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TNO report

TNO-033-HM-2008-01259

Alternative fuel options for urban bus application in the Netherlands. A comparative study.

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Project number	033.16513

Classification report
Title
Abstract
Report text
Appendices

Number of pages	59
Number of appendices	0

Summary

Today, a large number of urban areas in the Netherlands face significant local air quality problems. One source of this local pollution is road traffic and, in urban areas, public transport by city bus. For this reason, there is a lot of interest in different opportunities to lower the harmful emissions from city buses. A possible method to so is the introduction of alternative fuels.

This study compares a number of alternative fuel options for use in Dutch urban city buses. The compared fuels are:
1) regular low-sulphur (EN590) diesel
2) GTL (Gas To Liquid, a synthetic diesel engine fuel made from natural gas)
3) B100 (biodiesel)
4) Ethanol, to be used in a diesel cycle engine
5) CNG (Compressed Natural Gas; fast- and slow-fill fuel station option)
6) CBG (Compressed BioGas, upgraded and cleaned biogas; slow-fill option)

The main topics of comparison were regulated emissions, costs and global warming potential. Comparisons were made for buses compliant with Euro 3 to Euro 5/EEV emissions legislation.

Of course the outcome of such a comparative study is influenced by the assumptions made. Different assumptions can and will lead to different conclusions. In this respect, the most important assumptions are on the kind of fleet envisioned and on the price level.

- This study considers an urban bus fleet with the following specifications :

– Annual mileage per vehicle	60.000 km
– Number of vehicles in the fleet	80
– Number of passengers per bus	40 (on average)
– Life cycle of a vehicle	8 years

- These numbers are based on the specifications of the bus fleet operated by Connexxion in the of Haarlem in The Netherlands and are assumed to reflect the typical situation in the Netherlands. The duration of 8 years reflects the duration of a concession (contract) between a local authority and the fleet operator in the Netherlands.
- Furthermore, this study considers the price levels for (new) vehicles, fuel station modification and fuel as per december 2007.
- Finally, fuel consumption and emissions are based on the assumption that the driving pattern of the buses would be well represented by the so-called Dutch Urban Bus Driving Cycle. For these calculations a city bus vehicle model available with TNO was used. In this model vehicle specifications typical of the current Dutch urban buses were used (typical weight, frontal area, automatic transmission etc.)

The main conclusions are as follows:

For a given available budget, drop-in replacement of diesel by GTL would be the cheapest and fastest pathway to realize a significant improvement in local air quality (reduction in NO_x and PM emissions). If it were possible to adjust the current vehicles for optimum use of GTL even larger benefits could be possible.

When comparing different fuel options for the introduction of a new fleet of best-in-class vehicles (Euro-5/EEV emissions targets), the outcome of the comparison is summarized in the table below (ethanol was not retained for this comparison):

	Best	Second best	Third	Fourth
Total Fleet Cost$^{1)}$	GTL	B100	CNG stoich.	CBG stoich.
NO_x emission reduction	CNG/CBG stoich.	GTL	B100	CNG lean
Global Warming Potential	CBG	B100	CNG lean	CNG stoich. GTL$^{2)}$
Cost-effectiveness of NO_x reduction	GTL$^{3)}$	CNG stoich.	CBG stoich.	B100

$^{1)}$ Assuming december 2007 price levels
$^{2)}$ Not assuming CCS technology implementation; assuming engine design and calibration optimised for best thermal efficiency on GTL
$^{3)}$ For GTL an indicative (best-available) value only has been used

The Euro-5/EEV diesel vehicles in this table use (open-loop controlled) SCR+DPF aftertreatment technology.

This table compares the different fuels on their own merits. That is : no fuel taxes or subsidies of any kind were assumed for the different fuels. Furthermore, in principle, in this table GTL refers to the GTL drop-in situation[1]. With drop-in GTL-application, GTL would come in fifth place for GWP. However, if new engines were developed that would be dedicated towards application of GTL then it would be possible to further improve fuel efficiency and reduce Global Warming Potential of the GTL fuel. Of course, with such an engine (aimed at improving fuel efficiency) the NO_x emissions benefits could potentially be reduced.

In this study, two scenario's are investigated: GTL drop-in replacement and GTL application in an engine optimised for maximum thermal efficiency. For the latter, it is assumed that the engine thermal efficiency can be improved by 5% compared to the GTL drop-in situation. In the scenario with maximized fuel efficiency, the NO_x benefit of GTL will be strongly reduced, but as far as GWP is concerned, GTL moves close to CNG stoichiometric.

The table does not mention particular matter emissions. PM_{10} (or PM) emissions of all new (Euro 5/EEV) are low enough (<0,02 g/km) not to be significant when compared to other transit bus-related sources of PM_{10} emissions such as tyres and brakes.

Of course this table is a simplified representation of the results and as the report shows it should not be used without explaining also its limitations and caveats.

Below, a more detailed description of the outcome of this study is given.

Regulated emissions

- When comparing regulated emissions only drop-in replacement scenario's have been considered. It was assumed that no engines would be available that would be dedicated for lowest emissions with GTL. (Such engines have however been developed for natural gas.)

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[1] Drop-in refers to the situation where the engine design and calibration is that for regular diesel. That is : no modifications are made to correct/adjust for the fuel switch.

- As it was expected from the start of the project, it has proven to be difficult to obtain statistically robust data on a back-to-back comparison of the emissions of new diesel vehicles (Euro-4 and Euro-5 emissions class) on alternative fuels versus low-sulphur regular diesel. Using the limited data available an as good as possible estimate was made of the emissions behaviour of the alternative fuels in these engines. These data should be considered as best available indications. Most likely more data will come available in the near future to substantiate and/or improve these numbers.
- The emissions data that were arrived at in this study indicate that significant emission reductions compared to the diesel baseline are possible by using GTL :
  - For the older (Euro-3) engines, the absolute reductions both on NO_x and PM are highest with drop-in replacement of diesel by GTL. GTL is more favourable than B100 due to the fact that GTL lowers both PM and NO_x. With B100, only PM is reduced and NO_x normally increases. The GTL emissions advantages on Euro-3 diesel vehicles are however matched by the lean-burn CNG/CBG alternative.
  - For Euro-4 engines, drop-in GTL is also the cleanest option for NO_x; on particulates only the CNG/CBG alternative is better.
  - For new, Euro-5/EEV vehicles only NO_x emissions are relevant; PM emissions with these vehicles are below 0.02 g/km; this is considerably below the level of particulates produced by tyres and brakes (0.1 g/km). When considering only NO_x the GTL drop-in option is the cleanest liquid alternative fuel option. Only the CNG/CBG stoichiometric engine gives a better emissions performance. That is because these engines combine a very effective catalytic NO_x aftertreatment technology with a very accurate closed-loop control. Current Euro-5/EEV diesel engines only have open-loop aftertreatment control. Because of this open-loop control strategy the engine-out emissions advantage with GTL fuel is maintained (to a varying degree) after the aftertreatment system.

Additional costs compared to the diesel baseline

- First of all it is important to point out that the cost results are very case sensitive and specific to the Dutch situation. Changes in the size of the fleet, in the type of bus vehicle (articulated or not), in the driving pattern, in the average bus mileage or in the duration of a fleet concession will affect the outcome of the cost-comparison.
- For the price levels used, in general, drop-in replacement of diesel in the existing fleet by GTL or BTL are the best options. And between those 2 alternative fuels, GTL is the cheapest option. Drop-in replacement of diesel by ethanol is not competitive.
- Because of their high investment costs, the gaseous alternative fuel options are of interest only when the introduction of a new fleet is considered. When comparing the different fuels on their own merits (that is exclusive of tax and subsidies) GTL is at present also in that case the most cost-effective solution. The natural gas option would need a 15 % reduction in cost level to fall into the GTL range.
- If however taxes are included (as they are in the Netherlands) and if GTL is taxed in the same way as regular diesel, then the natural gas option and the GTL drop-in option come very close. The slow-fill option seems to be somewhat cheaper and the fast-fill option somewhat more expensive than the GTL drop-in alternative. Given the uncertainty level also in these calculations (especially in the natural gas application) one could argue that they are equivalent. To decide between these options a more detailed analysis is needed that would take into account local conditions/constraints, actual emissions and fuel consumption specifications of the candidate vehicles as well as actual price levels.

- If Euro-5/EEV GTL-dedicated engines would be put on the market that would be optimised for highest efficiency, then the costs with these engines would (even with diesel-like taxes) be lower than with the current CNG stoichiometric alternative. Of course, also with gas engines possibly further efficiency improvements could be introduced. Likewise, maintenance costs with CNG engines are expected to become smaller as time evolves.

Global Warming Potential.

- When comparing the fossil alternative fuels GTL and natural gas, GTL consistently has a higher GWP than the natural gas alternative. When considering only the newest generation of vehicles, the difference between GTL and the stoichiometric natural gas option becomes small. Then the WTT-GHG emission contribution starts playing an important role. When it is assumed that NG is piped from a long distance then the difference between GTL and stoichiometric CNG is smaller than 5 % (and almost zero for a Euro-5 engine that would be optimised for best fuel efficiency on GTL). Considering future potential efficiency improvements in GTL production technology this difference could become even smaller.
- If on the other hand it is assumed that the origin of the natural gas resembles that of the current NG mix in the Netherlands, the benefit of the natural gas option increases again.
- If lean-burn natural gas vehicles would be considered for Euro-5/EEV introduction, then these are expected to have the lowest GWP (even when the above issues are taken into consideration).
- In this comparison the possibility to reduce the WTT-GHG emission of GTL production through Carbon Capture and Storage (CCS) technology was not withheld. When this technology will be introduced in the future, then GTL would most likely become the fossil fuel with lowest GWP.
- For the biofuels, only B100 and CBG (compressed biogas) have been compared. Biogas clearly has the best GWP.
- If synthetic fuel would be produced from biomass (BTL), then most likely the difference between BTL and CBG would become small if the BTL fuel would be produced from waste woody material. If the BTL would be produced from farmed biomass then probably CBG would remain the best solution. A detailed analysis of BTL was outside the scope of this study, but would be highly recommended.

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Cost-benefit trade-off of reducing local emissions.

- Of course, when considering this issue, the comments on price-level and cost estimates mentioned above have to be kept in mind.
- When looking at the reduction of local PM emissions :
  - for drop-in replacement of diesel by alternative liquid fuels, only GTL and B100 are realistic options. In that case, GTL clearly is most cost-effective, more so than B100. This may come as a surprise since B100 is an oxygenated fuel (that is a fuel with oxygen bound to the fuel molecules).
  - When considering the introduction of a new fleet of Euro-5/EEV vehicles, PM-emissions are no longer important.
- When considering the NO reduction, the following observations can be made :
  - the results show that drop-in replacement of diesel by GTL in the existing fleet is also for NO_x by far the option with the highest cost-benefit trade-off (irrespective of taxation),
  - Drop-in replacement of diesel by biodiesel is allways more expensive.

- When new vehicles are considered for alternative fuels, Euro-5/EEV should be preferred above Euro-4 technology. This statement holds both for GTL and B100.
- When considering new Euro-5/EEV vehicles the GTL option is again the best one. Although the difference with the stoichiometric CNG version is small (as well as with the CBG version of the latter).
- If taxes are accounted for, and if diesel-like taxes are assumed for GTL, then the stoichiometric gas vehicles come out best.

Further research could focus on the potential fuel efficiency benefit when using GTL or the lowest possible emission level when using GTL. Both could be investigated by optimizing a current HD-engine with aftertreatment for maximum efficiency or for lowest emissions. An optimum in the specific tradeoff between fuel efficiency and emissions for a HD engine can then be determined, thus showing the maximum potential of synthetic fuels in current HD engines.

Contents

1 Introduction

Today, a large number of urban areas in the Netherlands face significant local air quality problems. One source of this local pollution is road traffic and, in urban areas, public transport by city bus. For this reason, there is a lot of interest in different opportunities to lower the harmful emissions from city buses.

One class of fuels that could play a role in this are the so-called synthetic liquid fuels. These fuels are non-distillate fuels that can be produced from different sources. At present one such fuel class is GTL (acronym for Gas To Liquid fuel). GTL is produced synthetically from natural gas.

At present a highly paraffinic (i.e. free of aromatics), sulphur free and high cetane number GTL diesel fuel is being produced by a number of fuel manufacturers. Shell is prominent amongst them. Other manufacturers have started producing similar fuels. GTL should therefore be considered a new class of fuels (with some variation in properties such as distillation range, cetane number and importance of different types of hydrocarbon compounds). Because of their abovementioned generic characteristics these GTL diesel fuels have shown to provide significant reductions in certain emissions. Furthermore – because handling of these fuels is similar to that of regular diesel – this alternative fuel is easy to implement.

Of course, GTL fuel is available only in smaller quantities today, but production will be scaled up to higher levels in 2010. This is likely to happen for a number of strategic reasons : synthetic fuels are not derived from petroleum, they can be produced from many other fossil fuels, and - very important – this technology can be used to produce a similar fuel from biomass material. In that case it is referred to as BTL (acronym for Biomass To Liquid). When properly produced, BTL fuel has the potential to drastically lower well-to-wheel greenhouse gas emissions from vehicles. Since both BTL and GTL as end product are similar products, GTL fuel introduction can thus prepare the market for BTL Fuel.

Europe is the largest potential market for GTL Fuel. In fact the European Parliament has already recommended the introduction of synthetic fuels both in the area of conventional energy sources as well as in the area of renewable energy. Specifically the European Parliament calls “on the Commission to support synthetic fuels technology, in view of its potential to reinforce security of energy supply and reduce emissions from the road transport sector in Europe".

The Netherlands in particular may represent a very interesting market for the synthetic fuels. Because of the high population density in a large part of the country there has been, for many years, a strong interest in reducing local emissions from automotive transportation. This has been the basis for a continued interest in and support of cleaner alternative options by (local) authorities. Large urban areas, with air quality issues, may therefore significantly benefit from the use of Synthetic/GTL Fuels.

The Netherlands are already supporting gas derived alternative fuels such as CNG and LPG, but the costs/benefits trade-off of these fuels seems to be challenging, requiring a high level of government support / tax rebates. (This also could explain why at - the start of 2008 - only a small fraction of the approximately 11000 buses in the

Netherlands were registered as gas fuelled buses. At that time 88 buses were registered as natural gas buses and 113 buses were registered as LPG buses. Of the 88 natural gas buses, 85 are part of the Haarlem fleet run by Connexxion. Eight more natural gas buses were scheduled to enter service in Groningen.) In this context, GTL fuel may represent an interesting option for the Netherlands.

This study investigates the potential impact of the use of a number of currently available alternative fuels (including GTL) in city buses on regulated emissions, costs and global warming potential.

This study was conducted by TNO during the first and second quarter of 2008 on behalf of Shell Global Solutions.

2 Assignment description

The main goal of this project is to obtain an independent evaluation on how GTL Fuel compares with other alternative fuels in city buses in the Netherlands. For this TNO studied the effect of this fuel choice on the following paramters :

- local emissions of NOx, PM, CO and HC
- Well-to-Wheel and Tank-to-Wheel GWP
- Cost effects of the various options, divided into:
  - Vehicle operational cost
  - Infrastructure cost
  - Capital cost

2.1 Background

The current Dutch city bus fleets consist almost exclusively of a mix of diesel powered vehicles. Depending on their age these vehicles will have different diesel technology implemented. Diesel technology is referred to as Euro-0, Euro-1, etc. until Euro-5. The Euro-x acronym refers in turn to the (European) emission legislation that the corresponding vehicle had to comply with at the time of its production. Table 1 below gives an overview of these different stages in the European emission legislation.

Table 1. Heavy-duty vehicle emission regulation in Europe (per January 2008).

	Year	**Test cycle**	**HC** g/kWh	**CO** g/kWh	**NOx** g/kWh	**PM** g/kWh
Euro-2	1998	R49	1.1	4.0	7.0	0.15
Euro-3	2000	R49	0.66	2.1	5.0	0.10
EEV	1999	ESC[2)]	0.25	1.5	2.0	0.02
	2000	ETC[3)]	0.4[4)]	3.0	2.0	0.02
Euro-4	2005	ESC [2)]	0.46	1.5	3.5	0.02
		ETC [3)]	0.55	4.0	3.5	0.03
Euro-5	2008	ESC	0.46	1.5	2.0	0.02
		ETC	0.55	4.0	2.0	0.03

[1)] R49 is a weighted average of steady-state emissions measured in 13 different operating points

[2)] ESC is a similar weighing but in other (supposedly more representative) operating points

[3)] ETC additionally required for engines with advanced aftertreatment systems such as SCR deNOx and particulates trap

[4)]This is the limit to Non-Methane Hydrocarbon emission; Methane emission is limited to 0.65 g/kWgh

To achieve the important reduction in nitrogen oxides and particulate matter emissions imposed by the increasingly stringent emission legislation the diesel engine manufacturers have had to introduce new technology to their engines.

To go from Euro-0 to Euro-3 emission levels the diesel combustion process was refined; this involved : increasing injection pressure, reducing in-cylinder angular momentum of the charge air, retarding injection timing and going from a 2-valve per cylinderhead towards 4-valve per head design (the latter enabling a vertical position of the diesel injector in line with the cylinder axis and with the axi-symmetric piston bowl axis). In addition the piston bowl geometry and compression ratio were optimised.

To go from Euro-3 towards Euro-4 two different paths have been taken (and both are presently sold on the market).
One approach implements exhaust gas recirculation as a means to further reduce NO_x formed in the engine; this is combined with a further increase in fuel injection pressure and an increase in boost pressure (to reduce particulate formation). This is referred to as the Euro-4/EGR approach. These engines will meet with the legislative NO_x targets. To meet with the PM targets some aftertreatment is needed. Particulate aftertreatment with current Euro-4 EGR engines is either an oxycat (e.g. Scania) or a so-called through-flow or “open” catalytic diesel particulate filter (such as the PM-Kat; e.g. Scania and MAN). The latter are passive systems (i.e. they use some catalytic loading of the filter for PM oxydation but they do not apply strategies for assisting this oxydation through exhaust system thermal management).
The alternative Euro-4 solution uses catalytic aftertreatment of the exhaust gases to reduce NO_x emissions. For this the vehicle manufacturer relies on a selective catalytic reaction between ammonia (NH_3) and the NO and NO_2 in the exhaust gas. The ammonia is produced by injection of a urea-water solution in the hot exhaust upstream of the catalyst. These engines do not need a PM aftertreatment system.

For meeting with the Euro-5 requirements both Euro4-technology paths are being continued. Recently Scania demonstrated Euro-5 engines using EGR for NO_x reduction without particulate aftertreatment. Also MAN continues this track (for part of its engine range). The majority of engine manufacturers (MB, DAF, IVECO, Volvo) will however opt for SCR-aftertreatment.

Already in 1999, as an incentive, a new class of so-called Enhanced Environmentally Friendly (or EEV) vehicles was defined. These vehicles would achieve very low emissions. As Table 1 shows, EEV is marginally lower in HC, CO and PM than Euro-5. At the time of the introduction of this EEV initiative (1999), only gas engines could meet with these emissions requirements. This situation continued until the start of 2007 when vehicle manufacturers presented diesel EEV vehicles. Essentially these are Euro-5 vehicles in combination with a diesel particulate filter (DPF). In some cases these vehicles combine enhanced EGR with aftertreatment (passive “open” catalytic DPF for Scania and – probably - future MAN vehicles) or even with a CRT (Continuously Regenerating Trap filter, a “closed” catalytic DPF used by early MAN/EEV vehicles). Others combine a SCR system with a “closed” catalytic DPF (VDL).

2.2 Fuel selection

A wide variety of fuels are being considered for application. After a first preliminary discussion with Shell Global Solutions, the following set of fuels were selected for more detailed investigation :

- EN590 Ultra Low Sulfur Diesel (<10ppm sulphur). This is the reference fuel. It is the most common diesel fuel quality in the Netherlands. Other (premium) diesel fuels als not considered.
- 100% Gas-To-Liquid, an innovative synthetic diesel fuel made from natural gas
- 100% Biodiesel (RME, Rape Methyl Ester), 1st generation biodiesel
- Dutch Natural Gas, in the form of compressed natural gas (CNG)

And, in less detail:

- 95% Ethanol with 5% lubricity and cetane improvers to be used in a diesel-cycle engine
- Biogas, which has been upgraded to Biomethane[i] and is used in standard CNG powered buses

2.3 Engine technology selection

2.3.1 Engine technology for liquid alternative fuels

Of course engine technology will change with alternative fuel type. In general, the selected liquid alternative fuels will be combined with the regular diesel engine technology. For gaseous fuels retrofitted or dedicated engines are used.

Although there are still some older generation vehicles on the road, the majority (≈ 65 %) of city buses in the Netherlands are diesel fueled and Euro-3 or more recent. Of these Euro-3 vehicles, some 25 % have been retrofitted with open catalytic DPF.
This study therefore considers buses from a Euro-3, -4 and -5 emission level.

In line with the current market situation, for the Euro-4 emissions class diesel vehicles two different engine technologies were considered:

- Euro-4 EGR (Exhaust Gas Recirculation) + particulate aftertreatment.
- Euro-4 SCR (Selective Catalytic Reduction) without particulate aftertreatment.

Both the Euro-4 EGR aftertreatment options (EGR+oxycat and EGR+passive “open” catalytic DPF) have been presented to the Dutch market, but TNO did not have info on their relative importance. The majority of Euro-4 engines (≈ 75 %) would be applying the alternative SCR technology.

When considering new diesel technology, this study considers only the cleanest diesel EEV option. In the report this is referred to as Euro-5/EEV. This is also the technology favoured by Dutch authorities.
For this study, TNO considered only vehicles with SCR aftertreatment technology and a “closed” wall-flow catalytic DPF. (Towards the end of 2007 the alternative technology without NO_x aftertreatment was just being presented to the market.)

2.3.2 Engine technology for gaseous fuels

Over the years, gas powered vehicles have been introduced that met with the emissions requirements of that time. In the Euro-3 and Euro-4 time frame these were (mostly) lean-burn engines. With the advent of the EEV initiative, attention with gas engine development turned towards stoichiometric combustion (with some amount of EGR). The stoichiometric + EGR engine concept offers the possibility to use three-way-catalytic aftertreatment of the exhaust gases. This enables the stoichiometric engine

concept to attain significantly lower regulated exhaust gas emissions than the lean-burn engine. Therefore, it is widely accepted that the natural gas engine of the future will be stoichiometric + EGR type.
Because of this, when considering state-of-the-art gas engines to compete with (Euro-5/EEV) diesel technology for urban bus application both options were retained :

- Lean burn
- Stoichiometric + EGR

2.4 Availability

For all alternative fuels, a comment must be made on the availability of the fuels. Whilst regular diesel and natural gas are available in large quantities, the same cannot be said of GTL, B100, ethanol, BTL and Biogas.

- GTL is produced in a number of pilot plants around the world at the moment and new facilities with production capacities larger by an order of magnitude are due to come online within the next year or so.
- At this moment, BTL is not yet produced on an industrial scale. B100 and Ethanol are often produced locally or need to be imported. Although certainly not impossible it might prove to be difficult to establish a stable fuel supply for a bus fleet of the size considered in this study.
- In the Netherlands, biogas has been getting quite some attention. However, also for biogas the availability is limited. At this moment a capacity of 75 MWe of biogas-derived electric power is in preparation/running, whereas biogas clean-up projects are still in preparation (info SenterNovem jan 2008).

3 Methodology

3.1 Cost calculation model

TNO developed a dedicated cost model for calculating the additional expenses of operating an urban bus fleet on an alternative fuel. The cost model is designed to compare different vehicle and fuel options.
The cost model needs input data on the bus fleet size and the annual mileage, infrastructure costs, fuel costs and specifications, vehicle costs and specifications and interest rates. An overview of all the required inputs is presented in the Table 1.1. For the outcome it is very important to have as accurate input data as possible. If the input factors are not correct, the outcome will not be trustworthy. It is furthermore important to point out that although certain subsidies are currently available (e.g. for the introduction of CNG powered buses) these are not included in this study.
The results from the calculator can be presented for example in Euros per kilometer or Euros per year. The results are also divided in several sectors such that the cost distribution can easily be studied.

Table 1 Required data for the cost model

Fleet info	**Fuels**	**Infra-structure**	**Vehicle**	**Capital costs**
Fleet size	Prices	Fuel station costs (initial and annual)	New vehicle prices	For infrastructure
Annual mileage	Taxes	Maintenance costs	Maintenance costs	For vehicles
	Additional costs (e.g. Pressurizing for CNG and CBG)	Training costs for personnel	Insurance & annual costs	Interest rate
	Density	Facility modification costs	Vehicle depreciation rate	
	Energy content	Fuel station Insurance cost	Fuel & additives consumption	

The inputs for the cost model are specified as follows:

1) fleet info
   a. Fleet size: the number of buses in the fleet (80)
   b. Annual mileage: the annual mileage of each bus in the fleet (60.000 km or approximately 37.500 miles per bus)

2) Fuels
    a. Prices: the raw (excluding taxes) fuel price per liter (liquids) or kg (gases)
    b. Taxes: the applicable (current) tax levels per liter (liquids) or kg (gases)
    c. Additional costs: the additional costs for fuel processing (if applicable; an example is the cost for compression of gaseous fuels)
    d. Density: the density of the fuel. Used to calculate the energy content of the fuel per commercial unit (kg or liter)
    e. Energy content: the lower heating value of the fuel. Used to calculate the energy content of the fuel per commercial unit (kg or liter)
3) Infrastructure
    a. Fuel station costs, initial: the initial cost for the realization of a fuelling station. It is assumed that the facility is fully depreciated over an 8 year (the duration of one concession) period. These costs are considered to be financed by a loan that is fully repaid within 8 years. Interest is included in capital costs.
    b. Fuel station cost, annual: the additional cost for operating the fuelling station. This includes the insurance cost related to the fuelling station. In case of the gaseous fuels (slow-fill) this also includes three people doing a nightshift to refuel all the vehicles. In case of fast-fill installation, buses can be fuelled quicker, which reduces the additional costs significantly.
    c. Maintenance cost: the annual cost for the maintenance (preventive and corrective) of the fuelling station, including inspections and certification.
    d. Facility modification cost: the initial cost for the implementation of the fuelling station, other than building cost. This includes mainly (refueling and maintenance) personnel training costs. For gaseous fuels, also investments are needed for modifications to the bus maintenance facility (installation of gas detectors etc.). These investments costs are part of the loan mentioned in item 3a above.
4) Vehicle
    a. New vehicle price: the price of one new bus. It is assumed that a loan is taken out to fund the purchase of the vehicles.
    b. Maintenance cost: the additional annual cost for each vehicle
    c. Insurance and annual cost: The cost of insurance and the obligatory annual technical check (APK)
    d. Vehicle depreciation rate: the rate of depreciation of the vehicle. It is assumed that the vehicles have a certain percentage of residual value after 8 years. The depreciation rate is assumed to be linear over these 8 years.
    e. Fuels and additives consumption: the cost of fuel for the vehicle. Adblue (the reagent for an SCR system) cost is also included for the vehicles that use SCR technology
5) Capital cost
    a. For infrastructure: the annual cost of the capital used for the realization of the fuelling infrastructure. Calculated by multiplying the effective interest rate (5c) by the loan necessary to realize the fuelling infrastructure.

b. For vehicles: the annual cost of the capital used for the investment in the vehicles. Calculated by multiplying the effective average interest rate (5c) with the investment cost (loan) for the vehicles.
c. Interest rate: the (inflation corrected) average interest rate used to calculate the capital cost. (4,15%)

3.1.1 Cost model inputs

The input values for this study have been obtained from several different sources. All the values are presented in chapter 4. The input values that have been used for this study are only valid for the case determined by the customer.

- Information concerning the fleet size and the annual mileage were determined by the customer. These values are based on the mileages and number of vehicles in the city of Haarlem in The Netherlands.
- Fuel quality values are based on the fuel quality standards and information received from the fuel producers. These values also match with the values used in other studies.
- Infrastructure costs are estimations based on different studies and values received from the manufacturers.
- Vehicle costs are average prices that a bus operator has to pay for a certain vehicle and service.
- For capital costs a constant average annual interest rate (corrected for inflation) of 4.15 % has been used. The vehicle depreciation value is considered in the total vehicle cost, but not in the capital costs.

3.1.2 Simulations

Different vehicles powered by different engines will have different efficiencies and thus fuel consumption. To make a fair comparison amongst fuels, a simulation model was used. This approach allows to keep the vehicle specifications constant (unless they would change as a result of the fuel choice). Typical vehicle specifications were :

- vehicle length : 12m
- vehicle weight (on diesel) : 11000 kg
- load : 40 passengers

Also, the different engine maps were all scaled towards the same maximum power of 190 kW.
The simulations were carried out with a VersitPlusHD-simulation software, which has been developed for an EU collaboration project ARTEMIS[ii].
The vehicle specifications that have been used are representative for the city buses (a.o. MB Citaro, Iveco Citelis, MAN Lion’s City, VDL) currently on the road in the Netherlands.
The driving cycle used for the simulations was the DUBDC cycle (Dutch Urban Bus Driving Cycle). This cycle has been developed by TNO and is based on real-life data collected from urban city buses. The speed/time profile of the DUBDC cycle is presented in Figure 1.

To calculate the regulated emissions TNO used an internal emission data bank. This data bank contains emission factors for several vehicle types and engine technologies. The same values are also being used for assessment studies on behalf of Dutch authorities.

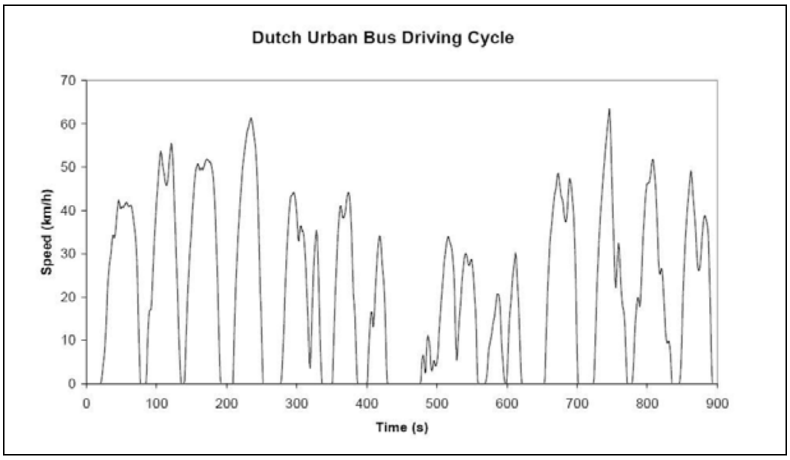

Figure 1 The speed-time trace of the DUBC (Dutch Urban Bus Cycle)

3.2 Emissions

3.2.1 Regulated emissions

The emissions of carbon monoxide (CO), hydrocarbons (NMHC + methane = HC), nitric-oxides ($NO + NO_2 = NO_x$), and particulate matter (PM) are regulated in Europe. For heavy-duty vehicles, like trucks and buses, the engine (with its after-treatment system) emissions are based on measurements on an engine test bench using the ESC and ETC test cycles. It is not a priori clear how these test-cycle emissions relate to real world emissions on the road. The ESC and ETC tests are performed with hot engines. The cold start has so far been considered as having a small effect on real-world emissions of heavy-duty diesel vehicles. The presence of after-treatment systems, like DPF and SCR which require a high operating temperature, is changing this situation.

In this investigation real world emissions values have been estimated for different emission and technology classes and for different fuel types. Due to the nature of the study, these emission values are indicative only.
Real world emission values (g/km) have been obtained for the following emission- and technology classes for diesel, biodiesel and GTL:

- Euro-3,
- Euro-4 EGR,
- Euro-4 SCR,
- Euro-5, EEV.

The number of emissions data was large for the Euro-3 generation of vehicles. This number was much more limited for the Euro-4 generation of vehicles (introduced since end of 2004). For the Euro-5 vehicles (that are just entering the market) the information was even more limited (2 independent studies from good research groups).

For CNG average emission values were estimated for the following categories:

- Euro-3 (lean burn)
- Euro-4 (lean burn)
- Euro-5/EEV (lean burn and stoichiometric)

As a first step emission values have been estimated for regular diesel and CNG buses. Real world emission values (for in-city use) have been obtained from the VERSIT+ emission model and from literature reporting experimental studies with buses where real world emissions were measured. This was completed with expert judgment. Resulting emission values are based on an average of emission values found for the different categories.
In this first step emission values were selected only from data that were (with respect to driving pattern and load) representative for use of a bus in the city. City buses have a particular low average velocity with many stops. The typical engine load varies therefore greatly, with a large fraction spent at reduced load. Therefore, special driving cycles for city bus use have been developed that represent this behaviour. Representative drive cycles used in the literature are DUBDC, 9040 Citybus, Braunschweig, Orange County, Helsinki 2 and De-Lijn cycle.

Based on a second literature review the change of emission levels was estimated for GTL and biodiesel when compared to diesel. Due to the large variation in results found in the literature, the focus was on comparisons done with the same vehicle or engine (GTL and diesel tested in the same engine / vehicle). From the results found in literature a relative range has been developed and typical reduction values were selected for both GTL and biodiesel compared to diesel.
It should be noted here that most studies found in literature compare GTL with a lower grade diesel (sometimes even with high sulphur content). As this is not representative for the European situation, also an estimate of the typical reduction relative to a higher grade diesel (representative for the EU situation of 2008: sulphur < 50 ppm, CN > 51) has been made. The improvement in the fuel-quality of diesel has decreased the emissions, with the decrease of sulphur content mainly affecting the PM emission, and the increase in cetane number affecting both PM and NO_x, only less pronounced. From the two sets of data, the final emissions benefit when replacing high-grade diesel with GTL could be determined. For this a regression analysis was applied to the different data.
The typical relative values thus found for GTL and biodiesel have then been combined with the real world emission factors for diesel to determine the actual typical absolute emissions (g/km) for these alternative liquid fuels.

In a last step typical emissions per passenger kilometre have been calculated from the derived emission factors for GTL, biodiesel, diesel and CNG. This calculation has been performed with the assumption of 40 passengers in the bus.

Remarks
In the course of this investigation the following relevant points came to light:
- In emissions the main interest is in PM and NO_x. For modern after-treatment systems, such as in Euro-4 / Euro-5/EEV, the CO and HC emissions when using GTL and B100 are reduced compared with diesel. However these emissions are low anyway, due to the presence of an oxidation catalyst in the after-treatment. These emissions are therefore considered irrelevant.
- Among the two major components PM and NO_x a different balance may be struck for different engines. In emission control there is a trade-off between the NO_x and the PM emissions. Occasional high numbers quoted for one emission, may be accompanied by low values for the other. Engines can be optimised for a particular fuel, yielding a more balanced reduction in NO_x and PM. For CNG the trade-off seems to be between HC and NO_x. The methane emission is relevant for CNG

buses, in particular due to the high fraction of CH_4 (a potent green-house gas) in HC.

- PM_{10} emissions provided in this study are engine emissions only, whereas also tyre and brake wear contribute significantly to the total PM_{10} emissions. A a number of 66 mg/km has been used for wear emissions, by de Task Group "Verkeer en Vervoer" of the project "Emission registration" that is performed on behalf of the Dutch government (VROM and V&W). This number takes into account contributions from tyre, brake, and road surface wear.
- Biodiesel has characteristics which are clearly different from diesel and GTL, due to the oxygen in biodiesel. The burning process is quite different. Many different types of biodiesel are used. For the European situation biodiesel from rapeseed oil is appropriate.

3.2.2 GWP

The total global warming potential (GWP) is calculated for every option using the well-to-wheel methodology.

Basis for the Well-To-Tank part of these calculations is the JRC/Concawe study in its most recent form (the updated version published march 2007). For every fuel, a pathway or a combination of multiple pathways is selected from the JRC/ Concawe study that (as closely as possible) resembles the current situation in the Netherlands. By doing this, the GWP and energy consumption per MJ of fuel can be calculated.

The Tank-To-Wheel part is calculated from the data provided by the cycle simulations. These simulations provide the energy consumption of every fuel option in MJ/km. We then combine this data with the data from the JRC/Concawe study to obtain the GWP and energy consumption per (passenger) km. The schematic below shows this methodology.

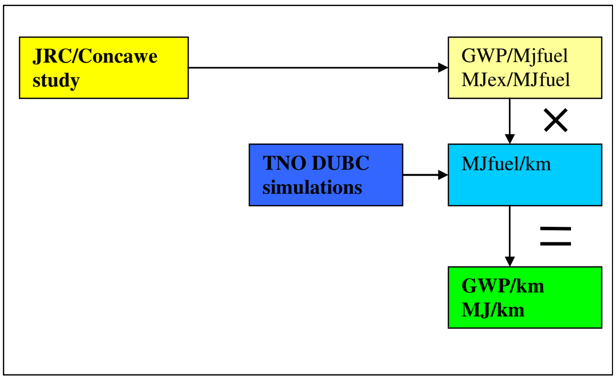

Figure 2 The method used to calculate the Well-To-Wheel global warming potential explained

Not only CO_2 is included in the GWP calculations. Also methane (CH_4) and nitrous oxide (N_2O) are included with weighting factors of 23 and 296. These weighting factors are also used in the JRC/Concawe study and are in line with the IPCC "*Third Assessment Report–WG I*" report. In this report, methane has a 100-year global warming potential of 23 indicating that it is estimated to be 23 times more effective than carbon dioxide at trapping heat in the atmosphere over a 100-year period. Nitrous oxide's 100-year global warming potential is assumed to be 296 in this report. For fuel / emission level combinations where the N_2O emissions were not known it was estimated to be 2% of the NO_x emissions; i.e. if a certain engine produces 2g/kWh NO_x, the N_2O emissions were assumed to be 0,04 g/kWh. This methodology is also used in the

JRC/Concawe study and it was checked against relevant in-house emissions measurement data. This revealed that it is appropriate to use this assumption.

4 Assumptions made in this study and resulting input values for the cost model

Comment: for this chapter, part of details from the original version have been removed for confidentialiy reasons.

4.1 Costs

4.1.1 Fleet information

The fleet size and mileage are based on the numbers in the city of Haarlem in The Netherlands.

Annual mileage per vehicle	60.000 km
Number of vehicles in the fleet	80
Life cycle of a vehicle	8 years

4.1.2 Fuel specifications and prices

Fuel prices and energy density (based on lower calorific value) originate from various studies and from figures received from the suppliers. They are summarised in Table 2. For the determination of the tax rates, several agencies were contacted and various reports studied.

Table 2 Fuel prices and related fuel properties

	EN590 diesel	**Shell GTL**	**Dutch natural gas (DNG)**	**B100 (RME)**	**Biogas (upgraded)**	**Ethanol**
Density kg/l	0.832	0.78	0.000873	0.89	0.000746	0.794
Energy density MJ/kg	43.0	44.0	37.4	36.8	46.9	26.8
€ct/MJ	*Conf.*	*Conf.*	*Conf.*	*Conf.*	*Conf.*	*Conf.*

The price for diesel fuel is the average diesel price in December 2007 in The Netherlands. Of course, it is more difficult to give a robust cost estimate for the alternative fuels.

For the liquid alternative fuels (B100, GTL and Ethanol) the prices were received from the fuel producers. In particular, for GTL a price indication from Shell Global Solutions has been used : 4 % above diesel before tax (on a volume base).

For gaseous fuels a different source was used. Natural gas prices are based on average market prices in December 2007 in The Netherlands and on additional costs mentioned by different suppliers for transportation through the gas grid and for making available peak flow rates (capacity).

When determining the cost of biogas, an essential parameter is the biogas feedstock. For the Netherlands that is biogas production from waste, followed by upgrading to acceptable (methane-like) quality.

4.1.3 Infrastructure costs

As is to be expected, the infrastructure costs when switching from diesel to a different liquid alternative liquid fuels will be small and very similar for the different fuel options. The small premium was assumed to be 40.000,- € for GTL and B100. Ethanol is assumed to have twice that amount as cost.

Infrastructure costs are a much more important issue with gaseous fuels. In the Netherlands there is limited experience with CNG fleets. At present there is such a fleet (85 buses) in the city of Haarlem, operated by Connexxion. For this fleet a so-called slow-fill fuelling station has been selected. In this approach all the bus vehicles are fuelled only overnight. Typically a large number of these buses are hooked simultaneously to a combination of compressors. Gas storage volume is limited. With this approach buses are driven from their place to the fuel line for filling and back after filling. To make this work for a fleet of 80 buses typically three extra fuel station operators have to work a night shift. Of course this results in higher annual costs for the fuelling station.

An alternative set-up is the so-called fast-fill approach. In this approach high powered compressors in combination with a large gas storage volume (typically pressurized towards 275 bar) allow to fill multiple buses simultaneously within a time period of between 3 and 7 minutes (depending on the fuel station lay-out). Such fast-filling installations are not yet applied at commercial Dutch bus stations today. However, they are by far the preferred option in the US, probably because this set-up allows to run the fleet in a diesel-like manner. Of course with this approach the need for people servicing/manning the fuel stration (i.e. filling the vehicles) is strongly reduced.

Another issue with implementing a NG urban bus fleet is the need to modify the bus maintenance and depot buildings to comply with NG practicalities and safety regulations. For this study it was assumed that the bus maintenance facility would have to be modified. At the same time it was assumed that the buses will be parked outside (i.e. they are not stationed in a building). For the Dutch climate conditions this assumption is a valid one, and it was also the choice made by Connexxion for their NG bus fleet in Haarlem. This does not mean however that in-door parking does not occur in the Netherlands, rather this choice reflects that for CNG application it will not be the preferred choice. Of course, in countries / states with a cold climate (Sweden or North of US and Canada) this will be different.

For estimating the infrastructure costs of the slow-fill approach we have used info from from a Dutch CNG equipment supplier, from in-house internal information and from some other studies in the literature. With this information we arrived at an estimated cost for the slow-fill station of 1.830.000,- €. This can be considered a conservative but realistic value. As mentioned above this does not include the cost for adapting an eventual bus depot.

For estimating the cost of the fast-filling station again representative data were collected with the above mentioned sources. At the same time more info was gathered from CNG bus projects in the US. When combined towards simulating the slow-fill station described above these data were found to match the data in the literature very well. Then the cost of a state-of-the-art fast-fill station was calculated. The estimated cost (including all the items listed above) was now 3.150.000,- €. TNO considers that this estimate is somewhat at the higher end of the scale.

Table 3 Fuel-related infrastructure costs

	EN590 diesel	**Dutch natural gas (DNG) (slow-fill)**	**Dutch natural gas (DNG) (fast-fill)**	**B100 (RME)**	**Shell GTL**	**Biogas**	**Ethanol**
Fuelling station building costs[*]	0	1.830.000	3.150.000	40.000	40.000	1.830.000	80.000
Interest rate %	4,15	4,15	4,15	4,15	4,15	4,15	4,15
Fuelling station annual costs	8.200	240.590	258.550	8.450	8.450	197.290	13.825

[*] Gas fuel station build costs include maintenance facility modification costs

In this respect some important additional statements are to be made :

- the cost for a CNG fuel station will depend on a number of variables, a.o. the distance to the high-pressure natural gas grid, the effort needed to increase the peak electric power that can be delivered to the station (compression of natural gas is mostly done using electric power), the extent of the efforts to upgrade the bus maintenance facility,
- in the above costs we have assumed that no special investments are needed to limit noise resulting from the (overnight) refueling activities,
- according to a Dutch supplier the layout of a fast-fill station could be different from the one we assumed, i.e. they would suggest a cheaper approach using a bigger storage volume and smaller compressor power,
- costs will be higher if the buses would be parked inside a building; then also this bus depot would have to be modified to meet with safety regulations.

With the assumptions mentioned above, TNO expects that actual costs for an 80 bus fleet slow-fill station in the Netherlands will therefore be in the range : 1.830.000,- € ± 250.000,- €.
Similarly we expect that the actual cost for an 80 bus fleet fast-fill station in the Netherlands will be in the range : 3.150.000,- € ± 400.000,- €.

4.1.4 Vehicle costs

Table 4 Fuel related vehicle costs

	Diesel Euro3	**Diesel Euro4 SCR**	**Diesel Euro4 EGR**	**Diesel Euro5 SCR+ DPF**	**CNG Lean-burn Euro5/EEV**	**CNG Stoichiometric Euro5/EEV**	**Ethanol Euro4 EGR**
Vehicle price	-	Conf.	Conf.	Conf.	Conf.	Conf.	Conf.
Interest rate %	4,15	4,15	4,15	4,15	4,15	4,15	4,15
Annual cost (maintenance / insurance / MOT)	15.900*	16.150*	16.150*	16.150*	21.850	16.500	18.350
Energy consumption MJ/km	Confidential	Confidential	Confidential	Confidential**	Confidential	Confidential	Confidential
Urea consumption %-vol.	-	5	-	6	-	-	-
Vehicle depreciation value when resold (%)	-	62.5	62.5	62.5	82.5	82.5	90

*€/annum; for GTL maintenance costs are approx. € 200 lower compared to diesel
**with GTL fuel and a dedicated / optimized engine, energy consumption in MJ/km is assumed to be 5 % lower

4.2 Emissions

4.2.1 Regulated emissions

Modern after-treatment systems in combination with different drop-in fuels may have effects which warrant further studies beyond the scope of the current investigation. In some cases one can expect the engine and after-treatment system to be stable for a variety of fuels. However, one can not automatically assume that the engine management optimizes over a whole range of fuel parameters. In particular the following issues were touched upon:

- The number of studies using GTL and biodiesel for buses and trucks are limited, in particular in combination with modern after-treatment technology. Therefore, every study was carefully analysed for its merits and pitfalls. For example, the emission results from engine stands, in particular the ESC test, are not necessarily representative for on-road emissions. In comparative studies, however, they can be correlated with known on-road emissions.
- For a vehicle, like a bus, that runs almost non-stop from morning till evening, the cold-start emissions represent only a small part of the total emissions, unless the driving behaviour is so tame that the after-treatment system (DPF, OXI-cat, SCR) has trouble reaching the operational temperatures (these are typically above two hundred degrees Celsius).

- For the next European legislation (Euro-6), it is being considered to include cold start in the test cycle, particularly for this reason. However, since the study of cold-start heavy-duty emissions is in a preliminary stage, there is no sensible means to include its effects. In particular, since the driving behaviour plays such an important part in the heating of the after-treatment system.

4.2.2 Regulated emissions: Cold start emissions impact on GWP of NG vehicles, additional information.

During cold start, catalysts will not work for some time. Then emissions will be higher. This can occur with diesel engines that use an oxycat and/or SCR catalyst for aftertreatment. The impact of this on greenhouse gas emission will be limited with diesel engines running on diesel or one of the alternative fuels. This is however different with stoichiometric natural gas vehicles in particular in a slow-fill approach. When cold, these engines have a much higher engine-out THC and NO_x level.

An additional cold start after refueling the natural gas vehicles (due to the slow-filling) would cause THC emissions around 10 g/kWh @ 10kW engine power (idle crawling / maneuvering) for 3 minutes. This equals 5g of methane. The methane emission from the entire day of running (approx. 150km @ 1,63 g/km for lean; @ 0,62 g/km for stoich) are 244,5 g for the lean burn bus and 93 g for the stoichiometric bus. The cold start emissions then equal 2% of total methane emissions for the lean burn bus and 5% of total methane emissions for the stoichiometric bus. The methane emissions of the CNG stoichiometric buses account for only 0,8% of the WTW GWP. For the lean-burn bus, this is 2,6%. Therefore, the methane emissions from an additional cold-start is assumed to be insignificant.

4.2.3 GWP: Fuel pathways

To calculate the total GWP of all the options, a combination was used of the following pathways from the Concawe/JRC well-to-wheel study. These combinations were selected after discussing with relevant TNO experts and (based on their opinion) they reflect - as closely as possible - the current (early 2008) situation in the Netherlands.

Table 5 Fuel pathways used from the JRC/Concawe study

Fuel	**Pathway 1**	**Share (%)**	**Pathway 2**	**Share (%)**	**Pathway 3**	**Share (%)**	**pathway WTT CO2 (gCO2eq/MJf)**	**pathway WTT energy (Mjex/MJf)**
Diesel	**COD1**	100					**14,2**	**0,16**
GTL	**GRSD2**	100					**25,1**	**0,68**
B100	**ROFA1**	50	**ROFA2**	50			**-26,3**	**1,22**
CNG_A	**GMCG1**	80	**GPCG1a**	10	**GPCG1b**	10	**10,3**	**0,15**
CNG_B	**GMCG1**	0	**GPCG1a**	50	**GPCG1b**	50	**18,3**	**0,24**

Ethanol	**SCET1**	100					**-60,9**	**1,79**
CBG	**OWCG1**	50	**OWCG2**	50			**-87,1**	**0,92**

The used pathway acronyms mean the following:

Table 6 explanation of pathway acronyms

COD1	Crude oil to diesel
ROFA1	Rapeseed to biodiesel, glycerin is used as a chemical
ROFA2	Rapeseed to biodiesel, glycerin is used as animal feed
GMCG1	EU mix natural gas to CNG
GPCG1a	Piped (7000km) Natural gas to CNG
GPCG1b	Piped (4000km) Natural gas to CNG
GRSD2	Remote natural gas to synthetic diesel on a remote plant. Fuel for neat use.
SCET1	Sugar cane to ethanol
OWCG1	Municipal waste to compressed biogas
OWCG2	Liquid manure to compressed biogas

A number of comments can be made on the WTT-values.

The WTT-value used for diesel is valid for the current situation. Future refineries will process heavier crudes and they will have to cope with more stringent fuel specifications. This will increase the energy intensity of diesel production and narrow the gap between diesel and GTL. This (expected to be smaller) effect was not retained in this study for lack of sufficient data.

For the GTL case, again the value presented reflects current levels. Three options for future improvement are possible.

1) It is possible to lower the WTT CO_2 emissions of GTL production by using Carbon Capture and Storage technology. CCS is not currently used technology, but a lot of research is being invested in this option. The JRC/Concawe study quotes WTT CO2 emissions of 13[gCO_2eq/MJf] with CCS instead of 25 [gCO_2eq/MJf]. If this option is used, the WTW CO_2 emissions of the GTL options are lowered by some 12%. The additional costs for this option are not yet known. Currently, CCS development projects are aiming for a cost of 20-30€ per ton of stored CO_2 by 2020, which is on par with the current CO_2 prices.[iii] The actual future cost difference of this option (GTL+CCS) with other fuel options will depend on the regulatory framework towards that time. In its enery scenarios to 2050, Shell states that large-scale deployment of CCS is not expected to takes place until at least 2020.
2) GTL is a fuel with the same engine-relevant properties as BTL, which is made from biomass. The introduction of GTL can prepare the market for the introduction of BTL. If we assume the JRC/Concawe numbers for CO_2 WTT emissions for BTL (around -65 [gCO_2eq/MJf]), the WTW CO_2 emissions are lowered by approximately 90% compared to the GTL scenario. WTW CO_2 emissions then become almost equal to the WTW CO_2 emissions of the ethanol scenario. BTL is however not yet available on the market, and the fuel costs for BTL are at this moment therefore difficult to estimate.

The biodiesel pathway is based on the former situation within Germany, since that is the origin of most of the biodiesel used in the Netherlands. However, the tax regime in Germany has changed recently, decreasing the profitability of producing biodiesel. As a consequence the biodiesel production capacity (and the corresponding representative pathway) is expected to change. The pathway used in the report does not yet reflect this expected change. This is because the outcome of this change is unknown at this point in time.

In the case of CNG, two numbers are presented. One number considers that the natural gas used for bus application is part of additional import into the EU. This marginal natural gas would then be imported through pipelines of between 4000 km and 7000 km length. This explains its high WTT CO2 value. This same reasoning is used by a.o. Concawe when comparing fuel options. It must be pointed out that this marginal value is a very conservative one, as one would expect that even marginal NG into the Netherlands would tend to come more from the closer (4000 km) distance.
In other studies it is assumed that a consumer of NG will use its gas from the same mix of sources available to other consumers and therefore he must have its emissions impact determined consistent with that mix. We have therefore retained also that option. In line with the latter option, the Dutch natural gas mix is largely composed of local natural gas from the Slochteren field and a number of smaller local gas fields.[iv] Taking these considerations into account TNO has assumed (for the second option) that 80% of the natural gas used in the buses has a GWP equal to the average EU-mix and that the remaining 20% is imported through pipelines of 7000 and 4000 km length (10% each) respectively.
Finally: no difference in the values for GHG WTT emissions are used for slow-fill / fast-fill. It is assumed that such differences will fall within the uncertainty range of these WTT numbers.

In the case of ethanol, it is assumed that all of the ethanol is imported from Brazil. If other assumptions are made, the carbon intensity of ethanol production increases, reducing the relatively large advantage of ethanol in this area.

For CBG, it was assumed that 50% of the biogas is made from liquid manure and 50% from municipal waste. In fact, in the Netherlands most of the biogas is made from liquid manure and sewage water. The substitution of sewage water by municipal waste for biogas production is an assumption that very probably leads to higher WTT GWP for biogas since sewage water that is not used to produce bio-methane emits methane into the atmosphere.

5 Results

5.1 Cost results

The costs are divided in several sectors as explained in the methodology. In this way it is easier to study different cost factors.

The following scenarios were used for the calculations:
- existing Euro-3 vehicles
- existing Euro-4 SCR vehicles
- new Euro-4 SCR vehicles
- new Euro-4 EGR vehicles
- new Euro-5/EEV SCR vehicles
- new lean-burn natural gas vehicles (EEV class)
- new stoichiometric natural gas vehicles (EEV class)
- new ethanol Euro-4 EGR vehicles.

For the diesel vehicles three different fuels were considered:
- Regular diesel (EN590)
- GTL (Gas To Liquid)
- B100 (RME).

The results are presented in Euros per passenger kilometer. Variation in the fuel prices and the fleet details will have a major effect on the final classification. Therefore the results presented in the figures below are only valid for the input values determined in the assumptions. All costs presented here are differential costs to the baseline (regular EN590 diesel) scenario. To convert to annual additional fleet cost, the costs per passenger km should be multiplied by 192.000.000, i.e. a 1 cent increase per passenger km yields a €1,92 million Euro total operational fleet cost increase for the assumed 80 bus fleet over an 8 year period. This relation can be seen in figure 3.

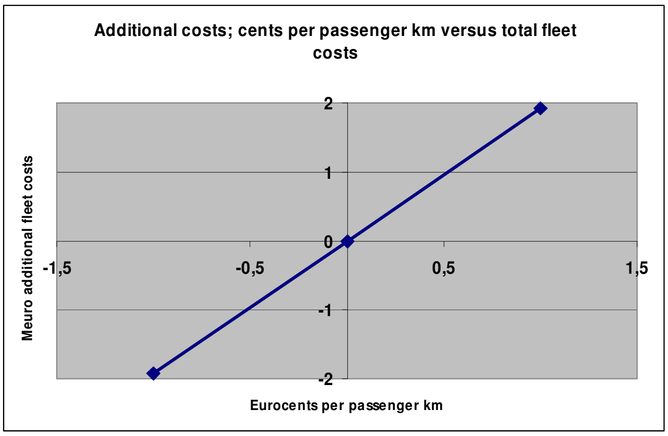

Figure 3 Additional costs, costs per passenger km versus total fleet costs

All fuel options are compared in Figure 4a. As indicated, the numbers in this figure do not include taxes. This is because :

- to the knowledge of TNO, a specific tax regime for GTL has not been determined,
- this compare compares the differrent fuels on their own merits (not influenced by taxation or subsidies).

It is clear from Figure 4a that GTL is indeed the most cost-effective alternative fuel option. The costs are only slightly above those of the regular low-sulphur diesel duel. The next best fuel option is biodiesel, while CNG (slow-fill and fast-fill) come in third position. As the figure shows this is mainly the result of the higher (fuel station and vehicle) investment costs with these fuels. Biogas is even more expensive that natural gas while ethanol is least economical.

Of course, fleet operators in the real world are confronted with taxation. That is why all the fuel options are compared again, now with taxes and assuming that GTL would be taxed as regular diesel. The result is shown in Figure 4b.

- Replacing diesel for GTL (the so-called drop-in scenario) in the existing Euro-3 vehicles increases the fleet operation costs with approximately 0.10 €ct per passenger km. This same difference holds when considering Euro-4 vehicles
- An ethanol bus fleet is approximately 2.75 €ct per passenger km more expensive than a conventional diesel Euro-4 EGR bus fleet. This is due to the lower energy density of ethanol and the high consumer price of ethanol in The Netherlands.
- A B100 (RME) fleet with existing vehicles would cost some 0.45 €ct per passenger km more than the conventional diesel fleet. If the price of the new vehicles is included (Euro-4, Euro-5), the B100 fleet is some 0.45 – 0.51 €ct per passenger km more expensive.
- Natural gas vehicles are considered only in the context of buying new vehicles, that is : in competition with other Euro-5/EEV technology. Figure 4 (a and b) consider only the cheaper slow-fill options. Of the natural gas vehicles the stoichiometric version is cheaper than the lean-burn one. The difference is 0.08 €ct per passenger km. Compared to the diesel reference, the slow-fill stoichiometric option is 0.082 more expensive.
- The biogas variants are on average 0.40 €ct per passenger km more expensive than the diesel version.

Obviously, GTL and CNG-stoichiometric are the two alternative fuel options that are most cost-competitive. That is why they are compared in more detail in Figures 5 and 6. In these figures not only the slow-fill option but also the fast-fill CNG option is shown. Furthermore also two Euro-5/EEV GTL versions are included. When considering GTL for new Euro-5/EEV vehicles, GTL can be used as a drop-in fuel (without any engine modifications) but also in combination with an engine that has been optimised for best fuel efficiency on GTL. In this study it is assumed that such an engine would have a 5 % lower energy consumption. Since the PM and NOx emissions tend to be lower with a GTL fuel, this engine would have a lower fuel consumption while still fulfilling the emission regulations[v]. Of course this optimised engine would require modifications to engine design and calibration that would in turn increase vehicle costs. These additional costs are expected to remain limited and are not included in the calculations.

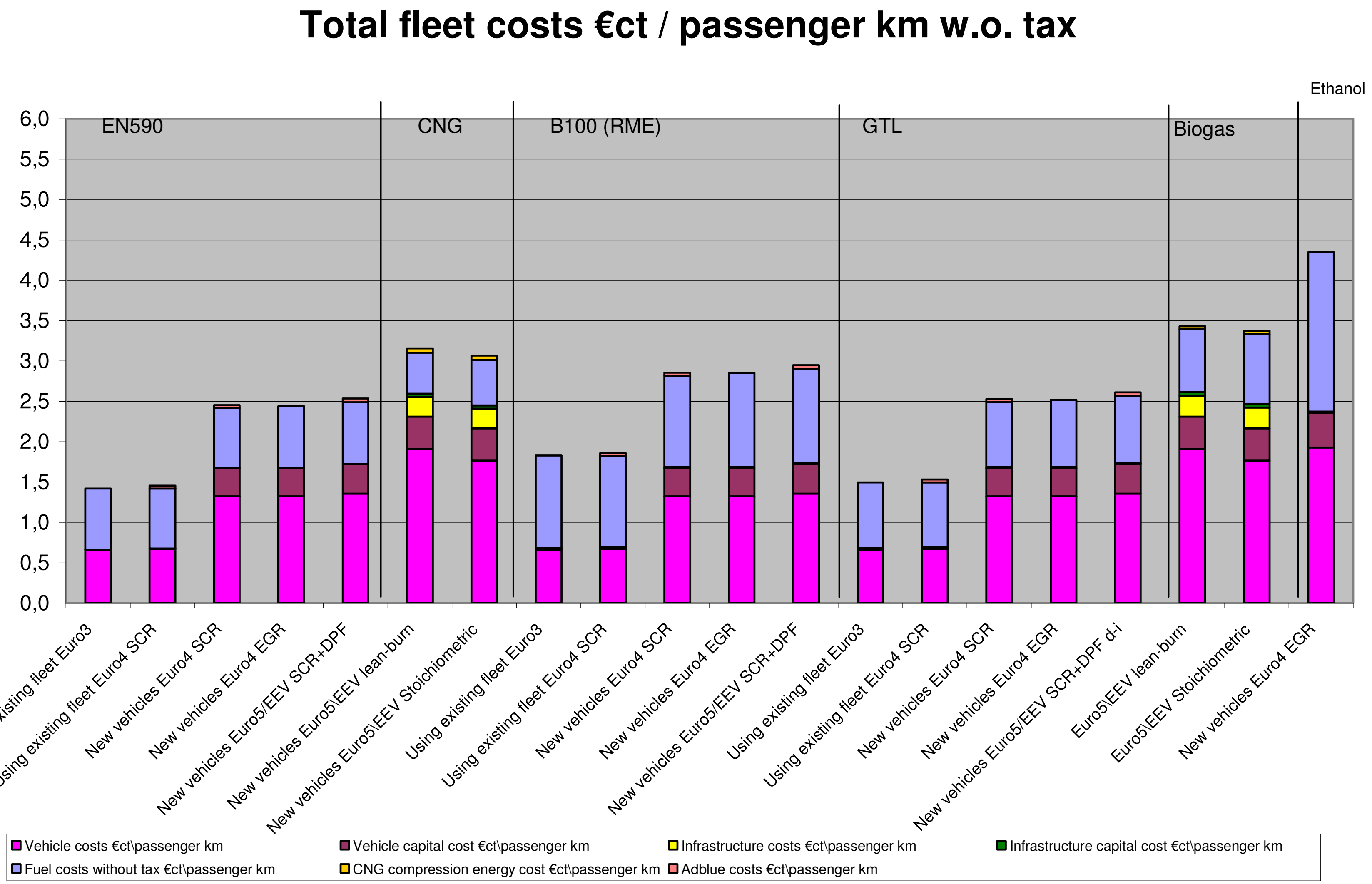

Figure 4a. Comparsion of total fleet costs for all fuel options. Costs are exclusive of tax. Acronym d.i. refers to “drop-in”

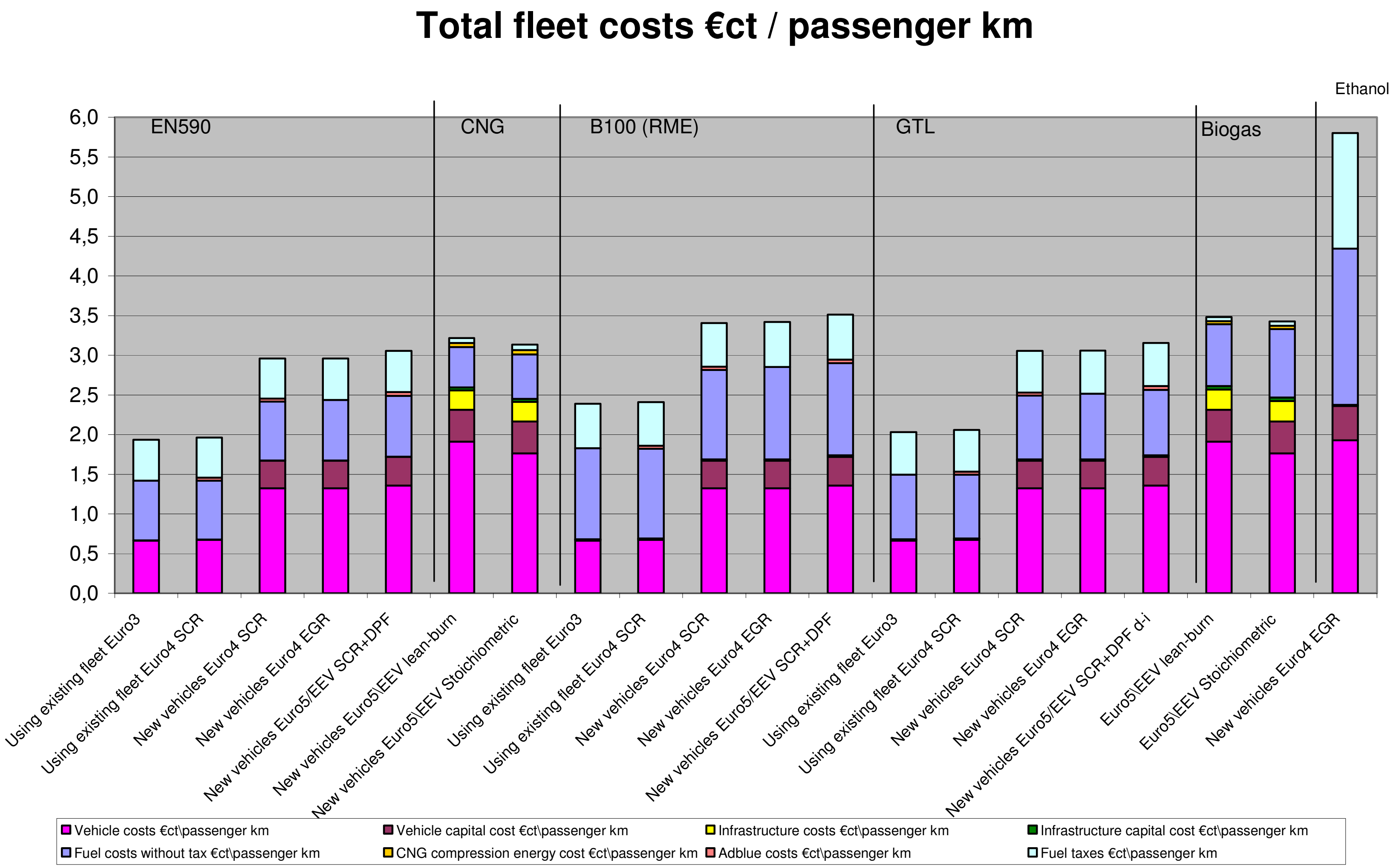

Figure 4b Comparsion of total fleet costs for all fuel options. Costs are inclusive of tax..

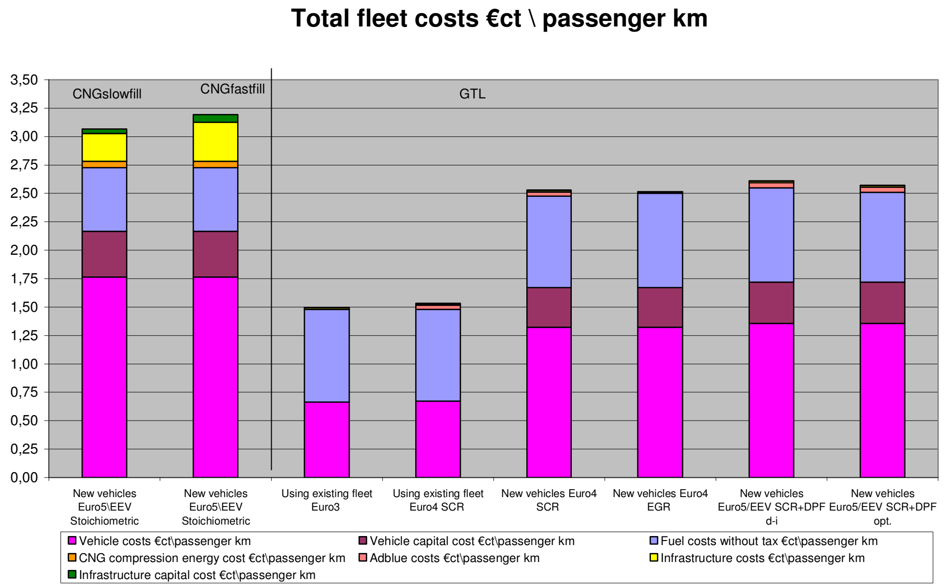

Figure 5 Fleet costs per passenger km. Euro-5/EEV versions only. No taxes / subsidies included.

Figure 5 confirms that GTL is – on its own merits – the most cost-effective option. In Figure 6 also taxes are added (assuming again a diesel-like tax for GTL). Then, compared to the diesel reference, the CNG-stoichiometric option is 0.082 €ct more expensive in the slow-fill scenario and 0.207 €ct more expensive in the fast-fill version. Compared to the GTL drop-in version, these CNG versions are 0.019 €ct cheaper respectively 0.106 €ct per passenger km more expensive. These differences are small considering the uncertainties linked to their calculation :

- fuel station cost estimates could be between 250.000,- and 400.000,- € too high/low,
- with CNG application possibly also additional costs would occur because of the need to modify the bus depot.

With new GTL-optimized Euro-5 vehicles (optimised for maximum efficiency) the total fleet costs would be only 0.034 €ct per passenger km more expensive than with regular diesel. This option would then be 0.048 €ct per passenger km cheaper than the slow-fill CNG option and 0.173 €ct per passenger km cheaper than the fast-fill option. Of course, also with gas engines possibly further efficiency improvements could be introduced. Likewise, the maintenance cost estimate used with CNG engines is considered conservative and is expected to become smaller as time evolves.

With these uncertainties, one can only conclude that the GTL and CNG options come very close. In addition one should be observe that :

- this assumes a diesel-like taxation of GTL, giving it a disadvantage compared to NG; this could be considered an unfair situation by supporters of this new generation of synthetic fuels,
- GTL implementation has an intrinsic lower risk / uncertainty -level.

If GTL would be taxed as NG, then it is clearly the most cost-effective option for driving an urban bus fleet.

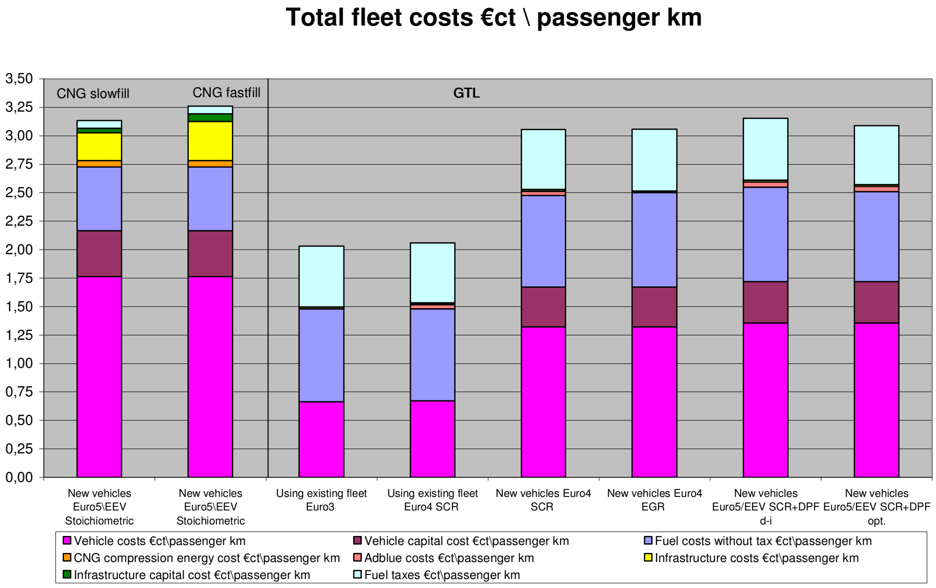

Figure 6 Fleet costs per passenger km. Euro-5/EEV versions only. Taxes included. No subsidies.

5.2 Emission results

For this comparison the ethanol option has been excluded for lack of data. This decision was made easier in view of the high cost of this option. Alternative fuels options that were retained are : CNG, CBG, GTL and B100.

5.2.1 Regulated emission

The regulated emission components (CO, HC, NO_x, PM, CH_4) and unregulated greenhouse gases (CO_2, CH_4, N_2O) were considered in this study. The values for regulated emissions in different vehicles are obtained from the TNO emission data bank as explained in the methodology. For the greenhouse gas (GHG) estimation TNO has used data from the JRC/Concawe [vi]. The emission values for the regulated components are presented below. The PM figures are to be compared with the approximate amount of PM_{10} produced by tyres and brakes. This is estimated to be 0.1 g/km (this level is shown as a red line in the corresponding figures.

At this point it is important to introduce some caveat :

- the emission levels shown in the figures are expected averages,
- actual emissions benefits of the different fuel options will be influenced by the actual composition of the reference diesel fuel respectively alternative fuels (there is a variation in composition of regular diesel and in GTL, likewise also Swedish Class I could be used instead of regular diesel),
- actual emissions benefits will change with differences in engine/aftertreatment design and calibration,
- actual emissions benefits will also be influenced by the actual driving pattern.

- Furthermore, especially for the Euro-4 and Euro-5 vehicles only limited data were available. The emissions reductions shown in the following graphs are based on best judgement and are considered unbiased estimates. They are averages and in reality there will be a considerable spread around these values.
- In particular for the Euro-4/EGR variant, the values shown are for the situation where the liquid fuelled vehicles are based in equal amounts on the two diesel technologies available (EGR+oxycat resp. EGR+PM-Kat).
- TNO, for good reason, has a policy of being conservative with benefit numbers.
- As the report is primarily aimed to investigate the benefits of GTL, also the spread expected in emissions advantage with this fuel is shown in the graphs.

For the GTL cases, only the “drop-in replacement” scenario emissions are shown here. It is important to note that it is possible to optimize the engine control (and if possible, also the hardware) to maximize the emissions reduction potential of GTL fuel. Such optimization is not considered in the rest of this report. The GTL engine can also be optimized for lowest fuel consumption (that is the option that was retained in the cost comparison). The emission of NO_x will then be similar to the baseline diesel scenario, since the NO_x benefit of GTL is then effectively traded for a lower fuel consumption. The emissions of HC, CO will in this case also be very similar to the baseline diesel scenario, since these components are very effectively reduced by the exhaust gas aftertreatment system installed on these vehicles. PM emissions with this type of vehicle will likely be 25 to 50 % lower than with diesel. Because this vehicle has an SCR+DPF aftertreatment system implemented, the absolute difference in PM emissions will however be very small.
The results of the comparison are shown in Figures 7 to 9.

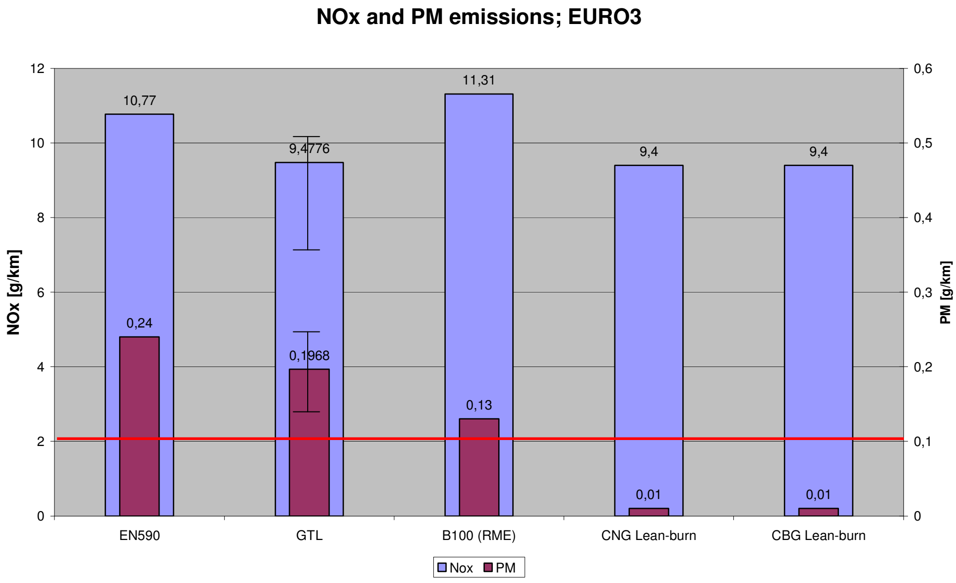

Figure 7 NOx, PM emissions. All Euro-3 options. GTL as drop-in replacement. The red lin represents vehicle PM emisson resulting from other sources.

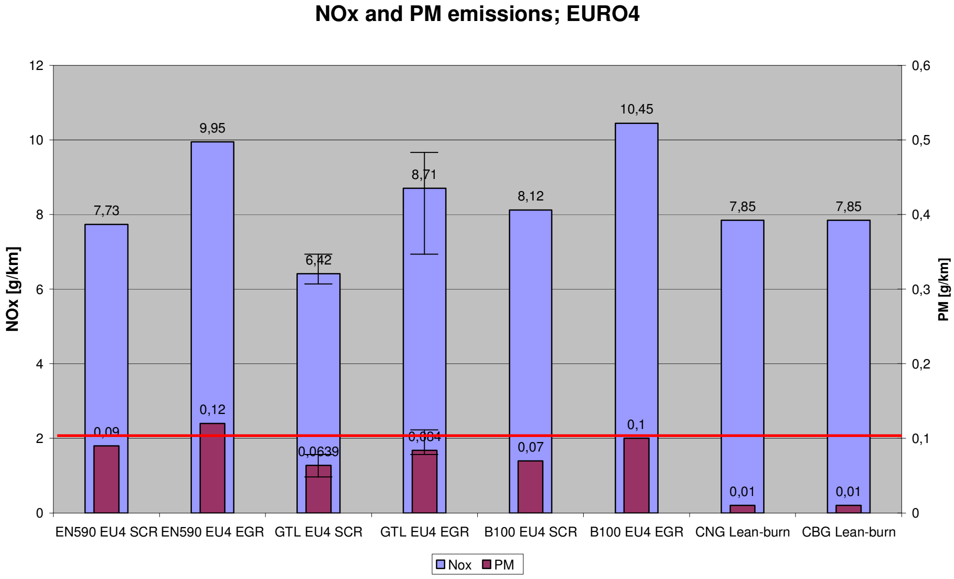

Figure 8 NOx, PM emissions. All Euro-4 options. GTL as drop-in replacement. The red lin represents vehicle PM emisson resulting from other sources.

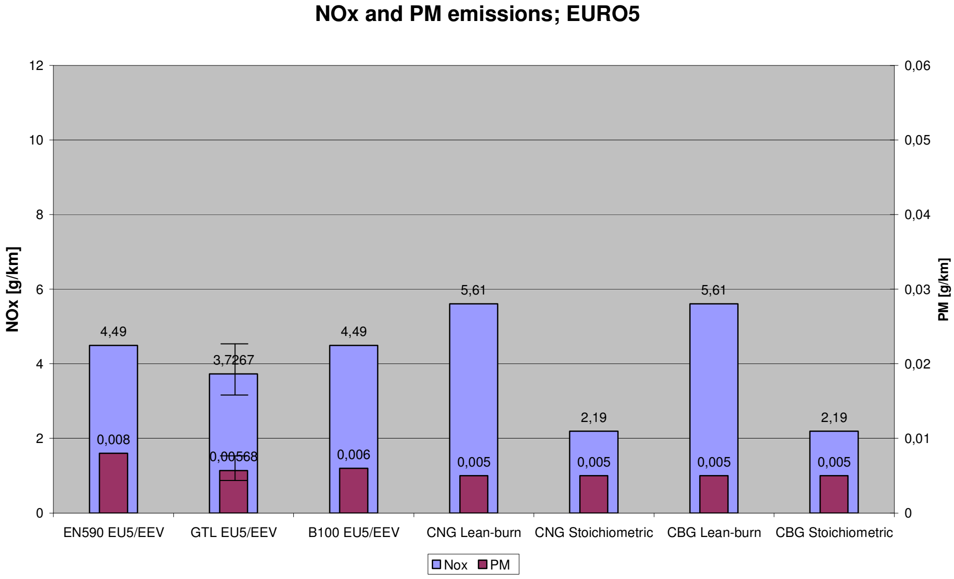

Figure 9 NOx, PM emissions. All Euro-5/EEV options. GTL as drop-in replacement.

For nitrogen oxides (NO_x) emissions GTL fuel brings larger benefits than B100. The NO_x reduction with GTL fuel in a Euro-3 vehicle is typically some 12 %, while with B100 fuel the emissions tend to increase approximately 5 % in all the cases. In Euro-4 EGR vehicle the NO_x reduction with GTL fuel is typically 12.5 % and in Euro-4 SCR and Euro-5 SCR 17 %.

NO_x emissions from a Euro-3 lean-burn natural gas vehicle are some 13 % lower than in a Euro-3 diesel vehicle using conventional diesel. This is more or less the same level as with drop-in GTL. A Euro-4 lean-burn vehicle produces slightly more NO_x than a Euro-4 SCR vehicle, but some 20 % less than a Euro-4 EGR bus. A Euro-4/SCR engine on GTL clearly is better. The Euro-4/EGR would be in the same range as NG.

The same picture holds when we consider Euro-5/EEV versions. A lean-burn NG Euro-5/EEV vehicle emits some 20 % more NOx compared to conventional diesel with the same emission class (and some 40 % more than the GTL alternative). Only the stoichiometric natural gas Euro-5/EEV is lower than GTL: thanks to its 3-way catalyst technology NO_x reduction is more than 50 % when compared to a conventional Euro-5/EEV diesel vehicle.

When evaluating the particulate matter emission levels, first two statements need to be made :

- the emission values shown for Euro-3 vehicles in Figure 7 are for engines without retrofit PM aftertreatment. As mentioned before, some 25 % of Euro-3 vehicles in the Netherlands have been retrofitted.
- Similarly, the PM emission values shown in Figure 8 for Euro-4 EGR vehicles are based on measurements with engines using oxycat aftertreatment only. A smaller (but unknown) fraction of the Dutch Euro-4 EGR fleet may use an "open" catalytic DPF. With these vehicles, PM emissions would be somewhat lower (≈ 25 to 30 %).

By using GTL or B100 fuel as a drop-in fuel significant particulate matter (PM) emission reductions can be achieved. In Euro-3 vehicle switching from the conventional diesel to GTL fuel typically gives some 18 % reduction in PM emissions. The same scenario with B100 fuel would reduce PM emissions by some 46 %. In case of Euro-4 EGR vehicle PM reductions with GTL fuel are on average some 29 % and with Euro-4 SCR around 22 %. Changing the fuel to B100 would reduce PM emissions in Euro-4 EGR vehicle by 17 % and in Euro-4 SCR vehicle by some 22 % compared to the conventional diesel. The PM emission levels in Euro-5/EEV vehicles are so low that even the tires produce larger amounts of particulate mass.
Natural gas vehicles emit hardly any particulate matter. The quantities are lower than produced by tires, so the PM emissions from natural gas vehicles are negligible.

The results of the comparison of THC and CO emissions are shown in Figures 10 to 12.

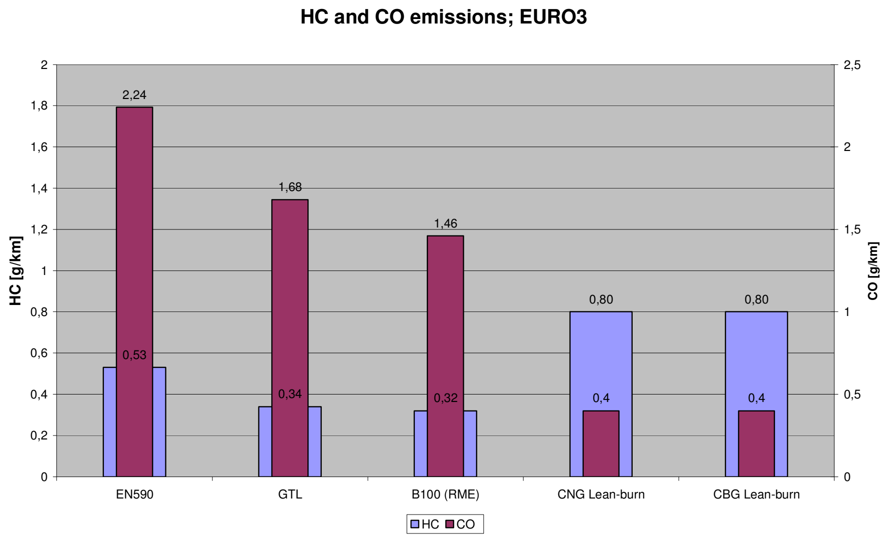

Figure 10 THC, CO emissions. All Euro-3 options. GTL as drop-in replacement.

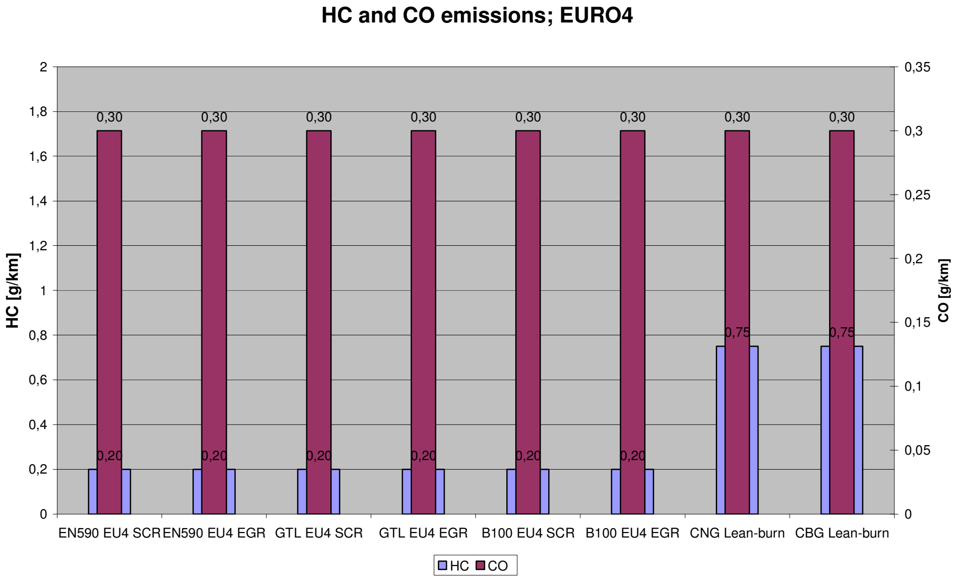

Figure 11 THC, CO emissions. All Euro-4 options. GTL as drop-in replacement.

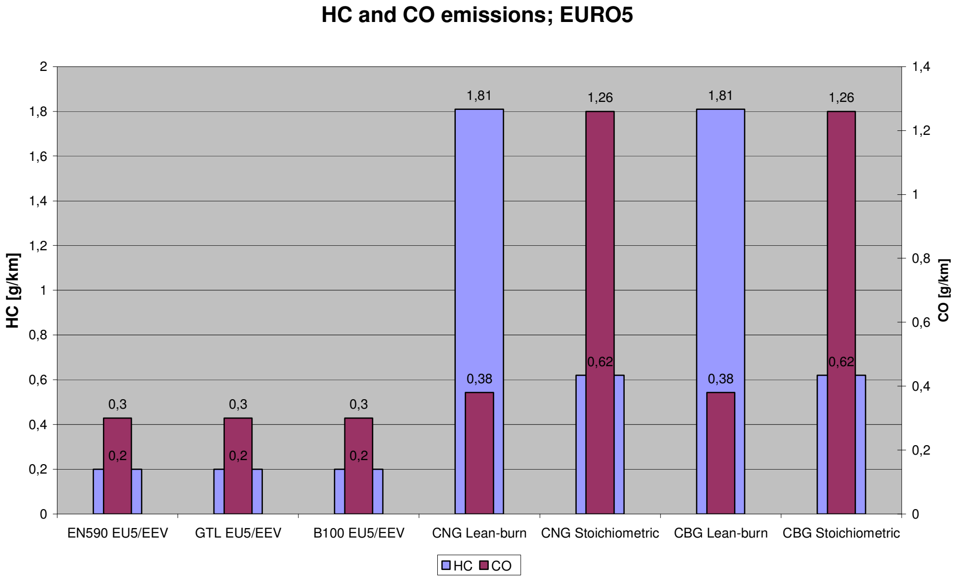

Figure 12 THC, CO emissions. All Euro-5/EEV options. GTL as drop-in replacement.

The carbon monoxide (CO) and hydrocarbon (HC) emissions from a modern diesel engine are normally on a very low level, so the reductions in these components are not that important. Reductions of CO below 0,01 g/km and of THC below 0,2 g/km are considered to be insignificant. Only in a Euro-3 vehicle some significant reduction can be achieved. With GTL fuel in a Euro-3 vehicle the CO reduction is some 25 % and HC reduction some 36 %. For B100 fuel the reductions would be some 35 % in CO and 40 % in HC.

Natural gas vehicles tend to emit some methane which can be seen in the THC (total hydrocarbons) emissions. CO is on a low level with all the lean-burn natural gas vehicles. A stoichiometric vehicle produces twice as much CO than a conventional diesel vehicle, but in practice this amount is really not significant. THC emissions from a stoichiometric vehicle are mainly consisting of methane, which is not a toxic emission component but a greenhouse gas (GHG) and therefore considered in the next paragraph.

5.2.2 Greenhouse gases

Greenhouse gases include e.g. carbon dioxide, methane, nitrous oxide, ozone and CFCs. Greenhouse gases that are produced in a combustion engine are CO2, N_2O and CH_4 (methane), thus only these components are considered in this study. Methane has a 23 times higher global warming potential (GWP) than CO2 and nitrous oxide 296 times higher. All the results of GHGs are presented as CO2 equivalent. More details on the GHG estimation can be found in the methodology chapter. The global warming potential (GWP) results are presented in the Figures 13-15.

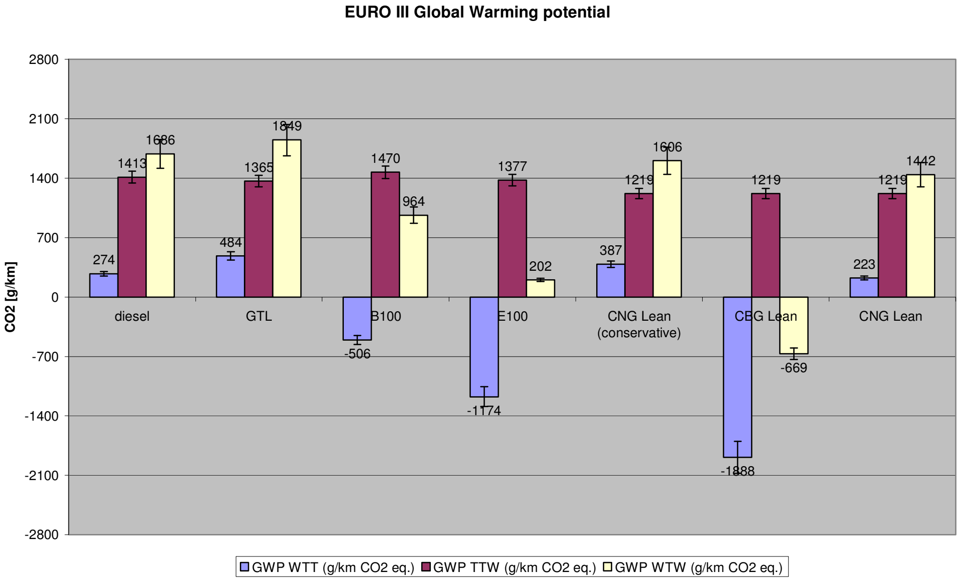

Figure 13 GWP; all Euro-3 options

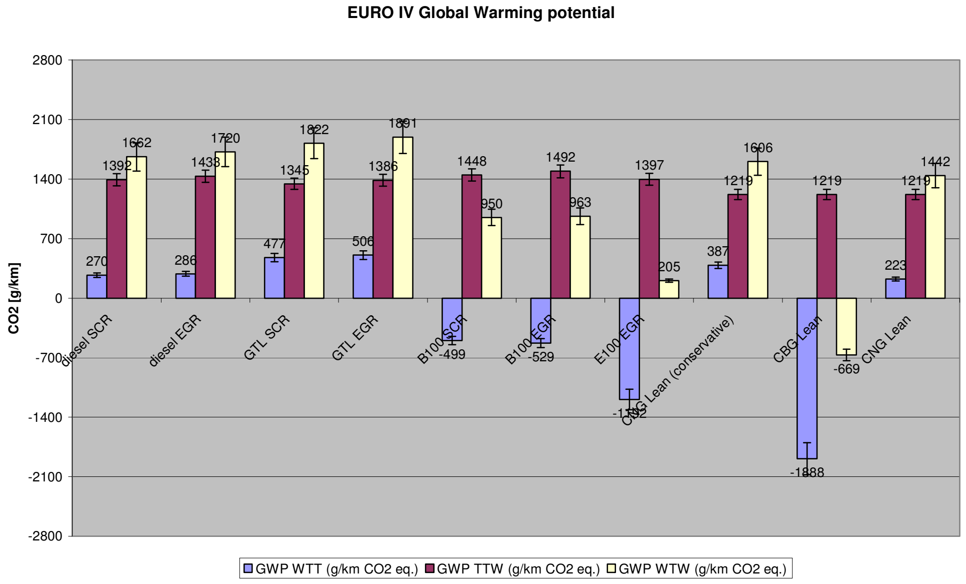

Figure 14 GWP; all Euro-4 options

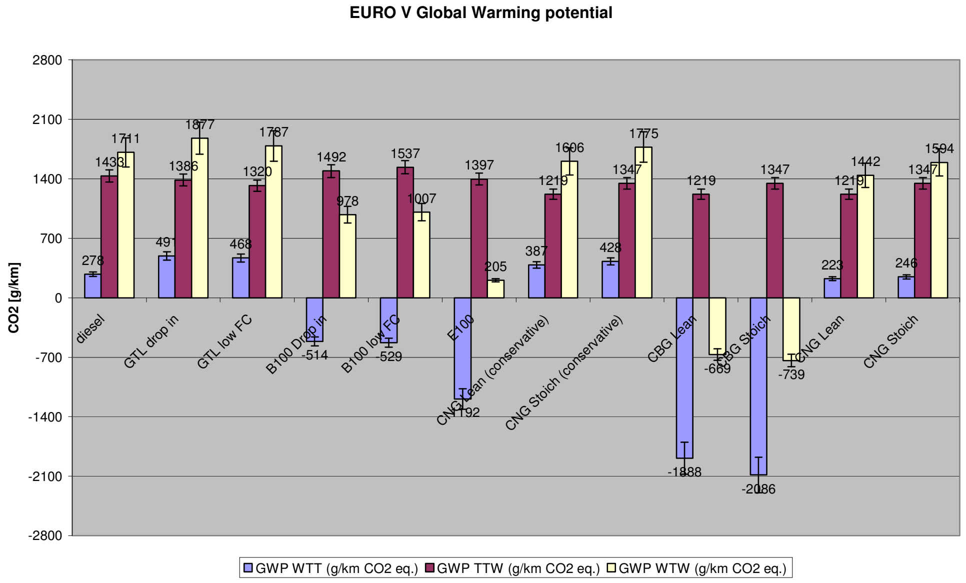

Figure 15 GWP; all Euro-5/EEV options

The above graphs show error bars of +/- 10% on the WTT emissions and 5% on the TTW emissions. As can be seen, the WTW CO_2 emission error bars tend to overlap for regular diesel, GTL and CNG (both lean burn and stoichiometric).

Of course, diesel is the reference. Compared to conventional diesel, GTL fuel has some higher GWP. For the EEV variant this amounts to 10 % higher GWP. If however an efficiency optimized GTL vehicle is used, GTL's GWP comes close to its diesel counterpart (4 % higher). Again, in view of the uncertainties in the GWP estimation (and considering the fact that diesel GWP might increase in the near future), these fuel options come very close.

This is to be compared with the results of the other fossil-fuel option : NG. As mentioned before, for NG two WTT-paths have been retained. A conservative one (all NG is piped from large distances, on average 5500 km) and an alternative (Dutch mix) one.

When considering the Dutch mix we observe :

- that the GWP of the lean-burn option is 15 % below that of the corresponding Euro-3 and Euro-4/SCR version; with the less efficient Euro-4/EGR-diesel the difference is -16 %,
- that the stoichiometric NG option has a 7 % lower GWP than diesel.

Compared to GTL, the NG option has a somewhat higher benefit of :

- 22 % respectively 24 % when compared to the Euro-3/Euro-4/SCR respectively Euro-4/EGR GTL equivalent when considering lean-burn gas engines,
- 15 % for the stoichiometric NG version when compared to the Euro-5/EEV GTL drop-in version and 11 % benefit when compared to the Euro-5/EEV efficiency-optimised GTL engine (GTL low FC in Fig. 15). The lean-burn version has even larger benefits.
- If CCS would be applied in the future then the difference would become small.

If we consider the conservative (long distance piping) values, then we observe :

- that the GWP of the lean-burn option is some 5 % below that of the corresponding Euro-3 and Euro-4/SCR diesel and 9 % below the Euro-4/EGR diesel option
- that the stoichiometric NG option has a 6 % higher GWP than the Euro-5/EEV diesel reference.

Compared to GTL, the NG option has a benefit of :

- 13 % for the Euro-3 and Euro-4/SCR options and 17 % benefit for the Euro-4/EGR option, when considering lean-burn gas engines,
- 5 % for the stoichiometric NG version for the Euro-5/EEV drop-in GTL version and equal GHG emission as with the Euro-5/EEV efficiency-optimised GTL engine. Again, the lean-burn option has even larger benefits.

If in the future, GTL would be combined with CCS then (assuming a corresponding 50 % reduction in WTT GWP) the overall WTW GWP of the GTL variants would typically be 12 % lower. Then GTL would beat the diesel reference. Also the stoichiometric EEV gas engine would then have a higher GWP.

Of course the best results are achieved with the bio-fuels.

- A natural gas vehicle using biogas can lower the total amount of greenhouses gases in the atmosphere. This is due to the high greenhouse effect of methane which would be released into the atmosphere without a biogas production.
- Ethanol's GWP is some 89 % lower than the conventional diesel's. (It is worth pointing out that the GWP for ethanol could be very different if the fuel would be produced from European raw material).
- A vehicle using B100 has around 40 % lower GWP than conventional diesel fuel.
- If synthetic fuel would be produced from biomass (BTL), then most likely the difference between BTL and CBG would become small if the BTL fuel would be produced from waste woody material. If the BTL would be produced from farmed biomass then probably CBG would remain the best solution. A detailed analysis of BTL was outside the scope of this study, but would be highly recommended.

5.3 Other issues

Besides cost and emissions, a number of other issues have also been taken into account. These issues are summarized in Table 7 below.

Table 7 Other issues

	Exterior noise	**Residual value**	**Insurance**	**Guarantee**	**Refueling safety**	**Fuel spill effects** (biodegradability)	**Fuel smell**	**NO$_2$ emissions**	**Avaialbility**
Diesel	0	0	0	0	0	-	-	0	0
GTL	+	0	0	0	0	+	++	0	-
CNG	++	--	-	0	0/-	++*	-	++	0
B100	0	0/-**	0	-(--)	0	+	++	0	-
Ethanol	0	--	0/-	0	-	-/0/+	-	0	-
CBG	++	--	-	-	0/-	++*	-	++	--

- * Though gas spills have no direct influence on the local environment, fuel spills do cause an increase in GWP
- ** Some manufacturers have produced B100 engines but TNO has no info on the residual value of these vehicles. Most manufacturers will presently not accept liability for higher than 20 % biodiesel blends. This is expected to have some negative impact on the residual value of such vehicles.

The details of the different columns are further specified below. Again this table reflects the situation in the Netherlands (in particular for instance with respect to the widespread availability of CNG).

- Insurance: has to do with the willingness of insurance companies to provide cover for these vehicles. Due to the relatively low numbers of CNG / CBG and ethanol powered buses, some insurance companies might be hesitant to insure these vehicles.

- Guarantee: For B100 and CBG, it could be that these fuels fall outside of the approved fuel quality range (this is most notably the case with B100) or need continuous monitoring to ensure quality (in the case of CBG, the H_2S content needs to be monitored, for instance). There might also be issues on the attainable useful engine life when B100 is used.

- Safety: Although gaseous fuel could be seen as inherently more dangerous to handle than diesel fuel, the larger risks are almost fully abated by the additional safety features present on the refueling sites and on the vehicles.

- Fuel spill effects: this column details the effects a fuel spill has on the local environment. Therefore, fuels that are biodegradable (like GTL) are scored higher. Because the quantity of fuel spilt is normally not significant when compared to the fuel consumed during normal service, the possible fuel spill effect on GWP is not calculated.

- Fuel smell: Both B100 and GTL fuel score positively on this, since they do not have the unpleasant smell of regular diesel. This can be seen as an advantage for the refueling personnel.

- NO_2 emissions: While not regulated, it is well documented that NO_2 emissions can cause respiratory problems and are more harmful than NO. Although NO is also oxidized to NO_2 in the atmosphere, high NO_2 emissions can lead to elevated local levels of NO_2.

5.4 Differences between the Netherlands and other countries

From the previous results, it can be concluded that modern stoichiometric CNG buses are a cost-effective concept (in combination with a slow-fill fuelling station). To some readers this can come as a surprise as a number of similar studies (but for other countries) have come to a different conclusion. The calculations above indicates that this is due to a number of particular circumstances that are present in the Netherlands. A number of the most influential ones are:

1) The CNG price in the Netherlands is relatively low in comparison to the Diesel price because of the differentiated tax level. CNG prices (including tax) in other EU countries are between 35 and 110 % higher (Gas Vehicles Report, http://www.ngvgroup.com/pdf/gvr80-092008.pdf).
2) Buses are most often parked outside in the Netherlands. In some other (in particular US) studies, it is assumed that the buses need to be parked indoors because of the climate or some other reason. If the CNG buses need to be parked inside, the infrastructure costs will be higher since the garage then needs to be modified to be able to cope with an eventual gas leak.
3) Also possible measures to reduce refueling noise impact have not been included.
4) In the Netherlands, the slow-fill option as been applied for the Haarlem fleet. In Europe the same approach has been followed in a number of biogas demonstrator projects (France / Spain). In the US on the other hand (with a much larger number of CNG fuelled buses) fast-fill is the preferred option. This option can make the infrastructure costs for CNG much higher.
5) If the size of the fleet does not match the (modular) fuelling system, costs will also increase.

6 Cost-benefit trade-off

The previous results have been used to make cost-benefit trade-off calculations. These calculations take the diesel Euro-3 scenario as the baseline. Costs are calculated to reduce PM and NOx by one tonne.
The following graphs show the results. Values shown are both with and without taxes. Again, a comparison without taxes is the proper one as it compares the different fuels on their own merits. The data including taxes have however also be added as they represent the current situation. Again, in the latter case it is assumed that GTL is taxed as diesel.

Figure 16 shows the results for PM emissions. These values are relevant only for the Euro-3 and Euro-4 options. This is because Euro-5/EEV PM levels for all vehicles are well below the emissions resulting from tyres and brakes.

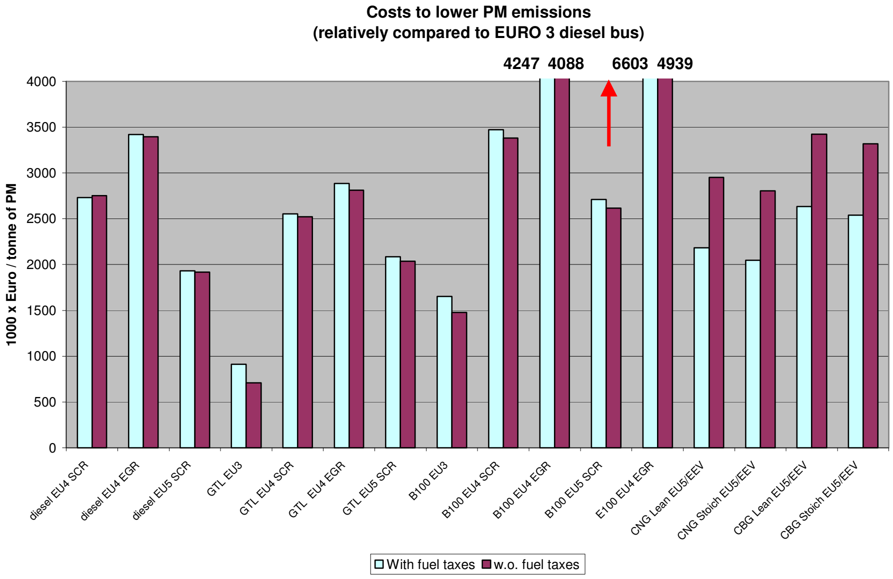

Figure 16 Costs to lower PM emissions per tonne with and without fuel taxes. Values for B100 EU4-EGR and E100 EU4-EGR are outside the range of the figure and are mentioned above the corresponding column.

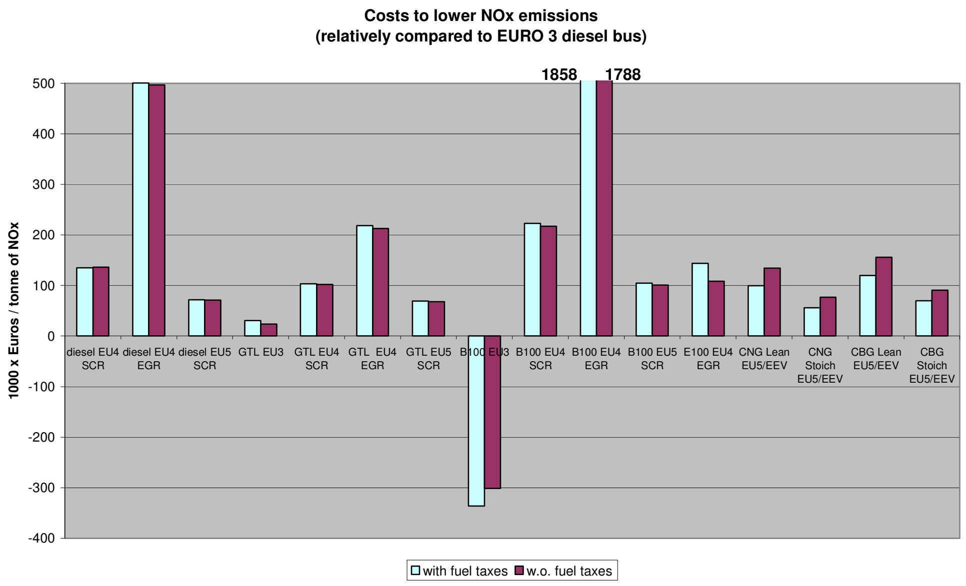

Figure 17 Costs to lower NO_x emissions per tonne with and without fuel taxes.Values for B100 EU4-EGR are outside the range of the figure and the corresponding values is mentioned above the corresponding column.

When considering the NO reduction, we can observe the following :

- the results show that drop-in replacement of diesel by GTL in the existing fleet is by far the option with the highest cost-benefit trade-off (irrespective of taxation).
- For the B100 EU3 variant the cost-effectiveness is negative. This is because with B100 drop-in, Euro3 engine-out NO_x-emissions are higher than with EN590. The corresponding NO_x-reduction is therefore negative and hence also the cost-effectiveness value.
- Drop-in replacement of diesel by biodiesel is always more expensive.
- When new vehicles are considered for alternative fuels, Euro-5/EEV should be preferred above Euro-4 technology. This statement holds both for GTL and B100.
- When considering new Euro-5/EEV vehicles the GTL option is again the best one. Although the difference with the stoichiometric CNG version is very small (as well as with the CBG version of the latter).
- If taxes are accounted for, and if diesel-like taxes are assumed for GTL, then the stoichiometric gas vehicles come out best.
- Because the value for the typical NOx-reduction achieved with drop-in GTL on Euro-5/EEV is an indicative value only, the latter ranking should be used with the appropriate care.

7 Conclusions

From the results in this study, a number of main conclusions can be drawn. These will be grouped into four categories:
Regulated emissions
Costs
Global warming potential
Cost-benefit trade-off in reducing local emission

Please note that these conclusions only hold for a bus fleet with the characteristics as assumed in this study. Different assumptions can and will lead to different conclusions.

Regulated emissions
When comparing regulated emissions only drop-in replacement scenario's have been considered. It was assumed that no engines would be available that would be dedicated for lowest emissions with GTL. (Such engines have however been developed for natural gas.)

As it was expected from the start of the project, it has proven to be difficult to obtain statistically robust data on a back-to-back comparison of the emissions of new diesel vehicles (Euro-4 and Euro-5 emissions class) on alternative fuels versus low-sulphur regular diesel. Using the limited data available an as good as possible estimate was made of the emissions behaviour of the alternative fuels in these engines. These data should be considered as best available indications. Most likely more data will come available in the near future to substantiate and/or improve these numbers.

The emissions data that were arrived at in this study indicate that significant emission reductions compared to the diesel baseline are possible by using GTL :
- On Euro-3 engines, the absolute reductions both in NO_x and in PM emissions are highest with drop-in replacement of diesel by GTL. GTL is more favourable than B100 due to the fact that GTL lowers both PM and NO_x. With B100, only PM is reduced and NO_x normally increases. The GTL emissions advantages on Euro-3 diesel vehicles are however matched by the lean-burn CNG/CBG alternative.
- For Euro-4 engines, drop-in GTL is also the cleanest option for NO_x; on particulates only the CNG/CBG alternative is better.
- For new, Euro-5/EEV vehicles only NO_x emissions are relevant; PM emissions with these vehicles are below 0.02 g/km; this is considerably below the level of particulates produced by tyres and brakes (0.1 g/km). When considering only NO_x the GTL drop-in option is the cleanest liquid alternative fuel option. Only the CNG/CBG stoichiometric engine gives a better emissions performance. That is because these engines combine a very effective catalytic NO_x aftertreatment technology with a very accurate closed-loop control. Current Euro-5/EEV diesel engines only have open-loop aftertreatment control. Because of this open-loop control strategy the engine-out emissions advantage with GTL fuel is maintained (to a varying degree) after the aftertreatment system.

Additional costs compared to the diesel baseline
First of all it is important to point out again that costs are case sensitive and specific to the Dutch situation. Changes in the size of the fleet, in the type of bus vehicle

(articulated or not), in the driving pattern, in the average bus mileage or in the duration of a fleet concession will affect the outcome of the cost-comparison.
Similarly, the results are strongly influenced by the fuel price level. In this comparison the fuel price level that was valid towards the end of 2007 was used. Important changes in the price level from that moment in time for any of the fuels concerned could have a strong impact on the cost comparison. Looking at the current (mid 2008) crude-oil price levels it is recommended to investigate this effect. The same remark can be made on vehicle price and interest rate.

For the price levels used, in general, drop-in replacement of diesel in the existing fleet by GTL or BTL are the best options. And between those 2 alternative fuels, GTL is the cheapest option. Drop-in replacement of diesel by ethanol is not competitive.

Because of their high investment costs, the gaseous alternative fuel options are of interest only when the introduction of a new fleet is considered. When comparing the different fuels on their own merits (that is exclusive of tax and subsidies) GTL is at present also in that case the most cost-effective solution. The natural gas option would need a 15 % reduction in cost level to fall into the GTL range.

If however taxes are included (as they are in the Netherlands) and if GTL is taxed in the same way as regular diesel, then the natural gas option and the GTL drop-in option come very close. The slow-fill option seems to be somewhat cheaper and the fast-fill option somewhat more expensive than the GTL drop-in alternative. Given the uncertainty level also in these calculations (especially in the natural gas application) one could argue that they are equivalent. To decide between these options a more detailed analysis is needed that would take into account local conditions/constraints, actual emissions and fuel consumption specifications of the candidate vehicles as well as actual price levels.

If Euro-5/EEV GTL-dedicated engines would be put on the market that would be optimised for highest efficiency, then the costs with these engines would (even with diesel-like taxes) be lower than with the current CNG stoichiometric alternative (assuming the optimisation achieves a 5 % increase of thermal efficiency). Of course, also with gas engines possibly further efficiency improvements could be introduced. Likewise, maintenance costs with CNG engines are expected to become smaller as time evolves.

Global Warming Potential.
When assessing the global warming potential of the different alternative fuel options, of course the biofuels will come out best.

When comparing the fossil alternative fuels GTL and natural gas, GTL consistently has a higher GWP than the natural gas alternative. When considering only the newest generation of vehicles, the difference between GTL and the stoichiometric natural gas option becomes small. Then the WTT-GHG emission contribution starts playing an important role. When it is assumed that NG is piped from a long distance (on average 5500 km) then the difference between GTL and stoichiometric CNG is smaller than 5 % (and almost zero for a Euro-5 engine that would be optimised for best fuel efficiency on GTL). Considering future potential efficiency improvements in GTL production technology this difference could become even smaller.

If on the other hand it is assumed that the origin of the natural gas resembles that of the current NG mix in the Netherlands, the benefit of the natural gas option increases again. If lean-burn natural gas vehicles would be considered for Euro-5/EEV introduction, then these are expected to have the lowest GWP (even when the above issues are taken into consideration).

For the biofuels, only B100 and CBG (compressed biogas) have been compared. Biogas clearly has the best GWP. If synthetic fuel would be produced from biomass (BTL), then most likely the difference between BTL and CBG would become small if the BTL fuel would be produced from waste woody material. If the BTL would be produced from farmed biomass then probably CBG would remain the best solution. A detailed analysis of BTL was outside the scope of this study, but would be highly recommended.

Cost-benefit trade-off of reducing local emissions.
Of course, when considering this issue, the comments on price-level and cost estimates mentioned above in the cost comparison should be kept in mind. Furthermore, in principle a comparison should be on costs exclusive of taxes.

When looking at the reduction of local PM emissions by drop-in replacement of diesel by alternative liquid fuels, only GTL and B100 are realistic options. In that case, GTL clearly is most cost-effective, more so than B100. This may come as a surprise since B100 is an oxygenated fuel (that is a fuel with oxygen bound to the fuel molecules). This class of fuel is known for its PM reducing tendency.

When considering the introduction of a new fleet of Euro-5/EEV vehicles, PM-emissions are no longer important.

When considering the NO reduction for a new fleet of Euro-5/EEV vehicles, the following observations can be made :

- the results show that drop-in replacement of diesel by GTL in the existing fleet is also for NO_x by far the option with the highest cost-benefit trade-off (irrespective of taxation),
- Drop-in replacement of diesel by biodiesel is allways more expensive.
- When new vehicles are considered for alternative fuels, Euro-5/EEV should be preferred above Euro-4 technology. This statement holds both for GTL and B100.
- When considering new Euro-5/EEV vehicles the GTL option (without tax) is again the best one. The difference with the stoichiometric CNG version is however small (as well as with the CBG version of the latter).
- Because the typical NOx-reduction mentioned for drop-in GTL on Euro-5/EEV is an indicative value only, the latter ranking is to be used with the appropriate care.
- If taxes are accounted for, and if diesel-like taxes are assumed for GTL, then the stoichiometric gas vehicles come out best.

Even with these taxation levels, for a given available budget drop-in replacement of diesel by GTL would be the cheapest and fastest pathway to realize a significant reduction in local emissions. This imply that sufficient amounts of GTL would come on the market (at the price level used in this study). This enables a more flexible approach to emission reduction than for instance CNG, where entirely new vehicles need to be purchased.

Table 8 summarizes the findings of this comparative assessment for the scenario where a decision has to be made on which fuel option is to be selected for a new fleet (not considering ethanol).
In this table GTL refers to the GTL drop-in situation. Only when comparing the GWP of the different options, the GTL in combination with an efficiency optimised engine was considered instead of the drop-in variant.

Of course this table is a simplified representation of the results and as the report shows it should not be used without explaining also its limitations and caveats.

	Best	Second best	Third	Fourth
Total Fleet Cost^1)	GTL	B100	CNG stoich.	CBG stoich.
NO_x emission reduction	CNG/CBG stoich.	GTL	B100	CNG lean
Global Warming Potential	CBG	B100	CNG lean	CNG stoich. GTL^2)
Cost-effectiveness of NO_x reduction	GTL^3)	CNG stoich.	CBG stoich.	B100

1) Assuming december 2007 price levels
2) Not assuming CCS technology implementation
3) For GTL an indicative (best-available) value only has been used

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9 Signature

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10 Endnotes

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[i] Biomethane is assumed to be a gas that has been cleaned (to remove H_2S and siloxanes, for instance) and upgraded. The upgrading process involves removing the inert (CO_2, N_2) gases from the biogas, thereby increasing its lower heating value. The composition of the biomethane that is used in the calculations is an average composition from a number of sites producing biomethane for road transport.

[ii] ARTEMIS, Assessment and Reliability of Transport Emission Models and Inventory Systems 2000-2005

[iii] www.pointcarbon.com quoted an “over the counter” price in the EU market of 23,43€ for one tonne of CO_2 on April 3rd, 2008.

[iv] Total NG consumption in the EU is 420,6 MTOE
Total import from outside the EU to the EU is 250,78 MTOE
This gas is imported as LNG and NG from:
  Russia (151,46 MTOE)
  Turkmenistan (0,21 MTOE)
  Other EU / Eurasia (7,52 MTOE)
  Algeria (59,88 MTOE)
  Lybia (8,68 MTOE)
  Nigeria (14,58 MTOE)
Total NG consumption in Netherlands is 34,5 MTOE
Total import from outside the EU to NL is 2,97 MTOE
This gas is imported as NG from:
  Russia (2,97 MTOE)

Therefore, (and assuming all imported gas is consumed and not exported again) The EU uses (250,78/420,6)*100=60% imported gas from outside the EU (relatively long distance gas). Also, the Netherlands uses (2,97/34,5)*100=9% imported gas from outside the EU (relatively long distance gas). Source: BP statistical review of world energy; 2007 edition (using 2006 data; latest available)

[v] This study therefore considers 2 Euro-5/EEV variants on GTL : a drop-in variant and a variant where the engine is optimised for lowest fuel consumption on GTL. TNO estimates that the fuel consumption could be lowered 5 % (compared to the drop-in GTL variant).

[vi] Concawe, 2007 Well-to-Wheels analysis of future automotive fuels and powertrains in the European context CONCAWE / EUCAR / JRC, final version 2c, March 2007