THE USE OF COMPRESSED GAS IN PUBLIC TRANSPORT IN SOUTH AFRICA

L D EMSLIE, A B TAYLOR and R GOOSEN *

Cape Advanced Engineering (Pty) Ltd, Private Bag X7, Dassenberg Atlantis, 7350
Tel: 083 412 7931; Email: ldemslie@mweb.co.za
Tel: 082 775 1001; Email: andrewtaylor@cae.co.za
*Industrial Development Corporation of SA, PO Box 784055, Sandton, 2146
Tel: 082 458 1969; Email: Raoulg@idc.co.za

ABSTRACT

To investigate the use of clean burning methane in the form of compressed natural gas (CNG) and compressed bio-gas (CBG) in public transport in South Africa, the Industrial Development Corporation of South Africa and Cape Advanced Engineering (Pty) Ltd implemented a real world vehicle fleet trial. The vehicles involved were mini-bus taxis and urban buses. Vehicles were fuelled at three commercial filling stations in Gauteng, of which two provides pipeline CNG and the third a blend of compressed bio-gas and pipeline CNG.

The 10-month programme investigated fuel consumption, vehicle operating cost, oil analysis – also to assess extending the oil drain interval to reduce related operating costs – and the financial viability of conversion to bi-fuel or dual fuel.

The fleet of mini-bus taxis obtained a 22% saving in fuel operating cost when using gas or petrol (bi-fuel) compared to standard (petrol) vehicle operation. The actual savings depend on the level of petrol displacement with CNG, the route operating conditions and the efficiency of the bi-fuel operation. Oil degradation and engine wear were found to be favourable with bi-fuel operation compared to standard petrol operation, thus it seems that equivalent or better engine life could be achieved with bi-fuel operation.

Financial feasibility was favourable, as converting commuter mini-bus taxis to bi-fuel showed a payback period ranging from less than a year (for 225km travelled per day, at a R20,000 conversion cost and a 25% lower than petrol CNG pump price), to six months (if the daily distance increased to 300km and the conversion cost reduced by 20%).

Evaluation of the diesel dual fuel commuter bus compared to a diesel (standard) commuter bus of similar configuration found a fuel operating cost saving of 76c/km (19.2%), based on a diesel substitution of 71%. There is clear indication from the measured oil analysis results that the oil drain interval could be extended by up to double depending on the substitution of diesel by CNG, although this would require more extensive monitoring and trials.

Measured fuel cost savings showed that the conversion and operation of diesel dual fuel vehicles are economically feasible if the vehicles operate over a distance of more than 220 km per day and/or if the conversion costs is limited to R150 000 and/or if the CNG fuel can be purchased at a discount of at least 15% relative to the existing retail price of diesel on an energy equivalent basis.

1 INTRODUCTION

To investigate the use of clean burning methane in the form of compressed natural gas (CNG) and compressed bio-gas (CBG) in public transport in South Africa, the Industrial Development Corporation of South Africa I(DC) and Cape Advanced Engineering (Pty) Ltd (CAE) in 2012/2013 implemented a real world vehicle fleet trial.

The objective of the gas vehicle pilot project and fleet trial was to evaluate a range of different types of engine/gas combustion systems in different vehicles under different driving/duty cycles. Vehicles under evaluation were fuelled with either CNG or CBG, and powered with either spark-ignition bi-fuel engines (petrol or gas), spark-ignition dedicated gas engines (gas only) or dual-fuel combustion engines (diesel and gas).

Pipeline CNG was used predominantly throughout this fleet trial, and vehicles were fuelled at commercial filling stations located at three sites in Gauteng. Two of the sites provided pipeline CNG, while the third site provided a blend of compressed bio-gas and pipeline CNG.

Pipeline gas from Mozambique is already distributed to the Gauteng province and to Richards Bay and Durban where vehicle filling stations are already operational. Bio-gas has traditionally been derived from sewage plants and landfills in South Africa, and is derived from organic waste and energy crops in Europe. In recognising that energy cropping may threaten food security in Africa, CAE has developed bio-reactors for bio-gas production from maize and wheat crop residue and from surplus grasses. These processes enable soil fertility to be enhanced, leading to increased food production, with gas being recovered as a by-product in a sustainable manner.

The fleet trial evaluated the operation of eight bi-fuel commuter taxis, a diesel dual fuel commuter bus, a dedicated CNG commuter bus and a conventional diesel bus over 10 months of operation, and recorded, analysed and reported on parameters including fuel consumption, oil analysis and vehicle operating cost. The trial also evaluated the oil analysis results to assess the possibility of extending the oil drain interval when operating with CNG so as to possibly reduce the related operating costs.
Owing to the carbon to hydrogen ratio of methane being approximately 25% lower than that of conventional fuels on the basis of equivalent energy, the greenhouse gas emissions of a vehicle operating on methane will be 25% lower, even when using natural gas, which is a fossil fuel. If the vehicle operates on bio-gas, then the effective reduction in greenhouse gases can be far greater and even well in excess of 100% in the case of sewage and landfill gas[1].

2 COMMUTER TAXIS: EVALUATING BI-FUEL VERSUS STANDARD (PETROL-ONLY) OPERATION

The commuter (“minibus”) taxi vehicles participating in this fleet trial were evaluated, first, to establish a baseline, operating in a standard configuration as manufactured by the Original Equipment Manufacturer (OEM), on petrol, for 20 000 km, which included two oil drain intervals of 10 000 km each.

The commuter taxis were then converted to bi-fuel operation (in a CNG spark-ignition configuration) and subjected to a further evaluation of 20 000 km (which included two oil drain intervals of 10 000 km each). During this 20 000 km evaluation, the participating minibus taxis were able to drive on either petrol or CNG, but were expected to run mainly on CNG. The proportion of CNG used was monitored as one of the objectives of this fleet trial, and is reported as the percentage petrol displaced.

[1] www.epa.gov/climateleadership/documents/emission-factors.pdf, accessed on 15 May 2014.

The vehicle fleet trial started with eight commuter taxi vehicles, of which six were Toyota 2.7-litre Quantum, one was a CAM 2.4-litre Indlovu and one a CMC 2.4-litre Ses'buyile.

The four minibus taxis participating as "fleet 1" in this vehicle trial (T#1 to T#4) all completed the full baseline period, operating a standard vehicle configuration (petrol) and under standard operating conditions as per OEM specification. Except for T#4 they all also completed the bi-fuel operating phase. T#4 was removed from the fleet trial after numerous attempts to ensure accurate fuel fills data was captured by the driver failed and when the driver of the vehicle, after conversion to bi-fuel, failed to fill the vehicle with gas but continued to only fill with petrol. The four minibus taxis participating as "fleet 2" in this vehicle trial (T#5 to T#8) all completed the baseline period, operating a standard vehicle configuration (petrol) and under standard operating conditions as per OEM specification. T#5 to T#7 were converted to a bi-fuel configuration and operated as such for another two oil drain intervals (2 x 10 000 km). T#8 was removed from the fleet trial after the standard operation phase as the vehicle suffered engine failure and was therefore not converted to bi-fuel.

2.1 **Fuel consumption: data recording methodology**

For this fleet trial, fuel consumption was calculated by dividing the fuel consumed by the kilometres travelled for the same period (petrol operation). Under bi-fuel operation, the petrol and CNG calculated fuel consumptions were added together to achieve a total fuel used, expressed in petrol-equivalent litres, which is based on the energy of the fuel.

The fuel consumed was often difficult to determine accurately, first because the fleet trial was reliant on the drivers of participating fleet trial vehicles (the commuter taxi drivers) to report on fuel purchased for the week, which reporting was occasionally inaccurate or inadequate. Secondly, to plot the data over the evaluation period, the fuel consumed for a period (from 'fill' to 'fill') can only be measured accurately if the vehicle is always filled to exactly the same level, which in this fleet trial was seldom or never the case, as the participating taxis were almost never filled to the "full" level each time fuel was filled.

Still, these daily variations did not have a significant effect on the accuracy of the data collected, as the "fill" effects were averaged out to determine a more reliable average fuel consumption for the vehicle, under its specific driving conditions, influenced by the driver behaviour and route travelled. The average fuel consumption is calculated through two methods – as a rolling average and accumulative averaged data.

2.2 **Fuel operating cost: data calculation methodology**

One of the objectives of this gas vehicle fleet trial was to estimate the operating cost of a bi-fuel vehicle compared to a standard petrol-driven vehicle. The fuel operating cost was calculated for both standard operation and bi-fuel operation as follows: the total amount of fuel used per phase of operation (standard and bi-fuel), in petrol-equivalent litres, was multiplied by the price of the fuel per petrol-equivalent litre, and divided by the total number of kilometres travelled during each phase, expressed in Rand per kilometre.

To calculate fuel operating cost, the fleet trial used standardised fuel prices – R 8.25 per petrol-equivalent litre for CNG and R 11.65 per litre for petrol.

Data summary for two commuter taxi fleets under standard (petrol-only) and bi-fuel operation

The four bi-fuel commuter taxi vehicles which participated in the gas vehicle pilot project fleet trial as “fleet 1” ran a full urban cycle, characterised by high traffic congestion and as a result mainly stop-start operation, whereas the trial cycle of the four bi-fuel commuter (minibus) taxi vehicles which participated as “fleet 2” also included some highway driving.

We reiterate here that the completeness and accuracy of the data collected for the bi-fuel commuter taxi vehicles during the fleet trial were dependent on the information on distance travelled and fuel consumed captured in the participating taxi drivers’ logbooks, in particular during the standard (petrol) operation phase of the trial. Although participating taxi drivers were incentivised to provide the required data in as accurate and consistent a manner as possible, the accuracy and completeness of information received varied widely and were in some instances so inadequate that such recorded data was unusable for the purpose of analysis and providing concluding observations for this fleet trial.

The fuel operating cost savings apparent under bi-fuel operating conditions compared to standard (petrol only) operation were calculated at a fuel price of R11.65 per litre for petrol and R8.25 per petrol-equivalent litre for CNG.

Table 1 – Bi-fuel commuter taxi vehicles: "fleet 1" and "fleet 2" data summary

"Fleet 1" commuter (minibus) taxi vehicles				
Vehicle ID	**T#1 BP 71 LT GP**	**T#2 ZN C2 76 GP**	**T#3 BC 29 GY GP**	**T#4 BF 48 LW GP**
Vehicle type	Toyota 2.7L Quantum	Toyota 2.7L Quantum	CAM 2.4L Indlovu	CMC 2.4L Ses'buyile
Baseline distance travelled	25 990 km	29 210 km	33 314 km	15 112 km
Baseline average fuel consumption	14.2 l / 100km	13.5 l / 100km	Inaccurate data provided	Inaccurate data provided during standard operation; no data provided after bi-fuel conversion; removed from trial; see sections 4.1 and 4.5
Bi-fuel distance travelled	19 467 km	20 864 km	27 404 km	
Bi-fuel gas substitution	95%	85%	Inaccurate data provided	
Bi-fuel average fuel consumption	14.82 l / 100km	14.1 l / 100km	Inaccurate data provided	
Fuel running cost – petrol (R/km)	R 1.66	R 1.58	-	-
Fuel running cost – bi-fuel (R/km)	R 1.25	R 1.22	-	-
Fuel running cost saving on bi-fuel (R/km and percentage)	R 0.41 25%	R 0.35 22%	-	-
Calculated saving at 95% substitution	R 0.41 25%	R0.39 25%	-	-

"Fleet 2" commuter (minibus) taxi vehicles				
Vehicle ID	**T#5 WY V8 18 GP**	**T#6 XF R1 18 GP**	**T#7 BT 08 XH GP**	**T#8XK S3 95 GP**
Vehicle type	Toyota 2.7L Quantum	Toyota 2.7L Quantum	Toyota 2.7L Quantum	Toyota 2.7L Quantum
Baseline distance travelled	24 167 km	28 019 km	32 725 km	27 658 km
Baseline average fuel consumption	12.6 l / 100km	13.7 l / 100km	13.3 l / 100km	11.4 l / 100km
Bi–fuel distance travelled	20 397 km	14 531 km	24 393 km	Removed from fleet trial: vehicle suffered engine failure and was not converted to bi-fuel operation
Bi-fuel gas substitution	61%	-	53%	
Bi-fuel average fuel consumption	11.6 l / 100km	Vehicle not operational from conversion to 5/3/13. Since then to end of trial, fuel consumption data inconsistent; unusable	12.8 l / 100km	
Fuel running cost – petrol (R/km)	R 1.47	-	R 1.55	
Fuel running cost – bi-fuel (R/km)	R 1.11	-	R 1.26	
Fuel running cost saving (R/km and percentage)	R 0.36 24%	-	R 0.30 19%	
Calculated saving at 95% substitution	R 0.49 33%	-	R 0.55 36%	

2.3 **Bi-fuel commuter taxis: operating cost savings**

Table 2 summarises the measured fuel operating costs together with the actual petrol substitution and fuel cost saving achieved, and the estimated cost saving that would be achieved if the petrol substitution were to be 95%, as had been achieved by T#1. It is interesting to note that despite the cost of CNG being 29.2% lower than the cost of petrol, T#5 and T#7 achieved theoretical savings of 33% and 36% respectively for the calculated scenario of 95% petrol substitution. This implies that the vehicles were more fuel efficient when operating in bi-fuel mode than they had been prior to conversion to operate with CNG, which is consistent with the measured reduction in fuel consumption. This benefit was not achieved with vehicles T#1 and T#2, which were slightly less efficient when operating on CNG relative to their efficiency with petrol.

Apart from the fact that these two fleets operated on different driving cycles, the most probable reason for T#5 and T#7 having responded more favourably that T#1 and T#2 to the conversion to bi-fuel operation is that the engines of fleet 2 (T#5 and T#7) was equipped with timing advance devices. These devices exploit the higher octane number of CNG to accommodate for the slower combustion rate of methane, while the engines of fleet 1 (T#1 and T#2) were operated at the standard engine manufacturer's timing advance. The improved fuel efficiency is also possibly related to the fact that manufacturers often release engines into "harsh third-world" markets with conservative ignition timing to limit the risk of warranty claims, albeit at the cost of reduced fuel efficiency and higher operating cost. The ignition advance devices are thus possibly eliminating both the effect of slower methane combustion and the manufacturers' compromised ignition settings.

Table 2 – Summary of measured fuel operating costs, petrol displacement and savings

Vehicle ID	**T#1 BP 71 LT GP**	**T#2 ZN C2 76 GP**	**T#5 WY V8 18 GP**	**T#7 BT 08 XH GP**
Fuel running cost – petrol (R/km)	R 1.66	R 1.58	R 1.47	R 1.55
Fuel running cost – bi-fuel (R/km)	R 1.25	R 1.22	R 1.11	R 1.26
Average petrol substitution achieved	95%	88%	61%	53%
Fuel running cost saving on bi-fuel (R/km and percentage)	R 0.41 25%	R 0.35 22%	R 0.36 24%	R 0.30 19%
Calculated saving at 95% substitution	R 0.41 25%	R0.39 25%	R 0.49 33%	R 0.55 36%

2.4 **Bi-fuel commuter taxis: life cycle cost analysis**

The factors influencing the analysis of life cycle costs (or vehicle operating costs) include the fuel operating cost, as dealt with in the section above, vehicle maintenance costs and the engine life expectancy or durability of the engine.

To quantify the impact of bi-fuel conversion on the durability of the engine, this gas vehicle pilot project evaluated the oil analysis data recorded under standard (petrol-only) operation and compared this to the oil analysis data recorded during the bi-fuel operation phase.

The oil data results include an analysis of wear metal accumulation, oil additive component concentrations, the level of contaminants in the oil, and changes in lubricant viscosity, the rate of oxidation and the ability of the oil to neutralise acids (as measured by the oil's total base number).

Wear metal accumulation monitors the accumulation of metal and metal oxides in the oil resulting from abrasive and corrosive degradation in the engine. Accumulation of microscopic quantities of metals is normal. Oil additives are required in the oil for the oil to perform its functions of engine protection. Additives can become depleted, thus necessitating monitoring of these additives. Dirt ingested into the engine and combustion soot and other combustion products accumulate in the oil as contaminants, which can also contribute to formation of acids which are neutralised by the oil additives that are progressively depleted.

On average, oil samples were taken from the commuter (minibus) taxis participating as "fleet 1" and "fleet 2" in the gas vehicle pilot fleet trial, four times during each 10 000 km cycle.

Oil samples were also taken from two "fleet 1" test vehicles that did not complete the trial – BB 34 SB GP (a CMC 2.4-litre Ses'buyile which was removed from the vehicle trial in October 2012 because of the driver's continued inability to supply the trial with accurate fuel fill data) and BF 48 LW GP (described as T#4 in this paper and also removed because of inaccurate fuel fill data provided during the petrol-only evaluation phase and no data provided during the bi-fuel operation phase). Oil samples were also taken from two "fleet 2" test vehicles that did not complete the trail – T#6 (which failed to provide accurate and consistent fuel consumption data) and T#8 (which suffered engine failure and was not converted to bi-fuel). Oil samples were also taken and analysed for vehicle XSS 359 GP, a commuter taxi converted to bi-fuel in March 2013 (which was too late to join the vehicle trial in terms of baseline and bi-fuel operation evaluations, but was useful in terms of oil analysis evaluation.)

The oil analysis results and our conclusions on these results are summarised in Table 3 below. The oil analysis results indicate that the conventional high quality passenger vehicle oil used in the fleet trial was substantially degraded in the commuter taxi operation, to the extent that after 20 000 km the oil was no longer fit for use. This situation contradicts motor industry norms in that the oil no longer has adequate functional reserve to protect the engine in the event of the vehicle not being serviced at the scheduled time. The result of this is that even in the case of a 10 000 km oil drain interval being retained, a more specialised oil is required in order to offer appropriate levels of protection in commuter taxi operations.
Bi-fuel operation was found to result in reduced rate of oil degradation, but even with bi-fuel operation, a more specialised oil is required to ensure that better oil condition is maintained throughout the service period.

Analysis of the results in the context of other oil drain extension projects carried out in South Africa indicates that the formulation of an appropriate specialised oil for use with bi-fuel operation would enable an oil drain interval of 30 000 km with an acceptable margin of protection at the end of the period, in the event of oil drain being delayed. In this manner a significant cost saving could be achieved.

Table 3 – Oil data analysis summary: "fleet 1" and "fleet 2" bi-fuel commuter taxi vehicles

"Fleet 1"	**"Fleet 2"**
Wear metals	
Iron accumulation recorded for T#1 to T#3 is the result of corrosion/erosion rather than friction wear. T#1 (the lowest mileage vehicle) shows a higher apparent corrosive wear rate than T#2 and T#3 on the basis of higher iron accumulation. The reason for this is higher workload and lower rates of oil consumption and fuel dilution in the newer engine.	Accumulation of iron in the engine oil recorded for T#5 and T#7 are the result of normal corrosion/erosion mechanisms rather than friction wear. Some of the older test vehicles experienced high levels of engine wear in the form of iron and aluminium accumulation but this was not relevant to the test or bi-fuel operation.
The corrosive wear recorded is similar during standard operation and during bi-fuel operation. It is not possible to identify any significant differences from the available data.	The corrosive wear recorded is similar during standard and bi-fuel operation. It is not possible to identify any significant differences from the available data.
The concentration of copper wear metals for T#3 was higher than for T#1 and T#2 as a result of differences in the engine technology, but no noticeable differences were recorded in this regard between the bi-fuel and the standard operation phases.	No noticeable differences were recorded in the concentration of copper, tin or lead wear metals between the bi-fuel and the standard operation phases.
Additive components	
There are no noticeable changes apparent in additive components concentrations between the bi-fuel and standard operation phases. The molybdenum concentration increased within oil drain cycles and from oil drain to oil drain, and was already noticeable at the second drain interval (operating under standard configuration), but then stabilised at a higher value (at an average of 100 ppm) under bi-fuel operation, compared to a 78 ppm average at the start of the fleet trial. This was most likely related to the change to the high quality oil used for the fleet trial – the molybdenum may have accumulated within the engine until an equilibrium was achieved.	There are no noticeable changes apparent in additive component concentrations between the bi-fuel and standard operation phases, except that for T#7, the P, Ca and Zn additive package component slightly decreased during bi-fuel operation owing to low oil top-up and reduced fuel dilution.
Oil contaminants	
Sodium concentrations remained low during both the standard and bi-fuel operation phases of the fleet trial, an indication that coolant leaks did not occur. Silicon remained below 20 ppm for all participating taxis, except for T#2, which saw an increase to 24 ppm at the end of the second oil drain interval, at the same time when viscosity and TBN changed out of the norm.	Silicon and sodium concentrations in the engine oil remained normal for T#5 and T#7, both during standard and bi-fuel operating conditions.
Viscosity	
Viscosity increases due to oxidation (or possible polarisation) were recorded for all the vehicles except for T#2, where other viscosity increasing effects played a larger role. Other factors could include losing the lighter oil fraction to boil-off, and fuel dilution.	T#7 shows higher initial viscosity loss during bi-fuel operation compared to the standard operation phase owing to low top-up, reduced fuel dilution and reduced levels of oxidation.
TBN	
TBN depletion has been found to be the parameter which limits the useful life of the oil in the commuter ("minibus") taxi fleet. The results show that if the oil is not replaced at the appropriate time, then the TBN declines to a level where corrosive/erosive wear begins to increase, which will reduce engine life. The results indicate that the rate of TBN depletion may be lower with CNG operation than with petrol operation, although confirmation of this observation would require more extensive fleet data.	For T#7, the rate of TBN depletion seems to be lower during the bi-fuel operation oil drain interval than during the standard operation oil drain interval although the actual TBN levels are lower. The difference is most probably attributable to less fuel (petrol) being diluted into the oil.

2.5 Commuter taxis: the financial viability of conversion to bi-fuel

Based on the results obtained from the commuter taxis participating in this vehicle trial, an analysis was done to determine the financial viability of bi-fuel conversion, expressed as internal rate of return and payback period.

To be consistent with the actual measured results from T#2, which delivered a consistent set of data while also providing a conservative representation of the savings achieved by the participating vehicles, we used the measured saving of 35 cents as a representative fuel operating cost saving per kilometre, based on a petrol price of R 11.65 and R 8.25 per petrol-equivalent litre for CNG. These scenarios are further based on a mixed operating cycle for four of the commuter taxis which have participated in this vehicle trial – T#1 and T#2 from the participating "fleet 1" vehicles, which operate on an urban stop-start duty cycle, and T#5 and T#7 from the participating "fleet 2" vehicles, which operate on a more mixed cycle encompassing a combination of highway and urban stop-start driving. The calculated fuel operating cost saving is conservative considering that T#2 and T#5 achieved cost savings of this extent with 88% and 61% petrol displacement by CNG respectively (when one takes into account, for example, that T#1 achieved a 95% average substitution of CNG for petrol during the evaluation period).

We identified that i) the distance travelled per day, ii) the bi-fuel conversion cost and iii) the price of CNG will mainly impact on the financial viability of bi-fuel conversion. Except for travel distance per day, these factors are viewed as outside of the control of the taxi operator. Other factors that will also play a role but are not directly evaluated (albeit indirectly through the fuel operating cost saving) are the difference in fuel consumption, the vehicle duty cycle and driver behaviour.

Seven different scenarios were modelled. Scenarios 1 to 3 evaluated the impact of kilometres travelled per day (between 150 km and 300 km per day), while scenarios 4 and 5 evaluated the cost of bi-fuel conversion. Scenarios 6 and 7 investigated the influence of the CNG price on the viability of conversion. This simple analysis has generated various outcomes for different scenarios, and it would seem that all these scenarios could be considered financially viable. These scenarios contribute towards the objective of developing a better understanding of the factors that influence the financial feasibility of bi-fuel conversion of commuter taxi vehicles, and to what extent they influence such viability. It is clear from the analysis performed here that bi-fuel conversion in the commuter taxi industry is financially extremely attractive, even for the least attractive scenarios modelled.

Table 4 – Financial viability of bi-fuel conversion

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
Price of fuel - petrol	R 11.65	R 11.65	R 11.65	R 11.65	R 11.65	R 11.65	R 11.65
Price of fuel - CNG	R 8.25	R 8.25	R 8.25	R 8.25	R 8.25	R 7.22	R 6.19
Fuel running cost - petrol	R 1.58	R 1.58	R 1.58	R 1.58	R 1.58	R 1.58	R 1.58
Fuel running cost - bi-fuel	R 1.22	R 1.22	R 1.22	R 1.22	R 1.22	R 1.10	R 0.97
Fuel running cost - saving	R 0.35	R 0.35	R 0.35	R 0.35	R 0.35	R 0.48	R 0.61
Kilometres a day	150	225	300	225	225	225	225
Kilometres a year	42 900	64 350	85 800	64 350	64 350	64 350	64 350
Conversion cost	R 20 000	R 20 000	R 20 000	R 17 500	R 15 000	R 20 000	R 20 000
NPV (10-years)	R 68 970	R 110 265	R 151 560	R 111 967	R 113 670	R 155 149	R 200 034
IRR	75%	114%	151%	130%	151%	155%	196%
Payback period (yr)	1.39	0.92	0.69	0.80	0.69	0.67	0.53

Bi-fuel commuter taxis: vehicle trial summary and concluding findings

The test methodology implemented in this compressed natural gas and compressed bio-gas vehicle fleet trial is not ideal to generate fuel consumption data of which the accuracy is beyond doubt, but was a necessary compromise to evaluate vehicles under actual commuter taxi operating conditions. The test methodology also gave us insight into the "workings" of the taxi industry, which is valuable for assessing the potential success of implementation of CNG supply to the commuter taxi industry. In summary, the most important findings are as follows:

- The level of maintenance of vehicles in the industry is on average low, low quality replacement parts and lubricants are used, and maintenance personnel and facilities are mostly informal.
- The condition of many of the vehicles is questionable, vehicles with odometer readings of 500 000 km and over are common, and oil consumption is often high. Selecting serviceable vehicles for conversion is therefore not an easy task.
- The quality of the Toyota Quantum vehicles evaluated as part of this fleet trial were beyond doubt, and these vehicles do extremely well in a limited or no maintenance environment. Where the CAM and CMC vehicles are concerned, although only the CAM vehicle was evaluated for an extended period of time and both were new vehicles, they did relatively well under the standard operating conditions of the vehicle trial, comparable on fuel consumption and engine durability, based on the limited data available, to the Toyota Quantum vehicles.
- It was apparent from this vehicle trial that the convenience / proximity of CNG filling stations has a significant impact on petrol displacement with CNG. Vehicles T#1 and T#2 that filled at the Langlaagte filling station achieved much higher petrol displacement than vehicles T#5 and T#7 which filled at the Lincoln Road (Benoni) filling station which was evidently less accessible from the normal driving route.

Of the eight vehicles that participated in the commuter taxi vehicle trial, only four vehicles (T#1, T#2, T#5 and T#7) generated consistently acceptable fuel consumption data which could be used for a rigorous comparison of standard versus bi-fuel operation.

The fuel related operating cost saving results calculated from these four commuter taxis participating in the vehicle trial ranged from 30 cents to 41 cents per km, depending on the accuracy of the data captured, the level of petrol displacement with CNG, the operating condition on the route and the efficiency of the bi-fuel operation, which may be related to the bi-fuel conversion technology. For calculation purposes, we used a 35 cents per km saving, resulting in a 22% saving in fuel operating cost compared to standard (petrol) vehicle operation.

Based on the data captured for bi-fuel operation compared to standard operation, this paper concludes that the bi-fuel operation had no negative effect on engine durability and the cost of maintaining the vehicle. With the amount of data that is available it is, however, difficult to rigorously quantify any maintenance cost saving or engine durability life cycle cost savings that could be achieved with bi-fuel operation. Therefore, from the results of this vehicle trial, the fuel operating cost saving is the only element adequately quantified for use in the formal evaluation of life cycle operating costs for bi-fuel operation compared to petrol / standard operation in commuter taxi vehicles.

It is possible to conclude that all differences in oil degradation and engine wear were found to be favourable with bi-fuel operation, thus it can be stated that equivalent or better engine life will be achieved with bi-fuel operation, thereby ensuring a no-harm result. Oil analysis over extended drain intervals illustrated that after 20 000 km, the conventional passenger vehicle lubricant used was often not suitable for further use, thus leaving no margin of reserve protection. It is thus concluded that a more specialised lubricant is required for extended oil drain intervals to be achieved.

After careful evaluation of the results, we concluded that it is possible and highly appropriate to formulate a specialised oil for use in bi-fuel commuter taxis that will greatly enhance the service costs and durability of the vehicles. Such a specialised oil should be formulated and evaluated in subsequent trials, which should accompany the roll-out of bi-fuel vehicle fleets. Such a specialised oil is highly recommended on the basis that it has been noted that some vehicles are operated for greatly extended periods without oil change, which results in accelerated engine damage and economic loss.

The financial feasibility, based on only the differences in the fuel related life cycle cost as calculated from the data captured, is favourable towards converting commuter taxi vehicles to bi-fuel. The calculated payback period ranges from under one year for an average distance travelled per day of 225 km, at a R 20 000 conversion cost at the existing CNG pump price of R 8.25, to as low as 6 months if the distance travelled is increased to 300 km a day, the conversion cost is reduced by 20% and the CNG price is kept constant.

3 DIESEL DUAL FUEL EVALUATION: PARTICIPATING COMMUTER BUSES

This gas vehicle fleet trial also included the evaluation of a diesel dual fuel (DDF) commuter bus, which was compared to a diesel (standard) commuter bus of similar size and configuration. The two buses operate on a similar route – between Lenasia and the Johannesburg city centre – with the exception that the diesel (standard) vehicle completes an additional trip to Lenasia and back, and as a result travels 70 kilometres further per day than the DDF bus.

A summary of the data collected since the start of this vehicle trial is given below.

Table 5 – Diesel dual fuel and standard diesel commuter buses: vehicle trial participation record

Vehicle	**ZD C1 55 GP**	**DB 00 MG GP**
Vehicle type	Volksbus Explorer 17.210 OD – DG Flex DDF	Volksbus Explorer 17.210 OD
Fuel type	Dual fuel: diesel and CNG	Diesel
Pilot commencement date	21 August 2012	21 August 2012
Pilot monitoring commencement date	14 August 2012	1 August 2012
Pilot end date	28 March 2013	28 March 2013
Total distance travelled (km) since pilot commencement	20 047 km	31 574 km
Fuel consumption, accumulative [l / 100km]	35.5 l / 100km	36.0 l / 100km
Diesel substitution [%]	71 %	0 %
Energy consumption, accumulative [MJ / 100km]	1 287 MJ / 100km	1 312 MJ / 100km
Fuel running cost, accumulative [R/km]	R 3.19	R 3.97

3.1 **Fuel operating cost saving analysis**

The reader of this paper should keep in mind that in a dual fuel vehicle, the fuel consumption is made up of both a diesel and a gas (CNG) fuel consumption portion. In this vehicle both fuels are consumed simultaneously.

The diesel dual-fuel (DDF) bus versus the diesel (standard) bus participating in the fleet trial pilot has in the main generated consistent results, with both vehicles accumulating at least 20 000 km under evaluation.

The data indicates that the DDF system installed on the VW commuter bus engine substitutes diesel fuel with CNG to a level of 70.8% under an extra-urban driving cycle (a driving cycle that includes steady-speed driving, but also accelerations, decelerations and some idling). It is therefore expected that the diesel dual fuel commuter bus evaluated in this vehicle trial would be able to produce a higher substitution rate under highway or long-distance travelling conditions.

The duel fuel technology offers the additional benefit of being able to operate unconstrained, beyond the limits of gas fuel (CNG or bio-gas) availability, because the vehicle can seamlessly go back to running on diesel when the gas supply is depleted / unavailable.

The total fuel consumption for the DDF commuter bus compared well with that of the diesel-only commuter bus, the former expressed in diesel-equivalent litres of CNG (based on energy content). This is to be expected if the two vehicles operated at the same efficiency, since the vehicles drive a similar route, with the only difference being the diesel bus making three trips per day while the DDF bus only makes two trips per day, under the same load conditions.

The DDF commuter bus' average fuel consumption was calculated at 35.5 l / 100 km and that of the diesel-only commuter bus at 36.0 l / 100 km, which indicates a slightly better efficiency for the DDF bus than for the diesel-only commuter bus over the period of evaluation of the two vehicles.

As this vehicle trial only compares one DDF vehicle to one diesel-only vehicle (both commuter buses, though), it is not possible to make a conclusive statement regarding the efficiency of the standard diesel technology compared to the DDF technology, except that the vehicles operate at similar efficiency.

Still, the results of this vehicle trial are in line with those reported in literature[2], where in the case of a DDF engine at Euro II and III emissions levels, its efficiency is between 2% and 5% lower than that of a diesel engine. At Euro V, the DDF engine's efficiency drops to 10% lower than that achieved in diesel engines.

For the calculation of fuel operating cost for this DDF commuter bus and standard diesel commuter bus vehicle trial, we used R11.06 per litre of diesel, which is the average diesel price during the evaluation period, while R7.74 was used as the per petrol-equivalent litre of CNG price (as available from the Langlaagte CNG filling station). The diesel-equivalent price per litre for CNG is calculated at R 8.13.

For the diesel (standard) commuter bus, the fuel running cost, based on the accumulated fuel consumption as calculated, is R3.97 per km, versus R3.21 per km for the DDF commuter bus, which indicates a saving of 76c per km for the latter.

[2] Stålhammer, P., Erlandsson, L. & Willner, K. Assessment of the dual-fuel technology. AVL MTC 9913. Report prepared for Swedish Gas Centre (SGC). June 2011, p47.

This amounts to a 19.2% reduction in the fuel running cost for the DDF bus compared to the diesel (standard) bus.

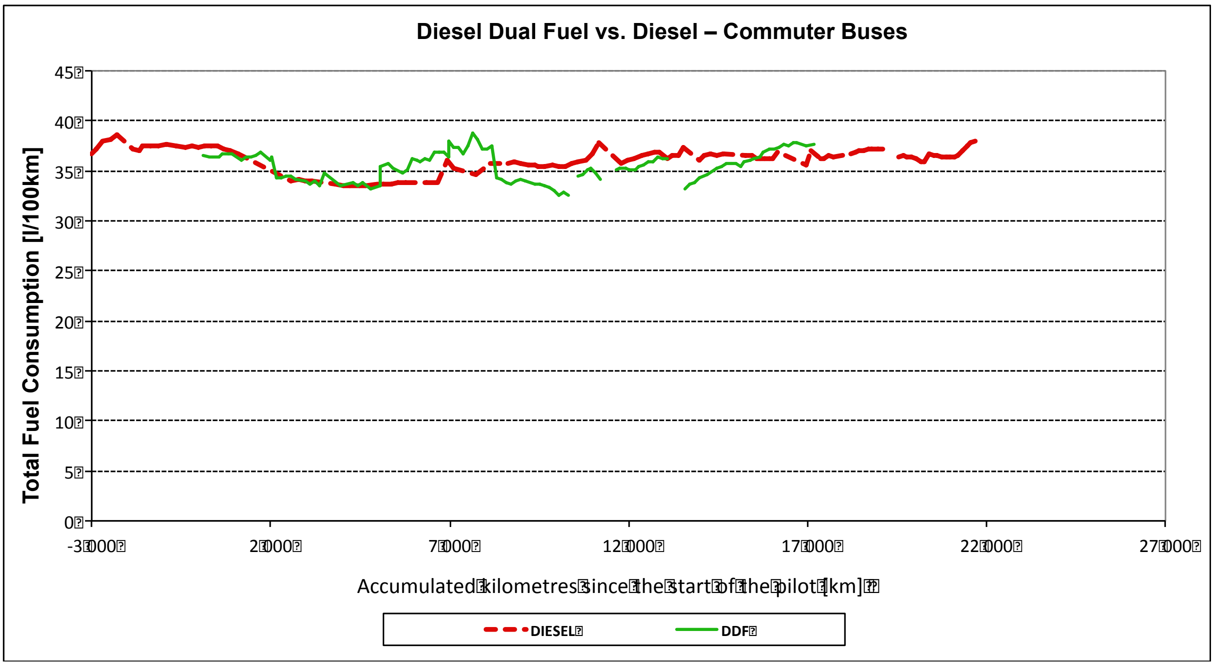

Figure 1 – Total fuel consumption: DDF commuter bus versus standard diesel bus

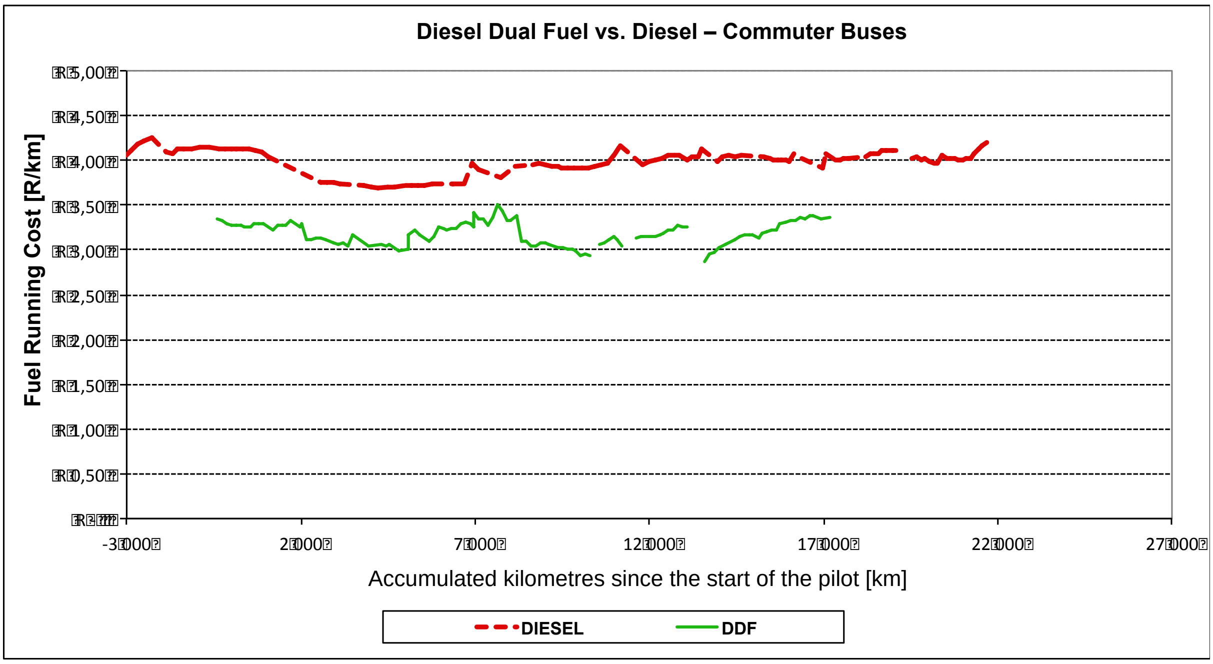

Figure 2 – Fuel operating cost: DDF commuter bus versus standard diesel bus

3.2 **Diesel dual fuel evaluation: life cycle cost analysis**

The factors influencing the analysis of life cycle costs (or vehicle operating costs) include the fuel operating cost, vehicle maintenance costs and the engine life expectancy or durability of the engine. To quantify the impact of dual-fuel conversion on the durability of the engine, this gas vehicle fleet trial analysed the oil analysis data recorded under standard (diesel-only) operation and compared this to the oil analysis data recorded during the diesel dual-fuel operation phase.

The oil data results include an analysis of wear rates, oil additive component concentrations, the level of contaminants in the oil, and changes in lubricant viscosity, the rate of oxidation and the ability of the oil to neutralise acid (as measured by the oil's total base number).

Oil samples were taken from both the standard diesel and the diesel dual fuel commuter buses on average seven times in a 20 000 km oil drain cycle.

The oil analysis results and our conclusions on these results are summarized in Table 6. The oil in both the standard diesel bus and the diesel dual fuel bus was found to be in excellent condition at the end of the 20 000 km oil drain interval, which indicates that these vehicles should be operated on significantly longer oil drain intervals. The results indicate that the oil drain interval should be extended substantially with standard diesel engine lubricating oil, but a more comprehensive evaluation will be required to determine the appropriate oil drain interval. The results do indicate that an oil drain interval of more than 40 000 km can be expected to be achieved with diesel dual fuel operation, which would contribute to reduced operating costs. However, additional trials would be required to make a reliable recommendation on the extent to which oil drain intervals can be extended. The positive impact of the low sulphur (CNG) fuel on oil degradation and the life expectancy of the engine should be quantified with the aid of additional vehicle trials under more stringent control conditions.

Table 6 – Oil data analysis summary for the DDF commuter bus versus the diesel standard commuter bus

Wear metals
The iron wear metal concentration is higher for the standard diesel-only bus than for the diesel dual fuel bus, but since the PQ index remains low, it is concluded that the iron accumulation in the oil is the result of normal corrosion-erosion rather than friction wear. Given that the rate of iron accumulation in the oil in the diesel dual fuel bus was less than half of that observed for the standard diesel bus, it can be concluded that diesel dual fuel was not responsible for increased wear rates in as far as iron is concerned.
Aluminium wear metal concentrations also increased at almost double the rate in the standard diesel bus relative to the diesel dual fuel commuter bus, which again illustrates that diesel dual fuel operation most certainly did no harm. It is clear that the cylinder liner, piston and piston ring assemblies in the diesel dual fuel engine were not negatively affected by the introduction and indeed seemed to experience lower wear rates that the standard engine although verification of extended engine life would require evaluation of more engines over a longer period of time.
Copper wear metal concentrations were very low in both engines until copper increased in the diesel dual fuel vehicle owing to a copper corrosion and leaching event resulting from the holiday shutdown of the vehicle. Since no abnormal increases were evident in the lead or tin concentrations in the vehicle's oil, the origin of the increased copper concentration is certainly not from bearing material. The generally low levels of copper, tin and lead indicates that the journal bearing assemblies of both engines were functioning correctly and that the introduction of CNG was not related to any increased wear or degradation.
Additive components
There are no noticeable differences in the concentrations of additive components between the diesel dual fuel and standard diesel operating conditions.
Oil contaminants
Silicon and sodium concentrations in both test vehicles remained normal over the oil service interval.
Viscosity
Viscosity decreased by a relatively small amount and at a similar rate for both test vehicles over the oil service interval.
TBN and oxidation
The rate of TBN depletion is slightly lower for the diesel dual fuel bus than for diesel-only operation, although the extent of the TBN depletion was relatively low. Oil oxidation was also relatively low.

The financial viability of conversion to diesel dual fuel

The life cycle costs calculated from the fuel operating cost data measured during this vehicle trial was used to develop nine different cash flow analysis scenarios. The scenarios were based on the 76 cents per km fuel operating cost saving, a diesel price of R 11.06 and a CNG price of R 8.13 per diesel-equivalent litre, and taking into account the operating conditions of the diesel dual fuel commuter bus during this vehicle evaluation. We identified that the distance travelled per day, the diesel dual fuel conversion cost and the price of CNG will mainly impact on the financial viability of diesel dual fuel conversion. Except for distance travelled per day, these factors are viewed as outside of the control of the commuter bus operator.

The nine different scenarios were modelled, as follows.

Table 7 – The financial viability of diesel dual fuel conversion

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Price of fuel per litre - diesel	R 11.06	R 11.06	R 11.06	R 11.06	R 11.06	R 11.06
Price of fuel per diesel-equivalent litre – CNG	R 8.13	R 8.13	R 8.13	R 8.13	R 8.13	R 8.13
% of the existing pump price	100%	100%	100%	100%	100%	100%
Fuel running cost – diesel	R 3.97	R 3.97	R 3.97	R 3.97	R 3.97	R 3.97
Fuel running cost - diesel dual fuel	R 3.21	R 3.21	R 3.21	R 3.21	R 3.21	R 3.21
Fuel running cost – saving	R 0.76	R 0.76	R 0.76	R 0.76	R 0.76	R 0.76
Kilometres a day	120	170	220	270	170	170
Kilometres a year	34 320	48 620	62 920	77 220	48 620	48 620
Conversion cost	R 197 500	R 197 500	R 197 500	R 197 500	R 150 000	R 100 000
Net present value (10-year period)	R 8 577	R 68 048	R 127 520	R 186 991	R 100 055	R 134 104
Internal rate of return (IRR)	5.5%	13.5%	20.6%	27.2%	21.1%	35.3%
Payback period (yr)	9.3	6.2	4.6	3.7	4.54	2.93

	Scenario 7	Scenario 8	Scenario 9
Price of fuel per litre - diesel	R 11.06	R 11.06	R 11.06
Price of fuel per diesel-equivalent litre – CNG	R 7.00	R 6.00	R 6.00
% of the existing pump price	86%	74%	74%
Fuel running cost - diesel	R 3.97	R 3.97	R 3.97
Fuel running cost - diesel dual fuel	R 2.92	R 2.67	R 2.67
Fuel running cost - saving	R 1.05	R 1.30	R 1.30
Kilometres a day	170	170	220
Kilometres a year	48 620	48 620	62 920
Conversion cost	R 197 500	R 197 500	R 150 000
Net present value (10-year period)	R 143 982	R 152 096	R 345 447
Internal rate of return (IRR)	22.5%	24.1%	54.0%
Payback period (yr)	4.31	4.03	1.94

This analysis generated various outcomes for different scenarios, with some being financially viable and others not, but all contributing towards the objective of developing some understanding as to the factors that influence the financial feasibility of dual fuel conversion discussed here, and the extent to which they influence such viability.

From this analysis it is clear that for a financially feasible scenario to exist, the converted vehicle will have to travel an average daily distance of at least 220 km, for 5.5 days a week, while the conversion cost should be limited to R150 000. Every effort should than also be made to source CNG at less that R7.74 per petrol-equivalent litre or R 8.13 per diesel-equivalent litre.

3.3 Diesel dual fuel evaluation: vehicle trial summary and concluding findings

The fuel operating cost saving result measured from the fleet trial vehicles was 76 cents per kilometre which amounts to a 19.2% cost reduction for the DDF bus compared to the diesel (standard) bus. The 76-cent saving is based on a diesel substitution of 71%.

Based on the data captured for the DDF operation compared to the standard operation, the project concluded that the DDF operation had no negative effect on engine durability or the cost of maintaining the vehicle. With the limited data available it is difficult to quantify the actual extent of maintenance cost saving that can be achieved as a result of the DDF operation. There is, however, clear indication from the measured oil analysis results, and supported by literature, that the oil drain interval can be extended by as much as 100% depending on the substitution of the diesel by CNG, although this would require more extensive trials. It should thus be noted that the actual life cycle cost saving may well be significantly greater than 76 cents per km which will result in substantially higher internal rates of return.

The measured fuel cost savings indicate that the conversion and operation of diesel dual fuel vehicles are only economically feasible if the vehicle operates over a distance of more than 220 km per day and / or if the conversion costs is limited to R150 000 and / or if the CNG fuel can be purchased at a discount of at least 15% relative to the existing retail price of R8.13 per diesel litre equivalent. However, if the diesel dual fuel conversion can be carried out at a cost of R150 000, if the vehicle is operated for 220 km per day and if the fuel is made available at 74% of the existing retail price, then cost of conversion is recovered within 1.94 years, which is adequate to justify the investment.