Institute of Road Transport Engineers of New Zealand
Third International Heavy Vehicle Seminar
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EXPERIENCE WITH NATURAL GAS FUELLING OF HEAVY TRANSPORT ENGINES

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ABSTRACT

The use of CNG as a fuel for heavy transport engines is still in the development stage. However, experience with dedicated S.I. conversions has shown promising results in certain applications. While most of the recent work done in New Zealand on CNG use has been centred around non-turbocharged, high speed, S.I. conversions, there is still likely to be a role for dual fuel engines in some applications.

This paper presents a review of New Zealand experiences with the use of compressed natural gas (CNG) as a fuel in heavy transport diesel engines. Both dual fuel and 100% CNG fuelling, (dedicated spark ignition conversions), are discussed. The advantages and disadvantages of each are reviewed in terms of vehicle performance, fuel costs and operational experiences. Brief reviews of experimental results and discussions of technical aspects of conversions, experience in fleet use, economic and operational aspects and computer modelling of fleet performance are also included.

INTRODUCTION

Since the time of the 'oil shocks' in the 1970s and the steep rise in transport fuel prices which occurred at that time, New Zealand has spent much time and effort developing natural gas as an alternative transport fuel. In the early stages of this work, petrol was displaced in cars and light vans in a relatively straightforward conversion operation. Since these vehicles had spark ignition engines, only changes to the fuel supply system were required.

With the subsequent relative decline in the cost of transport fuels, the economics of the conversion option has changed. Although the capital cost of converting a car or van has reduced during the last few years, it has not reduced by as much as the relative price differential between CNG and petrol. There are benefits other than simple economics in converting - such as cleaner burning and reduced exhaust emissions - but in many cases, the private motorist is less aware or concerned about these.

However, at the same time that interest in conversion of small vehicles has waned, large fuel users in the transport industry and bus operators have become aware of the potential benefits of using CNG. There are particularly some cases overseas where the emissions benefits are all important. The use of natural gas as a vehicle fuel is increasingly being described by the collective term Natural Gas Vehicles (NGV).

In general, these users have traditionally used diesel-powered vehicles, but options are available for fuelling these engines with natural gas. These options are discussed in this article.

The potential benefits of the use of CNG in this transport application include:

- o Economics
- o Clean burning
- o Reduced noise
- o Reduced exhaust emissions.

Because of the fact that very few large automotive spark ignition engines are available from the engine manufacturers, the options for using natural gas in this application has required modifications to original diesel engines.

OPTIONS

Two basic options are available for the use of natural gas in diesel engines. These are described below.

Dual Fuel Operation

In this mode the quantity of diesel fuel supplied in each cycle may be reduced, and gas mixed with the intake air makes up the total fuel energy required by the engine [1].

Spark Ignition Operation

In this mode all diesel injection equipment is removed from the engine, the combustion chamber modified, and a spark ignition system and gas carburettor are fitted to the engine.

Each option has benefits and disadvantages compared with the other and compared with the original diesel engine. Some of these are noted in Table 1. New Zealand has experience of both types of engine option as test bed and on-road operation. The following sections will deal with some of the results from these operations.

Dual Fuel Conversions

Dual fuel engines have been in use as stationary power producers for over 40 years. These engines would normally operate at a steady speed and load condition and can therefore be optimised for the minimum diesel fuel consumption and maximum gas consumption. They are often used where gas is cheaply or freely available, such as in sewage treatment plants and at gas transmission pumping stations.

The application of dual fuel operation to transport engines is a far more complex problem because of the wide speed and load range over which such engines are required to operate. For this reason, the key to successful dual fuel engine use in transport applications lies in the choice of a suitable control system to adjust diesel and gas flowrates. Successful systems have been in use for some time. Development is continuing in this area, particularly in the application of electronic controls.

To give some idea of the requirements for such a control system, Figure 1 shows typical engine efficiency characteristics of a dual fuel engine over a range of operating conditions. In this figure, efficiency is plotted against diesel fractions for a range of engine loads. Diesel fraction is defined as the diesel fuel use in dual fuel operation, divided by the diesel fuel use in normal diesel operation to achieve the same engine load and speed. Thus, for example, a diesel fraction of 30 percent represents operation in which the dual fuel engine is using 30 percent of the diesel fuel that would be used to produce the same load and speed in normal diesel operation. Note, however, that in a case where the engine efficiency is lower in dual fuel operation than in normal diesel operation (diesel fraction = 100 percent), the energy content of the gas used will be greater than that of the diesel displaced. Under these conditions, the cost of gas and diesel fuel will determine an economic substitution level. As an example, Figure 2 indicates regions in which the dual fuel engine would have cheaper fuel costs than the diesel for assumed gas/diesel price ratios of 80/100 and 67/100. Of course, in a full economic analysis many other factors must be taken into account as well as the fuel costs, and these are addressed in a later section.

Some dual fuel programmes which have been undertaken in New Zealand are summarised in Table 2. These programmes indicate the variety of engine types and end use operations which have been investigated. More data are available on these projects in reference 1.

Spark Ignition Conversions

In the heavy transport application, diesel engines displaced petrol-fuelled spark ignition engines because of the higher overall efficiency of the diesel engine, the long engine life and the lower cost of the fuel. For this reason, very few large automotive spark ignition engines are available worldwide. It has therefore been necessary to modify diesel engines in order to produce spark ignition engines which can use 100 percent gas.

A number of New Zealand projects have developed methods of conversion and undertaken research on the converted engines and vehicles. Table 3 lists some of these projects.

In general, the performance of diesel engines converted to SI and fuelled with natural gas has similar operation characteristics to conventional SI engines.

In the conversion process, it is necessary to lower the compression ratio from the high values found in diesel engines (of order 18 to 20:1), but a high compression ratio can still be maintained with natural gas because of its high octane rating. Compression ratios in the range 11 to 15:1 have been used in SI conversions. Many researchers have demonstrated that in most engines peak efficiency occurs at a compression ratio in the range of 14:1 to 15:1 so there is not necessarily a loss in engine efficiency incurred when lowering the compression ratio for CNG use.

There is a complex optimisation process which must be carried out for a new engine type in order to achieve:

- Torque characteristics compatible with the original diesel engine.
- Good fuel economy.
- Adequate margin from knock.
- Engine integrity in the context of altered combustion pressures and temperatures.

Figure 3 shows typical data for the efficiency of a 6.4 litre direct injection diesel engine and the corresponding SI converted engine. This illustrates some general characteristics, namely that:

- At high load and/or high speed, the SI engine can be as efficient as the diesel engine.
- At low load the SI engine (throttled) has lower efficiency than the diesel.
- The torque output of the SI engine can exceed that of the diesel (in this case at low engine speeds).

As is the case with the dual fuel engine, a difference betwen the cost of gas and diesel fuel will allow the engine to be run at less efficient conditions, while still achieving a fuel cost saving when using natural gas. Lines showing the break-even operation based on gas/diesel cost of 80/100 and 67/100 are shown in Figure 4.

THE NGV IN FLEET USE

The factors that must be studied when considering the introduction of NGVs into a fleet operation are now taken up. The detailed data required for such studies are only now becoming available. New Zealand has some advantages over other countries in that reliable long term data are being obtained from the operations of the New Plymouth City Council fleet and, increasingly, from the Auckland Regional Authority.

When considering the use of NGVs it is important to recognise that changes -albeit generally minor ones - must be accepted when converting from the use of diesel fuel. Changes will be needed in refuelling procedures, maintenance schedules, spares holdings and in driver and maintenance staff procedures. Some training will be required to meet these changes. In particular, the selection of refuelling equipment and sites is crucial to successful conversion to the new fuel.

When discussing the viability of the commercial use of an NGV, a number of economic and operational factors stand out. These are considered below. Care must be taken to consider any operational disadvantages in the light of the potential fuel savings, which should generally be better than 30 or 40 percent.

Economics

Since economic advantages form a large part of the incentive for considering natural gas in heavy transport engines, the factors which must be considered are outlined here.

The primary influence on the economics of conversion, will, of course, be the cost differential between the two fuels. In many applications natural gas will be compressed by the user, in which case the capital cost or rental cost of the compressor and associated equipment must be taken into account. In addition, road user charges and other taxes, which may differ between the two fuels, must be accounted for.

Closely associated with the cost of fuels in the economic analysis is the amount of each fuel used (in the dual fuel option) and the energy efficiency of the converted engine compared with the original diesel engine. As discussed above, it is not normally the case in the dual fuel engine that diesel fraction is held constant over the whole engine speed and load map. Typically, a high (up to 100 percent) diesel fraction is used at light load and a low diesel (down to 10 percent) fraction at high load. The average diesel fraction obtained in use will therefore depend on the operational characteristic of the vehicle. Thus, for the dual fuel vehicle, a larger proportion of operation at high load would typically result in a higher ratio of gas to diesel fuel use.

In the case of both SI and dual fuel engines the efficiency with which the fuels are used compared with the original diesel will affect the economics. Examples of pay back times based on specified relative fuel costs are shown in Tables 4 and 5 based on reference 3.

The capital cost of engine and vehicle conversion used in Tables 4 and 5 differs, depending on which option is selected - dual fuel or SI. The dual fuel option will be cheaper, requiring on-vehicle CNG cylinders, gas supply to the engine and a gas and diesel control system to be fitted external to the engine. In the case of the SI option, more CNG cylinders will be required for the same range as the dual fuel option. In addition, internal engine modifications are required to reduce compression ratio, and the installation of a complete ignition system in place of the original injection system is required.

Careful evaluation of the range requirement of the vehicle must be carried out to avoid excessive cost and weight associated with fitting too many CNG cylinders.

The cost of conversion may also need to include costs associated with the vehicle being off the road for a period during conversion.

Other minor items which may need to be considered include costs relating to

- Periodic inspection certificates for installation or for cylinders.
- Extra maintenance.

- o Insurance charges on CNG equipment.
- o Road tax due to increased weight of cylinders.
- o Loss of on-board storage space.
- o Extra refuelling time.

Maintenance and Operations

Information on SI conversions show that, with careful planning, there should not be any significant increase in maintenance requirements or costs or decrease in engine life. The requirements are different from those of the diesel engine, hence the need for an adequate training programme.

Planning must take into account the short spark plug life - short, that is, compared to the life of diesel injection equipment. Provided the task of a spark plug change can be combined with other regular servicing, at intervals of about 20 000 km, few problems should arise from the ignition system. In the longer term it can be hoped that improvements in spark plug selection and design will extend this period.

Long term operations indicate that the clean burning properties of the gaseous fuel may lead to minor savings as compared with the diesel configuration. Further experience, however, is required before such claims can be confirmed.

As far as the dual fuel conversion is concerned, the development of reliable long life electronic control equipment should result in engine life and maintenance costs that differ little from the standard diesel engine.

PERFORMANCE MODELLING

As a part of the work with fuels conversions, a computer program has been developed to model the performance of heavy transport vehicles. The program was developed as an aid in determining the performance and suitability of different engine configurations to different environments and also to help estimate economic factors in fuel conversions. When diesel engines are modified for natural gas use, especially with spark ignition conversions, there are a number of engine parameters which may be altered. These parameters include compression ratio, ignition timing, air-fuel ratios and boost pressure for turbocharged engines. All these factors can have a significant effect on the peak power output, torque curve, fuel efficiency and longevity of an engine, [4].

The program models the performance of a given vehicle over real routes. Several routes in the Auckland area have been defined with data from Ministry of Works survey maps and by actual surveying of specific areas. The routes are broken up into a series of small segments, each of which is characterized by grade, road surface and speed limit.

The vehicle is described by its total mass, frontal area for aerodynamic drag, drag coefficient and a detailed description of its power train. Rolling friction is determined by vehicle weight, speed, tire type and road surface condition. The engine is described by its torque curve. The program contains curve fitting routines so that engine data can be entered as series of dynamometer readings. The dynamometer data can be taken either from a chassis dynamometer or from an engine dynamometer. The instantaneous fuel consumption is calculated by an interpolation routine which uses fuel map data.

Testing of the program with various trucks and buses has shown that performance predictions over short routes are accurate to within approximately one percent. Testing of fuel consumption predictions using buses over longer routes (100 km) has shown good agreement with measured results although final verification has not yet been completed.

Output from the program includes instantaneous vehicle and engine speeds, transmission gear, acceleration, fuel consumption and also the total trip time, fuel consumption, average speed, and number of gear changes. This data has several applications. For example it can be used to model fuel use over given routes for vehicles with different engine and fuels configurations to determine the suitability of a particular vehicle to fuels modifications. Other applications include use by fleet operators to match vehicles to specific routes or when purchasing vehicles to determine an optimal engine transmission matches for specific applications. For CNG fuelled vehicles the program can be used to match the range of the vehicle to its application and thus avoid the weight and expense of excess fuel storage cylinders. The program can also be used in determining optimal tuning of modified engines for specific applications. While the engine is on the dynamometer, there is a large degree of latitude in how it is tuned. With this program, several different states of tune may be compared to select one for the final application.

CONCLUSION

While heavy transport vehicles are not suited to natural gas fuelling in all applications, there are some applications where there are significant benefits. The largest potential benefit is a 30 to 40 percent reduction in fuel costs. Other benefits, which include a reduction in engine noise of approximately 5 dB, reduction or elimination of particulate emissions and reduced overall emissions, are important from an environmental aspect particularly in crowded cities. Experience has shown that with a well implemented conversion there should be no reduction in engine life or increase in maintenance costs. Operational drawbacks of SI conversions are the space required for fuel cylinders and reduced vehicle range. Dual fuel conversions require an additional fuel control system but do not suffer the limit on range. Both systems require that a source of compressed gas be available which may represent an additional cost to the conversion. For fleets, such as city or suburban buses, where the vehicles travel only limited distances and return to the depot on a regular basis, the limit on range and the space required for storage cylinders has a minimal effect.

Most SI conversions of heavy transport vehicles are done on diesel engines. By now, the technology for these conversions has been worked out to the point where they are straightforward and result in reliable operation. There is also current work being done at Auckland University on sophisticated electronic engine management systems for SI applications and on the design of combustion chamber shapes for use in SI converted engines, which should further improve drivability and performance.

Overall, there is existing technology for the conversion of diesel engines in heavy transport vehicles to natural gas fuelling. In the right circumstances, natural gas fuelling can offer significant economic as well as environmental advantages without maintenence or service life penalties. The technology for conversions is steadily improving and there is increasing experience in fleet use which demonstrates the potential advantages.

REFERENCES

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FIGURE 1:
TYPICAL THERMAL EFFICIENCY OF A DUAL FUEL ENGINE AS A FUNCTION OF DIESEL FRACTION AT CONSTANT ENGINE SPEED AND VARIOUS LOADS.

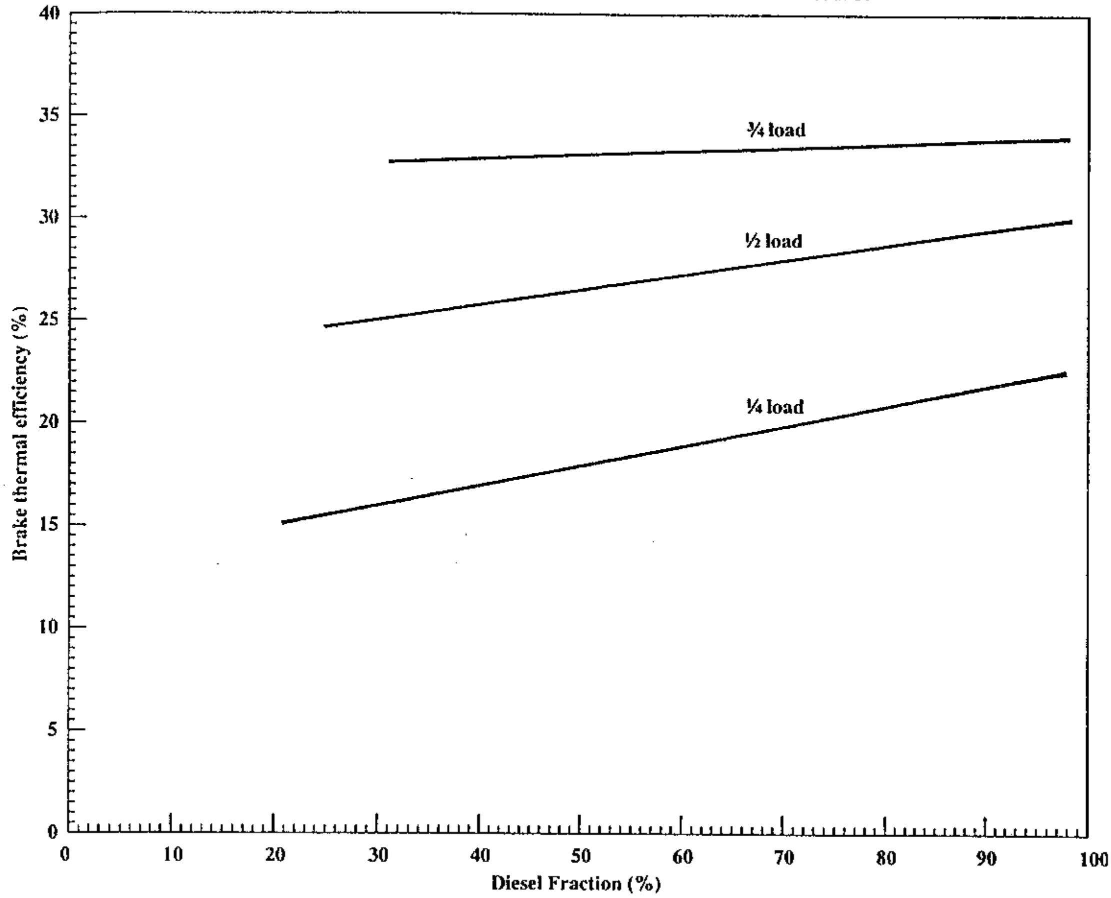

FIGURE 2:
ECONOMIC REGIONS OF DUAL FUEL OPERATION BASED ON ENGINE EFFICIENCY DATA FROM FIGURE 1 AND GAS/DIESEL COST RATIOS INDICATED. REGIONS ABOVE THE BREAK-EVEN LINES INDICATE DUAL FUEL COST LESS THAN DIESEL FUEL COST.

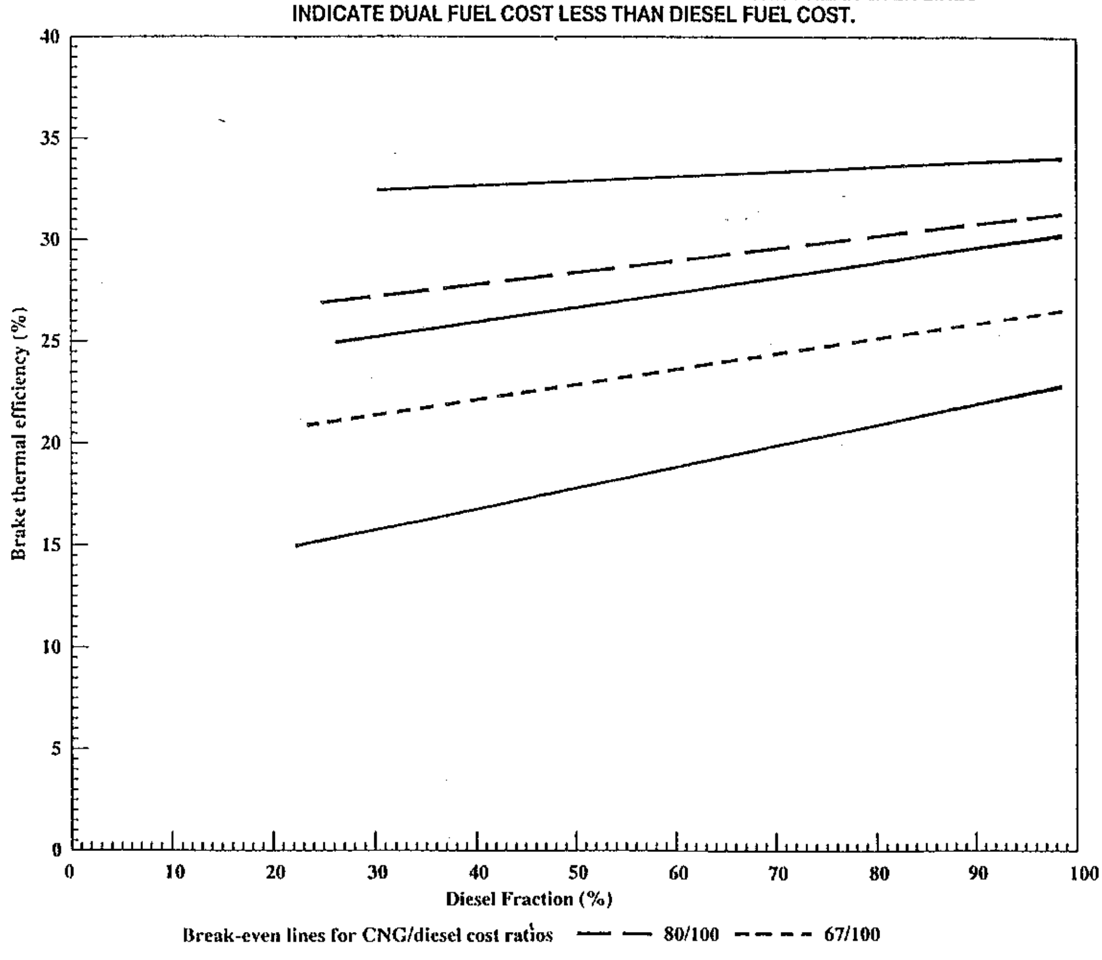

FIGURE 3A:
MEASURED BRAKE THERMAL EFFICIENCY – CONTOURS OF CONSTANT EFFICIENCY INDICATED.
ORIGINAL DIESEL ENGINE, COMPRESSION RATIO 18:1.

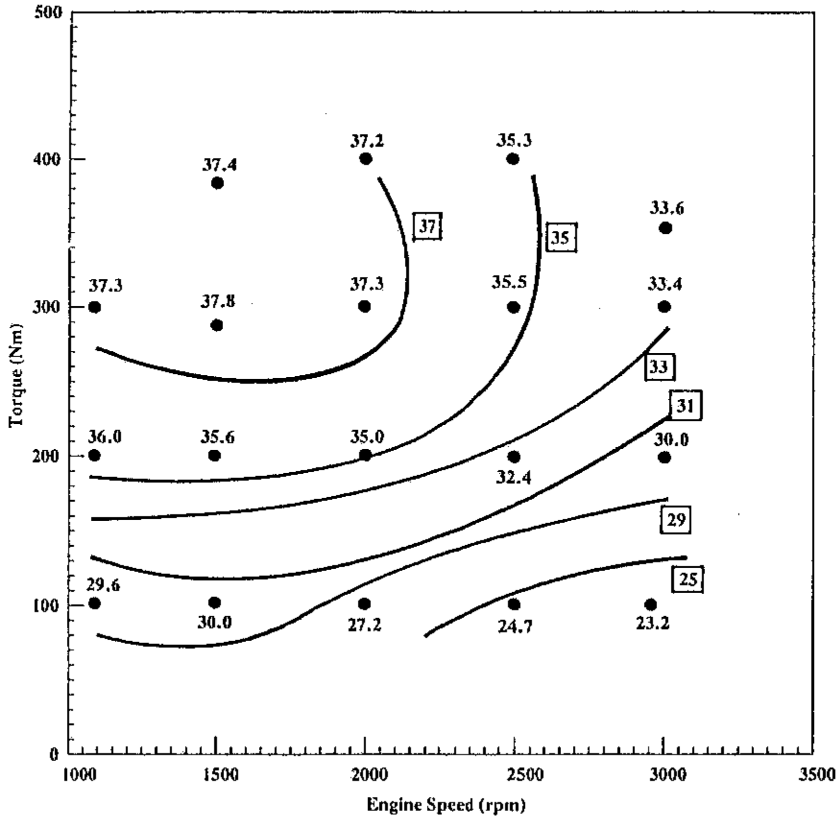

FIGURE 3B:
MEASURED BRAKE THERMAL EFFICIENCY – CONTOURS OF CONSTANT EFFICIENCY INDICATED.
CNG FUELLED SPARK IGNITION ENGINE, COMPRESSION RATIO 15:1.

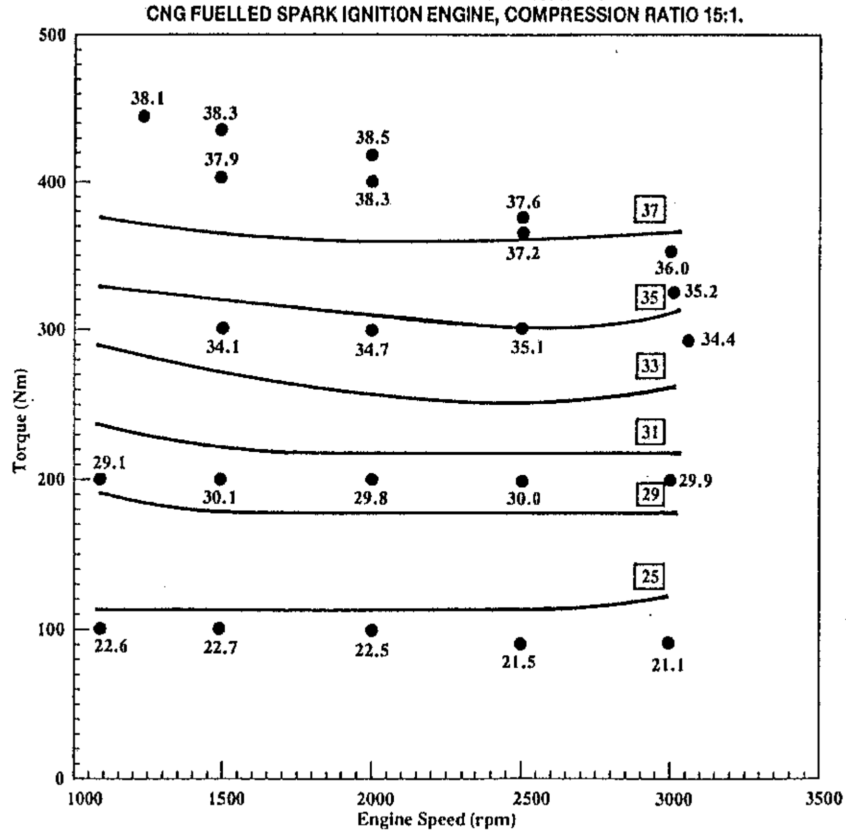

FIGURE 4:
ECONOMIC REGIONS OF SI NATURAL GAS OPERATION BASED ON ENGINE EFFICIENCY FROM FIGURE 3 AND GAS/DIESEL COST RATIOS INDICATED. REGIONS TO THE RIGHT OF THE BREAK-EVEN LINES INDICATE SI FUEL COST LESS THAN DIESEL FUEL COST.

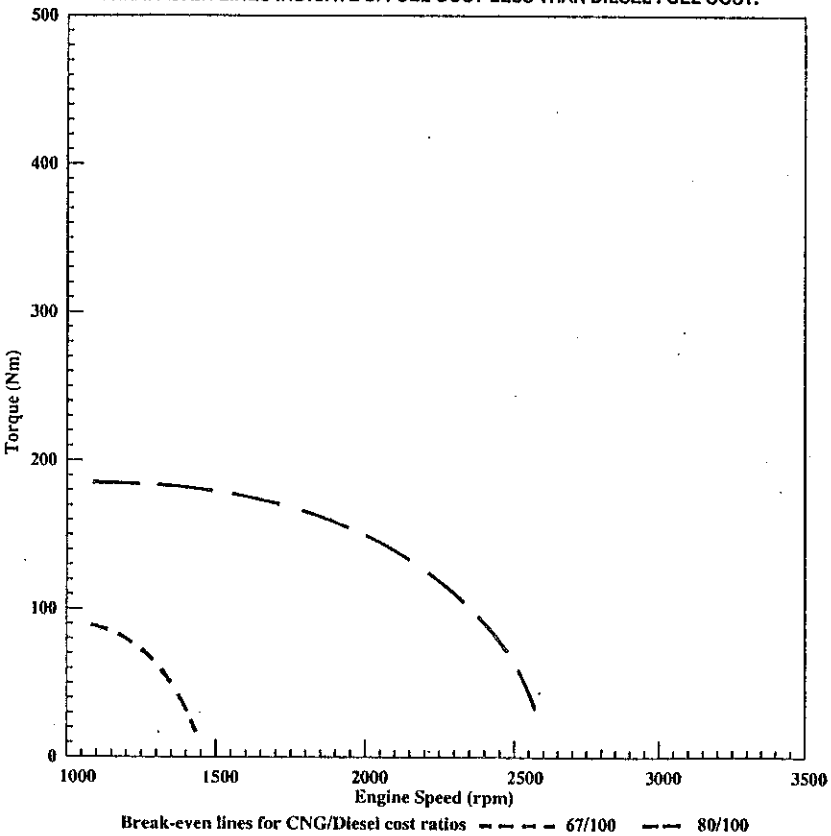

TABLE 1
COMPARATIVE ADVANTAGES AND
DISADVANTAGES OF CNG/DIESEL OPTIONS

	ADVANTAGES	DISADVANTAGES
Dual fuel operation	Can be returned to 100% diesel operation with minimal effort	Two fuels required - associated fuel tanks and supply systems
	Lower cost of conversion compared to SI option	More complex fuel control systems
	No spark ignition electrical system	Poor part load efficiency
	Minimal modifications to engine	
	Can be used at low substitution levels to lower emissions- especially particulates.	
Spark ignition conversion	Single fuel systems required	Modifications required to engine
	Simple fuel control system	Complete installation more expensive
		Spark ignition system and associated technical expertise required
		Engine cannot easily be returned to diesel operation.

TABLE 2
EXAMPLES OF DUAL FUEL CONVERSIONS
OF DIESEL ENGINES IN NEW ZEALAND

ENGINE TYPE	SUPPORTING ORGANISATION	CONVERTING/TEST ORGANISATION	END USE
Fiat 352 hp V-8	Caltex Oil	Transport Fuel Systems Ltd (TFSL)	Oil tanker
Mitsubishi FM215	Premier Softgoods	TFSL	Long Haul Transport
Isuzu 6BD1-T, T/C	Cooper & Curd	TFSL	Transport vehicle
Isuzu 6BD1-T 6 litre , IDI, T/C	Liquid Fuels Trust Board (LFTB)	Vehicle & Fuels Research Unit (VFRU)	Dynamometer testing
Nissan RD8 14 litre, V-8	LFTB	VFRU	Dynamometer testing
Nissan PD6T 10 litre, T/C	LFTB	VFRU	Dynamometer testing

Footnotes:
T/C: turbocharged. IDI: Indirect injection.
A report by Worley Consultants (1985) identified 36 dual fuel vehicles that had been converted in New Zealand.

TABLE 3
SPARK IGNITION CONVERSIONS OF DIESEL ENGINES TO CNG IN NEW ZEALAND

ITEM	ENGINE	SUPPORTING ORGANISATION	TEST ORGANISATION	END USE
1.	6.4 litre DI	Liquid Fuels Trust Board (LFTB)	Vehicle and Fuels Research Unit (VFRU)	Bus trial
2.	5.7 litre DI	LFTB	VFRU	
3.	5.7 litre DI T/C	LFTB	VFRU	
4.	6.4 litre DI	Palmerston North City Corporation	TransGas Services Ltd	Bus fleet operation
5.	6.2 litre DI	Greyhound Buses	TransGas Services Ltd	Bus fleet operation
6.	6.22 litre DI	-	Transport Fuel Systems (NZ) Ltd	Agricultural tractor
7.	14 litre DI T/C	Carter Holt Harvey/LFTB	Transport Fuel Systems (NZ) Ltd	Short haul logging truck
8.	5.7 litre DI	Ministry of Works and Development	Transport Fuel Systems (NZ) Ltd	General fleet use
9.	5.3 litre DI	Ministry of Works and Development	Transport Fuel Systems (NZ) Ltd	General fleet use
10.	9.5 litre DI, V6	ARA Auckland Gas Co.	Transport Fuel Systems (NZ) Ltd	Bus fleet operation
11.	9.5 litre DI, V6	ARA/Auckland Gas/Welgas Ltd	TransGas Services Ltd	Bus fleet operation
12.	11 litre DI T/C	Natural Gas Corporation	Transport Fuel Systems (NZ) Ltd VFRU	Demonstrator vehicle, Haulage Company
13.	6.5 litre DI	Auckland Gas Company	Universal Diesel Services	Local Authority & Food Distribution
14.	5.7 litre	Auckland Gas Company	Universal Diesel Services	1. Local Utility 2. Local Authority 3. Waste Disposal
15.	6.2 litre	Auckland Gas Company	Universal Diesel Services	Food Distribution
16.	5.7 litre	Auckland Gas Company	VFRU/Universal Diesel Services	Utility
17.	15.5 litre	Natural Gas Corporation	TransGas Services Ltd	Dairy use

TABLE 4
ECONOMIC ANALYSIS FOR BUS OPERATION

		SI	SI	Dual-fuel	Dual-fuel
GAS FUEL					
Price	$/kg	0.427	0.427	0.427	0.427
Compression cost	$/kg	0.09	0.18	0.09	0.18
Price of outlet	$/kg	0.517	0.607	0.517	0.607
LIQUID FUEL					
Diesel price	$/L	0.604	0.604	0.604	0.604
CONVERSIONS					
Gas to liquid equivalent	kg/L	0.840	0.840	0.840	0.840
Gas to diesel effy ratio	%	1	1	0.9	0.9
Equivalent cost of CNG	$/L	0.434	0.510	0.483	0.567
OPERATIONAL					
Dual fuel ratio %	-	1	1	0.8	0.8
Number of vehicles	-	10	10	10	10
Distance travelled	km/y	70000	70000	70000	70000
Diesel fuel economy	L/100km	32	32	32	32
Substitutable fuel use	L/y	22400	22400	17920	17920
Number of cylinders		5	5	4	4
Conversion cost/vehicle	$	11000	11000	7600	7600
MISCELLANEOUS					
Extra labour hr/vehicle	hr	12	12	6	6
Labour cost @ $25/hr	$	300	300	150	150
Other costs/vehicle	$	100	100	50	50
Total extra costs/vehicle	$/y	400	400	200	200
Equipment residual value	$	1500	1500	1200	1200
SAVINGS					
Annual before tax savings		34080	17056	19683	4630

Economic analysis for column 1	Year	Net cash flow $	Discount factor @ 10%	Cumulated savings $	Discounted cash flow $	Cumulated discounted savings $
	0	-110000	1.00	-110000	-110000	-110000
	1	34080	0.91	-75920	31013	-78987
	2	34080	0.83	-41840	28286	-50701
	3	34080	0.75	-7760	25560	-25141
	4	34080	0.68	26320	23174	-1967
	5	35580	0.62	61900	22060	20093

NET PRESENT VALUE = 20093 $
SIMPLE PAYBACK PERIOD = 3.23 YEARS

TABLE 5
ECONOMIC ANALYSIS FOR HAULAGE OPERATION

		SI	SI	Dual-fuel	Dual-fuel
GAS FUEL					
Price	$/kg	0.427	0.427	0.427	0.427
Compression cost	$/kg	0.09	0.18	0.09	0.18
Price of outlet	$/kg	0.517	0.607	0.517	0.607
LIQUID FUEL					
Diesel price	$/L	0.604	0.604	0.604	0.604
CONVERSIONS					
Gas to liquid equivalent	kg/L	0.840	0.840	0.840	0.840
Gas to diesel effy ratio	%	1	1	0.9	0.9
Equivalent cost of CNG	$/L	0.434	0.510	0.483	0.567
OPERATIONAL					
Dual fuel ratio %	-	1	1	0.8	0.8
Number of vehicles	-	10	10	10	10
Distance travelled	km/y	100000	100000	100000	100000
Diesel fuel economy	L/100km	30	30	30	30
Substitutable fuel use	L/y	30000	30000	24000	24000
Number of cylinders		8	8	5	5
Conversion cost/vehicle	$	13700	13700	8500	8500
MISCELLANEOUS					
Extra labour hr/vehicle	hr	12	12	6	6
Labour cost @ $25/hr	$	300	300	150	150
Other costs/vehicle	$	1500	1500	50	50
Total extra costs/vehicle	$/y	1800	1800	200	200
Equipment residual value	$	2400	2400	1500	1500
SAVINGS					
Annual before tax savings		33000	10200	27040	6880

Economic analysis for column 3	Year	Net cash flow $	Discount factor @ 10%	Cumulated savings $	Discounted cash flow $	Cumulated discounted savings $
	0	-85000	1.00	-85000	-85000	-85000
	1	27040	0.91	-57960	24606	-60394
	2	27040	0.83	-30920	22443	-37951
	3	27040	0.75	-3880	20280	-17671
	4	27040	0.68	23160	18387	716
	5	28540	0.62	51700	17695	18411

NET PRESENT VALUE = 18411 $
SIMPLE PAYBACK PERIOD = 3.14 YEARS