Examining the optimal fuel type for urban bus operations

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ABSTRACT

Public service fleets offer an attractive option for introducing renewable fuels and alternative technologies on a large scale, which allow for the reduction of both greenhouse gas emissions and exhaust air pollutants. This paper examines the use of biomethane (bio-CNG) and compressed natural gas (CNG) for part of the bus fleet in Dublin. Dublin is typical of many international urban centres with a large bus fleet; therefore the results detailed in this paper could be applied to other urban bus fleets. The emissions produced from the 2008 fleet based at one of the city's seven bus depots were compared to use of new diesel and bio-CNG buses, which were modelled using COPERT 4, a road transport emissions model developed by the European Commission. The optimum feedstock for bio-CNG production in Ireland was investigated, as well as the quantity of feedstock needed to produce the required bio-CNG to fuel the bus fleet examined. The merits of producing bio-CNG in Ireland were analysed in order to determine the best policy. As expected the results showed a substantial decrease in all exhaust emissions from the use of bio-CNG buses compared the 2008 fleet. Grass silage was chosen as the optimum feedstock for production of bio-CNG in Ireland, and it was calculated using a sensitivity analysis that 1,349 ha is the land take needed to produce the grass silage for bio-CNG required to run the bus fleet examined.

INTRODUCTION

In 2004, the Irish government launched a pilot scheme for excise relief on biofuels *(1)*. The aim of the scheme was to stimulate the initial development of a biofuel market and concerned the production of pure plant oil, biodiesel and bioethanol in approved pilot projects. The scheme was subject to a maximum production capacity of 8 million litres per annum of biofuel, and was valued at €3 million *(1)*. The pilot scheme was expanded in 2005 to include 16 million litres of biofuel per annum *(2)*.

The two main bus operators in Ireland, Bus Éireann and Dublin Bus have used biodiesel on a limited scale. Bus Éireann is a government owned Bus Company which provides bus services across Ireland and regional services in the cities of Cork, Galway, Limerick, and Waterford. Bus Éireann piloted the use of biofuel in the tour buses operating in its fleet in Cork city in 2006. A blend of 5% biodiesel was used, with a view to possible extending it to its entire fleet of 160 vehicles. Dublin Bus is also state owned and operates urban bus services in Dublin. Dublin Bus also trialled the use of biodiesel as a 5% blend in five of its open-top tour buses *(3)*. More recently, the Department of Transport has instructed public transport operators to move to a 5% biodiesel blend in the current fleet, and this is expected to be implemented in 2009 *(4)*. The Department of Transport has also instructed public transport operators to ensure that all new buses, as part of future fleet replacement, can operate on a 30% biodiesel blend, subject to technical and logistical constraints. This paper examines the potential benefits of switching 81 buses in the Dublin bus fleet to alternative fuels. Currently, Dublin Bus operates a fleet of 1,008 buses *(5)*. This paper uses COPERT 4, an emissions model, to estimate the reductions in green house gas emissions and air pollutants from introducing alternative fuels to the Dublin Bus fleet.

An evaluation of vehicle emission projections using COPERT III was carried out by Lumbreras et al. *(6)*. The authors conducted this review of vehicle emission projections in Madrid from 2004 to 2012 using several control strategies. The paper presents the assessment of several mobility and technology scenarios that can be used for emission reductions in Madrid. The pollutants which were analysed were sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), particulate matter (PM), non-methane volatile organic compounds (NMVOC), heavy metals, and carbon dioxide (CO_2), which is the most significant anthropogenic greenhouse gas. Cohen *(7)* examined cost effectiveness of running school buses in the United States on both enhanced diesel engines and compressed natural gas (CNG) in terms of reducing local air pollution. Conventional diesel engines were taken as the reference scenario, with emission controlled diesel (ECD) and CNG modelled as the alternatives. The pollutants which were considered were PM, NO_x and SO_2 only. The author found that the use of CNG buses resulted in substantial health benefits compared to ECD buses.

The Euro standards referred to in this paper relate to a rating given to buses to measure how efficient the buses are in terms of emissions. These standards are set by the European Union and classify vehicles in accordance with their emissions. Karlström *(8)* completed a study which expressed the local air pollution benefits in monetary terms from hydrogen fuel cell buses, CNG buses and Euro V diesel buses. Euro V standard is the current mandatory limit for new buses purchased in the European Union. This study presented a quantitative assessment of the local environmental benefits of using each type of bus along a central bus route in Götenburg, in 2006. Euro II diesel buses were used as a reference scenario. The environmental benefits included were ambient levels of NO_x, particulates, noise, and greenhouse gas reduction potential. The emissions data for the Euro V diesel bus was quantified using COPERT III. The benefits in monetary terms were then compared with the capital and fuel costs. The author found that the present local environmental benefits for a hydrogen fuel cell bus are much smaller than the annualised purchase cost, although the local monetary benefits would be meaningful to consider if compared with the incremental costs of a mass-produced fuel cell bus.

Schimek *(9)* examined the bus fleets in New York City, Los Angeles, Chicago and Boston to ascertain how moving to alternative fuels could reduce PM and NO_x emissions. The results of this study suggest that increasing the turnover of diesel fleets could produce more rapid emissions reductions. Schimek *(9)* suggests that the little difference in the cost of CNG relative to diesel, and the shorter range of CNG vehicles, explains why CNG fuelled buses haven't been adopted, on a larger scale. Clark et al. *(10)* examined the use of CNG and hybrid electric buses in Mexico City. The results of this study suggest that while hybrid electric buses produced significant fuel economy, while CNG buses had the lowest PM emissions.

Gonçalves et al. *(11)* examined the effects of the introduction of natural gas vehicles on the urban air quality of Barcelona and Madrid greater areas. The model used was a three dimensional air quality modelling system. The model had a high spatial-temporal resolution of 1 km^2 and 1 hour respectively. The use of such a powerful modelling system was to assess the hypothesis that air quality improvement plans should be designed considering the local characteristics. The authors considered seven feasible scenarios of emissions reduction, based on the introduction of natural gas vehicles. The pollutants which were of concern were ozone (O_3), nitrogen dioxide (NO_2), SO_2, and particulate matter passing a ten micrometer sieve (PM_{10}). From the results the authors were able to conclude that air quality improvement plans should in fact be designed considering the local characteristics.

A number of studies have been undertaken to examine the production of biogas for use as a transportation fuel. Murphy and Power *(12)* and Murphy and McCarthy *(13)* both investigated the optimal feedstock for production of bio-CNG in Ireland. Murphy and Power *(12)* suggest that using bio-CNG generated from grass as a biofuel is the optimal feedstock in Ireland. The paper highlights the benefits of using grass silage as a feedstock in Ireland, especially in relation to other first generation biofuels such as biodiesel from rapeseed.

METHODOLOGY

In order to calculate the quantity of emissions produced by the fleet examined, it was necessary to obtain the necessary input data for COPERT. Table 1 details the bus fleet modelled in this paper including Euro level, the number of kilometres travelled, and the number of kilometres travelled per-bus. An average speed of 13 km/hr was assumed. Four different scenarios or models are estimated in this paper. The first model measures the status quo; the second model assumes that the current fleet is replaced with Euro V buses (current enforced limit set by the European Commission for new heavy duty vehicles). The third model assumes that the bus fleet is replaced with Enhanced Environmental Vehicle (EEV – voluntary extra low emission limits introduced by the European Commission in 1999) buses that run on CNG. The final model assumes that the fleet is replaced with EEV buses which run on bio-CNG. Apart from the figure for CO_2, all results for the fourth model are the same as those for the third model. The long-term CO_2 value is taken as 40% of the tailpipe CO_2

given by COPERT. The mileage used for the three alternative scenarios was based on the weighted average of the mileage in model 1.

It is necessary to acknowledge the possible uncertainty in different modelling aspects. There is a small error assumed from using COPERT as its emissions factors are averaged from studies performed in many different countries. In the alternative scenarios the weighted mileage is a conservative figure as newer buses in the current fleet have higher mileages.

TABLE 1 Summary of the four models estimated

Model	Subsector	Technology	Number of Buses	Mileage (km/year)
1	Urban Standard 15t Bus	HD Euro II – 91/542/EEC Standards	38	59,293
	Urban Standard 15t Bus	HD Euro III – 2000 Standards	28	72,161
	Urban Standard 15t Bus	HD Euro IV – 2005 Standards	15	87,754
2	Urban Standard 15t Bus	HD Euro V – 2008 Standards	81	69,012
3	Urban CNG buses (15t)	EEV	81	69,012
4	Urban bio-CNG buses (15t)	EEV	81	69,012

The greenhouse gases which are considered in this paper are Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which can each be described in the form of carbon dioxide equivalents (CO_{2e}), where CO_2 is given the value of 1 CO_{2e} (IPCC, 2007). The actual weighting used to convert CH_4 and N_2O to CO_{2e} depends on the particular global warming potential lifetime used. For this study it was taken as 100 years, and as such CH_4 and N_2O assumed weightings of 25 and 298 respectively (*15*).

COPERT also requires temperature data for the period modelled. Temperature data was obtained from the European Climate Assessment & Dataset *(16)*. Table 2 contains the monthly min and max temperatures used in the model.

TABLE 2 Temperature data

Month	January	February	March	April	May	June
Min (°C)	2.63	2.07	3.29	4.62	6.85	9.99
Max (°C)	8.65	9.00	10.96	13.22	15.95	18.55
Month	**July**	**August**	**September**	**October**	**November**	**December**
Min (°C)	11.46	11.49	10.04	7.35	4.72	3.23
Max (°C)	19.86	20.12	18.15	14.48	10.77	8.70

Despite there being an advanced fuel specification provided by COPERT 4 for 2005 and 2009 stage fuel. This differs slightly from the values which are currently used in Ireland, which are defined in the Air Pollution Act 1987 (*17)*. The only difference between the 2005 and 2009 stage fuel used in Ireland is that the new fuel is practically sulphur free, having its sulphur level reduced from 50 parts per million (ppm) to 10 ppm.

TABLE 3 Fuel specifications

Parameter	Units	Value
Cetane Number	-	51
Density at 15°C	kg/m^3	845
Distillation: - 95% Point	°C	360
Polycyclic aromatic hydrocarbons	% v/v	5
Sulphur Content	mg/kg	50

The polycyclic aromatic hydrocarbon value given in the Irish Statutes is in % m/m, and not in % v/v as demanded by COPERT 4, so the default figure was used instead. Through the EU Fuel Regulations, efforts have been made to improve the quality of automotive fuel and reduce the resulting emissions. These efforts have mainly focused on reducing the sulphur content of the fuel as well as increasing the cetane number. The combustion of diesel containing sulphur generates sulphur dioxide, which reacts with atmospheric water and oxygen to produce sulphuric acid. Sulphuric acid is a component of acid rain, which lowers the pH of soil and freshwater bodies, often resulting in substantial damage to the environment and chemical weathering of statues and structures. The use of lower sulphur content is also expected to allow the application of newer emissions control technologies which can be damaged by sulphur.

The cetane number is a key fuel property of diesel and is a measure of a fuel's ignition delay, which is the time period between the start of injection and start of combustion of the fuel. In a particular diesel engine, higher cetane fuels will have shorter ignition delay periods than lower cetane fuels. This allows more time for the fuel combustion process to be completed, which leads to better combustion and reduced particulate emissions at the tailpipe. The minimum cetane number specified by EN 590 is 46, while the standard range that allows diesel engines to run efficiently is 40-55. After the maximum value of 55, the fuel's performance hits a plateau and does not improve further.

The carbon neutrality of bio-CNG from grass silage was taken as 60% (*18*). As there is no single answer for the carbon neutrality of bio-CNG due to the number of variables involved, an average figure of 60% was used. Variables include the source of heat and electricity used in the process, the fertilizer replacement by grass digestate, carbon sequestered and efficiency of the vehicle. Due to the time and resources available for this research project it was not possible to conduct an original lifecycle analysis of the bio-CNG.

RESULTS AND ANALYSIS

Emissions modelling

Four emissions models were estimated in this study. Each of the four models used to estimate the different emissions are defined in the methodology section. Table 4 presents the results of the modelled emissions from each of the four models estimated over a one year period. The results show that each of the alternatives examined would realise a significant reduction in air pollutants. The results demonstrate that changing the existing fleet to any of the three alternatives modelled would see a significant reduction in emissions. The findings show that the bus operator could realise a 64% reduction in CO_2 emissions from changing the fleet to EEV buses fuelled with bio-

CNG. The results from models 3 and 4 show a 71% reduction in CO emissions compared to the results from the base model. However it was estimated that by changing the fleet to Euro V vehicles there would be an 89% reduction in CO emissions. The results for models 3 and 4 suggest an 87% reduction in PM emissions which were less than 2.5 microns ($PM_{2.5}$) and a 77% reduction in PM_{10}. The results for model 3 also showed a considerable reduction of 60% in $PM_{2.5}$ emissions and 53% in PM_{10} levels. NO_x emissions were also shown to decrease by 87% for models 3 and 4 and by 65% for model 2.

Overall the alternative bus fleets modelled demonstrates a considerable saving in terms of emissions. A comparison between the three alternatives examined demonstrates that the bus fleet operated using bio-CNG (model 4) would result in the largest decrease in overall emissions.

TABLE 4 Emissions results

Pollutant	Model 1	%	Model 2	% change from model 1	Model 3	% change from model 1	Model 4	% change from model 1
CO_2	7,861	100	7,689	-2	7,022	-11	2,809	-64
N_2O	0.044	100	0.181	311	0	-100	0	-100
CO	19.45	100	2.23	-89	5.59	-71	5.59	-71
VOC	3.45	100	0.24	-93	5.59	+62	5.59	+62
SO_2	0.249	100	0.244	-2	0	-100	0	-100
NO_x	82.02	100	28.65	-65	13.97	-83	13.97	-83
NO_2	10.37	100	2.87	-72	0	-100	0	-100
$PM_{2.5}$	1.667	100	0.671	-60	0.221	-87	0.221	-87
PM_{10}	1.879	100	0.883	-53	0.432	-77	0.432	-77

Note: All values for pollutants are in metric tonnes

In order to assess the accuracy of COPERT modelling, the modelled emissions of CO_2 for the original fleet (7,861 t) was compared to the actual CO_2 emitted from the 2008 fleet. This was found using the range of 1400-1450 grams of CO_2 per kilometre (*19*). The margins of error for the COPERT figures compared to the actual were found to be 0.45%, -1.31% and -3.01% for the values of 1400 g/km, 1425 g/km & 1450 g/km respectively.

Economic value of reduction in emissions

The economic benefit analysis was based on the cost savings associated with a reduction in the emission of CO_{2e} and three air pollutants, NO_x, SO_2 and NMVOC. Table 5 presents the values used per tone of air pollutant in Ireland *(20)*.

TABLE 5 Values per-tone of air pollutant

Pollutant	2008 €/t
CO_2	82
NO_x	13,668
SO_2	1,367
NMVOC	13,668

Due to the high cost per tonne and large quantities involved, the most significant monetary savings are from the reduction of NO_x emissions. There is a similar pattern when the reductions from CNG and bio-CNG are compared to Euro V, although the CO_{2e} reduction from bio-CNG is larger in this instance. The value per-tonne of pollutant is multiplied by the number of tonnes of pollutant saved as a result of changing the fuel type and presented in Table 6. The economic benefits detailed in Table 6 monetise the decreases in pollutants relative to the status quo. The results presented in Table 6 demonstrate that operating the bus fleet using bio-CNG would yield the largest economic benefit.

TABLE 6 Economic benefits of reductions in air pollution

Pollutant (€)	Model 2 Euro V fleet	Model 3 HEV - CNG	Model 4 HEV - Bio-CNG
CO_{2e}	€14,922	€58,599	€402,989
NO_x	€729,430	€930,037	€930,039
SO_2	€7	€341	€358
NMVOC	€37,878	€37,488	€37,488
Total (€)	€782,238	€1,026,465	€1,370,874

Feedstock calculation

It was necessary to carry out a sensitivity analysis for the grass silage land area calculation as it was not possible to obtain values for the energy contents of the diesel and CNG used in the COPERT modelling. The sensitivity analysis for the production of the bio-CNG for the bus fleet examined was based on two separate methods, CNG and diesel calculations. The CNG calculation had one variable, the fuel's energy density (GJ/t), while the diesel calculation had two, the quantity of diesel used and its energy density. Table 7 details the quantity of fuels required for each of the vehicle types examined.

TABLE 7 Fuel balance for each fleet

Bus fleet	Quantity (t)
CNG	2543.44
Euro II-III-IV	2494.37
Euro V	2439.86

The values used for the energy density of natural gas in the CNG method were based on the Higher Heating Values (HHV) of three different references, and gave the likely range of values that could have been used in COPERT. The numbers 1, 2 & 3 from Table 8 correspond to the references *(21)*, *(22)*, and *(23)*. All three figures were given as higher heating value (HHV) figures, with the lower heating value (LHV) figures, which apply to the natural gas engine, being taken as 90% of the HHV. The mid range LHV value, corresponding to number "2", was used as it was close to the mean of the three values.

In order to calculate the land area need the energy required was calculated in terms of the volume of methane (m^3/a). This was found using the energy required (GJ/a) and the energy density of methane (37.78 MJ/m^3). The mass of silage figure assumes a biogas yield of 123 m^3/t of silage and a silage yield of 60 t/ha of land (*12*). Finally, the Life Cycle Analysis (LCA) Land area accounted for a parasitic energy demand during production of 42% (*24*).

TABLE 8 Land area calculation using energy density of CNG

CNG (t/a)	2543.44					
Energy density (GJ/t)	HHV			LHV		
	1	2	3	-	-	-
	55.6	52.41	50.3	50.04	47.169	45.27
Energy required (GJ/a)	141,415	133,302	127,935	127,274	119,972	115,142
As Methane (CH_4 - m^3/a)	3,743,125	3,528,367	3,386,316	3,368,813	3,175,530	3,047,685
As Bio-CNG (97% CH_4)	3,858,892	3,637,491	3,491,048	3,473,003	3,273,742	3,141,943
As Biogas (55% CH_4)	6,805,682	6,415,212	6,156,939	6,125,114	5,773,691	5,541,245
Mass of Silage (t/a)	55,331	52,156	50,056	49,798	46,941	45,051
Land area (ha)	922	869	834	830	782	751
LCA Land area (ha)	1,590	1,499	1,438	1,431	1,349	1,295

The diesel based calculation gave slightly lower results compared to the CNG calculations. This could be attributed to the higher efficiency of diesel engines compared to CNG. The first variable in the diesel sensitivity analysis was the mass of diesel combusted, i.e. the quantity used by the 2008 Euro II-III-IV fleet or by the new fleet of Euro V buses. In order to partly account for the lower CNG engine efficiency, the quantity of diesel used by the less efficient Euro II-II-IV was taken to be the more accurate value.

The second variable was the energy density of the diesel. Due to the smaller variation in energy contents of diesel compare to CNG, two values were used in the sensitivity analysis. These correspond to the number "4" *(23)*, which was assumed to be the more accurate, and the number "5", which was used in a similar calculation in "An argument for using biomethane generated from grass as a biofuel in Ireland" *(12)*.

The first step of land area calculation using diesel was to convert the quantity of diesel required from mass to volume using the density of 845 kg/m^3, and then to the energy required using the energy density of diesel. After this point the calculation was very similar to the Table 9 calculation and used the same values for energy density of methane, volume of biogas per tonne of silage, mass of silage per hectare, and parasitic energy demand.

TABLE 9 Land area calculation using quantity and energy density of diesel

Diesel (t/a)	Euro II-III-IV		Euro V	
	2,494		2,440	
Diesel (m^3/a)	2,951		2,888	
Energy density (GJ/m^3)	4	5	4	5
	36.9	36	36.9	36
Energy required (GJ/a)	108,910	106,253	106,551	103,953
Methane (m^3/a)	2,882,731	2,812,421	2,820,314	2,751,526
Bio-CNG (97% CH_4)	2,971,888	2,899,403	2,907,541	2,836,625
Biogas (55% CH_4)	5,241,330	5,113,492	5,127,844	5,002,775
Mass of Silage (t/a)	42,612	41,573	41,690	40,673
Land area (ha)	710	693	695	678
LCA Land area (ha)	1,224	1,195	1,198	1,169

The two values which were assumed to be the most accurate were 1,349 ha and 1,224 ha, corresponding to "LHV 2" and "Euro II-III-IV 4" respectively. The values were reasonably close, with the diesel value 9.3% lower. The lowest value obtained was approximately 74% of the maximum value.

CONCLUSIONS

The results showed a major decrease in all pollutants from the use of CNG EEV buses instead of the 2008 fleet for Euro II, III and IV buses. There was a minimum reduction of 70% in emissions of all air pollutants, and a 100% reduction in SO_2 and heavy metal emissions due to the fuel used. There was a decrease of 63% in the emission of greenhouse gases when bio-CNG was used instead of CNG. CNG showed a 7% reduction in CO_{2e} emissions. This showed that the use of CNG EEVs is an effective way of reducing air pollution from the current fleet, but that bio-CNG is needed in order to make large reductions in CO_{2e} emissions.

When the use of CNG and bio-CNG was compared to a new fleet of 81 Euro V diesel buses, there was still a significant reduction in the emission of most air pollutants, with NO_x and PM emissions down by a minimum of 50%. The two exceptions to this were CO, which a showed a major increase, and NMVOC, which showed a small increase. This validates the view that the gap between the air pollution emissions of natural gas buses and diesel buses has narrowed with an improvement in technology, and in some cases, such as for CO and NMVOC, diesel is preferable. The use of Euro V diesel buses showed only a very small decrease in greenhouse gas emissions of 2.3% compared to the 2008 fleet. This confirms the fact that improvements in bus engine technology will not be significant enough to help Ireland reduce its greenhouse gas emissions.

The social benefits in monetary terms due to a decrease in air pollution and greenhouse gases from the use of bio-CNG gave a value of approximately €1,300,000 and €600,000 per annum instead of Euro II-III-IV and Euro V respectively. While these values are not insignificant, they would not justify the use of bio-CNG EEV buses.

The diesel buses, which were modelled for the year 2008, were assumed to be using 2005 stage diesel. On January 1st, 2009, the use of 2009 stage diesel became mandatory for road transport in Ireland *(17)*. The new fuel reduces the sulphur limit from 50 ppm to 10 ppm. This has the effect of reducing SO_2 emissions from vehicles using diesel. Due to the very low SO_2 emissions produced by both the Euro II-III-IV and Euro V fleets, and the almost insignificant social benefit in monetary arising from a reduction, it was considered unnecessary to re-run the model using 2009 stage diesel.

When examining the results presented in this paper one must be mindful of the limitations of the approach followed in this study. The COPERT model is based upon international averages and as such may be subject to some error in the emissions calculated. The vehicle activity data may also be subject to some scrutiny in that the total number of kilometres travelled is correct, but the average speeds reached at any part of the buses journey may vary. This may therefore result in inaccuracies in the activity data modelled. The results for the land take required to produce the feedstock may also be subject to some question in that it uses percentages from other studies. Where possible in this study these limitations have been addresses and sensitivity analyses have been used to mitigate any uncertainty in the results.

This study examined the emissions that would have been produced by a fleet of bio-CNG buses had they been used instead of the 2008 fleet at Clontarf depot. Any future research should instead examine the emissions that would be produced by altering the future procurement strategy. This was done by the Federal Transit Administration *(25)*, and is a more suitable method of investigation for recommending future policy.

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