Alternative fuel options for urban bus applications in the Netherlands. Results of a comparative TNO study

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A Study by TNO

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Talk Synopsis

• Background to Study
• Outline of Study
• Methodology & Assumptions
• Results
  - Emissions (NOx, PM)
  - Global Warming Potential (GWP)
  - Cost impact
    - Emissions cost benefit trade-off
  - Other issues
• Conclusion
Background to Study

• Shell collaboration in 2007 with Connexxion
  - Largest bus operator in the Netherlands
    - Laboratory emission measurements

• Desire to build on trial data
  - Understand more about the use of GTL fuel from the viewpoint of a bus operator, in Netherlands context
    - Costs, Environmental pressures, Ease of use etc.
  - Broaden that understanding to cover a range of alternative fuels & engine technologies, comparison with conventional diesel

• TNO commissioned to perform this study
Outline of Study

• Like-for-like comparison of different alternative fuels for city buses
  - 1) Regular (EN590) “zero” sulphur diesel (<10ppm). Reference for study
  - 2) GTL (Gas To Liquid, a synthetic diesel fuel made from natural gas)
  - 3) B100 (biodiesel)
  - 4) CNG (Compressed Natural Gas)
    - Fast- and slow-fill fuel station option. From Dutch perspective
  In less detail
  - 5) Ethanol (with additives), to be used in a diesel cycle engine
  - 6) CBG (Compressed BioGas, upgraded & cleaned biogas; slow-fill case)

• Required outputs of study
  - Local emissions of NOx, PM, CO and HC
  - Well-to-Wheel and Tank-to-Wheel GWP [Global Warming Potential]
  - Cost effects of the various options, divided into:
    - Vehicle operational cost
    - Infrastructure cost
    - Capital cost
  - Other issues of interest
GTL-optimised vs. regular diesel

• Detailed parts of TNO study considered GTL as a “drop in” replacement for diesel in unmodified engines
  - Robust level of information, especially fleet costs

• However there are studies and publications to indicate further advantages of GTL in optimised engines
  - Lowering CR will reduce NOx emission while maintaining good cold starting behaviour
  - Lower CR also reduces in-cylinder pressure levels and therefore friction losses, particularly at the lower loads
  - For a given NOx-target, PM-levels will be lower, resulting in lowered fuel consumption for active DPF regeneration
  - True Zero-sulphur fuel is more aftertreatment-friendly
  - Time between oil replacement will be higher

• Potential for lower maintenance costs and up to 5% better energy efficiency (estimate)
Methodology – Cost Impact

- TNO have developed cost model for calculating additional expenses of operating urban bus fleet on an alternative fuel.
  - Cost model is designed to compare different vehicle and fuel options

<table>
<thead>
<tr>
<th>Fleet Info</th>
<th>Fuels</th>
<th>Infrastructure</th>
<th>Vehicle</th>
<th>Capital cost</th>
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<tbody>
<tr>
<td>Fleet size</td>
<td>Prices</td>
<td>Fuel station costs (initial and annual)</td>
<td>New Vehicle Prices</td>
<td>For infrastructure</td>
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<tr>
<td>Annual mileage</td>
<td>Taxes</td>
<td>Maintenance costs</td>
<td>Maintenance costs</td>
<td>For vehicles</td>
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<td>Additional costs (e.g. Pressurising for CNG)</td>
<td>Training costs for personnel</td>
<td>Insurance &amp; annual costs</td>
<td>Interest rate</td>
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<td>Density</td>
<td>Facility modification costs</td>
<td>Vehicle depreciation rate</td>
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<td>Energy content</td>
<td>Fuel station insurance cost</td>
<td>Fuel &amp; additives consumption</td>
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</table>
Methodology – Emissions and GWP

- Generation of real world emissions values, i.e. those expected for on-road city bus style driving. Taken directly from literature or using VERSIT+ emission model applied to data
  - First stage: emission values estimated for regular diesel & CNG buses
  - Second stage: 2nd literature review comparing emissions levels of 3 diesel engine options: diesel, GTL, biodiesel
    - Focus on fuel comparisons with same vehicle or engine, to extract fuel effects from engine-to-engine variation effects

- Total global warming potential (GWP) is calculated for every option using a well-to-wheels methodology.
  - Well-To-Tank part based on EU JRC study, most recent (Mar07)
  - Tank-To-Wheel part calculated from the data provided by the cycle simulations, giving energy consumption of every fuel option in MJ/km.
  - In addition to CO₂, the GWP calculations include methane (CH₄) and nitrous oxide (N₂O), with weighting factors of 23 and 296.
    - Same weighting factors as used in the JRC/Eucar/Concawe study
Assumptions

• Baseline diesel fleet:
  - 85 buses travelling 60,000 km/year each
  - 12 meter buses fuelled by regular diesel fuel
  - EU3, EUIV (SCR or EGR) and EUV/EEV emission level
  - Average occupancy: 40 passengers (2800 kg)

• Gas Fuelled fleets
  - Cost penalty per vehicle of 32,5K€uro if bought new
  - Depreciation rate 95% in 8 years [vs diesel buses 62,5% in 8 years]
  - Refuelling station [slow fill] 85 gas powered buses = 1,830,000 Euro
  - Refuelling station [fast fill] 85 gas powered buses = 3,150,000 Euro

• All alternative fuels, other infrastructure modifications
  - CNG / biogas: 110,000 Euro (+ extra shift for overnight refuelling)
  - B100 / GTL: 2,000 Euro
  - E100: 5,000 Euro
Results: -Emissions

- Air quality related emissions (NOx, PM) presented
  - HC and CO are also given in the full TNO report

- These are given by emissions legislation class & engine technology (Euro 3, Euro 4 and Euro5 / EEV)

- Euro 5 / EEV are combined and only “best available” technology is taken into consideration

- Note: other vehicle sources (tyres, brakes) emit around 0,08 g/km of PM
  - These become significant for the more modern technology
Results: EURO3 NOx and PM emissions

Red line represents other sources of PM10 (brakes, tires)
Results: EURO 4 EGR & SCR NOx and PM Emissions

Red line represents other sources of PM10 (brakes, tires)
Results: EURO5/EEV NO\textsubscript{x} and PM emissions

![Bar chart showing NO\textsubscript{x} and PM emissions for different fuels and combustion methods.](image)
Emissions Conclusions

**NOx Emissions**

- GTL shows benefit versus reference diesel, whereas B100 shows detriment
  - This trend is across all technologies Euro-3 to Euro-5
  - GTL benefit in 12-17% range

- Broadly similar levels of NOx for the GTL and CNG cases
  - Across all technologies Euro-3 to Euro-5
  - Exception Euro-5/EEV CNG lean burn, worse than diesel/GTL counterparts

- Modification of this simple picture via influence of engine technology
  - For diesel & GTL, SCR systems give lower emissions than EGR system
  - For CNG systems stoichiometric gives lower emissions than lean burn

**PM Emissions**

- GTL and B100 show benefit versus reference diesel
  - The show similar magnitude for Euro-4 & Euro-5, but B100 better for Euro-3 case
  - GTL benefit in 18-29% range

- PM emissions from natural gas vehicles are negligible, but this is also the case for all fuel options with Euro-5
  - e.g. For low emitting vehicle quantities lower than those produced from tyres
Results: -global warming potential

- GWP (global warming potential results presented as
  - Well-To-Tank (WTT)
  - Tank-To-Wheel (TTW)
  - Well-To-Wheel (WTW=WTT+TTW)

- CO₂ equivalent emissions are presented, these included
  - CO₂
  - CH₄
  - N₂O

- These are given by emissions legislation class & engine technology (Euro 3, Euro 4 and Euro5 / EEV)

- Euro 5 / EEV are combined and only “best available” technology is taken into consideration
Results EURO III Global Warming potential

- **CO₂ [g/km]**
  - diesel: 274, 1413, 1486, 1686
  - GTL: 484, 1365, 1849
  - B100: 964, 1470
  - E100: 202, 1377
  - CNG Lean (conservative): 387, 1219
  - CEG Lean: 223, 1219
  - CNG Lean: 1442

Legend:
- GWP WTT (g/km CO₂ eq.)
- GWP TTW (g/km CO₂ eq.)
- GWP WTW (g/km CO₂ eq.)
Results EURO IV Global Warming potential

![Graph showing CO2 emissions comparison for various technologies and exhaust treatments, with data points for GWP WTT, GWP TTW, and GWP WTW expressed in g/km CO2 eq.](image-url)
Results EURO V/EEV Global Warming potential
Global Warming Potential (GWP) Conclusions

**NOTE:** GWP graphs show error bars
+/- 10% on the WTT emissions & 5% on the TTW emissions

- WTW CO$_2$ emission error bars tend to overlap for regular diesel, GTL and CNG (both technologies). Against this background, non-bio fuel options come close
  - Important factor: diesel GWP might increase in near future

- CNG position can be significantly changed by gas source
  - Dutch mix CNG or conservative [long-distance pipeline option]?  
  - Conservative CNG stoichiometric case is worse than diesel reference

- Best GWP results are obviously obtained with those biofuels considered in the study, E100, B100, CBG
Results – Fleet Costs

• Sub-divided into the several different cost factors
  - Presented with and without tax

• Following scenarios were used for the calculations:
  - use of existing Euro-3 vehicles
  - use of 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).
Results: Total fleet costs €ct / passenger km w.o. tax

EN590 | CNG | B100 (RME) | GTL | Biogas

- Using existing fleet Euro3
- Using existing fleet Euro4 SCR
- New vehicle Euro4 SCR
- New vehicle Euro4 SCR+DPF
- Using existing fleet Euro5 SCR
- New vehicle Euro5 SCR
- New vehicle Euro5 SCR+DPF
- Using existing fleet Euro6 SCR
- New vehicle Euro6 SCR
- New vehicle Euro6 SCR+DPF
- New vehicle Euro6 SCR+DPF+4
- Euro6 SCR+4
- New vehicle Euro6 SCR+4
- New vehicle Euro6 SCR+4

Legend:
- Vehicle costs €ct/passenger km
- Vehicle capital cost €ct/passenger km
- Infrastructure costs €ct/passenger km
- Infrastructure capital cost €ct/passenger km
- Fuel costs without tax €ct/passenger km
- CNG compression energy cost €ct/passenger km
- Adblue costs €ct/passenger km
Results Total fleet costs €ct / passenger km
Fleet Costs Conclusions

Fleet costs – No tax
- GTL is the most cost-effective alternative fuel option
  - costs are only slightly above regular diesel
  - next best fuel option is biodiesel
- CNG (slow-fill and fast-fill) come in third position
  - mainly the result of higher (fuel station & vehicle) investment
- Biogas even more expensive than natural gas while ethanol is least economical

Fleet cost – Including tax
- GTL and CNG options now come very close on fleet costs
- Natural gas vehicles are considered only in context of buying new vehicles, that is in competition with other Euro-5/EEV technology
- Overview figures of all fuels only considers cheaper slow-fill option
Results: Total fleet costs €ct / passenger km w.o. Tax
-Focus on CNG & GTL options
Results Total fleet costs €ct / passenger km
Focus on CNG and GTL options
Emissions cost-benefit trade-off

- Costs are calculated to reduce PM & NOx by one tonne per annum
  - Using emissions & fleet cost results within the study, Euro-3 is taken as the baseline bus fleet

PM emissions
- GTL and CNG are the best options
  - Relative positions of CNG and GTL depend on tax regime
  - For identical tax regime, GTL is the best option

NOx emissions
- Replacement of diesel by GTL in existing fleet is the option with highest cost-benefit trade-off (irrespective of taxation)
- If new vehicles considered, Euro-5/EEV should be preferred above Euro-4
  - For new Euro-5/EEV vehicles, GTL option is again the best one.
  - Although difference versus stoichiometric CNG version is very small

- Drop-in replacement of diesel by biodiesel always more expensive.
Costs to lower PM emissions (relatively compared to EURO 3 diesel bus)
Costs to lower NOx emissions (relatively compared to EURO 3 diesel bus)
## Results, Other issues

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<th>Insurance</th>
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Overall Conclusions

- Broadly similar levels of NOx for the GTL and CNG cases. GTL & CNG shows benefit versus reference diesel. B100 shows a detriment.

- PM emissions GTL & B100 show benefit versus reference diesel. PM emissions from natural gas vehicles are negligible, but this is also the case for all fuel options for Euro-5.

- Global warming potential (GWP) data shows that diesel, GTL and CNG come close. Important consideration is the size of error bars associated with WTW data.

- Best GWP results are obviously obtained with those biofuels considered in the study, E100, B100, CBG.

- In the absence of tax or for a level tax regime, GTL is the most cost-effective alternative fuel option for a bus fleet.

- In the current Dutch fuel tax regime, GTL and CNG options now come very close on fleet costs.

- For emissions cost-benefit trade-off & consideration of both PM & NOx, then GTL is the best option, although the tax regime can distort this.
Thank you

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