistics were in approximate agreement (about ±5%) with those of the CUEDCs.

These cycles are referred to as 'Simplified CUEDCs' and are illustrated below each of the 6 complex CUEDC's in figures 18 to 23. The summary statistics of the 'Simplified CUEDCs' are compared with those of the CUEDCs in tables 4 to 9.

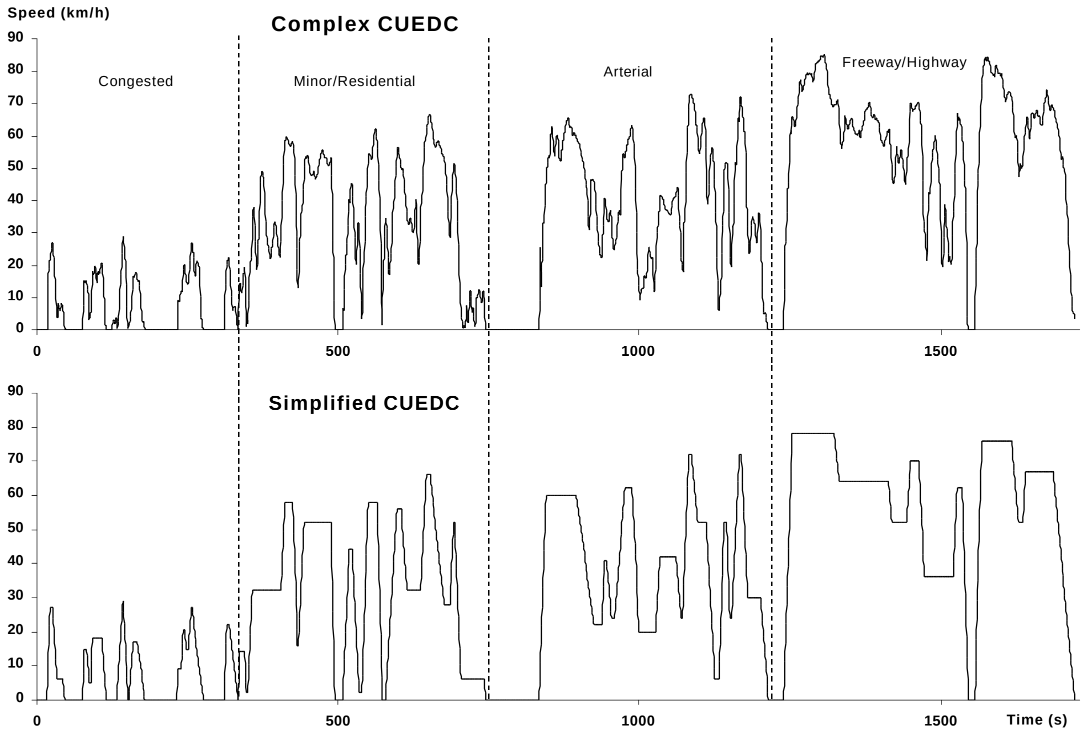


Figure 18: Complex CUEDC and simplified CUEDC for ADR category MC vehicles.

Table 4: Summary statistics for complex CUEDC and simplified CUEDC for ADR category MC vehicles.

Statistic	Congested		Res/Minor		Arterial		Fwy/Hwy		Overall	
	Complex	Simplified	Complex	Simplified	Complex	Simplified	Complex	Simplified	Complex	Simplified
Distance (km)	0.7	0.7	4.0	3.7	4.4	4.3	7.9	7.8	16.9	16.4
Time Spent (s)	333	333	412	412	468	468	509	508	1722	1721
Ave Speed (km/h)	7.1	7.2	34.5	32.6	33.9	32.9	55.7	55.1	35.3	35.3
Idle Time (s)	148	156	14	20	89	89	37	37	288	302
Idle Time (%)	44.4	46.8	3.4	4.9	19.0	19.0	7.3	7.3	16.7	17.5
Max Speed (km/h)	29	29	66.7	66	72.8	72	85.3	78	85.3	78

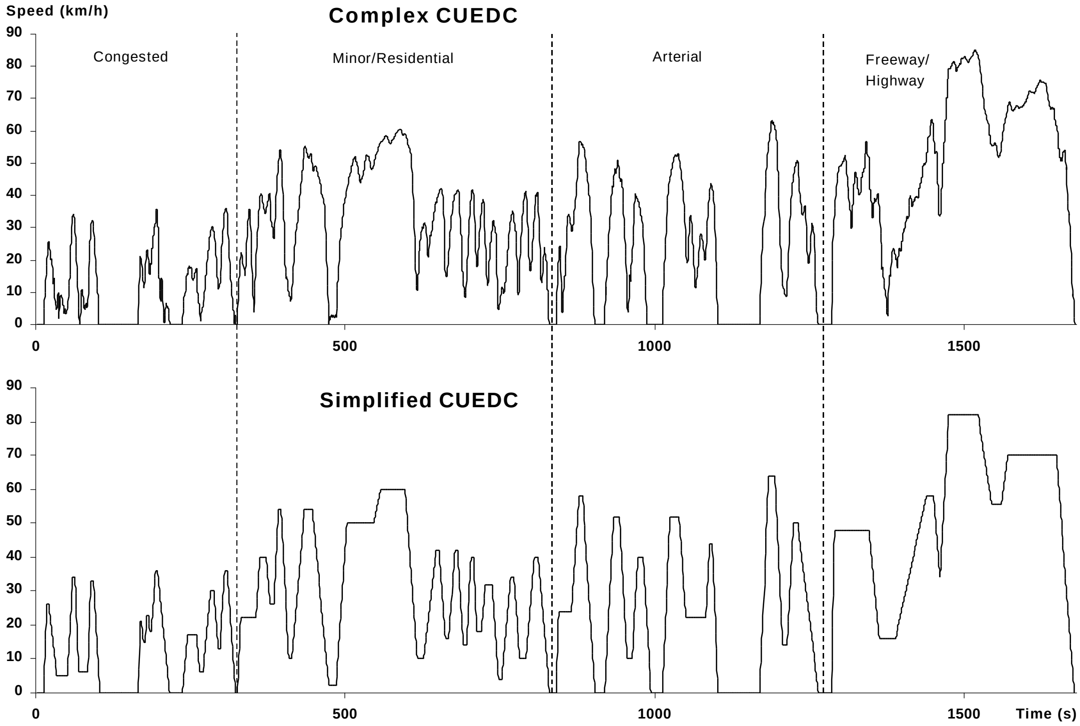


Figure 19: Complex CUEDC and simplified CUEDC for ADR category ME vehicles.

Table 5: Summary statistics for complex CUEDC and simplified CUEDC for ADR category ME vehicles.

Statistic	Congested		Res/Minor		Arterial		Fwy/Hwy		Overall	
	Complex	Simplified	Complex	Simplified	Complex	Simplified	Complex	Simplified	Complex	Simplified
Distance (km)	1.0	1.1	4.7	4.4	2.9	2.8	5.8	5.8	14.4	14.2
Time Spent (s)	322	322	506	506	435	435	414	413	1677	1676
Ave Speed (km/h)	11.1	12.2	33.3	31.6	23.7	23.3	50.8	50.7	30.9	30.4
Idle Time (s)	102	98	6	5	122	115	22	22	252	240
Idle Time (%)	31.7	30.4	1.2	1.0	28.0	26.4	5.3	5.3	15.0	14.3
Max Speed (km/h)	36.4	36	60.7	60	63.3	64	85	82	85	82

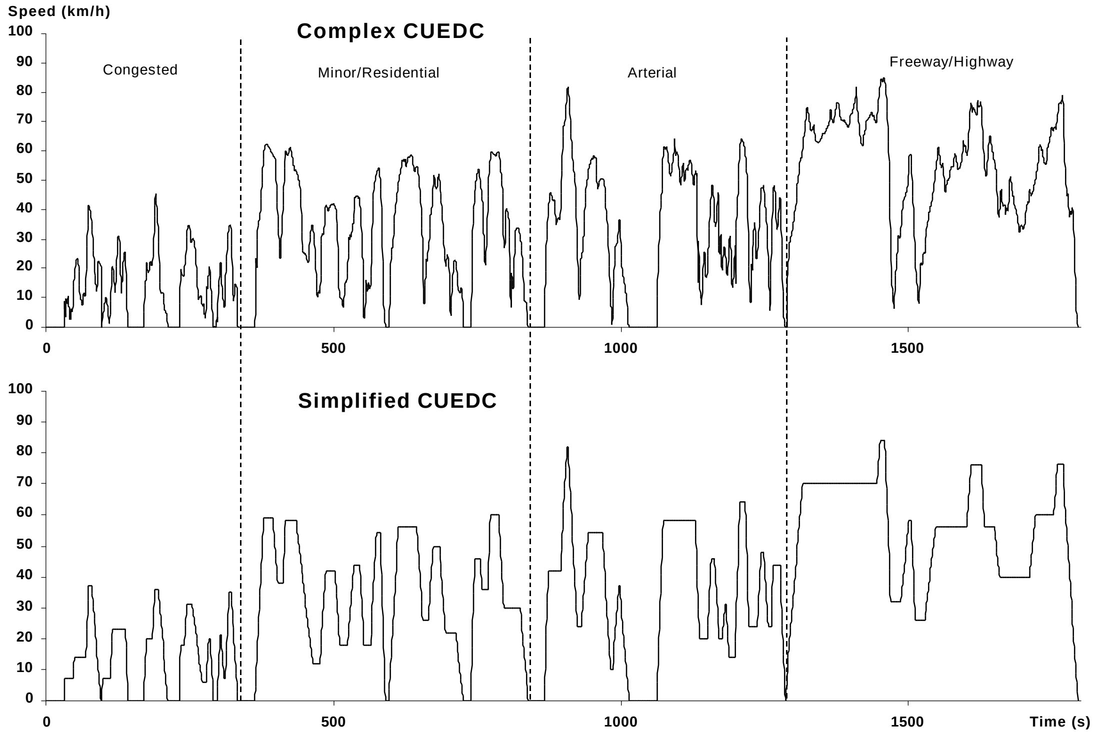


Figure 20: Complex CUEDC and simplified CUEDC for ADR category NA vehicles.

Table 6: Summary statistics for complex CUEDC and simplified CUEDC for ADR category NA vehicles.

Statistic	Congested		Res/Minor		Arterial		Fwy/Hwy		Overall	
	Complex	Simplified	Complex	Simplified	Complex	Simplified	Complex	Simplified	Complex	Simplified
Distance (km)	1.2	1.2	4.6	4.6	4.0	4.0	7.7	8.0	17.5	17.9
Time Spent (s)	334	334	504	504	447	447	509	509	1794	1794
Ave Speed (km/h)	13.0	13.1	32.8	32.9	32.0	32.2	54.5	56.8	35.1	35.3
Idle Time (s)	87	92	51	51	79	79	3	1	220	223
Idle Time (%)	26.0	27.5	10.1	10.1	17.7	17.7	0.6	0.2	12.3	12.4
Max Speed (km/h)	45.3	37	62.4	60	82.1	82	85	84	85	84

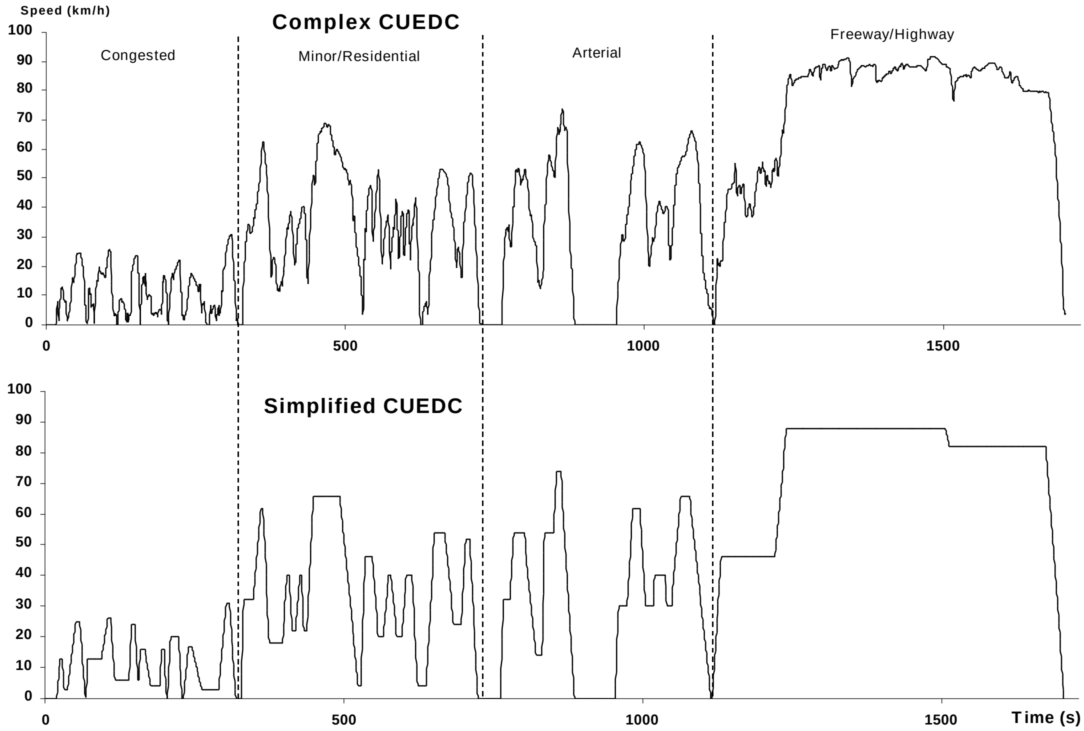


Figure 21: Complex CUEDC and simplified CUEDC for ADR category NB vehicles.

Table 7: Summary statistics for complex CUEDC and simplified CUEDC for ADR category NB vehicles.

Statistic	Congested		Res/Minor		Arterial		Fwy/Hwy		Overall	
	Complex	Simplified	Complex	Simplified	Complex	Simplified	Complex	Simplified	Complex	Simplified
Distance (km)	1.0	1.0	4.0	3.9	3.2	3.2	12.4	12.3	20.6	20.5
Time Spent (s)	319	319	405	405	390	390	591	591	1705	1705
Ave Speed (km/h)	10.9	11.3	35.8	34.9	29.9	29.9	75.3	74.9	43.5	43.2
Idle Time (s)	28	24	13	9	109	107	3	3	153	143
Idle Time (%)	8.8	7.5	3.2	2.2	27.9	27.4	0.5	0.5	9.0	8.4
Max Speed (km/h)	30.9	31	68.7	66	73.7	74	91.6	88	91.6	88

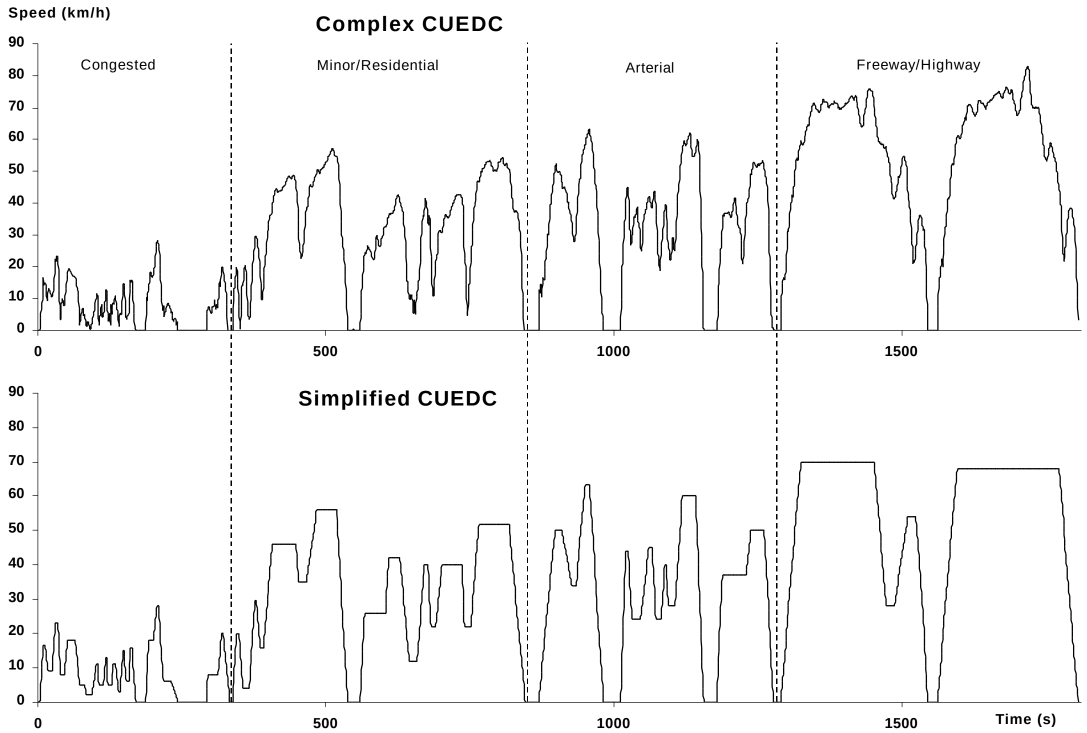


Figure 22: Complex CUEDC and simplified CUEDC for ADR category NC vehicles.

Table 8: Summary statistics for complex CUEDC and simplified CUEDC for ADR category NC vehicles.

Statistic	Congested		Res/Minor		Arterial		Fwy/Hwy		Overall	
	Complex	Simplified	Complex	Simplified	Complex	Simplified	Complex	Simplified	Complex	Simplified
Distance (km)	0.7	0.8	4.6	5.0	3.8	3.7	8.0	7.8	17.0	17.2
Time Spent (s)	328	332	509	512	431	430	528	527	1796	1801
Ave Speed (km/h)	8.0	8.2	32.4	35.1	31.5	30.7	54.2	53.5	34.1	33.7
Idle Time (s)	73	69	28	28	78	77	29	29	208	203
Idle Time (%)	22.3	20.8	5.5	5.5	18.1	17.9	5.5	5.5	11.6	11.3
Max Speed (km/h)	28.2	28	57.2	56	63.3	63.3	82.9	70	82.9	70

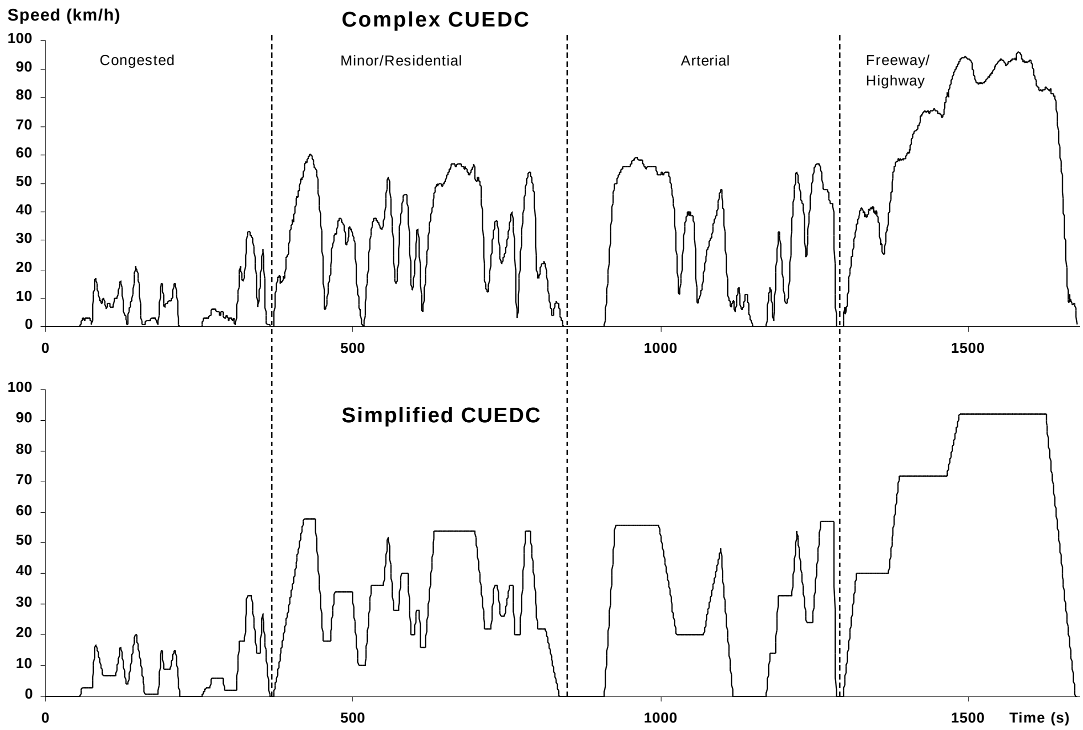


Figure 23: Complex CUEDC and simplified CUEDC for ADR category NCH vehicles.

Table 9: Summary statistics for complex CUEDC and simplified CUEDC for ADR category NCH vehicles.

Statistic	Congested		Res/Minor		Arterial		Fwy/Hwy		Overall	
	Complex	Simplified	Complex	Simplified	Complex	Simplified	Complex	Simplified	Complex	Simplified
Distance (km)	0.7	0.7	4.3	4.4	3.5	3.3	7.1	7.2	15.5	15.6
Time Spent (s)	364	364	477	470	444	444	390	387	1675	1665
Ave Speed (km/h)	6.7	7.1	32.6	33.6	28.1	26.9	65.2	66.6	33.4	33.5
Idle Time (s)	94	93	8	6	91	123	12	12	205	234
Idle Time (%)	25.8	25.5	1.7	1.3	20.5	27.7	3.1	3.1	12.2	14.1
Max Speed (km/h)	33	33	60.3	58	59	57	96.1	92	96.1	92

7 DISCUSSION

The work envisaged in Phase 2 of this Project is aimed to define the current and future impact of diesel vehicle emissions in Australia, and therefore to point the way in determining what needs there are for further emission control of current and future vehicles. The work will have significant cost, but if successful may show considerable benefit.

At this time, there are many uncertainties concerning the type of equipment required to carry out the phase 2 work to a successful and credible conclusion.

In particular, there is a level of uncertainty regarding the types and capabilities of medium and heavy-duty dynamometers that are currently available or could be economically upgraded, or that could feasibly be purchased for the work. Non-optimum equipment, which would require use of oversimplified driving cycles, would not produce a credible result. On the other hand, use of over-sophisticated equipment may increase the Phase 2 Project costs significantly.

The complex transient CUEDCs would require the use of a dynamometer with either inertia rolls, or computer-controlled dynamic load inertia simulation, together with a 'drivers aid'. While such equipment is available from Australian manufacturers, to our knowledge no Australian facilities currently include this capability for heavy-duty vehicles.

Testing using these CUEDCs (which have been developed from actual road-driving patterns and road-flow conditions) would yield emission test results that would reliably represent on-road emission levels. Therefore, assuming feasible availability of appropriate dynamometers, these CUEDCs are recommended for use in –

- determining the emissions performance of the diesel fleet for inventory development purposes.
- assessing the candidate list of short in-service inspection tests.

We have been advised by a number of equipment suppliers that equipment and drive cycle software, capable of performing the complex CUEDCs (excluding inertia on deceleration), is available at reasonable cost. However, we have not yet seen this demonstrated on a heavy-duty dynamometer.

Because of these equipment uncertainties, we are uncertain how to design the test cycles for the optimum degree of complexity/simplicity.

Having researched driving cycles extensively during the course of this work, it is our view that the complex transient cycles of the CUEDCs would produce the best technical result, but may not be able to be properly run on economically available dynamometers. The simple transient cycles in the 'Simplified CUEDCs' may also prove difficult, though less so.

We consider it is practical and would be low cost, to further simplify and possibly consolidate the CUEDCs in terms of road and ADR categories. While mathematical analyses did not suggest this could be done, we feel that further assessment of the cycles would be worthwhile. This could be achieved by selecting appropriate summary statistics (not the microtrips) from the complex CUEDCs, and using these to develop ‘stylised test cycles’ appropriately targeted for ease of inventory calculation and to be within the capabilities of dynamometers that may be more readily available.

Once developed, these ‘stylised test cycles’ could be evaluated/validated for practicability and correlation with the complex CUEDCs or even UEDCs, by testing a very small sample of vehicles in each of the ADR categories, on a suitably sophisticated dynamometer, if necessary overseas. The test cycles could then be refined if required, prior to or as an initial stage of the phase 2 work.

8 RECOMMENDATIONS

The following recommendations are made –

1. The UEDCs be used as the ‘real world inventory reference cycles’.
2. The CUEDCs be further simplified to ‘stylised test cycles’, prior to testing in Phase 2 of this Project.
3. The following three test cycles then be considered (in order of their technical suitability, practical application, and cost) for use in the Phase 2 Project for determination of the emissions performance of the diesel in-service vehicle fleet -
   (a) The complex CUEDCs.
   (b) The simplified (straight line) CUEDCs.
   (c) The ‘stylised test cycles’.

PART B – IN-SERVICE SHORT TEST EVALUATION

9 INTRODUCTION

The objective for this work was to identify practical, static and/or dynamometer-based diesel vehicle inspection procedures for in-service use, for further evaluation in phase 2 of this Project.

In this Part of the Report, we -

- identify and provide brief assessment of a number of short exhaust emission tests designed for use in inspection of in-service diesel engined vehicles.
- recommend 5 short tests for further evaluation through testing on a representative sample of in-service vehicles, in phase 2 of this Project.
- identify vehicle based causes of increased emissions from diesel engined vehicles in each ADR category.
- propose a non-invasive method of identifying high emitting vehicles, for further evaluation in phase 2 of this Project.

10 METHODOLOGY

The following investigative approach and methodologies were adopted -

- information obtained during Mr Brown's study tour of vehicle emission research organisations and government authorities in Europe and the US, was evaluated.
- the literature was searched for relevant information on in-service diesel vehicle emission testing overseas.
- the NSW EPA's library of diesel vehicle emission test protocols and research documentation, was searched.
- the driving pattern data developed in this work (contained in our first Interim Report), was examined.
- the NSW EPA's extensive records of repairs carried out to rectify faults on vehicles judged to be emitting excessive smoke under the EPA's '10 second smoke rule', were analysed.
- advice was solicited during two industry focus group meetings.

From this information -

- various short tests and inspection methods were identified and assessed, and 5 candidate short test procedures are recommended for further evaluation in Phase 2 of this Project.
- the most likely causes of high in-service emissions were identified.
- a non-invasive, '7-point inspection' procedure was developed.

11 IN-SERVICE SHORT TEST EVALUATION

Engine dynamometer testing has no practical application as an in-service tool for identifying high emitting vehicles, or for component fault diagnosis. Much research being undertaken overseas is targeted to develop practical and effective in-service inspection procedures, based upon static or chassis dynamometer tests.

It is widely accepted that measurement of smoke opacity provides a simple and acceptable approximation to particulate emissions suitable for inspection and maintenance type emission testing. Accurate measurement of particulate, usually by gravimetric means, requires sophisticated equipment and procedures more suited to certification type testing.

Many overseas authorities base diesel vehicle inspection/maintenance programs on use of a free acceleration test, specified as the ‘MOT’ test in Europe, and as the SAE J1667 test in the USA. It is generally conceded these tests have considerable shortcomings, and that a more scientific and ‘real world’ test is required for effective in-service fault discrimination.

In August 1998, the California Air Resources Board (CARB) issued a request for tender to develop a short in-service (inspection and maintenance type) test for heavy-duty vehicles based on loaded modes. The findings of this (likely high cost) project may be of considerable value in assessing what tests may be suitable for Australian in-service programs.

11.1 Identification and Assessment of Short Tests

There are a number of test modes that may be used in testing for diesel vehicle emissions. These modes, and our assessment of their ability to identify high emitting vehicles, are shown in table 10.

Table 10: Test modes used in testing for diesel vehicle emissions.

Test mode	Ability to identify high emissions		
	NOx	Particulate	Smoke
Free acceleration	no	no	fair
No load steady state	no	no	no
Part load steady state	poor	poor	poor
Full load steady state	good	fair	fair
Lug down	good	fair	fair
Part load acceleration	poor	poor	poor
Full load acceleration	good	good	good
Road observation	no	no	good

From the literature and from contacts with overseas agencies –

- the free acceleration smoke test is by far the most widely used for in-service I/M purposes, being used in USA, Canada, Europe, Japan and other countries.
- few jurisdictions outside the USA use any other test.
- no other tests have wide acceptance.
- no overseas jurisdictions apply any useful tests for enforcement of any in-service NOx or particulate (as opposed to smoke) standard.

The following test procedures are identified.

11.1.1 Free Acceleration Smoke tests

Free acceleration (or snap-acceleration, or snap-idle) tests for diesel vehicle smoke emissions are used in in-service I/M programs, in many overseas jurisdictions, including -

- Europe, subject to EU Roadworthiness Directive 92/55, and UNECE Regulation24
- Japan, subject to national regulation.
- USA, where EPA recommends (but does not mandate) the use of the free acceleration test described in SAE J1667, as the base for diesel vehicle I/M programs. Several jurisdictions have either implemented such programs, or have pilot programs under way.

The particular test procedures used are in all cases similar, though not identical. The most complete description is given in SAE J1667.

In principle, the tests are performed as follows -

- after engine preconditioning, the vehicle is held stationary, in neutral gear, with the engine at normal operating temperature and at idle.
- the engine is accelerated quickly to maximum governed speed (high idle), and held there for a second or two, before being returned to idle. This sequence is repeated a number of times.
- the maximum smoke opacity or density is recorded for each cycle, and averaged for all cycles for comparison with the standard.

Free acceleration tests do not match any on-road driving condition, or any condition simulated in engine-dynamometer driving cycles used for certification testing. Its results do not correlate well with loaded mode or transient mode dynamometer test results, nor with on-road smoke levels. The test cannot successfully be performed on some late model engines having electronic controls that limit free acceleration.

Nevertheless, the tests are widely accepted for I/M purposes due to their simplicity, low cost and ease of implementation.

California Air Resources Board (16, 17) provides extensive background information on the costs and benefits of California's heavy diesel vehicle I/M programs, which are based on the SAE J1667 test.

The SAE J1667 test is suggested for further evaluation, and is included as Attachment 2.

11.1.2 No Load, Steady State Tests

No load (idle) steady state emission tests are used in petrol vehicle I/M programs in many US jurisdictions. In some jurisdictions, these I/M tests have been extended to diesel vehicles.

Such tests do not produce the conditions under which significant NOx, particles or smoke emissions occur, and are therefore considered unsuitable for further consideration in this work.

11.1.3 Loaded Mode, Steady State Chassis Dynamometer Tests

The International Standards Organisation specifies a test method (ISO 7645) for measuring opacity using a loaded mode steady state, single speed, free roll dynamometer test. This method involves applying maximum load by applying the vehicle's footbrake (rather than by applying dynamometer load) while running on the free rolls. There may be safety implications for such a procedure. We were unable to identify any jurisdiction that uses the test.

Loaded mode steady state dynamometer tests are conducted for smoke I/M purposes in a few US jurisdictions (Arizona, Connecticut, Nevada, New York, Ohio), but specific information on test parameters has been difficult to obtain.

In Canada (Vancouver), a 30 mph loaded mode test is performed (in addition to free acceleration to SAE J1667).

In India, a full load/70% maximum engine speed test may be used as an alternative to a free acceleration test.

To date, we are not aware of other jurisdictions using loaded mode steady state chassis dynamometer I/M testing programs.

For maximum effectiveness, steady state tests would need to be performed at high, or full load. The following two new test procedures are suggested.

11.1.3.1 The D550 test

A loaded mode steady state chassis dynamometer procedure for testing in-service smoke and NOx, designated the D550 test, has been suggested by Anyon, see Attachment 3. This is based upon testing at 50 km/hr with application of dynamometer load equivalent to a 5% gradient for the vehicle loaded to its GVM. This procedure would test many vehicles at or close to full load and would be relatively simple to perform on existing equipment. It is suggested for further evaluation.

11.1.3.2 Full load/2-speed test

Diesel vehicles sold in Australia since 1976 were required to be certified to ADR 30 (equivalent to ECE R24). This test for smoke is carried out on an engine dynamometer under full load conditions, at rated engine speed and at 3 intermediate speeds (67%, 78%, and 89% of rated speed for rated speed greater than 2220 rpm, and a little higher for rated speeds below 2220 rpm). It would be relatively simple to adapt this test for chassis dynamometer testing and for measurement of NOx as well as smoke. This would likely be quite effective, since these conditions tend to produce relatively high emission levels. Smoke results would likely correlate well with results from the ADR procedure.

Testing for smoke rather than particulate, would avoid the complexity and additional test time that would be required for particulate sampling and measurement.

There may be little disadvantage in testing at only one or two, instead of all four, test speeds. Rated speed, and the first intermediate speed (usually 67% of rated speed), are suggested.

On some older vehicles, testing at rated speed (under full load conditions) might be considered to introduce potential safety risks. Nevertheless, testing at both speeds is suggested for further evaluation. A copy of ADR 30 is included as Attachment 4.

11.1.4 Lug-down Tests

The International Standards Organisation specifies a test method (ISO 7644) for measuring opacity using a dynamometer based lug-down test. The vehicle's footbrake is used to provide the loading, which may be considered to have safety implications.

Some US jurisdictions (eg Colorado, New Jersey) have introduced on-road lug down testing for smoke in their I/M programs. These appear to have been adapted from the US Federal smoke test procedure (18).

Colorado has also introduced dynamometer lug down tests, which for heavy-duty diesel vehicles are contained in Regulation 12, Part A.IV.C.4 and Part B.III.C.4.b (see Attachment 5). In this test, the vehicle is run on the dynamometer at wide-open throttle during the following sequence –

- the vehicle is run at no load and at maximum engine speed, in a gear that produces a road speed between 60 and 70 mph (or the maximum that can be obtained).
- load is applied to bring the engine to its rated speed, and held for 10 seconds while opacity is measured.
- load is applied to lug the engine to 90%, 80%, and then 70% of rated speed, pausing at each speed for 10 seconds while opacity is measured.

The maximum smoke opacity is compared with the standard.

NOx measurements could be taken through the test.

This test might be considered to introduce potential safety risks, but this risk should be small given the short time spent under test. It is suggested for further evaluation.

11.1.5 Transient (Acceleration Mode) Chassis Dynamometer Tests

We could find no evidence of any jurisdiction using a transient mode chassis dynamometer test procedure for in-service I/M purposes. There are some overseas agencies and organisations conducting associated research, but no such procedure has yet obtained significant acceptance.

The highest on-road emissions, especially for smoke and particulate, occur during acceleration under wide-open throttle conditions (which is typical for heavy duty diesel vehicles). Therefore, compared to other procedures discussed above, acceleration-mode tests would produce results more likely to identify high emitting vehicles and provide diagnostic information to guide repairs.

Transient mode testing of particularly the heaviest vehicles, would require sophisticated and expensive dynamometers and emission measurement equipment. Therefore, thorough evaluation may show this not to be cost-effective for these vehicles.

Nevertheless, given moves to transient engine certification testing in the USA and Europe, and CARB's intention to develop a transient-test based I/M procedure, we consider such a test should be included for further evaluation.

Therefore, we have developed an acceleration mode test using information gathered in development of the CUEDCs, and other information gained from focus group meetings, the literature and previous testing experience. This test is outlined below.

11.1.5.1 Full load acceleration, 80 km/hr cruise test.

This test has been designed to reflect some elements of real world driving, and would evaluate emission levels across the following modes of operation –

- an idle mode, primarily for preconditioning and diagnosis.
- 3 full-load acceleration modes for evaluating smoke opacity, as in SAE J1667, and for fault diagnosis.
- a moderately high-speed steady state cruise mode, for evaluating NOx, and for fault diagnosis.

We consider this test would be practical for light-duty diesel vehicles up to 3.5 tonnes GVM, using existing I/M dynamometers. It may also be practical for trucks and buses up to around 15 tonnes GVM, using existing heavy-duty dynamometers with electronic control of load simulation. It may not be practical, or cost effective, for the heaviest vehicles in the ADR NC category, given the high dynamometer loadings that would be required during acceleration.

The test is suggested for evaluation across all vehicle weights. A suggested test protocol and cycle is included in Attachment 6.

11.1.6 On-road Tests

Several US jurisdictions use road testing/observation for smoke evaluation in their I/M programs. Colorado, for example, uses lugging, acceleration, and (for automatic transmissions) stall procedures for on-road testing, and a ‘5-second rule’ with opacity limits for road enforcement (see Attachment 5).

In California, a ‘10-second rule’ with Ringlemann 1 opacity limit has been implemented through the California Vehicle Code CVC 27153.5(2).

The ‘10-second rule’ has been in use in New South Wales since the mid-1970’s, and in other Australian States/Territories since later dates. Although subjective, and under criticism from transport operators for this reason, this ‘rule’ is technically simple and administratively effective as an on-road enforcement tool.

The ‘10-second rule’ is suggested for comparative evaluation with the short tests discussed above.

11.1.7 ‘7-point’ Inspection

As discussed in section 13, a non-invasive, 7-point inspection procedure has been developed as part of this work.

This procedure is designed to provide a non-invasive indication that the vehicle may have high emissions due to poor maintenance or tampering. It could be used as a roadside screening tool, or it could be used in combination with any of the short tests suggested here.

This 7-point inspection is suggested for further evaluation alongside the short tests, as a diagnostic tool.

11.2 Short Tests Proposed for further Evaluation

The short tests proposed for further evaluation in Phase 2 of this Project, are shown below in table 11.

Table 11: Short tests proposed for evaluation

	Short tests						
Parameter	**SAE J1667**	**D550**	**Full load 2-speed**	**Lug down**	**Full load accel 80 km/hr cruise**	**10-second rule**	**7-point inspection**
Ability to identify high emitting vehicles under conditions likely to result in poor emissions - Nox	no	fair	good	good	good	no	no
- partic	no	fair	fair	no	fair	no	poor
- smoke	fair	fair	good	good	very good	good	poor
Objectivity	good	good	good	fair	good	subj've	fair
Precision	fair	good	good	fair	good	poor	poor
Repeatability	fair	good	good	fair	good	poor	poor
Simplicity	very good	good	good	fair	good	good	good
Ease of application	good	fair	fair	fair	fair	good	good
Safety of application	good	good	fair	fair	fair	good	good
Ability to identify reasons for poor emissions	poor	fair	fair	fair	good	fair	fair
Cost	low	med	med	med	high	low	low
Cost effectiveness for wide use as in vehicle regist'n	high	med	med	med	?	low	med
Suitability for wide use as in vehicle regist'n	fair	good	good	fair	fair	poor	fair
Ability to correlate with design standards	poor	fair	fair	fair	fair	poor	poor

12 VEHICLE-BASED CAUSES OF INCREASED EMISSIONS

12.1 Causes Identified in the Literature

California Air Resources Board (16) analysed the reasons for poor smoke emission performance in 70 vehicles that had failed the I/M free acceleration test. These were categorised in 3 main areas and were shown as –

- Improper transient air fuel ratio control -
  - tampered smoke puff limiter (eg 'aneroid' or 'throttle delay').
- Problems with the fuel injection system or timing -
  - worn/failed injectors.
  - maladjusted fuel pump timing.
  - boosted fuel pump.
  - enlarged injector tips.
- Inadequate intake air -
  - clogged air filter.
  - damaged turbocharger.
  - worn engine.

TNO Road-Vehicles Research Institute (19) reported that in a sample of 63 trucks in use in the Netherlands, mostly aged between 1 and 4 years, 70% had settings which did not correspond with the manufacturer's specification. The faults, all of which would be likely to increase emission of one or another pollutant, were as follows –

Deviation fuel pump delivery	- 12% of 63-vehicle sample.
Deviation rated speed	- 7% of 63-vehicle sample.
Combination of both	- 8% of 63-vehicle sample.
Injection timing too late	- 15% of 63-vehicle sample.
Injection timing too early	- 13% of 63-vehicle sample.
Condition fuel injectors	- 27% of 63-vehicle sample.
Remaining	- 23% of 63-vehicle sample.

12.2 Causes Identified in NSW EPA's Smoky Vehicle Program

For more than 20 years, the EPA has conducted a diesel vehicle smoke enforcement program based upon random on-road observation of vehicles in use, according to the '10-second rule'. In this program, vehicles judged to emit excessive smoke are required to undergo maintenance and to be submitted for inspection. Various sanctions and penalties may be applied.

Considerable information on the maintenance carried out on these smoky vehicles is contained within the EPA files. These files were scanned, and a random selection of 304 maintenance reports compiled during 1993 to 1997 were analysed, to yield the most common items of required maintenance for different categories of vehicles. A summary of the results is presented in figure 26 below.

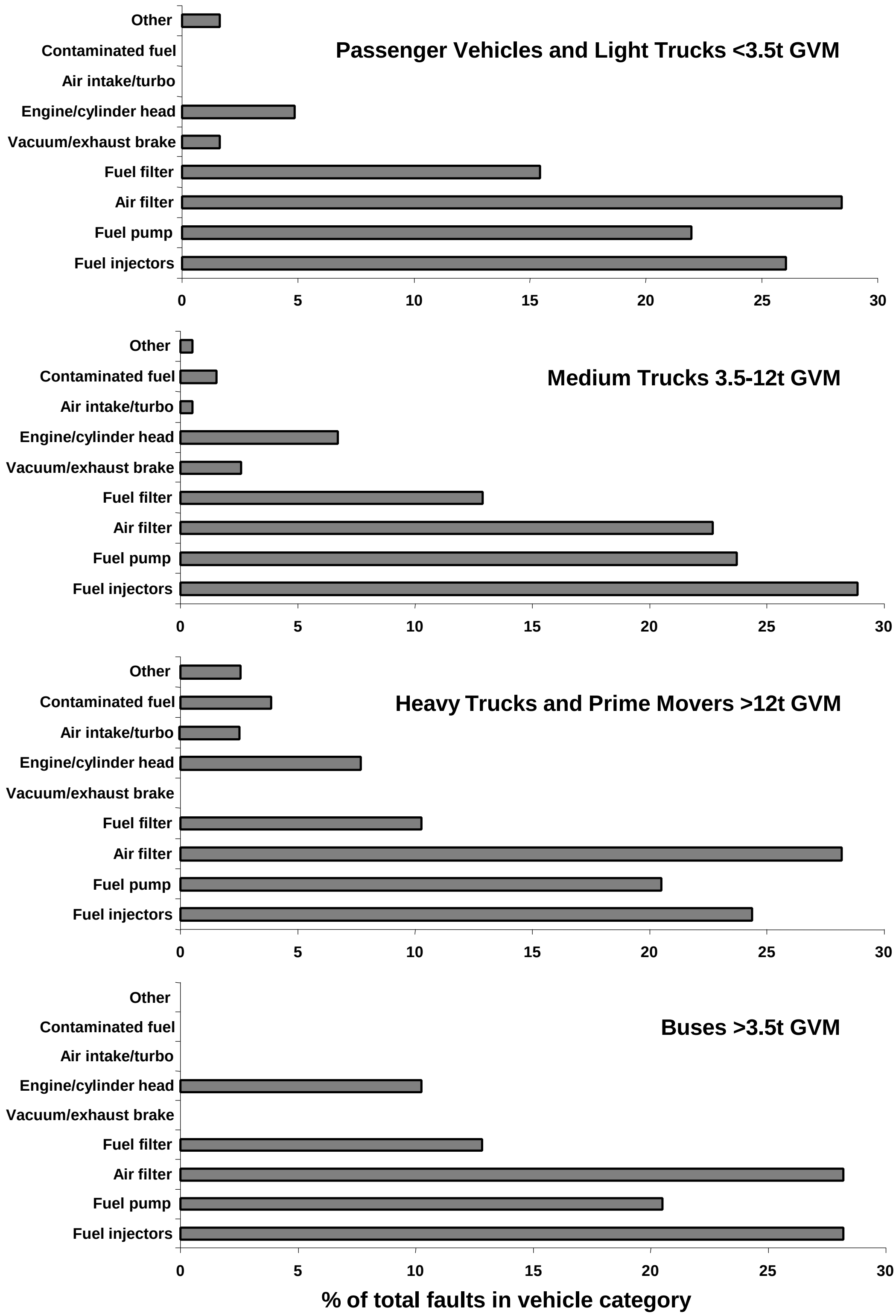


Figure 24: Most common faults from EPA Diesel Vehicle Smoke Enforcement Program.

From the data -

- the breakdown of vehicle faults was very similar across all vehicle categories.
- the most common faults stated as a cause of high emissions were associated with the fuel pump, fuel injectors and air filter. These three areas, in approximately equal proportions, together accounted for 73 – 77% of total emission related faults.
- the vehicle categories most commonly reported for excessive smoke emissions were medium trucks, followed by light vehicles, heavy trucks and then buses.
- the vehicle categories having the highest proportion of reports for excessive smoke emissions were buses and medium trucks, followed by heavy trucks. The light vehicle category had the smallest proportion of reports.

The complete analysis of the data is included as Attachment 7.

12.3 Causes Identified in Industry Discussions

Two separate Focus Group discussions were held, on 12 and 13 November 1998.

The first group was organised with assistance from the Institute of Automotive Mechanical Engineers (IAME), and comprised a number of their members who were involved principally in maintenance and repair of diesel vehicles.

The second group was organised with assistance from the Road Transport Forum, and comprised technical managers of haulage and bus companies together with representatives of their industry associations.

These Focus Groups provided interesting and informed commentary on maintenance issues.

The groups gave broadly consistent accounts of the likely most common vehicle-based causes of high emissions, and both agreed with the causes identified in the EPA's smoky vehicle program.

A summary of the Focus Group discussions is included at Attachment 8.

13 NON-INVASIVE INSPECTION FOR FAULTS

The two Focus Group meetings presented very similar views on practical, non-invasive inspection that might detect faults leading to increased emission levels.

It was agreed that it is not possible to detect all problems by a simple visual check. For example, fuel injection equipment problems normally require component removal for diagnosis on specialised equipment by skilled technicians. Nevertheless, a number of checks, which could be carried out with minimum disturbance to engine and auxiliary equipment components, were considered to be practical and useful. These checks would normally be carried out as a first step in any engine performance diagnostic procedure.

We have adopted the list of inspection points compiled by the Technical Managers' Focus Group, as our suggested '7-point Inspection'.

7-Point Inspection

This inspection requires lifting the bonnet but little other 'hands on' activity. It is designed to provide a non-invasive indication that a vehicle may have high emissions due to poor maintenance or tampering. The inspection could be used as a roadside screening tool, or it could be used in combination with any of the short tests suggested for further evaluation as I/M procedures. It comprises visual checks as follows -

- check condition of air filter and air inlet system to see if faulty or restricted.
- check seals on fuel pump and suspect tampering if seal is broken.
- check for missing parts.
- check for blue smoke from engine breather and exhaust pipe indicating oil by-pass.
- check body of turbocharger for oil leaks.
- check integrity of intercooler and compressed air inlet pump hoses.
- check a sample of fuel for discoloration or other signs of adulteration/blending with engine oil or non-diesel fuels. (The sample could also be checked chemically, using the non-excise fuel tracer test.)

14 DISCUSSION

We have not limited our assessment of short tests to the few that are currently in use in IM programs around the world. To have done so would have severely limited the range of tests considered for evaluation, and would have required inclusion of some tests we consider unsatisfactory.

Rather, we have included 3 newly derived chassis dynamometer tests, which we consider have merit –

- the D550, credited to Anyon.
- a full load, 2-speed test derived from the ADR 30 engine dynamometer procedure.
- a transient test cycle derived from examination of actual diesel-vehicle driving traces.

We have suggested 2 currently existing I/M tests for further evaluation –

- the free acceleration test used in many countries, in the version specified as SAE J1667.
- a chassis dynamometer lug-down test currently used in Colorado.

We are of the view that depending on results of thorough evaluation, individual tests might be combined for optimum cost effectiveness, for example –

- SAE J1667 + '7-point inspection.
- SAEJ1667 + 'D550'.

We are also of the view that thorough evaluation may show different tests to be most cost effective for different ADR categories, for example –

- 'full load acceleration/80 km/hr cruise' test for light and medium trucks and buses.
- SAE J1667 for heavy vehicles.

We consider –

- There is potential for refinement or modification of the proposed tests, to meet equipment and/or vehicle limitations. For example there may be benefit in refining the 5% gradient and/or the 50 km/hr speed setting suggested in the 'D550'.
- The '7-point inspection', should be evaluated as a roadside screening tool, as well as a low-cost addition to any of the suggested short tests.
- The '10-second rule', is primarily a road-enforcement tool, and may be complementary to any of the suggested short tests.
- NOx is primarily a design issue that can only be satisfactorily addressed through the ADR requirements. In most cases it would be difficult to establish if NOx is a result of engine design or of an in-service fault. There are very limited in-service adjustments or repairs that can be carried out to reduce NOx, and some may increase particulate emissions. Therefore, it may be appropriate, to give less emphasis to NOx than to smoke or particulate, in any I/M procedures.
- Particulate measurement significantly increases the cost and complexity of diesel vehicle emission testing. On the other hand, smoke opacity is simply and cheaply measured, and may provide a satisfactory low cost surrogate for particulate. Therefore, it may be appropriate to consider measurement of smoke opacity, not particulate, in any proposed I/M procedures.
- The findings of the work under tender for CARB, to develop a short in-service (inspection and maintenance type) test for heavy-duty vehicles, may be of considerable value in assessing what tests may be suitable for Australian in-service programs. When these findings are available, there may be value in having them considered as part of the Phase 2 Project. This may require an additional allocation of funds.

15 RECOMMENDATIONS

It is recommended that during Phase 2 of this Project –

(1) The potential benefits of combining tests and/or using different tests for different ADR categories be considered.

(2) The potential for refinement or modification of the proposed tests to meet equipment and/or vehicle limitations be considered.

(3) The '10-second rule' be considered an on-road enforcement tool (as it is now used), to be complemented by a short test or inspection-based inspection/maintenance procedure.

(4) The ‘7-point inspection’ be considered as a road-side screening tool, as well as an addition to the suggested short tests.

(5) Less emphasis be given to emissions of NOx than to smoke and particulates, in evaluation of the short test procedures.

(6) Smoke opacity be evaluated as a low cost surrogate for particulate emissions during evaluation of those short test procedures that do not specify smoke opacity as the unit of measurement.

(7) The findings of the CARB in-service short test project, when available, be considered as part of the Phase 2 Project.

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