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UNIVERSITY
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PERTH'S FUEL CELL BUS TRIAL 2004 - 2007

FINAL OPERATIONAL REPORT TO THE
DEPARTMENT FOR PLANNING AND
INFRASTRUCTURE
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PREFACE

This is the final report on the performance of the trial of three Hydrogen Fuel Cell Buses conducted in Perth, Western Australia, between September 2004 and September 2007. The DaimlerChrysler fuel cell buses, known here in Perth as the EcoBuses, took part in this international demonstration project under the Western Australian Government's Sustainable Transport Energy for Perth (STEP) program. The STEP project was managed by the Department for Planning and Infrastructure (DPI) the lead agency responsible for sustainable transport energy programs in Western Australia.

The STEP project involved numerous stakeholders including the Commonwealth Department of Environment and Water Resources, Australian Greenhouse Office, DaimlerChrysler, BP, BOC, Public Transport Authority, Path Transit, CSIRO and Murdoch University. Murdoch University was responsible for undertaking a number of research and evaluation programs under a Memorandum of Understanding with the Department.

This Bus Operational Report was one of five studies carried out by Murdoch University to evaluate the Fuel Cell Bus Trials. The other studies undertaken were: Life Cycle Analysis, Industry Development Opportunities, Public Perception, and Cost-Benefit Analysis.

This report is intended to provide a basis for evaluating and improving the fuel cell bus technology. These trials were part of a broad international effort involving the European Union, Iceland, China and Western Australia. Comparisons of the results obtained in twelve different cities will aid the development of this technology. The methodology used and the results obtained will be valuable for designing and assessing future trials of the next generation of hydrogen fuel cell buses.

This report was written by Colin Cockcroft who was supervised by Dr Trevor Pryor and Professor Philip Jennings of Murdoch University.

Table of Contents

1	EXECUTIVE SUMMARY	1
2	INTRODUCTION	3
2.1	HISTORY	3
2.2	OTHER SITES	3
2.3	FUNDING	4
2.4	PROJECT PARTNERS	4
2.5	DATA COLLECTION	6
2.6	REPORTING REQUIREMENTS.....	6
3	BUS DESCRIPTION	8
3.1	TECHNOLOGY.....	8
3.2	EFFICIENCY MAP.....	9
4	ROUTES	11
4.1	ROUTINE OPERATION	12
4.2	FUEL EFFICIENCY.....	14
5	COMPARATIVE EMISSIONS	17
5.1	GREENHOUSE GAS EMISSIONS	17
5.2	TOXIC AIR POLLUTANTS	19
6	PASSENGERS	21
7	MAINTENANCE	22
7.1	OVERVIEW	22
7.2	FUEL CELL BUS SYSTEMS	22
7.3	HyFLEET:CUTE MAINTENANCE CLASSIFICATIONS.....	25
7.4	MAINTENANCE HOURS.....	26
7.5	ROUTINE MAINTENANCE.....	26
7.6	REPAIRS	28
7.7	MAINTENANCE CALLOUTS	31
7.8	AVAILABILITY.....	33
8	REFUELLING STATION	36
8.1	INFRASTRUCTURE	36
8.2	EQUIPMENT RELIABILITY	37
8.3	OPERATING RELIABILITY	38
8.4	REFUELLING TIMES	39
9	CONCLUSIONS	41
9.1	DATA COLLECTION	41
9.2	AVAILABILITY.....	42
9.3	POTENTIAL DRIVE TRAIN IMPROVEMENTS.....	42
10	BIBLIOGRAPHY	44
	ANNEX A - OPERATIONAL DATA COLLECTION SHEET	45
	ANNEX B – MAINTENANCE DATA COLLECTION SHEET	47
	ANNEX C – ROUTE ELEVATION PROFILES	49
	ANNEX D - SUPPORTING DATA	51

Figures

Figure 2-1. Timeline for international trials	4
Figure 3-1. Fuel cell bus component layout.....	8
Figure 3-2. Sankey diagram of drive train efficiency	9
Figure 4-1. Map of typical Perth EcoBus routes.....	11
Figure 4-2. Types of bus operation	13
Figure 4-3. Cumulative distances travelled during the trial.....	14
Figure 4-4. CUEDC Segments.....	15
Figure 4-5. Correlation of fuel consumption and ambient temperature.....	16
Figure 5-1. GHG emissions	19
Figure 5-2. Toxic air pollutants per km	20
Figure 6-1. Monthly passenger loads.....	21
Figure 7-1. EcoBus maintenance subsystems	23
Figure 7-2. Breakdown of maintenance hours	26
Figure 7-3. Repair tasks	28
Figure 7-4. Repair labour hours	29
Figure 7-5. Cell row replacement	30
Figure 7-6. Inverter failures	31
Figure 7-7. Maintenance callouts over time	32
Figure 7-8. Maintenance callouts per bus	32
Figure 7-9. Bus availability of CUTE cities	33
Figure 7-10. Monthly bus availability	34
Figure 8-1. Perth hydrogen infrastructure.....	36
Figure 8-2. Refuelling stoppages from routine data sheets.....	38
Figure 8-3. Histogram of refuelling pressures	39
Figure D-1. Average operating hours per day	51
Figure D-2. Average km travelled per operating day	51
Figure D-3. Operating days per month	52
Figure D-4. Types of bus operation per year	52
Figure D-5. European seasonal fuel economy	53
Figure D-6. Breakdown of maintenance hours per bus	54
Figure D-7. Repair hours and operating hours.....	54
Figure D-8. Refuelling times per kg	55

Tables

Table 2-1. Perth's fuel cell bus trial reporting requirements	7
Table 3-1. EcoBus specifications.....	8
Table 4-1. Route details for Perth and CUTE routes	12
Table 4-2. Fuel cell bus efficiency on different routes	14
Table 4-3 - Fuel consumption for fuel cell, diesel and CNG buses.....	15
Table 5-1. Life cycle greenhouse gas emissions from diesel and CNG	18
Table 5-2. Toxic emissions (g/MJ)	19
Table 7-1. Traction motor specifications	25
Table 7-2. Routine maintenance tasks	27
Table 7-3. Average time to complete routine maintenance tasks	34
Table 8-1 Refuelling Station outages.....	37

1 Executive Summary

This report provides an analysis of operational data collected during Perth's fuel cell bus trial. The trial concluded on the 13th of September 2007, this report incorporates all data collected until the end of July 2007.

The Perth fuel cell bus trial was initiated as a two-year examination of the potential of hydrogen and fuel cells as a sustainable transport energy option for Western Australia. The trial was the flagship project for the Department for Planning and Infrastructure's (DPI) Sustainable Transport Energy for Perth (STEP) program. This was the first significant use of hydrogen as a transport fuel on public roads in Australia. To support the trial DPI established the only hydrogen supply and refuelling infrastructure in the southern hemisphere.

Hydrogen as a transport fuel does not fit well into existing legislation. Gaining the necessary regulatory approval to import and licence the hydrogen fuel cell buses (known as EcoBuses) and to establish the refuelling and maintenance infrastructure, took two years of negotiation and education.

The EcoBuses began operation in September 2004. The trial was due to finish in September 2006 but was extended for a further twelve months until September 2007.

The initial two-year trial was run in collaboration with 'sister' trials in nine European cities plus Iceland and Beijing, all of which operated three of the same model of fuel cell buses that operated in Western Australia. The nine European cities are participating in the Clean Urban Transport for Europe (CUTE) project and Iceland's trial in Reykjavik is part of their Ecological Cities Transport Systems (ECTOS) project. All are carrying out similar evaluations of the technology and are sharing results. Western Australia's participation in this significant international collaboration began after signing a formal data exchange agreement with the European Commission.

The Perth fuel cell bus trial was the only fuel cell trial in the world to examine the broad societal implications from a whole-of-government perspective, in addition to industry development and technical issues.

The EcoBuses were operated on normal Perth bus routes. Initially their operation was limited to the City Central Area Transit (CAT) routes, the City Link route and the Circle routes. These routes were chosen because they presented the buses with a range of different driving conditions and they maximised public exposure. As the trial progressed the buses operated on a wider selection of routes.

The EcoBuses have been operated, maintained and refuelled by Path Transit at their Morley depot.

By the end of July 2007 the EcoBuses had travelled approximately 258,000km, consumed over 46 tonnes of hydrogen and have carried over 320,000 passengers. This results in an average fuel efficiency of 18.1kg/100km (21.7 MJ/km). EcoBus 1 has been the most efficient at 17.8 kg/100km and EcoBus 3 has been the least efficient at 18.9 kg/100km. These efficiencies change according to the operating conditions. The CAT routes are congested with frequent stops and on these routes the buses achieve an average fuel consumption of 22 kg/100km. By contrast the City

Link route is free flowing with far less stops, resulting in an average efficiency of 16.3 kg/100 km.

Significant efficiency gains are possible for future fuel cell bus designs by:

- introducing a battery system for short term energy storage. This would remove the need for the dump resistor that maintains fuel cell operation during idle. It would also enable regenerative braking and reduce the load transients on the fuel cell which should the life of the cell rows;
- improving the design of the auxiliary drive systems to reduce the inefficiencies associated with electrical – mechanical – electrical energy conversion processes; and
- introducing an all electric drive train to reduce the mechanical inefficiencies of the current transmission.

The reliability of the Ecobuses exceeded expectations. They spent a total of 1,457 hours in maintenance, to achieve 10,553 hours of operation and achieved a monthly availability of between 75% and 95%. Routine maintenance made up 29% of the total maintenance effort while repairs accounted for 53%. The repair time was dominated by fuel cell repair, which was responsible for 37% of repair time. The next largest contributor was the electrical system, which accounted for a further 22%.

The EcoBuses required on-road maintenance at a rate of 35 incidents per 100,000km. Of these, the EcoBuses were repaired on the road and returned to service 9.5 times per 100,000km, required towing 3.9 times per 100,000km and were driven back to the depot under their own power for the remainder.

Conventional buses in the Transperth fleet require an onsite mechanic or towing approximately 5 times every 100,000km. This shows that, despite being prototypes, the EcoBuses are approaching the on road reliability of current technology buses.

The operating data collected for this study was primarily collected through daily operating sheets that are filled in by the drivers each day. This introduced uncertainty into some of the analysis because of omissions and inaccuracies in the sheets. There is an extensive automated data collection system fitted to the buses that Ballard Power Systems use to monitor the operation of each of the systems within each bus. This data set would have reduced uncertainty and provided a richer picture of the operation of the buses, but access to the data was not possible for contractual and technical reasons.

Comparison with existing diesel and CNG buses is difficult because of a lack of sufficiently detailed operating and maintenance records. Access to the data that does exist is limited because they are seen by the operators as commercially sensitive.

This limitation could be overcome if several specific CNG and diesel buses were allocated to the trial but this would add significantly to the resources required.

2 Introduction

2.1 History

Sustainable transport energy is fundamental to the future well-being of the entire Australian community.

More than 95% of Australia's transport energy comes from oil and the future availability of oil is not assured. In addition to concerns over supply security, there is increasing awareness of the effects of pollution and greenhouse gases on the environment and human health.

Many governments and vehicle manufacturers have identified hydrogen as a potential future transport energy carrier. When used in fuel cells, hydrogen produces no pollutants; the only emissions are water and heat.

Western Australia's participation in the fuel cell bus trial was first proposed in 1999 during discussions between the Western Australian Government and DaimlerChrysler. Following announcements by the Government, both major Western Australian political parties entered the 2001 State Election Campaign with promises to support a fuel cell bus trial in Perth.

In September 2004, the Western Australian Government brought three hydrogen fuel cell powered EcoBuses to Perth as part of the Sustainable Transport Energy for Perth (STEP) program and a worldwide trial. The trial has not only tested the technology but also the industry, community and Government systems required to support it.

2.2 Other sites

The Perth fuel cell bus trial was run in conjunction with similar trials in Europe called the Clean Urban Transport for Europe (CUTE) project and Iceland called Ecological City Transport System (ECTOS). The CUTE/ECTOS/STEP projects involved the trial of 33 DaimlerChrysler fuel cell buses and a range of different hydrogen production and refuelling solutions operating in 11 cities around the world. The nine European cities included Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Porto, Stockholm and Stuttgart. The sister trials began in 2003 and continued until 2006 as shown in Figure 2-1.

The aims of the CUTE, ECTOS and STEP trials were to develop and demonstrate an emission free and low noise transport system that would contribute to cleaner environmental conditions, increase public knowledge and acceptance of hydrogen and fuel cell technology and build a strong foundation for regulation and certification of fuel cell technology.

Many of the buses have continued operation beyond the two-year trial under extensions through the HyFLEET:CUTE program which is also trialling hydrogen Internal Combustion Engines (H₂ICE)ⁱ.

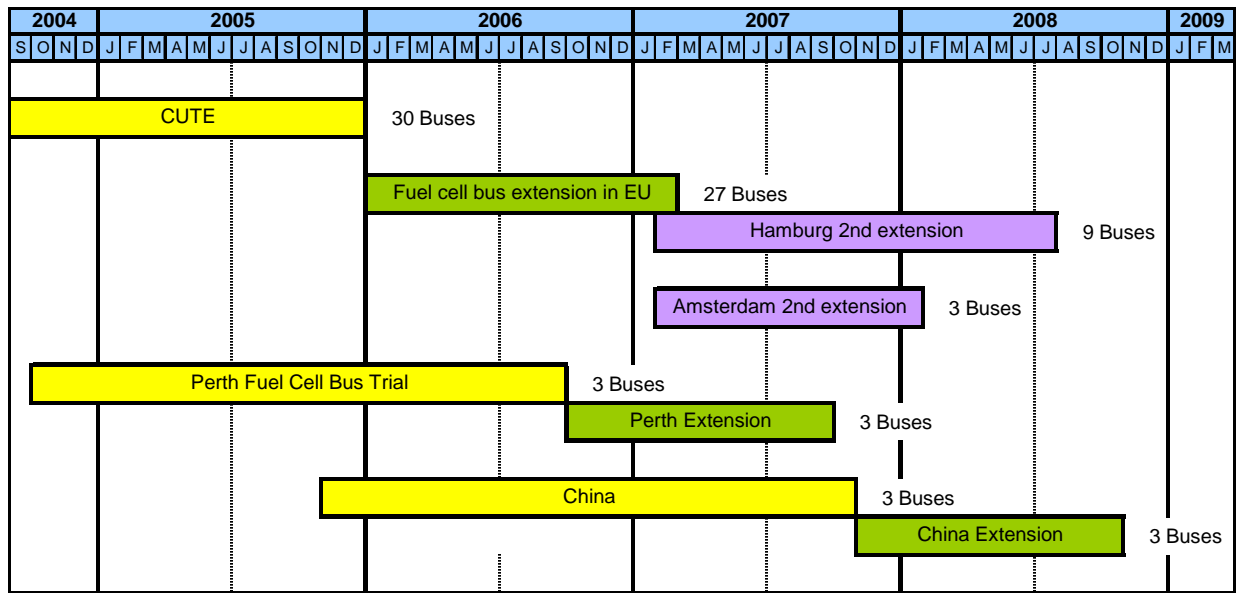


Figure 2-1. Timeline for international trials

2.3 Funding

The Perth fuel cell bus trial was funded from several Government and private sources. The Western Australian Government contributed \$8 million, the Federal Government through the Department of the Environment and Heritage's (now Department of Environment and Water Resources) Australian Greenhouse Office contributed \$2.5 million and BP contributed approximately \$5 million by establishing and subsidising the hydrogen supply chain and refuelling infrastructure.

2.4 Project Partners

The STEP fuel cell bus trial was a complex undertaking that required the cooperation of several key partners including the Western Australian Government through the Department for Planning and Infrastructure, DaimlerChrysler, BP, Ballard Power Systems, the Public Transport Authority, Path Transit, Murdoch University and the Australian Government.

The roles played by each of the major partners are described in the following paragraphs.

2.4.1 Western Australia Government

The Government of Western Australia led the project and provided the majority of funding. The Department for Planning and Infrastructure (DPI) in Western Australia was responsible for the management of the STEP trial.

2.4.2 Commonwealth Government

The Department of the Environment and Heritage (now the Department of the Environment and Water Resources) and the Australian Greenhouse Office committed \$2.5M to the Perth trial and was a member of the project steering committee.

2.4.3 DaimlerChrysler

DaimlerChrysler AG is one of the world's leading automotive companies involved in developing fuel cell vehicles. EvoBus, Germany (as part of the DaimlerChrysler group) manufactured the limited series of Mercedes-Benz Citaro fuel cell buses that were used in the trial. The fuel cell engines for the buses were designed and manufactured by Ballard Power Systems of Canada.

DaimlerChrysler was also responsible for coordinating a series of work packages aimed at capturing all learning from the European and Australian trials.

2.4.4 BP

BP supplied the hydrogen and the refuelling station for the bus trial. The hydrogen was produced at BP's Kwinana oil refinery and the refuelling station was designed and built by Linde. BP contracted BOC Gases to undertake the engineering work and maintain the hydrogen infrastructure. BP was also responsible for supplying hydrogen to a number of the European cities involved in the CUTE project.

2.4.5 Murdoch University

An independent evaluation program was undertaken to capture all learning from the Perth trial. This evaluation included a public perceptions study, an operational analysis, a life cycle assessment and an economic assessment. The outcomes of these studies will be used to further the development of hydrogen and fuel cell technology and to identify opportunities for industry development. The majority of this evaluation program was undertaken by Murdoch University. CSIRO also supported part of the extension program and reporting via an unsolicited Flagship project with Murdoch University.

2.4.6 Path Transit

Path Transit is one of three private companies that are under contract to the Western Australian Government to provide Perth metropolitan bus services. Path Transit volunteered to operate and maintain the fuel cell buses from their Morley depot. They also provided land for the refuelling station, space within their existing maintenance facility and personnel to assist with maintenance and administration. All of this was provided for no direct financial advantage.

2.4.7 United Nations

The United Nations Environment Program and the United Nations Industrial Development Organisation both endorsed the Perth trial.

2.4.8 International Partnership for the Hydrogen Economy (IPHE)

The IPHE was established in 2003 as an international institution to accelerate the transition to a hydrogen economy. It does this by providing a mechanism for partners to organize, coordinate and implement activities related to the development, evaluation and commercialisation of hydrogen and fuel cell technologies. The IPHE endorsed the STEP fuel cell bus trial.

2.5 Data Collection

The data collected for the operational analysis of the EcoBuses included daily operating data, maintenance data, meteorological data and fuelling station reliability data.

Daily operating data included, distances travelled, engine hours, operating hours, operating status, hydrogen refuelling details, passenger loads and traffic conditions. This information was collected by the drivers who completed a routine data sheet for each shift. The sheet used to collect daily operating data is provided in Annex A.

Maintenance data included, the date that the work was logged, the type of maintenance performed, which systems were affected, any parts used, labour hours expended and who performed the work. Using that date that data was entered rather than the date it was conducted has caused some minor confusion since the date that the data was entered can be several days after the work was performed. This means that the date on the maintenance records can't be easily reconciled against daily operating sheets. It was decided to continue using the entry date since it has proved more important to be able to reconcile against other maintenance records than operating records. The maintenance data collection sheet developed for the trial is provided at Annex B.

Daily meteorological data is available from the Australian Bureau of Meteorology websiteⁱⁱ. The data collected includes, minimum, maximum and mean temperature, rainfall and humidity data at several periods throughout each day.

2.6 Reporting Requirements

The collaborative nature of the Perth fuel cell bus trial and distributed funding arrangements meant that there were several reporting obligations for the project which are listed below.

Western Australian Parliament – Regular reporting on the trial including attendance at public events was provided to the Western Australian Parliament through the DPI. This included a Two Year Summary of Achievements report, a detailed annex to the summary report and copies of all reports provided to (and received from) external organisations.

Australian Greenhouse Office – A report summarising all of the data collected over the three years of the trial will be provided in December 2007.

The end of trial report will also include a consolidated summary of the regulatory actions required to introduce and operate the buses. This section will identify further legislative and regulative work necessary to operate an expanded, permanent commercial fleet of hydrogen buses.

HyFLEET:CUTE – Monthly data including bus operation, refuelling and maintenance data was provided to the HyFLEET:CUTE project work package leaders.

The high level schedule of Perth's fuel cell bus trial data collection and reporting is provided in Table 2-1.

	2006				2007											
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Data Collection																
Monthly Bus Operating Data	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆		
Monthly Bus Call Out Data								◆					◆			
Monthly Bus Maintenance Data	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆		
Fuelling Station Data			◆		◆		◆		◆		◆		◆			
Reporting																
Western Australian Parliament							◆			◆						◆
AGO End of Trial Report																◆
CSIRO preliminary performance report									◆							
CSIRO Final performance report													◆			
Monthly Report to HyFLEET: CUTE	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆		
HyFLEET: CUTE work package participation (ongoing until 2010)	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
HyFLEET: CUTE Major meetings	◆						◆						◆			

Table 2-1. Perth's fuel cell bus trial reporting requirements

3 Bus Description

3.1 Technology

The Ecobuses are part of a limited series of Mercedes-Benz Citaro fuel cell buses manufactured in Mannheim, Germany by DaimlerChrysler. The Mercedes-Benz Citaro fuel cell buses are equipped with a HY-205 P5-1 fuel cell engine developed by Ballard Power Systems, Canada. The fuel cell engine is based on two of Ballard's Mk9 generation fuel cell stacks that supply power to a central electric motor with a maximum power of 205kW. The buses use compressed hydrogen stored in nine Dynetek high-pressure cylinders mounted on the roof of the vehicleⁱⁱⁱ. The total hydrogen storage capacity is 44 kg (15°C, 350 bar) providing a range of about 250 km. The bus design combines a fuel cell engine with standard bus components such as the automatic transmission and some auxiliary components; this was done to improve the reliability of the bus.

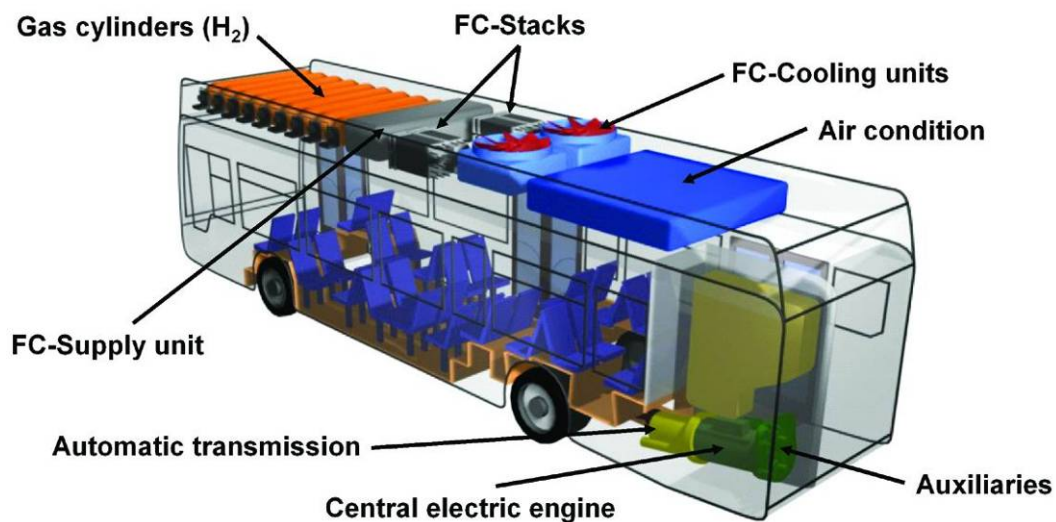


Figure 3-1. Fuel cell bus component layout

Bus Specifications	
<i>Passenger capacity</i>	60-70 ¹ people (30 seats)
<i>Net power of the Ballard fuel cell unit</i>	>250 kW
<i>Range</i>	200-300 km
<i>Length</i>	12m
<i>Weight</i>	approximately 15 tonnes
<i>Maximum weight of hydrogen</i>	approximately 44kg (1890 litres).
<i>Hydrogen purity</i>	99.999%

Table 3-1. EcoBus specifications

¹ Western Australian vehicle licensing regulations limited the bus load to a maximum number of 59 passengers.

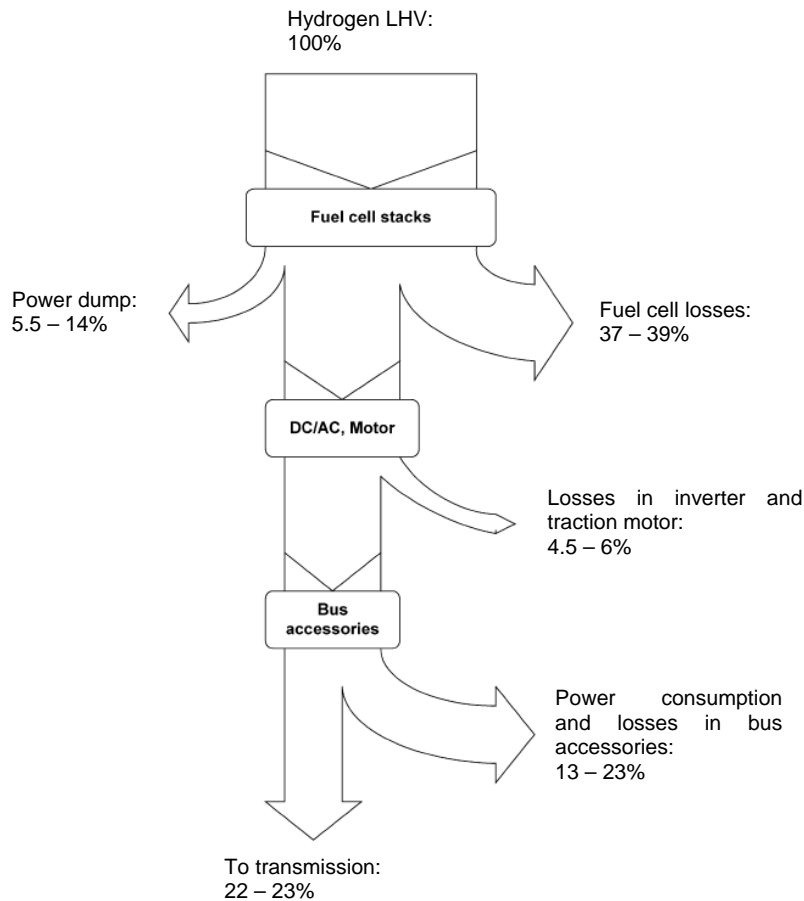


Figure 3-2. Sankey diagram of drive train efficiency

3.2 Efficiency Map

Figure 3-2 shows the efficiency of the EcoBus drive train. The values shown were taken from two European studies one conducted by CUTE^{iv} and the second by Haraldsson^v. It is important to note that the analysis stops at the input to the transmission and so does not include any mechanical losses through the drive train.

The CUTE testing was conducted over two different drive cycle tests performed on the same route (route 66) during a cold day and during a warm day in Stockholm. That testing showed that on a cold day the heating of the cabin can be responsible for as much as 16 % of the total fuel consumption.

The diagram shows where efficiency gains may be possible. These are discussed in more detail in section 9.3 however some obvious targets for improvement are:

- **Power Dump.** The power dump is a resistive load that ensures that at least 6kW is being drawn from the fuel cell. The rationale for this is that the fuel cell takes some time to build up from zero load (i.e. with the bus at idle) to the point where it is able to supply the power necessary to drive the bus. The load resistor ensures that a minimum load is maintained so that there is minimal lag between the driver depressing the accelerator and the bus beginning to move. The dump resistor could be avoided in a hybridised drive train where batteries would supply the initial power as the fuel cell warms up.

- Bus accessories: There are several loads that are driven from an auxiliary gear case such as the air conditioning compressor, the hydraulic pump, the oil pump, three belt driven alternators and the supercharger that is part of the air system. These could be more efficiently driven by separate electric motors to avoid the losses associated with the traction motor, the auxiliary crankcase and the associated belt drives.
- Transmission: Although not included in Figure 3-2, the mechanical losses of the transmission could be avoided if an all electric drive train was used.

4 Routes

For the first several months of the trial the buses operated on normal bus routes but outside normal scheduled service. Primarily the buses operated on the City CAT routes, the Circle routes and the City Link route. These are shown Figure 4-1.

The Circle and City Link routes are free flowing routes with dispersed stops while the City CAT routes are free services that operate in the CBD under congested traffic conditions with more closely spaced stops and heavier passenger loads.

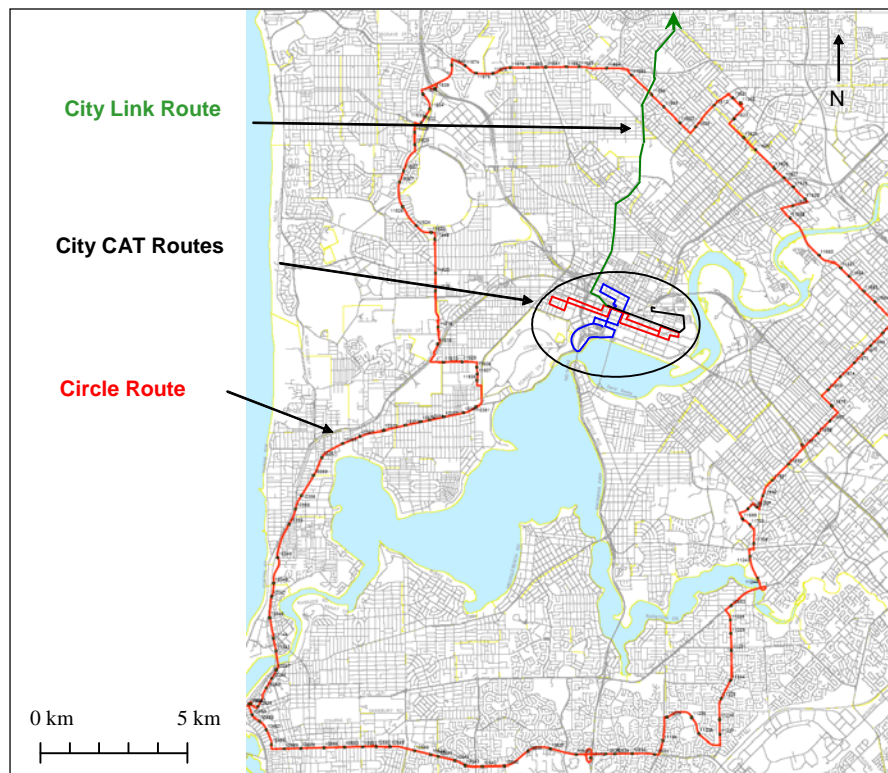


Figure 4-1. Map of typical Perth EcoBus routes

Elevation profiles of these routes are provided in Annex C. The profiles show the elevation above sea level at different points on each route. Examination of the profiles shows that routes in Perth are relatively flat and the highest elevation of any of these routes is 80 metres above sea level and the maximum gradient between stops is 5%.

The EcoBuses operated on normal scheduled service from the 21st of March 2005, which means that the buses often drove on several different routes each day. Normal scheduled service places greater pressure on the availability of the buses because if they were not able to operate according to their schedule then a replacement bus is required.

Table 4-1 shows the basic driving characteristics for key Perth routes and several European routes from the CUTE trial. Perth has achieved some of the highest fuel efficiencies of all sites. This is partly due to the higher average speeds possible on Perth routes and the lower number of stops per kilometre and partly due to different procedures at the depot that results in the buses spending less time at idle. The fuel economy shown for the European routes was the average of test runs and operational

results, the fuel economy for the Perth routes was the average operational efficiency for the three buses running on each route. Details of the fuel economy measured in Perth are provided in Section 4.2.

<i>City</i>	<i>Length (km)</i>	<i>Average Speed (km/h)</i>	<i>Stops per km</i>	<i>Fuel Usage Rate (kg/100km)</i>	<i>Maximum incline (%)</i>
<i>Amsterdam*</i>	10.3	21.6	2.1	21.8	-
<i>Luxembourg*</i>	22.2	19.8	2.2	20.6	-
<i>London*</i>	6.5	10.8	2.8	24.3	-
<i>Stockholm*</i>	7.5	10.9	3.6	25.2	-
<i>Perth – City CAT</i>	8.5-9.8	14.7	2.7-3.2	21.7	3
<i>Perth – Circle</i>	80	24.6	1.8	17	5
<i>Perth – City Link</i>	20	23.6	1.6	16.3	4.8

Table 4-1. Route details for Perth and CUTE^{vi} routes

4.1 Routine Operation

Each day of bus operation was classified as one of the following:

- Normal – routine revenue service;
- Maintenance;
- Special – bus at a public event or used as a charter vehicle;
- No operation (org) – the bus didn't operate because of organisational issues such as no driver available or the bus wasn't included in operating schedule; or
- No operation (fuel) – the bus didn't operate because of a lack of hydrogen supply or a fault in the refuelling station.

Figure 4-2 shows how the days of the trial were distributed across each type of operation. Further detail showing how this division has changed over the trial is provided in Annex D in Figure D-4. Figure D-4 shows that the majority of operating days lost due to non-availability of fuel occurred during 2005 when there were several major outages of the refuelling station this is again evident in Figure 4-3.

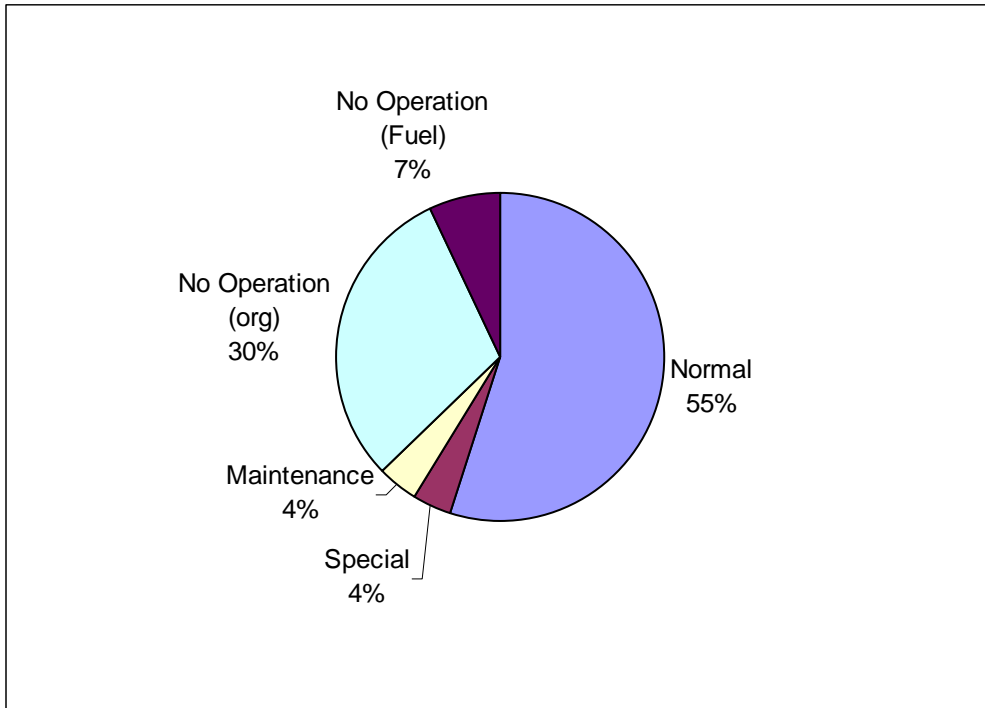


Figure 4-2. Types of bus operation

The buses operated on either normal or special service for an average of 15 days per month and were rarely scheduled for service on weekends. On those operating days the buses average 6.6 hours of operation per day which equates to 101 hours per month. In this case operating hours are taken as engine hours because they accurately represent the amount of time the bus actually ran each day. This can be significantly less than the difference between the start and finish times entered by the drivers. The average operating hours per day is far more regular than the average operating days per month. This shows that when the buses run they typically operate for close to the average time, however the actual operating days per month can vary greatly. This is shown graphically in Annex D section in Figure D-1 and D-2.

Anecdotally, the current fleet of diesel buses operates in excess of 20 days per month and 10 hours per day. The lack of detailed operational data on the conventional bus fleets made comparisons difficult.

The average distance driven on each operating day is 151 km and each bus travels on average 2,420km per month. The average daily distance travelled by each bus is dependant on factors such as the route, traffic conditions, average speed and passenger loads.

Figure 4-3 shows how the daily distances travelled have accumulated over the trial to achieve a final total distance of 258,000. The significant points to note are the flat periods between April and August 2005 and in March and April 2006. These are periods where the buses didn't run because the refuelling station was out of operation. The operation of the refuelling station is discussed in detail in Section 8.

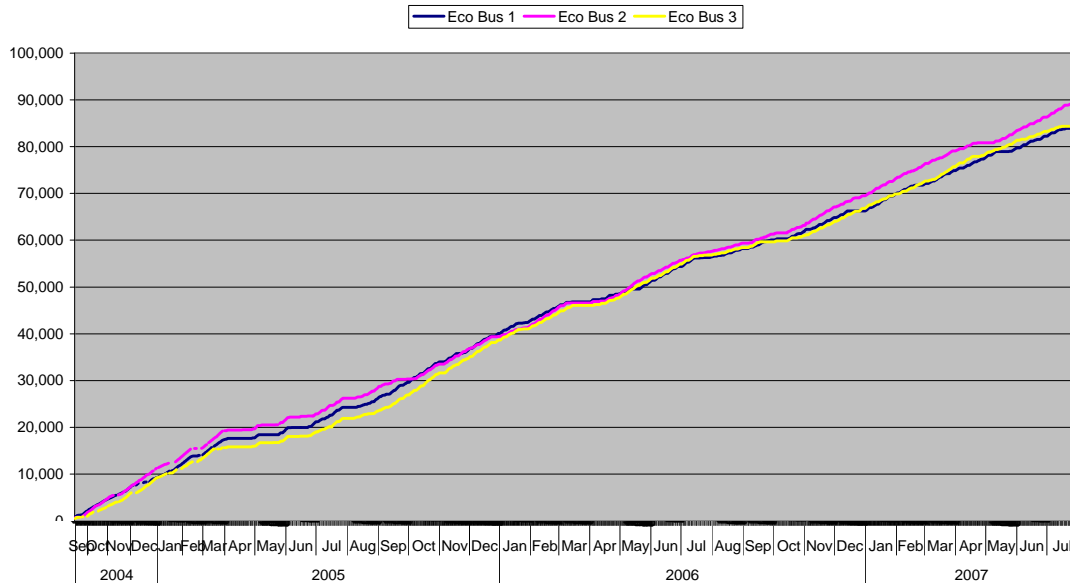


Figure 4-3. Cumulative distances travelled during the trial

4.2 Fuel Efficiency

The fuel economy of the buses over specific routes was calculated early in the trial when the buses were operated on the same route for the duration of the day. The results are provided in Table 4-2 and show the significant effect that driving conditions have on the rate that hydrogen is consumed.

	<i>Eco Bus 1</i> (kg/100 km)	<i>Eco Bus 2</i> (kg/100 km)	<i>Eco Bus 3</i> (kg/100 km)	<i>Average by Route</i> (kg/100 km)
City Cat	21.8	21	22.3	21.7
Circle	16.2	17.6	17.1	17
Link	Insufficient Data	15.8	16.7	16.3
Average by bus	19.0	18.1	18.7	

Table 4-2. Fuel cell bus efficiency on different routes

To compare the efficiency of the fuel cell buses with current diesel and CNG buses it is necessary to use a common basis of comparison in terms of energy and operating conditions.

Ideally comparative fuel consumption data would be collected while operating the different buses under the same conditions such as load, topography, traffic conditions etc. This was not possible due to resource constraints so the fuel efficiency of Perth's diesel and CNG buses was taken from the results of a Department of Environment and Heritage emissions testing program.

In 1998 the National Environment Protection Council developed a set of drive cycles specific to Australian driving conditions called the Combined Urban Emissions Drive Cycle (CUEDC). The CUEDC enables standardised dynamometer testing of different vehicles so that valid comparisons can be made of each vehicle's fuel economy and

emissions under a range of different driving conditions. The CUEDC is made up four segments that represent congested, minor road, arterial and freeway driving conditions. Each segment has different average speeds and different periods of idle, acceleration, cruise and deceleration. Figure 4-4 shows the speed profile of each segment. The fuel efficiency of Perth’s diesel and CNG buses were measured in 2003 during CUEDC based dynamometer testing.

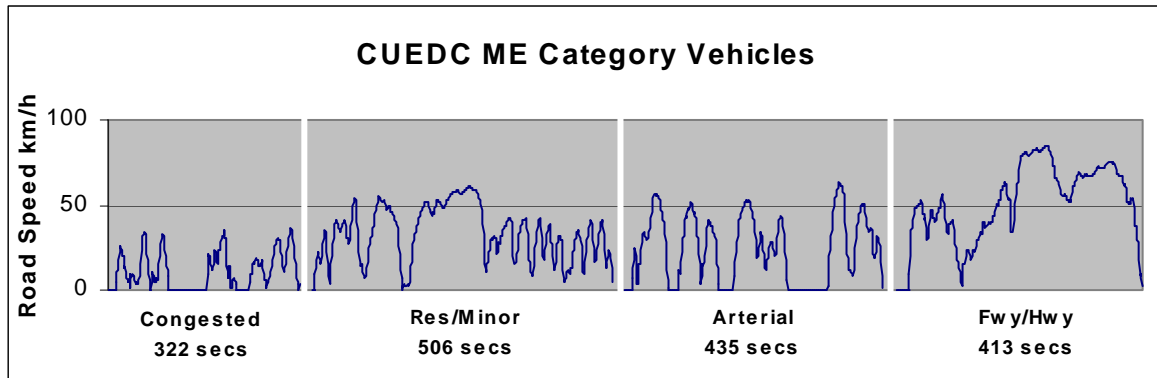


Figure 4-4. CUEDC Segments

Table 4-3 shows the fuel economy of the fuel cell buses and Perth diesel and CNG buses in terms of energy consumed per kilometre travelled. The second column of Table 4-3 shows the CUEDC segment that most closely matches the driving conditions of each Perth route.

	CUEDC Equivalent Segment	Fuel Cell (MJ/km)	Diesel (MJ/km)	CNG (MJ/km)
City Cat	Congested	25.99	24.2	32.9
Circle	Arterial	20.35	19.5	25.7
Link	Arterial	19.48	19.5	25.7
PTA fleet average	Combined	NA	16.2	24.2

Table 4-3 - Fuel consumption for fuel cell, diesel and CNG buses

4.2.1 Seasonal Effects

In the European trial sites, the effect of atmospheric temperature on fuel consumption in the buses was noticeable when the temperatures were below 0° C or above 18° C. The increase in fuel consumption in warmer periods was attributed to the use of the air conditioning unit. In cold periods the energy used to heat the cabin area consumed up to ~5 kg/100 km hydrogen^{vii}. The results of the European test were supported by the graph reproduced in Annex D as Figure D-5. However the results suggested above are not clearly evident in this graph.

The results of a similar analysis conducted on Perth data are displayed in Figure 4-5. The graph shows the monthly average median temperatures with error bars showing the range between average minimum and maximum temperatures. The average monthly fuel consumption is overlaid on the temperature data. Unlike the reported results from Europe, there is no obvious correlation between the ambient temperature

and fuel usage and there is no apparent increase in fuel consumption on days where the median temperature exceeds 18°C. To confirm this, the average fuel consumption was calculated for days where the temperature was above and below a range of cut off temperatures including 18°C. For days above 18°C the average fuel economy was 18.3 kg/100km with a standard deviation (SD) of 2.4. For days below 18°C the average fuel economy as 17.8 kg/100km (SD 1.5).

The largest difference was observed when the cut off temperature was set to 14°C where a difference of 1kg/100 km was observed, however given that the standard deviation of the average fuel efficiency is 2.05kg/100km, this result is not considered statistically significant.

The minimum temperature for Perth has not fallen below 0°C during the trial so the European result of 5kg/100km increase in fuel usage due to heating cannot be confirmed.

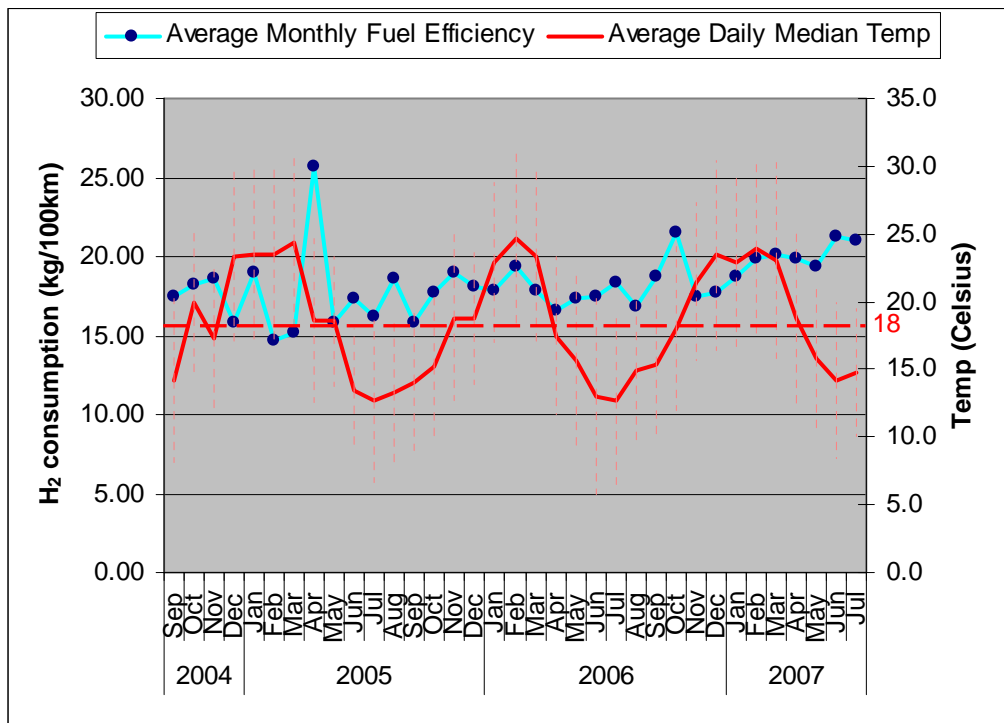


Figure 4-5. Correlation of fuel consumption and ambient temperature

5 Comparative Emissions

5.1 Greenhouse Gas Emissions

There are several methods used to calculate greenhouse gas emissions from transport. Each method produces different and sometimes contradictory results.

Emissions can be quoted as CO₂ or CO₂-e. CO₂-e usually refers to the combined greenhouse gas effect of CO₂, methane (CH₄), and N₂O. The quantity of CH₄ and N₂O are usually small compared to CO₂ but their potential for global warming is much greater. A kilogram of CH₄ has 21 times the global warming potential of a kilogram of CO₂ and N₂O has 310 times the potential of CO₂.

Emissions can also be due to combustion or lifecycle emissions which include pre-combustion and combustion emissions. Pre-combustion emissions take into account all greenhouse gas emissions released during exploration, production, refining and delivery of the fuel while combustion emissions are the exhaust pipe emissions produced when the fuel is burnt in the vehicle's engine.

The most accurate representation of a vehicle's total greenhouse impact is to consider not only the lifecycle CO₂-e emissions for the fuel but also for the emissions caused by the production and disposal of the vehicle.

This is particularly relevant for private passenger vehicles where, because of their comparatively low usage, the emissions released while building the vehicle and all of its associated components can be a significant portion of the total life cycle emissions.

Because buses travel significantly greater distances over their lives than cars, the production and disposal emissions are significantly less than the operating emissions. The greenhouse gas emissions released during the manufacture of a diesel, CNG or fuel cell bus are comparable. This makes it legitimate to ignore the production and disposal emissions and compare diesel and CNG buses purely on the basis of the lifecycle emissions of their fuel.

5.1.1 Lifecycle greenhouse gas emission rates

Emissions are often stated as either grams of CO₂-e per mega joule (MJ) of fuel or grams of CO₂-e per km. Emissions per MJ refer to the greenhouse gas emissions that result from the use of one MJ of a particular fuel. Different fuels have different energy densities (CNG is 39 MJ/m³, diesel is 38.6 MJ/l and hydrogen is 119.9 MJ/kg) so grams per MJ can be converted to grams per m³, litre or kg. Emissions per km are calculated by multiplying the emissions (g/MJ) for each fuel with the fuel efficiency of the vehicle (MJ/km) to determine the emissions per km (g/km).

	<i>Pre-combustion emissions factors</i> g CO ₂ -e / MJ			<i>Combustion emissions factors</i> g CO ₂ -e / MJ				<i>Fuel lifecycle emissions factors</i> g CO ₂ -e / MJ		
	<u>CSIRO</u>	<u>AGO</u>	<u>Perth LCA</u>	<u>CSIRO</u>	<u>AGO</u>	<u>CUEDC</u>	<u>Perth LCA</u>	<u>CSIRO</u>	<u>AGO</u>	<u>Perth LCA</u>
<i>CNG</i>	11.7	11.4		54.8	53.8	53.9		66.5	65.2	
<i>Diesel</i>	19.1	7.8		66.7	69.8	69.6		85.8	77.6	
<i>H₂</i>	-	-	76.9	-	-	-	0	-	-	76.9

Table 5-1. Life cycle greenhouse gas emission rates from hydrogen, diesel and CNG

The lifecycle greenhouse gas emission rates used in this analysis are provided in Table 5-1. These are drawn from three sources; the first is from a CSIRO report produced for the Australian Greenhouse Office (AGO)^{viii}, the second is the Australian Greenhouse Office’s work book for Australian greenhouse emissions reporting^{ix} and the third is a lifecycle analysis (LCA) of the hydrogen infrastructure used for the fuel cell bus trial which was conducted by Murdoch University^x. This LCA included the emissions associated with crude oil supply to the Kwinana refinery, operation of the BOC plant, delivery to Malaga by tube trailer and the operation of the refuelling station at Malaga. The delivery by tube trailer and the operations of the Malaga refuelling station account for over 60% of the total emissions. So there is significant scope to reduce these emissions if a more efficient means of transporting the hydrogen to Malaga was used and if the refuelling station was to use green power.

Both the AGO and CSIRO sources are provided to illustrate the level of agreement between different studies on the emission rates per megajoule. The grey column under combustion emissions provides the results of emissions testing on Perth buses in 2003. These test results were included to validate the tail pipe emission factors from the CSIRO report and the AGO workbook.

The results in Table 5-1 imply that there is a greenhouse gas advantage when using CNG buses however the figures do not take into account the fuel efficiency of vehicles using the different fuels.

The effect of fuel efficiency on lifecycle greenhouse gas emissions is shown in Figure 5-1. The results are based on PTA fleet average fuel efficiencies from Table 4-3 and the fuel cell bus trial average of 21.7 MJ/km. The “Future H₂” result shows the lifecycle greenhouse gas emissions per km if the efficiency gains discussed in section 9.3 are achieved. Efficiency gains in internal combustion engine vehicles would also result in reduced emissions, however, due to the immaturity of the fuel cell bus design there is greater potential for efficiency

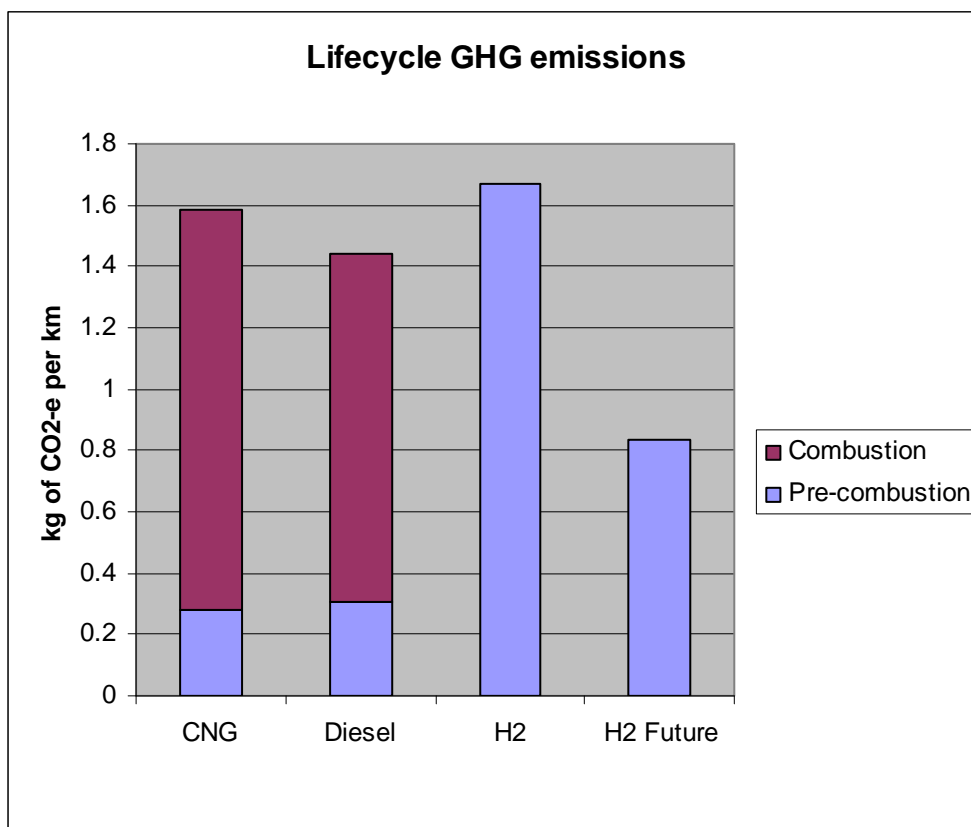


Figure 5-1. Greenhouse gas emissions from buses powered by CNG, diesel and hydrogen fuels

5.2 Toxic air pollutants

Toxic air pollutants can have a significant impact on human health. The emission rates of three key toxic air pollutants that result from the use of diesel, CNG and hydrogen are provided in Table 5-2. Again the emission rates for diesel and CNG were taken from the CSIRO report while the hydrogen results were taken from the Murdoch University LCA study.

		<i>NOx</i>	<i>CO</i>	<i>Particulates</i>
Diesel	Pre-combustion	0.1	0.023	0.00542
	Combustion	0.944	0.23	0.0354
	Lifecycle	1.044	0.253	0.0407
CNG	Pre-combustion	0.026	0.007	0.000439
	Combustion	0.114	0.003	0.0007
	Lifecycle	0.14	0.01	0.00114
H2	Pre-combustion	0.205	0.101	0.031
	Combustion	0	0	0
	Lifecycle	0.205	0.101	0.031

Table 5-2. Toxic emissions (g/MJ) for diesel, CNG and hydrogen fuels

The graph of Figure 5-2 shows the effect of fuel efficiency on these emission rates. The graph does not separate pre-combustion and combustion emissions but as is shown in Table 5-2, combustion emissions can be significantly higher than pre-combustion emissions. It is important to note that unlike greenhouse gases, the location where these emissions occur makes a big difference to their impact on society. Toxic emissions that occur close to a population centre will expose a greater

number of people to that pollutant and therefore have a much greater total health affect.

This is where fuel cell vehicles can have a significant advantage. Toxic emissions released during the production of a fuel can be located away from population centres and so have a lower health impact. It is not possible to isolate combustion emissions in the same way, so a vehicle with low or zero emissions can have a significant advantage when operated in densely populated areas.

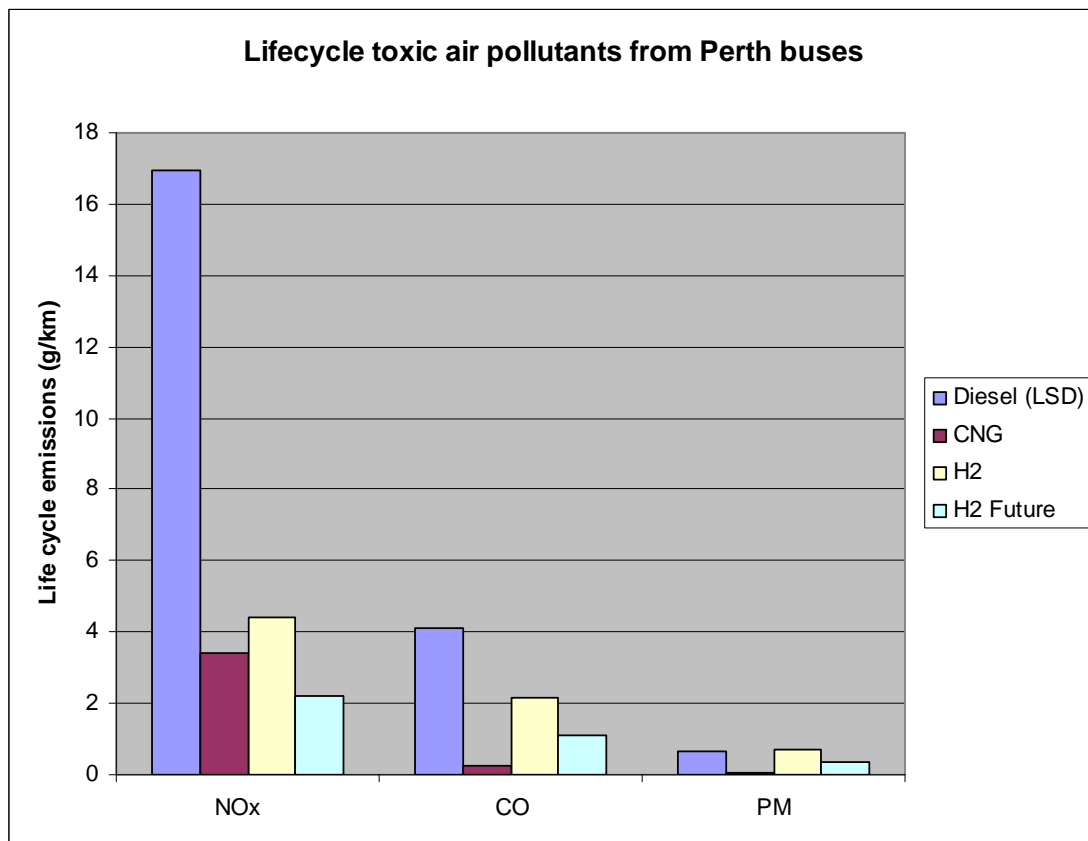


Figure 5-2. Toxic air pollutants per km for diesel, CNG and hydrogen fuels

6 Passengers

Up to the end of July 2007, the EcoBuses carried 283,000 passengers. The average daily passenger load during routine operation was 197 passengers. There is a high degree of uncertainty associated with this average which ranges between 3 and 1132 and has a standard deviation of 100. The monthly passenger loads vary greatly but are highly correlated with operating hours as shown in Figure 6-1.

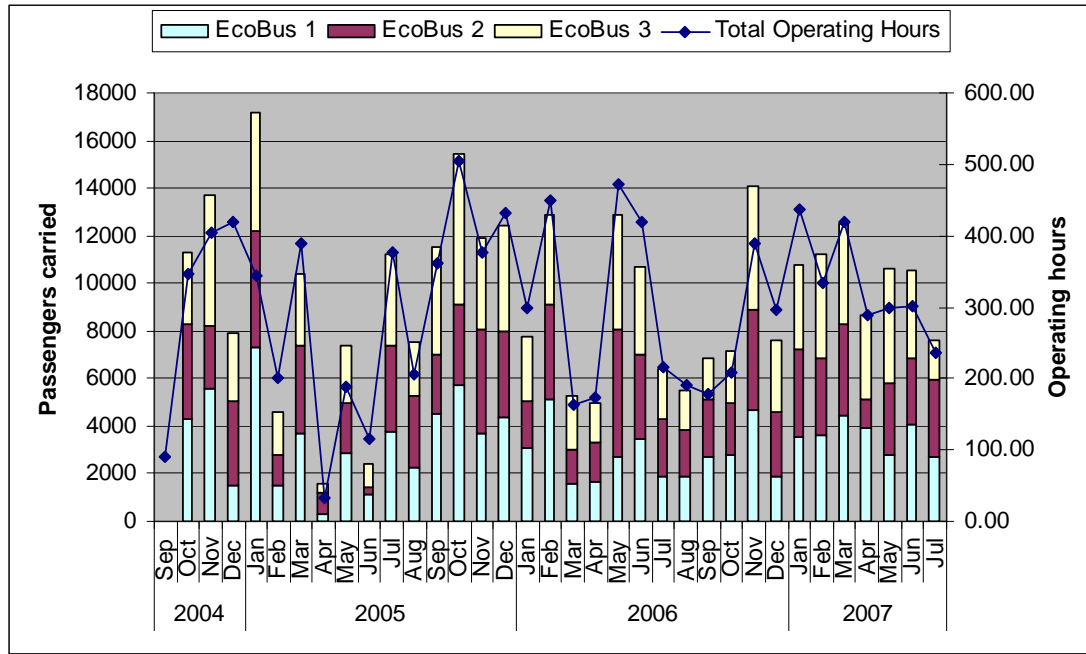


Figure 6-1. Monthly passenger loads

7 Maintenance

7.1 Overview

The maintenance work on the EcoBuses was classified as maintenance, upgrade, testing, trouble shooting or other. Each of these categories is described below.

- **Maintenance** encompasses routine inspections and maintenance conducted at regular intervals to ensure that the systems and components of the bus are performing as expected and to gauge the potential life and failure modes of each system and component. To avoid confusion this will be referred to as routine maintenance in this report.
- **Upgrade** is the implementation of hardware and software improvements that were developed as a result of knowledge gained from all trial sites.
- **Repair** includes any maintenance task required to correct system faults and replace faulty components in the bus.
- **Testing** is periodic testing of certain systems, such as air flow tests and taking samples of the de-ionised water for testing. Testing of potential upgrades before they are formally implemented would also be included in this category.
- **Trouble shooting.** The developmental nature of many of the systems on the EcoBus means that it is not always possible to clearly identify which systems are faulty or causing poor performance. The trouble shooting category was included to record the effort required to identify these systems. The subsequent repair of the relevant system was included in the repair category.
- **Other**, is a catch all category for any maintenance tasks that do not fall neatly into one of the above categories. This category was necessary because of the prototype nature of the EcoBuses.

7.2 Fuel Cell Bus Systems

Each maintenance task was classified by the type of maintenance and by the systems affected. Maintenance for the Perth fuel cell bus trial was divided into the systems described below.

The functional description of these groups has been drawn from the Clean Urban Transport for Europe, Detailed Summary of Achievements^{xi}. A high level schematic showing how these systems interconnect is provided in Figure 7-1.

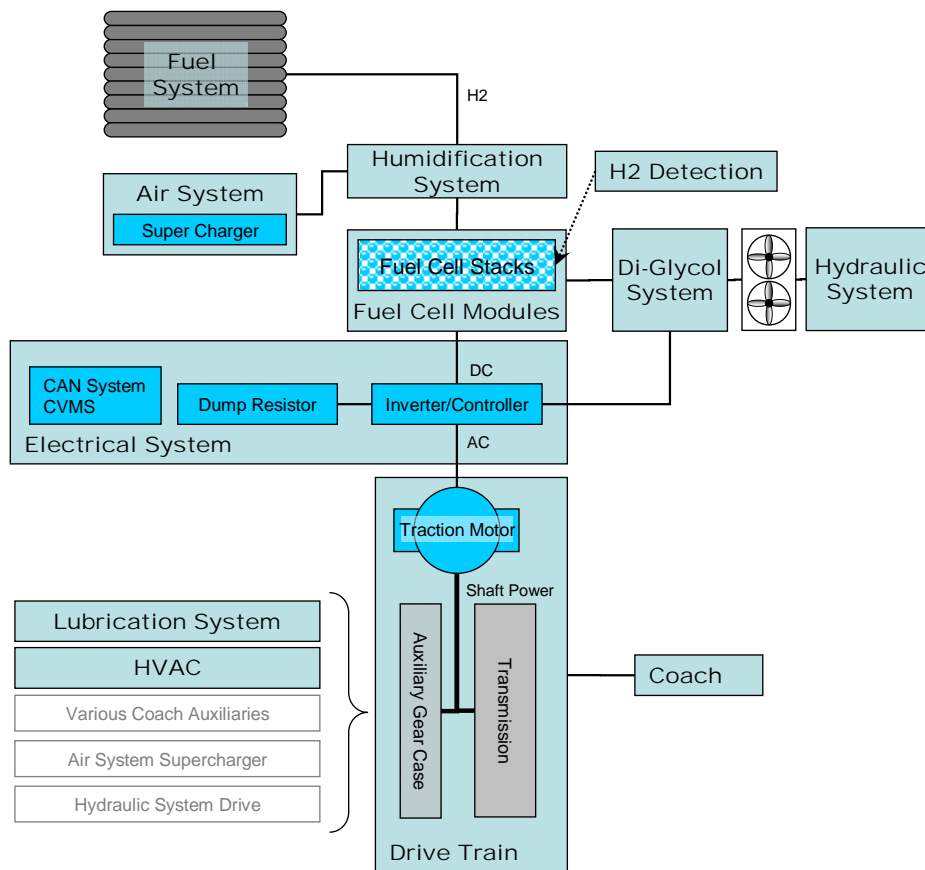


Figure 7-1. EcoBus maintenance subsystems

7.2.1 Fuel System

The fuel system consists of nine DyneCell 205 litre high-pressure cylinders and the associated valves, solenoids and piping necessary to deliver hydrogen to the fuel cell module. Each DyneCell cylinder is built from a seamless “thin wall” aluminium line with a full carbon fibre over-wrap. The total storage capacity of hydrogen at 15 °C and 350 bar is 44 kg.

7.2.2 Air system

The Air System provides pressurised air to the fuel cell stacks. The air is pressurised by a supercharger which is driven by the auxiliary gear case. A turbocharger is used to recover energy from the exhaust air leaving the stacks and used to provide a second stage of air compression. The air supply system also includes an inter-cooler to improve compression efficiency and an air filter to remove contaminants.

The air system intake and exhaust are fitted with mufflers to reduce the noise of the supercharger and turbocharger.

7.2.3 Humidification

The air and hydrogen supplied to the fuel cell is humidified to ensure that the correct moisture balance is maintained in the cell rows. Too little moisture will allow the membrane to dry out which causes a loss in power and can damage the membrane. Too much moisture will flood the membrane which again leads to a loss in power.

7.2.4 Fuel Cell Module and Stack

The fuel cell modules contain the fuel cell stacks (consisting of six discrete cell rows per stack) and their associated hardware which includes the hydrogen regulating and re-circulation hardware, the electronic cell voltage monitoring system (CVMS) and the humidification hardware discussed above. The modules can be removed as a complete unit for servicing but for the purpose of classifying maintenance tasks, the humidification hardware and CVMS are considered separately to the fuel cell module.

7.2.5 H₂ Detection

The hydrogen detection system is located within the fuel cell module and is used to detect hydrogen leaks within the module.

7.2.6 Di-Glycol

The fuel cells produce heat that must be removed from the fuel cell modules to maintain optimum operating conditions. This is done by the de-ionised (DI) water/glycol cooling system which includes a reservoir, a control valve, a de-ionising filter, a freeze-protection system and various control valves.

The water/ethylene glycol mixture in the cooling circuit is de-ionised to make it non-conductive. This is necessary to ensure that the cooling fluid doesn't short out the individual cells.

The di-glycol system also cools the inverter/controller.

7.2.7 Hydraulic system

The heat from the di-glycol cooling system is discharged to the atmosphere via a heat exchanger and two hydraulically driven fans. The hydraulic system includes a hydraulic pump driven by the auxiliary gear case, the hydraulically driven fan motors, and the hydraulic control valves and plumbing.

7.2.8 Lubrication

The lubrication system is also driven by the auxiliary gear case and lubricates the transmission and auxiliary gear case.

Several auxiliary units such as the HVAC and three belt driven alternators are driven from the auxiliary gear case.

7.2.9 Electrical System

The electrical system includes the inverter/controller module, the controller area network (CAN) and numerous sensors throughout the bus including the cell voltage monitoring system (CVMS) in the fuel cell module.

The inverter/controller module converts the DC electrical power produced by the fuel cell stacks into controlled AC power for the electric motor. This module is cooled by the normal water/glycol circuit.

7.2.10 Drive train

The drive train incorporates the 250kW, water cooled traction motor, the standard automatic transmission and auxiliary gear case. The traction motor specifications are in Table 7-1.

Nominal motor output	250 kW shaft power
Capacity	340 kVA
Rated output current	450 A (1200 VDC IGBT)
Maximum output voltage	3-phase 460 V or 0.7 x DC input voltage – whichever is less
Rated output frequency	400 Hz (maximum) at full torque
Overload capacity	150 % rated current / 1 minute
PWM frequency	minimum 2.5 kHz, maximum 5 kHz
Input current	425 A continuous 540 A maximum for 5 minutes
Rated voltage	600 VDC (full load) to 900 VDC (zero load) input

Table 7-1. Traction motor specifications

7.2.11 Heating, Ventilation and Air Conditioning (HVAC)

Air conditioning for the bus is provided by a standard air conditioning package that is driven by the auxiliary gear case.

Cabin heating is derived from several sources, the traction motor cooling oil, the second water/glycol circuit and an electric immersed heating device with an approximate heating power of 40 kW at full load.

7.2.12 Coach

The coach system includes all standard bus components after the transmission. This includes all other vehicle drive components such as the differential, suspension, brakes, tyres etc and all body components such as doors, ramps etc.

7.3 HyFLEET:CUTE Maintenance Classifications

HyFLEET:CUTE uses a different set of categories for maintenance reporting, which are listed below:

- Regular maintenance standard bus,
- Regular maintenance fuel cell propulsion,
- Upgrade fuel cell propulsion,
- Failure standard bus,
- Failure fuel cell propulsion,
- Failure fuel cell rest, and
- Failure hydrogen storage.

The HyFLEET:CUTE categories combine both the type of maintenance and the system affected. This simplifies reporting but limits the depth of analysis that can be preformed.

7.4 Maintenance Hours

The Ecobuses have required a total of 1,457 hours of maintenance to achieve 10,553 operating hours. This means that this model fuel cell bus requires 1 hour of maintenance for every 7 hours of operation.

The breakdown of those hours is provided in Figure 7-2. Over half of the maintenance effort is dedicated to fault rectification which is detailed in section 7.6. Routine maintenance is the next most significant contributor and is detailed in the following section.

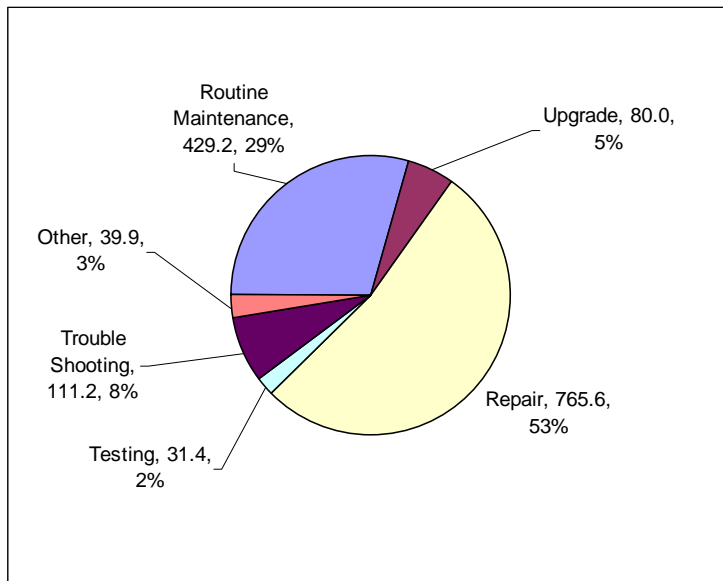


Figure 7-2. Breakdown of maintenance hours

7.5 Routine Maintenance

A summary of the routine maintenance tasks that were performed on the Ecobuses is provided in Table 7-2. This shows that the vast majority of routine maintenance tasks are conducted on the fuel cell engine. The exception to this is the 80 hour inspections which included coach components. The next time that routine maintenance was conducted on any coach components was in the 24,000km inspection and service. After several months of operation the frequency of the 80 hour inspection was reduced to 160 hours and the coach maintenance task was removed.

Maintenance Task	Affected Systems											
	Air	Drive Train	H ₂ detection	Hydraulic	Coach	Electrical	HVAC	Lubrication	Di-Glycol	Fuel	Humidification	Fuel cell
80 hour inspection				✓	✓	✓	✓		✓	✓	✓	
160 hour inspection and service		✓	✓	✓		✓	✓			✓	✓	
320 hour inspection and leak test	✓								✓	✓		
640 hour water pump rebuild											✓	
640 hour oil cooler fan replacement								✓				
640 hour inspection								✓				
6,000 km inspection and service	✓		✓	✓		✓	✓		✓			
12,000 km inspection and service									✓			
24,000 km inspection and service	✓			✓	✓	✓		✓	✓		✓	
48,000 km inspection	✓	✓			✓	✓			✓	✓		
3 month hydrogen sensor check	✓		✓						✓	✓		
4 month smoke detector test	✓											
Annual Dept of Transport inspection					✓							
Annual technical inspection						✓						
TÜV certification check	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

Table 7-2. Routine maintenance tasks

Routine maintenance was focussed primarily on the fuel cell engine so it is anticipated that the frequency and complexity of these tasks would reduce as the technology and system designs for fuel cell buses mature. Trouble shooting, upgrade and testing are largely due to the experimental nature of the buses and can also be expected to reduce significantly in a production model fuel cell bus.

There was no significant correlation between monthly routine maintenance and monthly bus operating hours. This was unexpected since it is reasonable to assume that as the operation of the buses intensified so would the frequency of routine maintenance tasks and component failures.

Two possible reasons for this relationship not being evident are firstly that the routine maintenance schedule was based on Ballard's best estimates for the need to check and replace certain components. A routine maintenance schedule for an operational bus would endeavour to minimise the effort required and spread it evenly over a reasonable period of time to reduce spikes in maintenance effort and maximise the availability of the bus.

A second reason is that the operating hours per month can vary greatly and the maintainers take advantage of quiet periods to catch up on routine maintenance. This effect would be reduced with a larger fleet where monthly operating hours are more consistent.

The proportion of time spent on different types of maintenance for the individual buses is shown in Annex D section in Figure D-6 and is very similar to the aggregate result in Figure 7-2. The only exception to this is a slightly higher repair time for Eco Bus 3. This can be traced to three repair tasks which were out of the ordinary and took a long time to repair. The worst of these was a bearing failure in the supercharger that also damaged the auxiliary gear case and took 40 hours to repair.

7.6 Repairs

Until the end of July 2007 there have been 250 repair tasks that have taken 766 hours to complete. The breakdown of this effort across the different systems is provided in Figure 7-3 (repair tasks) and Figure 7-4 (repair hours).

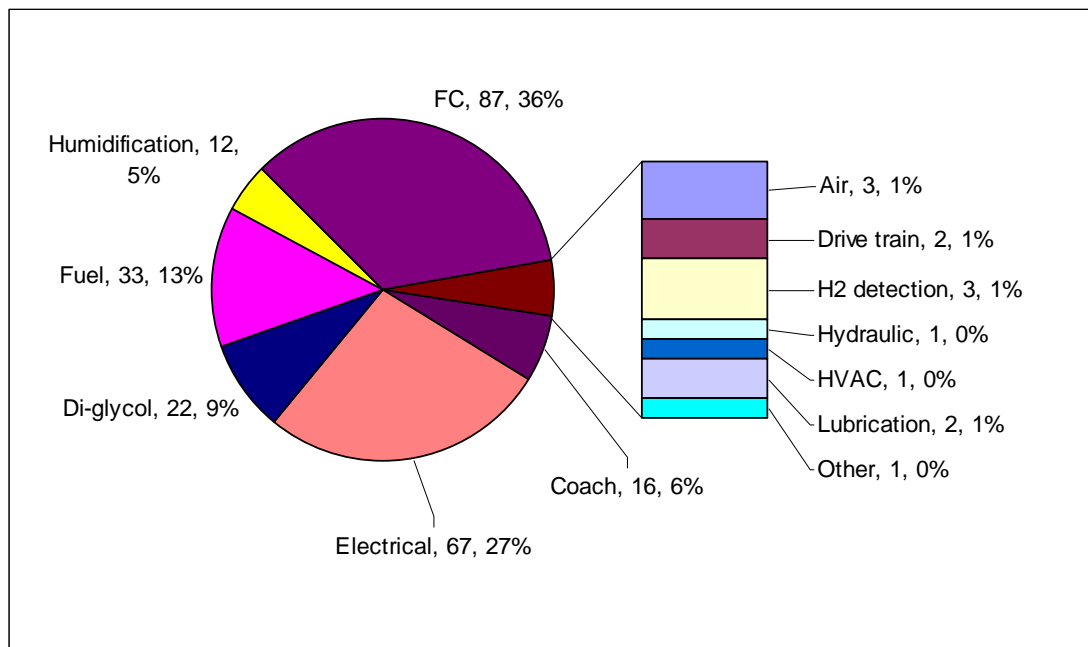


Figure 7-3. Repair tasks

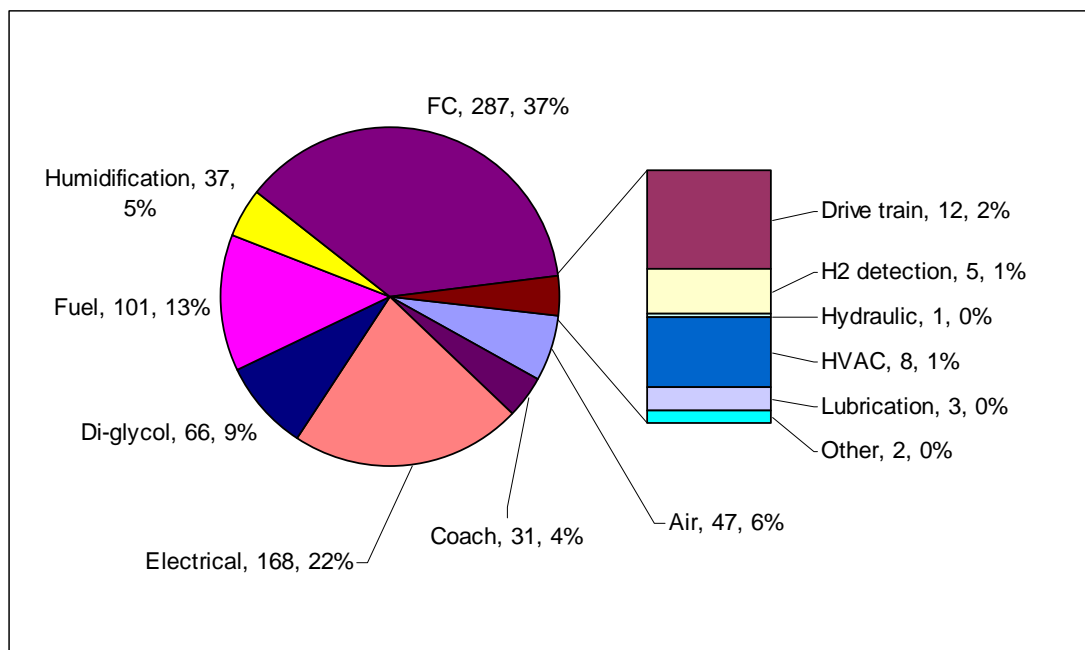


Figure 7-4. Repair labour hours

The data labels in each graph show the system, the total tasks or hours dedicated to that system, and the percentage contribution to the total number of tasks or hours. The column on the right of the graph separates out the lowest contributors to make the graph easier to read. The two graphs are very similar which indicates that the average time to repair each system is reasonably constant, particularly for the systems attracting the greatest repair effort. In both cases the di-glycol, fuel, fuel cell and electrical systems account for over 80% of the repair effort, the average time taken to complete each repair task for these systems is 3 hours with a standard deviation of 0.3 hours.

There is no obvious correlation between the total repair effort and the intensity of operation of the buses. This is not unexpected as increasing the operational tempo of the buses may only have an effect after a greater period of time than was available for the trial. A time series of repair effort per system compared with monthly operating hours is provided in Annex D in Figure D-7.

7.6.1 Key component replacement

The replacement of inverters and cell rows are examined as particular case studies to illustrate repair effort over the period of the trial. These particular components are chosen because their replacement rate was sufficient to begin to show trends.

It is important to note the cell rows and particularly their durability, are a key area of research by Ballard Power Systems and as such they are subject to intensive monitoring. The cell rows were replaced when their performance degraded to a predetermined point that was set and monitored by Ballard Power Systems. The cell rows were then removed and returned to Ballard Power Systems for analysis and refurbishment. The replacements shown in Figure 7-5 were primarily due to this refurbishment program and should not be seen as cell row failures. In production model fuel cell buses these thresholds could be adjusted or removed to improve the durability of the cell rows.

The replacement of cells rows in the fuel cell modules required 25 repair tasks and 187 labour hours to replace a total of 43 cell rows. The spread of this effort over the period of the trial is shown in Figure 7-5. Some of the markers in Figure 7-5 indicate the replacement of more than one cell row so there are less than 43 markers on the graph.

Ballard Power Systems recognises that the durability of their cell rows is a key market differentiator so they closely protect the details of which cell row is replaced and when. The reduced failure rate towards the end of the trial may indicate an improvement in cell durability or a reduction in the performance threshold where the cell rows are identified for replacement.

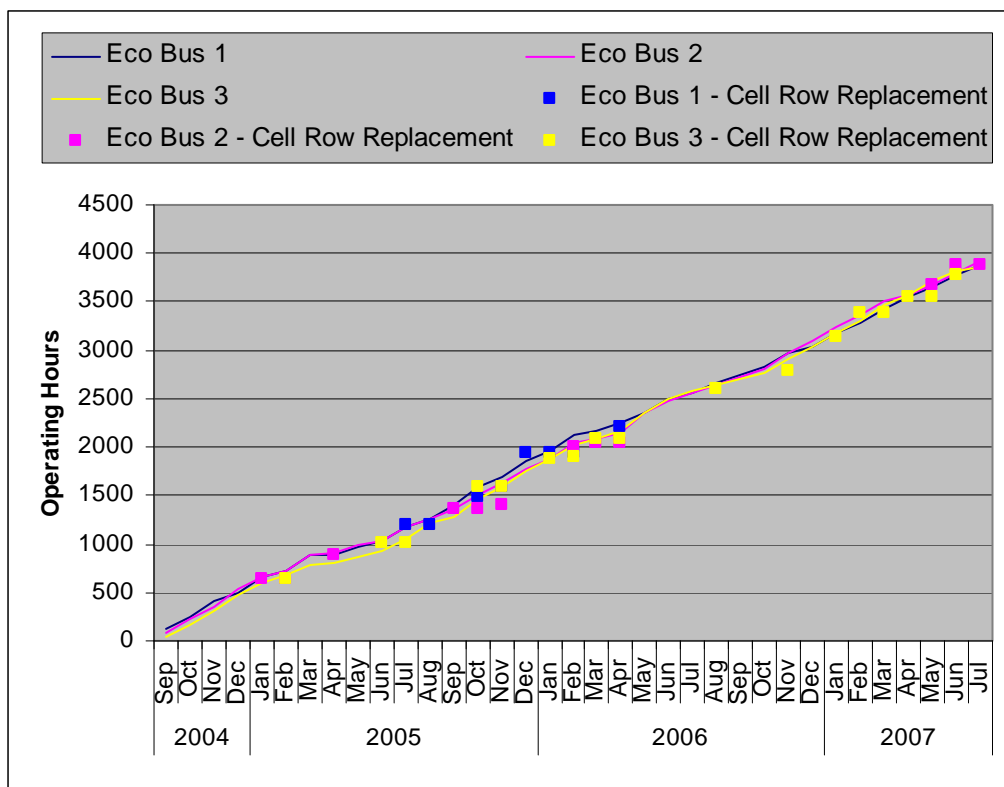


Figure 7-5. Cell row replacement

The replacement of inverters is shown in Figure 7-6. The inverter was designed specifically for this application and had significant reliability issues early in the trial due to particular temperature sensitive components. The design was modified and reliability improved.

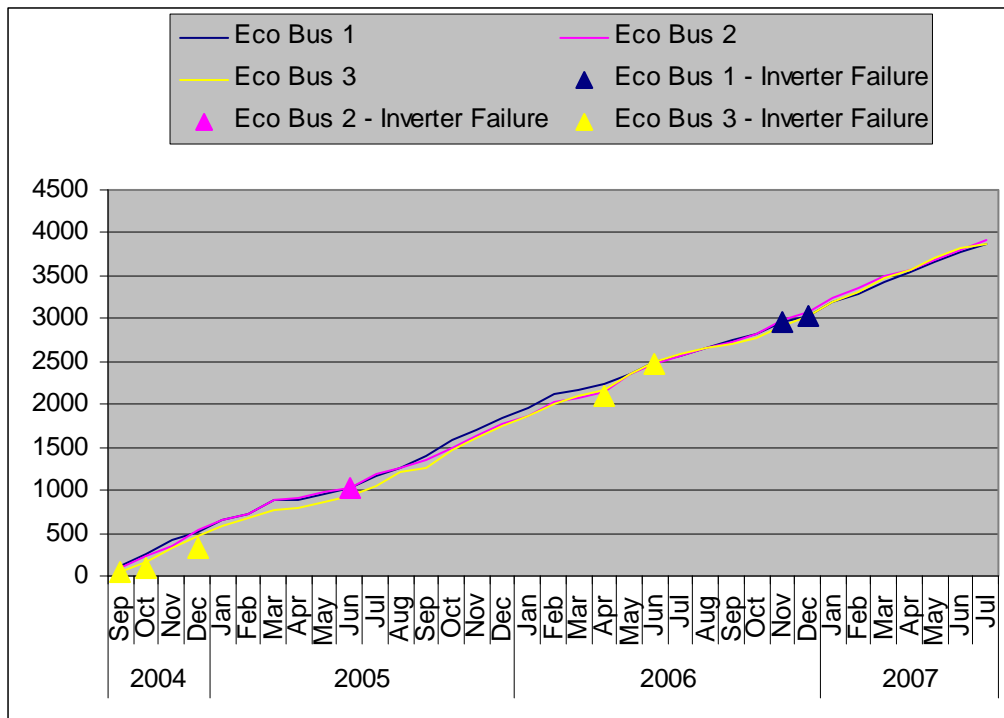


Figure 7-6. Inverter failures

7.7 Maintenance Callouts

Maintenance callouts or on-road service is where the buses required maintenance assistance while during *normal* or *special* operation. The buses were then recovered either through:

- phone assistance from a fuel cell bus technician and *returned to service*,
- removed from service and *driven* back to the depot, or
- removed from service and *towed* back to the depot.

Maintenance callouts are a key indicator of the reliability of individual buses and bus types, since removing a bus from service can cause a significant disruption to the schedule and inconvenience to passengers.

Figure 7-7 shows the distribution of the different types of maintenance callout incidents over the period of the trial. To account for distances travelled each month the callout rate is measured as the number of incidents per 100,000km. This measure is also used for conventional buses. All three types of callout trended downward as the trial progressed indicating that the reliability of the buses improved. This remained the case even when the high callout rates of September 2004 are not included.

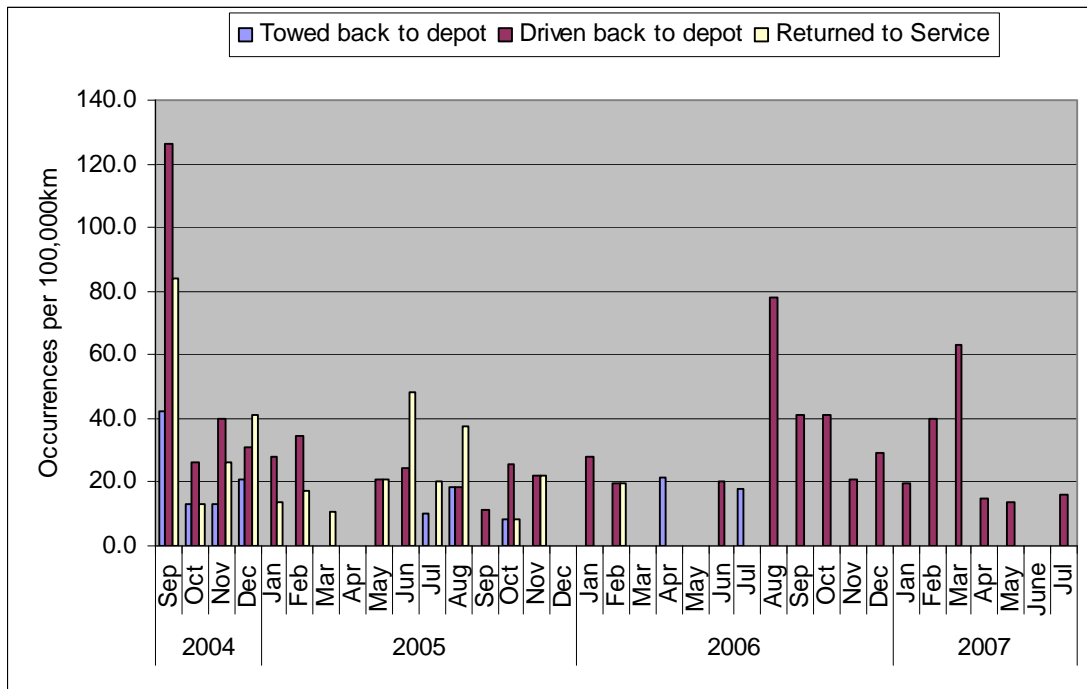


Figure 7-7. Maintenance callouts over time

Over the period of the trial the buses have required on road maintenance 90 times which equates to 35.4 incidents per 100,000km. Of these the buses have been towed back to the depot 3.9 times per 100,000km, they have been driven back 22.1 times per 100,000km and have been returned to service 9.5 times per 100,000km. The incidents are distributed reasonably evenly across the three buses as shown in Figure 7-8. Anecdotally, current diesel buses require towing at a rate of 4 to 5 times per 100,000km.

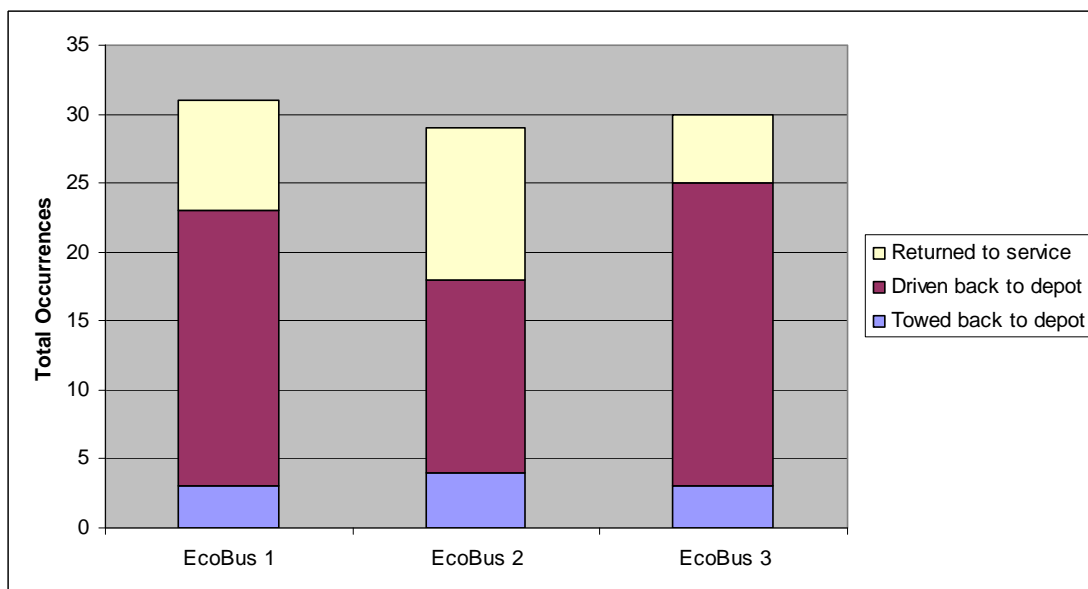


Figure 7-8. Maintenance callouts per bus

7.8 Availability

7.8.1 CUTE method

The definition for availability used in the CUTE project is “the number of downtime days per month as a proportion (%) of the total number of days in that month”^{xii}. In practice, a bus is defined as unavailable if it is not available for service for at least eight hours. This means that a bus could be out of service for seven hours in a day and still be considered available. Using this measure Perth’s fuel cell buses were available for more than 90% of the time. For comparison, the availability of the buses in the nine CUTE cities is shown in Figure 7-9.

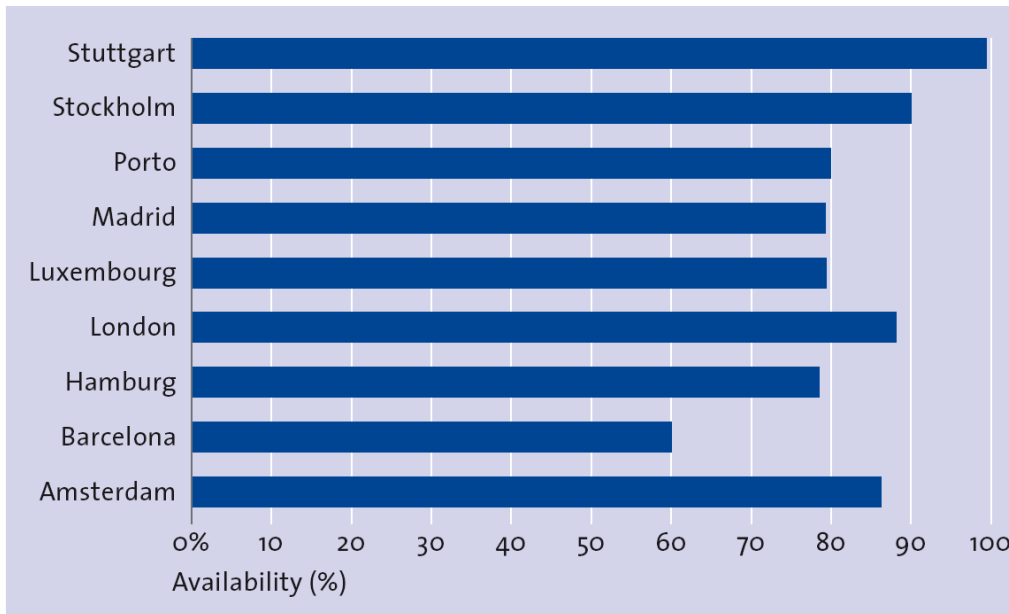


Figure 7-9. Bus availability of CUTE cities^{xiii}

A more detailed approach would be to consider the time required to maintain the vehicles in terms of mean time between failures, mean time to repair and the frequency and duration of routine maintenance.

The average time to complete each routine maintenance task was calculated from Perth maintenance data and is presented in Table 7-3.

Task	Average time to complete (minutes)
80 hour inspection	83
160 hour inspection and service	66
320 hour inspection and leak test	53
640 hour water pump rebuild	103
640 hour oil cooler fan replacement	53
640 hour inspection	30
6,000 km inspection and service	121
12,000 km inspection and service	116
24,000 km inspection and service	101
48,000 km inspection	120
3 month hydrogen sensor check	37
4 month smoke detector test	37
Annual Dept of Transport inspection	135
Annual technical inspection	30
TÜV certification check	300

Table 7-3. Average time to complete routine maintenance tasks

In section 4.1 it was determined that each fuel cell bus operates an average of approximately 100 hours and travels 2,400km per month. Analysis of repair data shows that the fuel cell buses require repair an average of 2.5 times per month and each repair takes an average 3 hours to complete. This information, combined with the routine maintenance data in Table 7-3, was used to determine the monthly availability shown in Figure 7-10.

If availability is then calculated as the ratio between the operating hours per month (which was 100 hours in this example) and the labour hours devoted to maintenance then the monthly availability varies between 75% and 95%.

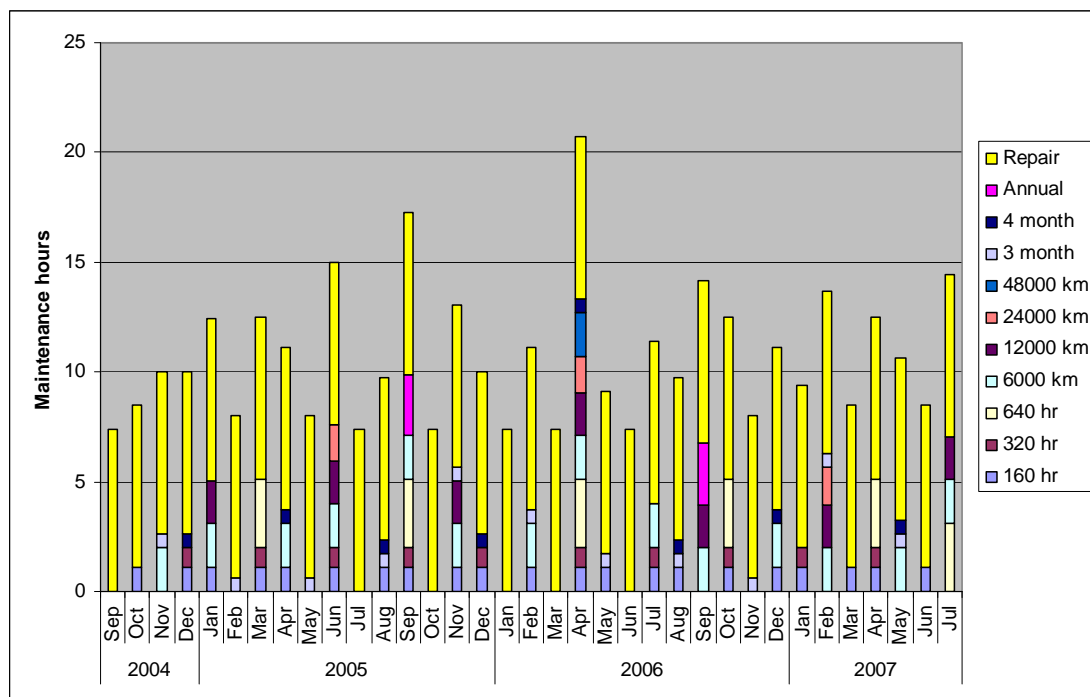


Figure 7-10. Monthly bus availability

This provides a bus operator with a more clear indication of the maintenance effort required to keep the buses on the road. This information can be used to determine the total number of buses needed to maintain an operational fleet.

A fuel cell bus trial being conducted in the USA and monitored by the National Renewable Energy Laboratory measured availability as the number of days a bus might be scheduled for service and the number of days it was not available for service due to any maintenance issues^{xiv}. During the evaluation period, their diesel buses had an availability rate of 84% and the fuel cell buses had an availability rate of 52%.

The availability of Perth's diesel and CNG buses was difficult to determine. Detailed maintenance records are often not maintained or when they are they are not publicly available because knowledge of maintenance effort and therefore cost may give competing bus operators a commercial advantage.

8 Refuelling station

8.1 Infrastructure

The trial required the installation of significant infrastructure to ensure that sufficient hydrogen of the required purity was available for the EcoBuses.

The hydrogen for the fuel cell bus trial was produced by BP as a by-product from their Kwinana refinery. The hydrogen was then piped to the adjacent BOC site where it is purified to 99.9999²% in a Pressure Swing Adsorption (PSA) unit that can purify up to 18kg/hr. The purified hydrogen is then compressed to approximately 160 bar using a dry lubricated Burton Corblin compressor.

The hydrogen was transported 66 kilometres in tube trailers to Path Transit's Morley bus depot in one of two 34.8 tonne tube trailers. Each truck trailer has nine storage vessels that hold a total of 350 kg of hydrogen.

A purpose built refuelling station then takes the hydrogen from the trailer and further compresses it to fill the EcoBuses.

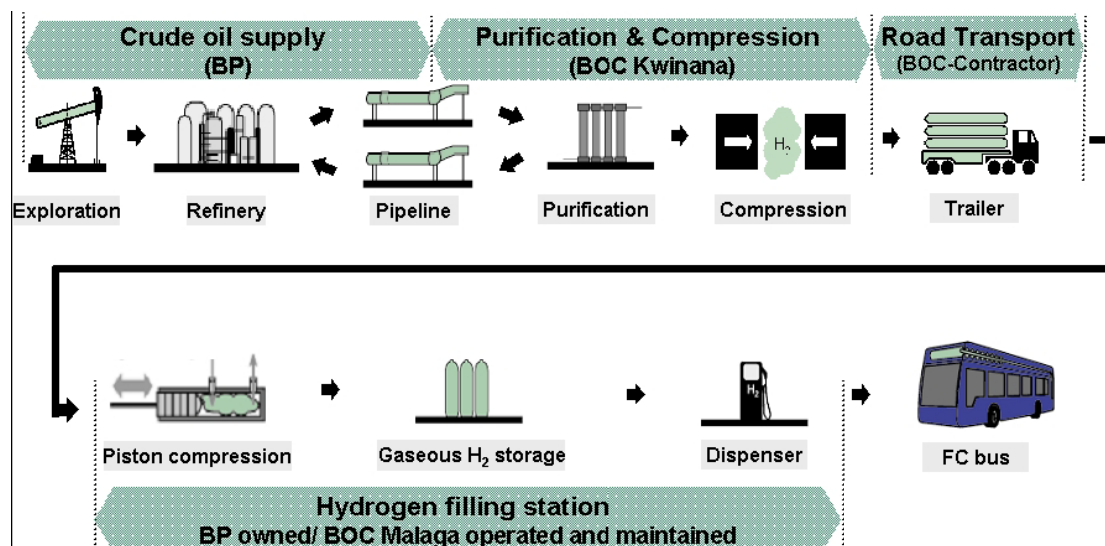


Figure 8-1. Perth hydrogen infrastructure^{xv}

The refuelling station was designed and supplied by Linde AG of Germany and comprises:

- a hydraulic two stage compressor with air cooling;
- a low pressure buffer storage bundle with 6 packs of 12 cylinders (295 bar);
- a medium pressure buffer storage bundle with 6 packs of 12 cylinders (295 bar);
- a single high pressure cylinder (450bar);
- a hydrogen chiller; and

² This exceeds the purity required by the EcoBuses

- a hydrogen dispenser, including a flow meter, control valve, break-away coupling and a filling coupling.

The refuelling station was designed to fill one bus in 12 minutes, a second bus in 14 minutes, and after a 41 minute pause, a third bus within 14 minutes.

8.2 Equipment Reliability

Failures in the hydrogen fuelling station were the cause of several major interruptions to the operation of the buses during the trial. Nearly three months of operation were lost in the nine months between January 2005 and September 2005. The most significant outages and their causes are provided in Table 8-1.

The EcoBuses could have travelled a further 74,000 kilometres during the trial if these outages had not occurred. The impact of later outages was reduced by decanting hydrogen directly from the tube trailers into the buses. This kept the buses operating but their range was reduced since the filling pressure was limited to less than 160 bar.

<i>Refuelling Station not Available</i>	<i>Fault</i>
18 Jan 05 to 21 Jan 05	Dispenser hose failed - original design defect
15 Feb 05 to 18 Feb 05	Dispenser hose failed - original design defect
5 Apr 05 to 29 Apr 05	H ₂ contamination – dust
6 May 05 to 25 May 05	Dispenser hose failed - small diameter
4 Jun 05 to 7 Jun 05	Waiting for 700 bar hose installation
8 Jun 05 to 25 Jun 05	H ₂ contamination - dust and compressor fragments
29 Jul 05 to 12 Aug 05	H ₂ contamination – oil
18 Jul 06 to 31 Aug 06	Significant leaks from multiple sources requiring a major rebuild including the compressor.

Table 8-1 Refuelling Station outages

Several design modifications and repairs were made to the refuelling station such as:

- an upgrade to the dispenser hose to a 700 bar rate hose,
- the installation of anti-whip devices to reduce the stress on the hose at its connection points,
- a venting system to reduce the pressure in the hose from 350 bar to 50 bar between fills,
- several additional filters, and
- several changes to the control system software.

These changes enabled the refuelling station to operate without major incident between September 2005 and July 2006.

8.3 Operating Reliability

The buses were refuelled 1927 times and of these 102 failed to complete the refuelling process because of stoppages in the fuelling station control system.

The operation of the refuelling station is internally monitored by numerous temperature and pressure sensors that provide feedback to the control system. When the signals from these sensors reach certain thresholds the refuelling process is stopped. In most cases these do not represent a safety risk and refuelling was continued after the station was reset.

These nuisance faults could be reduced if it was possible to adjust the threshold limits of certain parameters. This would be done in consultation with the OEM and is only suggested because of the developmental nature of the system. Technically this is possible to achieve but it is difficult practically because the system was delivered as a complete unit from the Austrian OEM. This made consultation with the manufacturer difficult due to the time and language differences. There were also contractual impediments relating to warranty and maintenance.

Figure 8-2 shows the increasing trend in failure rates that was reflected in the data. This data was collected by the drivers when they refuel the buses. It became evident that the drivers don't record every failed refuelling attempt, instead they filled in the refuelling data as one successful refuel instead of a partial fill followed immediately by a successful restart. Maintenance staff collected detailed information relating to the failure rate and failure mode of the refuelling station during April 2007. This data indicated a refuelling failure rate of 54% while the refuelling data derived from routine sheets for the same period indicated a failure rate of only 14%.

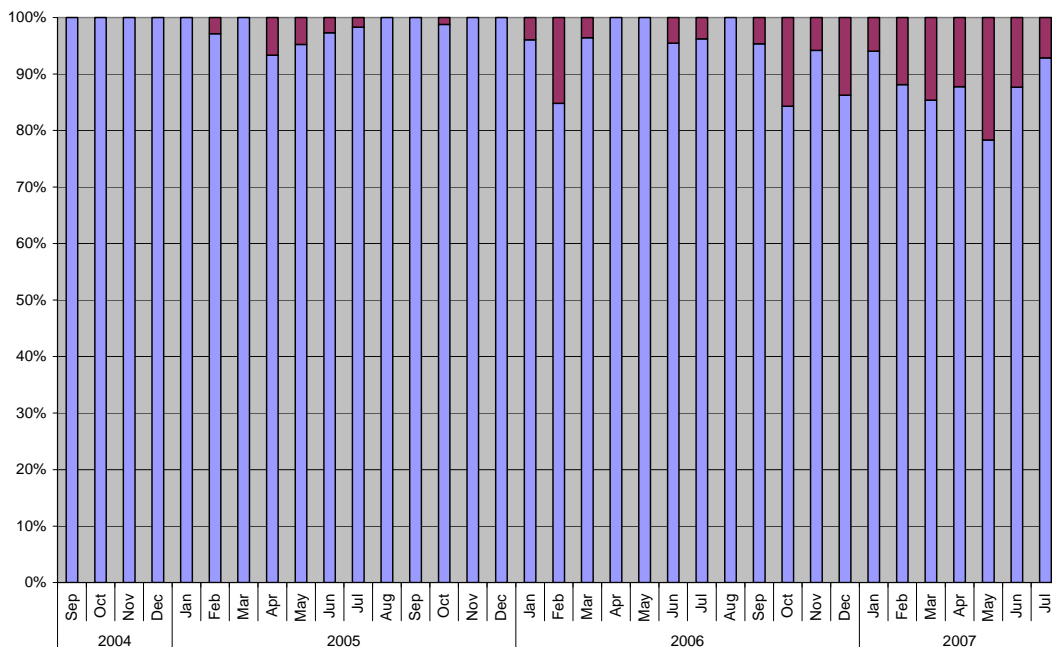


Figure 8-2. Refuelling stoppages from routine data sheets

8.4 Refuelling Times

Figure 8-3 shows a histogram of the final pressure of hydrogen stored on the bus after refuelling. There is a peak at around 160 bar which indicates the times where the bus was refuelled by decanting hydrogen directly from the tube trailer. The second peak centred at 260 bar indicates refuelling failures discussed in the previous section. The final peak centred at 390 bar represents successful refuels.

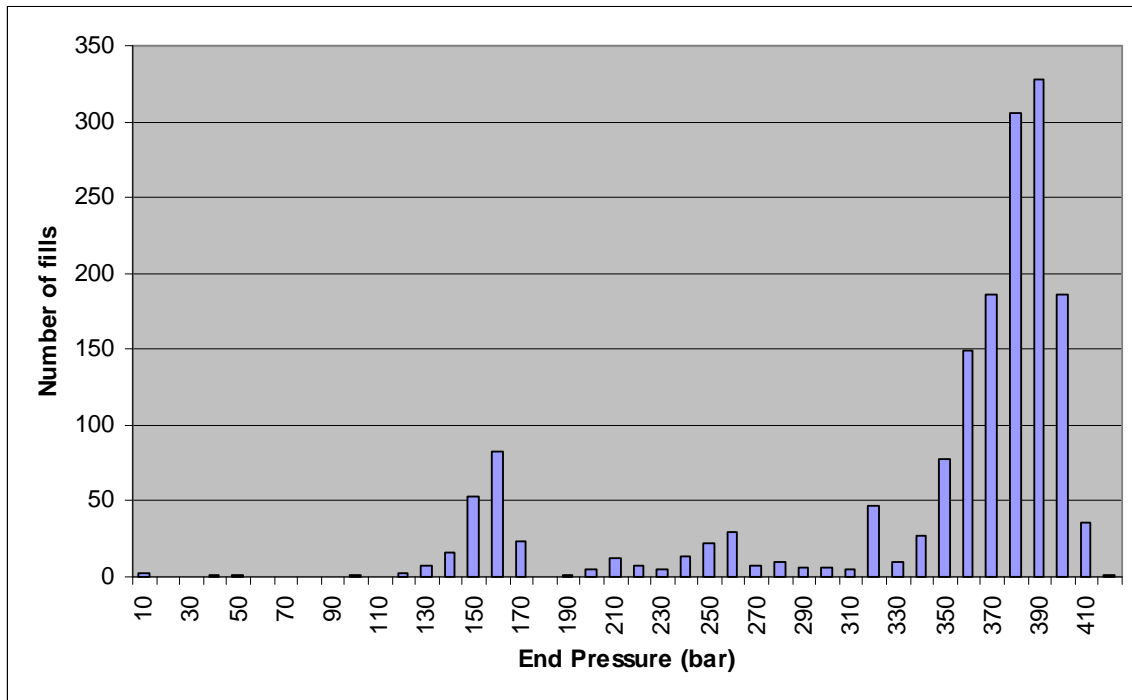


Figure 8-3. Histogram of refuelling pressures

Considering only the successful refills shown in Figure 8-3, the average time taken to load a kilogram of hydrogen into the bus' storage cylinders is 0.56 minutes (SD 0.18). A plot of these refuelling times against the total mass of hydrogen filled is provided in Annex D in Figure D-8.

It is reasonable to assume that the flow rate into the cylinders slows as the pressure in the cylinders approaches maximum. It was not practical to measure this change in flow rate directly but it is possible to gain an indication from the available data. Two subsets of the data were examined to evaluate how this flow rate may change during a refill. The first was based on a full fill where the final pressure was greater than 350 bar and more than 30 kg of hydrogen was loaded, the second was a top up fill where the final pressure was again greater than 350 bar but where less than 10kg was loaded. The top up fill implies that the cylinders were at least 75% full before refuelling began. The average time for the full fill was 0.52 minutes per kilogram (SD 0.13) while the average time for a top up fill was 0.91 minutes per kilogram (SD 0.36).

Compressed hydrogen storage systems are being developed with a maximum storage pressure of 700 bar. These results indicate that the total fill time will increase nonlinearly as the maximum storage pressure is increased.

As discussed in section 8, the refuelling station is designed to refill each bus in less than 14 minutes. Of the 1927 refills, 683 (or 35%) took greater than 14 minutes to complete. It is important to note that refuelling times are recorded manually by the drivers from the refuelling station clock, which introduces a level of uncertainty into all time measurements. So the actual number of times that the refuelling station has exceeded the refill time limit may vary from that stated above but the high percentage of exceedances is a strong indication that further investigation is required.

9 Conclusions

The intention of the trial was to assess the potential of hydrogen as a future source of sustainable transport fuel for Perth. A key part of this assessment was analysing the operational performance of the fuel cell buses.

For this assessment to be meaningful it needs to consider the lifecycle of the vehicle and the fuel in such a way that enables a comparison with other existing and potential solutions. The Perth fuel cell bus trial and the associated studies have provided an extensive data set against which other vehicles can be compared.

Hydrogen has the potential to be part of a sustainable fuel mix in the medium to long term. Demonstrations such as the Perth fuel cell bus trial facilitate the assessment and the development of alternatives. Information collected during the trial has, through the CUTE partnership, assisted bus and fuel cell engine manufacturers to further develop fuel cell technology. The successor to the CUTE project known as HyFLEET:CUTE will see the operation of 47 hydrogen powered buses in regular public transport service in 10 cities on three continents.

All participants agreed that throughout the course of the trial, the EcoBuses had performed beyond expectations and the project has demonstrated that hydrogen is a viable fuel and fuel cell technology is a potential option for future public transport.

It is important to note that the lessons learned by trialling three fuel cell buses do not directly scale up to running a commercial fleet of up to 100 buses. The centralised production of hydrogen and the use of tube trailers to deliver it to the refuelling site would quickly become impractical as the daily use of hydrogen reached 150kg or approximately half of the useable capacity of one trailer. This could happen for a fleet of less than ten buses. A more extensive trial would be required to fully assess the issues of supplying a sustainable source of hydrogen to a larger fleet of buses.

Solving these issues for fleet based transport (such as buses) that can be centrally refuelled and maintained will be a challenge, but these challenges would be multiplied by several orders of magnitude for fuel cell powered private cars. It will be necessary to show that these issues can be resolved for fleet transport before contemplating fuel cell powered private vehicles.

9.1 Data Collection

The majority of data collected for this study was collected manually by either the bus drivers or the maintenance technicians who recorded particular readings and results on hard copy operating sheets. These sheets were collected monthly and entered into a data base for analysis. There are several potential sources of error and uncertainty in this process such as incorrectly reading a meter or indicator, incorrectly recording the reading on the sheet, neglecting to fill in all of the necessary entries on the sheet and finally errors when entering the data into the data base.

Attempts were made to minimise these errors by:

- making the data sheets as simple and objective as possible,

- training the drivers on the importance of the data and how it will be used and then providing feed back, and
- including automated error checking in the database.

Despite all of these measures, human errors still occurred. The only way to completely eliminate them would be to automate the data collection by installing sensor and data collection equipment on the buses and refuelling station.

As previously discussed, there are numerous sensors already fitted to both the buses and the refuelling station however access to the data is very limited or non existent due to the proprietary nature of the data and contractual issues regarding warranty. Warranty issues can also limit or prohibit fitting additional data collection systems to the buses.

To assist the comparison of different types of vehicles similar maintenance and operating data should be collected on the different vehicles under the same or very similar conditions. To achieve this it may also be necessary to allocate the baseline or control buses to the trial for a significant period. This would require significant additional resources to collect and analyse the data.

The scope and nature of data collection needs to be determined early in the trial planning process to ensure that the data collection methodology (either manual or automated or a combination of both) can be decided, designed and tested. Designing a data collection process early provides additional time to gain the necessary resources and negotiate any contractual or warranty issues.

9.2 Availability

Ballard Power Systems have stated that durability of the fuel cells is approaching the US Department of Energy targets^{xvi} of 5,000 hours. Hybridisation of the drive train offers further improvements in durability by reducing the transient power demands placed on the fuel cell.

The average availability of the buses was 86%. Doubling the durability and reliability of the fuel cell system would reduce the total maintenance effort by 10%. Assuming that a production model would all but eliminate the hours spent on upgrade, troubleshooting, testing and other, the maintenance effort could be reduced by a further 18%. Halving the routine maintenance effort through greater knowledge of component life and failure modes would reduce maintenance by a further 14%. These improvements combined would reduce the total maintenance effort by 43% and improve the average availability from 86% to 92%.

The reductions indicated are reasonably arbitrary but they illustrate that there is significant potential to reduce the maintenance effort and improve the availability of fuel cell buses without significant improvements in technology.

9.3 Potential Drive Train Improvements

DaimlerChrysler are considering several improvements for their next generation of hydrogen fuel cell buses being developed for the HyFLEET:CUTE project. Under consideration are higher pressure hydrogen storage (increased from 350 bar to 700

bar), wheel hub motors, electrically powered auxiliary systems, fewer fuel cells with greater power density and a hybridised drive train. HyFLEET:CUTE will also trial two types of hydrogen internal combustion engine buses to be built by MAN. These improvements offer efficiency gains in the order of 50% over the fuel cell buses used in Perth's fuel cell bus trial.

9.3.1 Hybridisation

Hybridisation offers efficiency gains by enabling regenerative braking and by removing the need for a dump resistor. The dump resistor is required to ensure that a minimum of 20A is being drawn from the fuel cell stack. This maintains the operation of the fuel cell so that there is no delay when the driver accelerates from idle. In a hybrid system the initial energy required to move the bus would be provided by the batteries until the fuel cell reached full operation.

9.3.2 Full electric drive train

Replacing the central traction motor with smaller motors that directly drive the wheels may improve efficiency by eliminating the mechanical losses and weight of the existing transmission and differential.

9.3.3 Auxiliary systems

The existing method of driving auxiliary systems either from the auxiliary gear case or belts from the traction motor requires converting electrical energy to mechanical and in the case of the alternators, back to electrical again. This could be improved by using a number of smaller electric motors and dc/dc power conditioners that are driven directly from the fuel cell.

10 Bibliography

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- ^x Ilg, Robert. “Life Cycle Assessment (LCA) of the STEP hydrogen infrastructure in Western Australia.” Masters diss., Murdoch University, 2006.
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Annex A - Operational Data Collection Sheet



MURDOCH
UNIVERSITY
PERTH, WESTERN AUSTRALIA

Bus Operation Routine Data Collection for the STEP Fuel Cell Bus Trial

Motivation for collecting this information:

The aim of the Perth fuel cell bus trial is to assess the suitability of the buses, and fuel cell technology in general, for transport in Perth. This effectiveness of this assessment depends on accurate and complete information collected during routine operation. The information collected will then be analysed to identify any deficiencies in the operation of the buses and to develop recommendations for the future use of hydrogen and fuel cell transport in WA.

How the data will be used:

The data will be used to measure fuel consumption, the conditions that might effect fuel consumption and to collect routine data required by Ballard. Fuel consumption information is important to quantify the environmental effects related to hydrogen production and to calculate the reduction in exhaust emissions (e.g. CO₂) that is achieved by using fuel cell buses. The effects on fuel consumption of climate, traffic congestion, hill gradients and passenger loads will be examined.

The data will also be used in simulation tools that will be used to predict the performance of the buses under a range of conditions. This will enable fuel consumption and emissions to be estimated in situations where the buses have not actually be driven. The information collected here may also be helpful in explaining any inconsistencies in the maintenance cost for each of the buses.

Notes:

- Data collection is necessary for all buses involved in the STEP trial including fuel cell (FC), diesel and natural gas (CNG) buses on the same route. Data for the diesel and CNG buses will be collected separately.
- Please fill out one sheet per bus per shift. The completed sheets will be collected by the data collection coordinator Brendan Davis.

Information

- **Routes Driven**
Please enter the number of each route travelled in that day
- **Bus Operating Status**
Normal Operations is routine service on established bus routes.
Special Operation is non routine service such as the H2 conference, publicity events, etc.
Maintenance is when the bus is out of service due to maintenance.
No Operation is when the bus is out of service due to a shortage of H2 or a fault in the fuelling station.

Key On

- Hydrogen temperature is asked for in the "Key On", "Fuelling" and "Shut Down" sections. This reading is required to calculate the fuel used by the bus each day.
- Fuel pressure is to be taken from the dashboard fuel meter.

Fuelling

- It is anticipated that the bus will only be refuelled once per day but space is provided in case it is necessary to refuel the bus twice.
- If the bus could not be fuelled because of a problem with the fuelling station, such as a fault or a lack of hydrogen, then please tick the *Fuelling Unsuccessful* box. If the fault was with the bus then please indicate this in the "Key On" section.

Driving

- **Passenger Load**
Please estimate the average passenger load throughout the day where 1 indicates empty for most of the day and 5 indicates full for most of the day. Please use the "Comments" field for further explanation/ observations, if needed.
- **Traffic conditions**
Please give an estimation of the traffic situation during the day where 1 indicates very light throughout most of the day and five indicates very heavy throughout most of the day.
It is understood that traffic conditions will be different at different times during the day. This is just an estimate that may be helpful in explaining anomalies in other readings such as fuel usage or travel time. Please use the "Comments" field for further explanation/ observations, if needed, such as light traffic due to public holiday, heavy traffic due to road works, etc.

Enquiries regarding this form should be directed to Brendan Davis at:

B.Davis@path.com.au
Tel: 9248 9866

Bus Operation v7

15 Nov 04



MURDOCH UNIVERSITY
PERTH, WESTERN AUSTRALIA

Bus Operation Routine Data Collection for the STEP Fuel Cell Bus Trial

Information	Bus #	<input type="text"/>
Driver's Name	<input type="text"/>	Staff # <input type="text"/>
Date	<input type="text"/> / <input type="text"/> / <input type="text"/>	
Bus Operating Status	<input type="checkbox"/> Normal <input type="checkbox"/> Special <input type="checkbox"/> Maintenance <input type="checkbox"/> No Operation	
Routes Driven	<input type="text"/>	

Engine Off

Check for fluid leaks or puddles inspect parking area

Inspect air intake, FLT:A02, for Blockages

Inspect air exhaust, SIL:A02, for Blockages

Check lubrication oil level, MTR:M01, Record quantity added

Rear Clock [h]

Check DI glycol level, TNK:D01, Record quantity added

Check Pressure Relief Device, PRD:H01..PRD:H09, ensure foam is present

Confirm all access doors are secured or bus will not start

Ignition On

Check driver display and record all faults

Clear all faults in the fault register

Odometer [km]

H2 Pressure [bar]

H2 Temperature [°C]

Start Engine Start Time [24 hr] Cabin Air Conditioning On / Off

Fuelling	Before Fuelling	After Fuelling
1st Fuelling	Odometer [km]	<input type="text"/>
	Start Time [24 hr]	<input type="text"/>
	H2 Pressure [bar]	<input type="text"/>
	H2 Temperature [°C]	<input type="text"/>
	<input type="checkbox"/> Fuelling Unsuccessful	

2nd Fuelling	Odometer [km]	<input type="text"/>
	Start Time [24 hr]	<input type="text"/>
	H2 Pressure [bar]	<input type="text"/>
	H2 Temperature [°C]	<input type="text"/>
	<input type="checkbox"/> Fuelling Unsuccessful	

Driving

Average passenger load	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Average traffic conditions	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

Comments _____

Shutdown

End of clock sheet:	If parking overnight:
Time [24 hr] <input type="text"/>	<input type="checkbox"/> Connect Freeze Protection
Odometer [km] <input type="text"/>	<input type="checkbox"/> Connect Battery Charger
H2 Pressure [bar] <input type="text"/>	<input type="checkbox"/> Mirror folded in
H2 Temperature [°C] <input type="text"/>	<input type="checkbox"/> Battery Switch off
Rear Clock [h] <input type="text"/>	

Enquiries regarding this form should be directed to Brendan Davis at:

B.Davis@path.com.au
Tel: 9248 9866

Annex B – Maintenance Data Collection Sheet



Datasheet for fuel cell bus maintenance

Intention:

The availability and reliability of the fuel cell buses compared to existing buses is a very important aspect of the trial. Therefore it is necessary to collect detailed maintenance information covering all relevant aspects (description of maintenance work, downtime, etc.) to ensure that an accurate comparison is made.

Usage of the information:

The information will be used to compare the amount and type of maintenance required by each bus type and the failure rates and repair times for each bus type.

The cost of maintenance per km travelled will then be derived for each bus type.

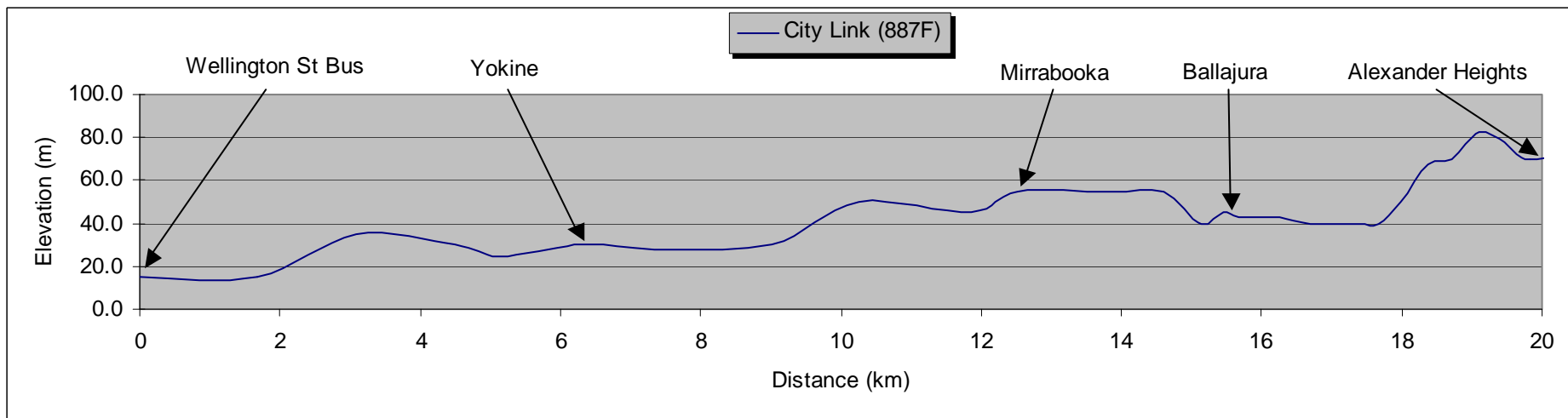
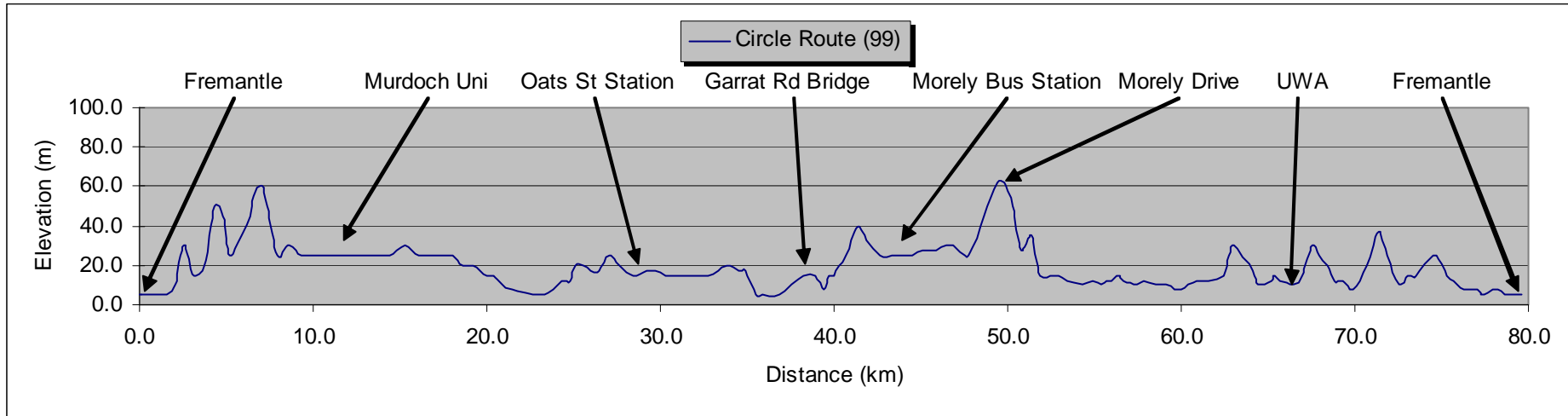
Notes:

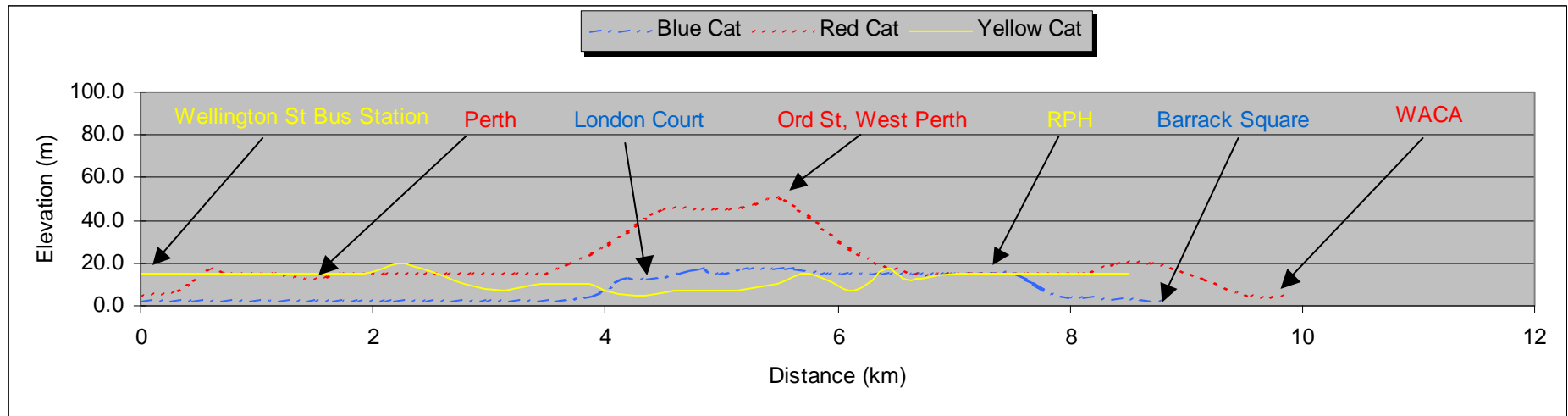
- Use as many lines as necessary to record the required information and rule off under the completion of each entry.
- **Maintenance Codes**
 - 1 - Maintenance - Includes routine maintenance and servicing
 - 2 - Upgrade - Refers to any retrofit or upgrades
 - 3 - Repair - Refers of fault correction.
 - 4 - Testing - Refers to the work necessary to identify if a fault condition exists such as hydrogen leak tests.
 - 5 - Trouble Shooting - Refers to work required to identify the nature of the fault
 - 6 - Other (Comments Required) - The code should be used when the work conducted does not fit into one of the above descriptions. A description of the work should be provided in the comments column.
- **Comments:**

Please use this field for any descriptive comments on maintenance and repair activities (optional) and to document if the bus was not operational and no work was done on the bus (e.g. no spare parts available)

Please use an extra sheet if you need more space for your own comments

Annex C – Route Elevation Profiles





Annex D - Supporting Data

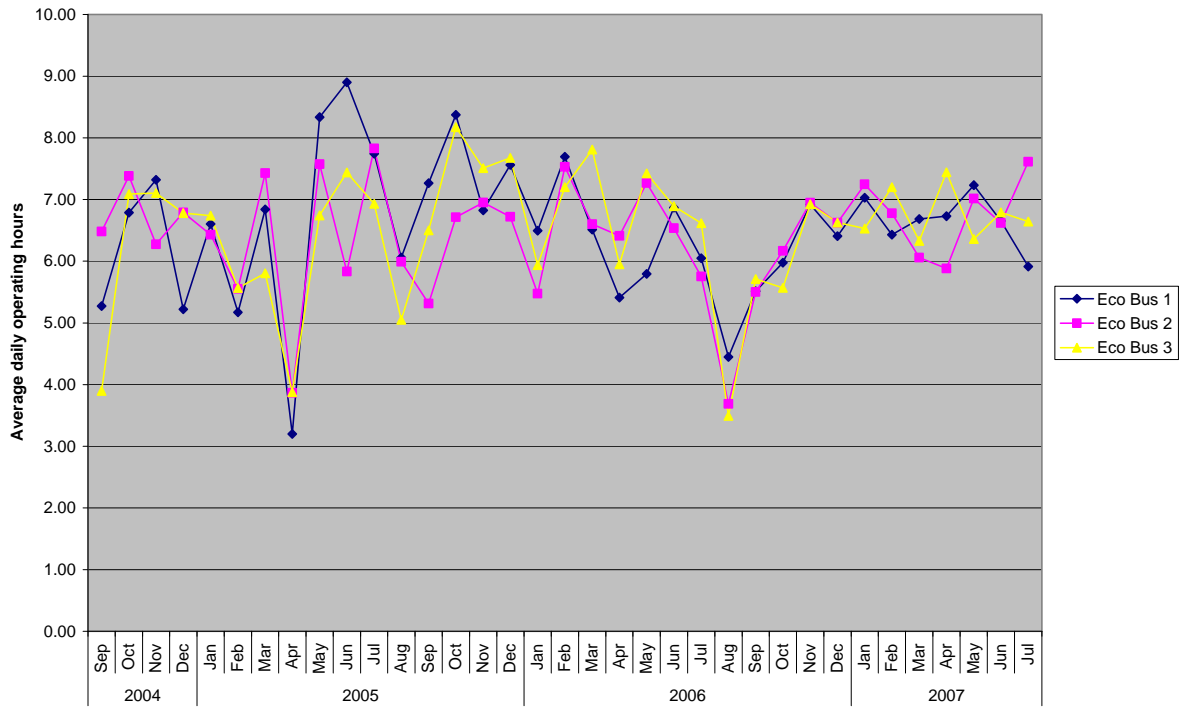


Figure D-1. Average operating hours per day

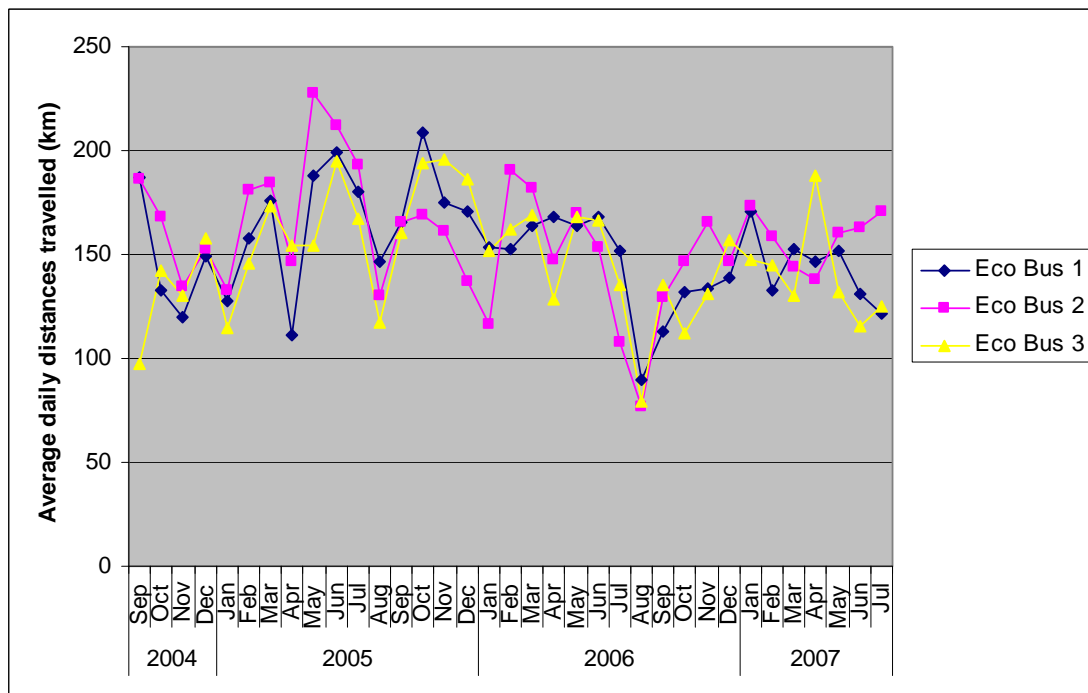


Figure D-2. Average km travelled per operating day

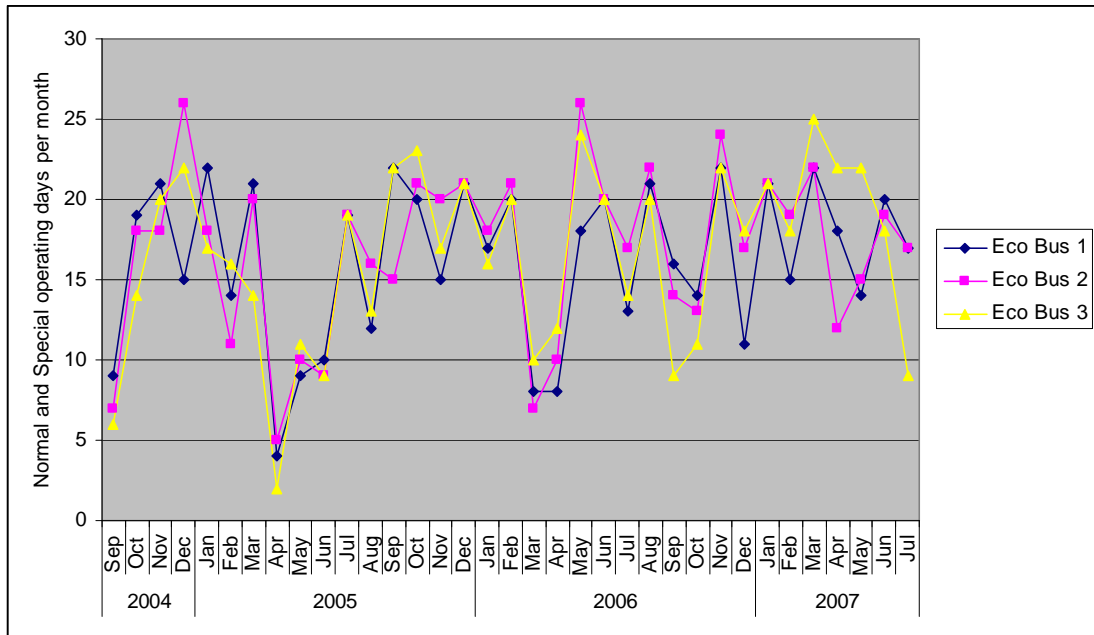


Figure D-3. Operating days per month

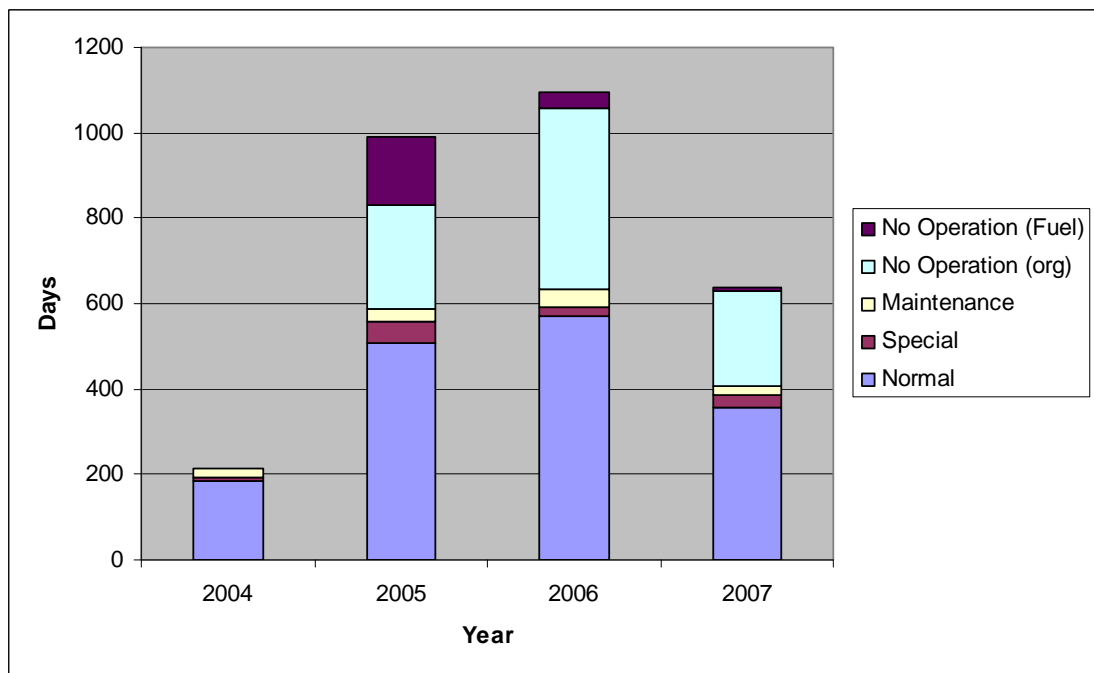


Figure D-4. Types of bus operation per year

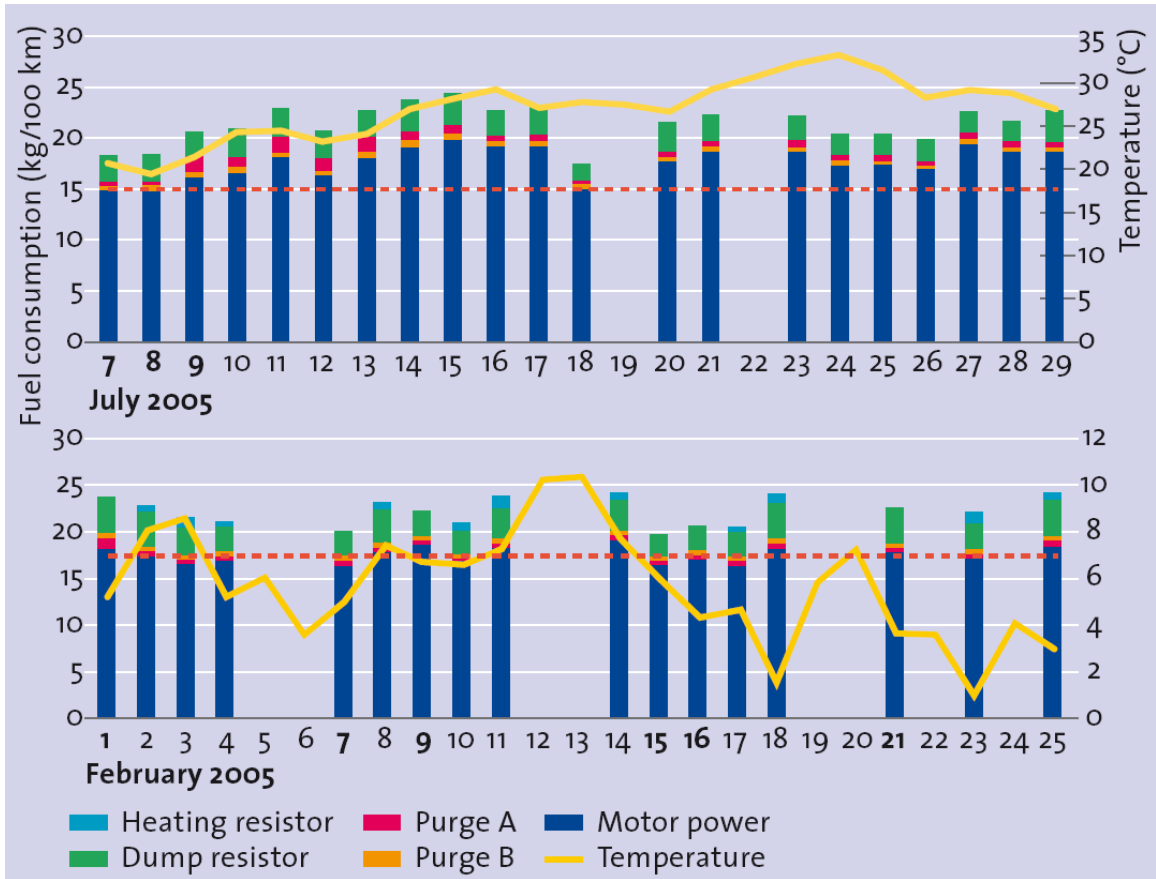


Figure D-5. European seasonal fuel economy

Power consumption charts for Madrid summer (above) and winter (below). The red line represents a base consumption calculated from the dates marked.

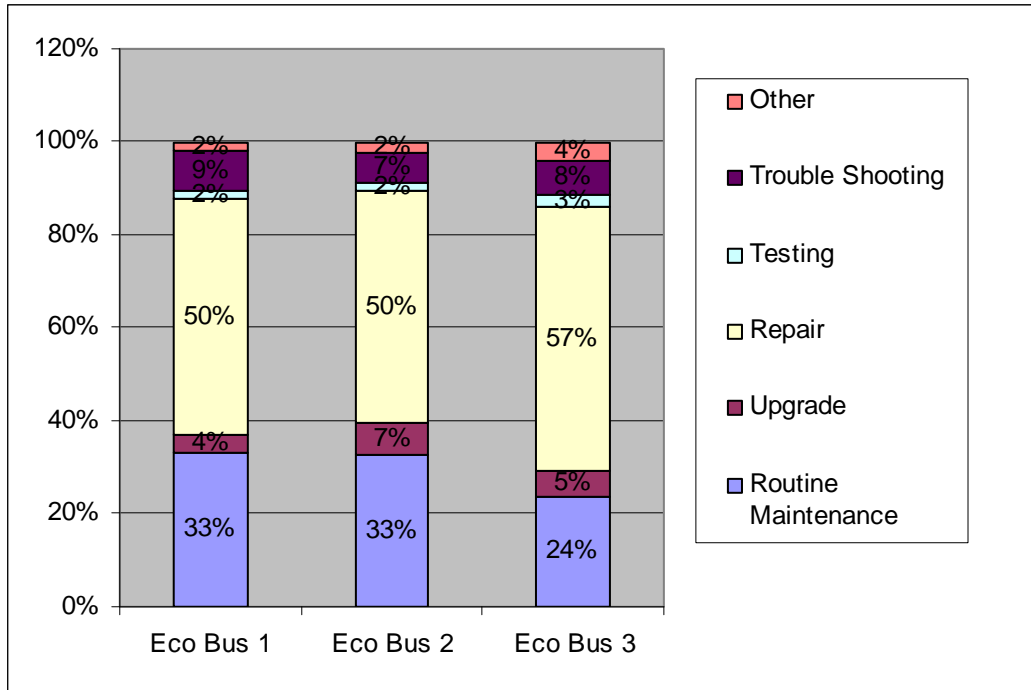


Figure D-6. Breakdown of maintenance hours per bus

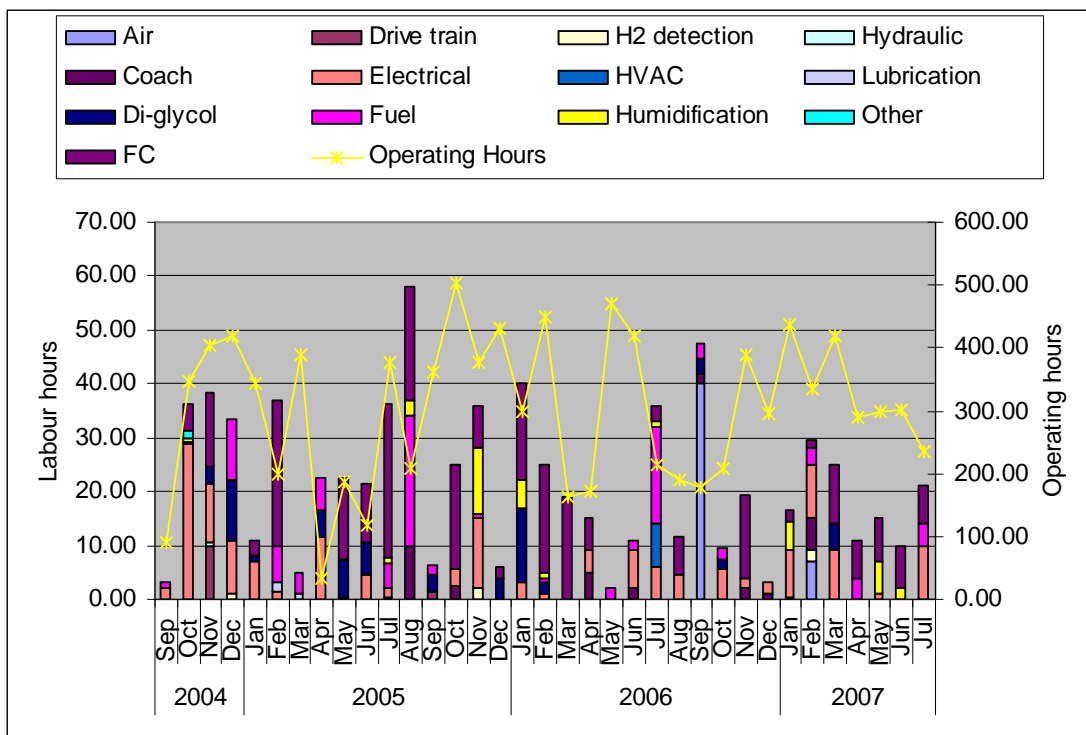


Figure D-7. Repair hours and operating hours

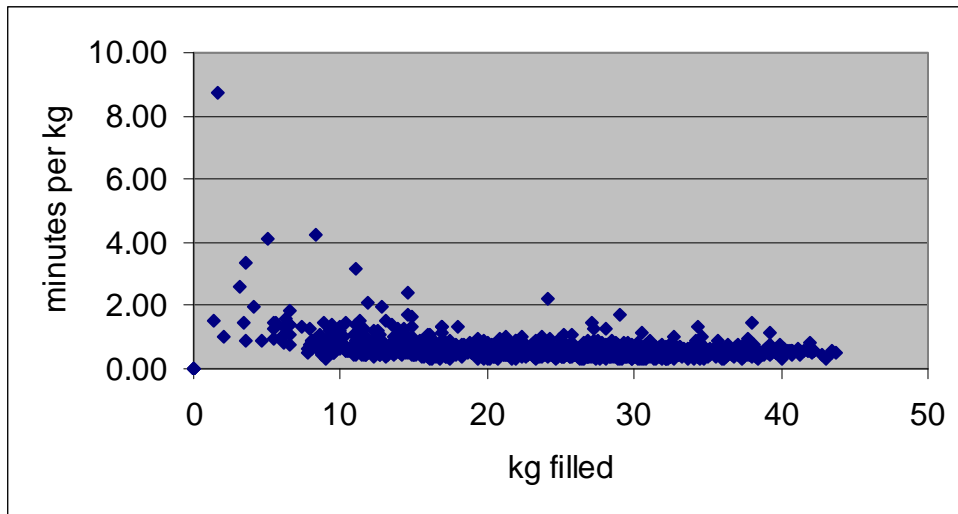


Figure D-8. Refuelling times per kg