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TNO report

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Current state and emission performance of CNG/LNG heavy-duty vehicles

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Contents

1 Samenvatting

Introductie van aardgas (CNG en LNG) voor zwaar wegverkeer zou een verschuiving van brandstof van diesel naar aardgas betekenen. Dit rapport geeft aan wat de ontwikkelingen, mogelijkheden, voordelen en risico's zijn van de toepassing van CNG en LNG voor vrachtwagens en bussen, op grond van de huidige situatie en ontwikkelingen en met de focus op voertuigemissies in de praktijk. Dit rapport is geschreven in opdracht van de afdeling Voertuigemissies & Brandstoffen van het Ministerie van I&M.

LNG is Liquefied Natural Gas. Het is sinds de jaren 60 de wijze om aardgas over zee te vervoeren. De dichtheid is ongeveer 450 gram per liter, afhankelijk van de precieze samenstelling en de druk. Hierdoor heeft LNG 1.8 keer het volume van diesel voor dezelfde energie. CNG daarentegen, wat gebruikt wordt voor stadsbussen, heeft ongeveer 5 keer het volume van diesel. Het daadwerkelijke benodigde volume voor CNG hangt af van de tankdruk en de calorische waarde van het gas. De tijdsduur tussen tanken is voor CNG korter dan voor LNG, ondanks dat de CNG tanks meer ruimte innemen. Daarom is LNG een meer natuurlijke vervanging van diesel dan CNG, bij hoog vermogen en langdurige operaties. De typische gevallen zijn zwaar wegtransport en scheepvaart.

De beschikbaarheid van LNG is nog beperkt in Europa: pilots worden vooral uitgevoerd met "back-to-base" distributie. Hier wordt de vrachtwagen dagelijks getankt op dezelfde locatie, met transport in de regio. In Engeland zijn de eerste corridors, met meerdere LNG tankstations langs de noord-zuid snelwegen. In Amerika, Korea en Japan, wordt LNG meer gebruikt voor wegtransport. Daar zijn er wel lange-afstand routes met voldoende tankstations.

1.1 Motorconcepten voor aardgas

Er zijn zowel motoren met vonkontsteking als dual-fuel motoren die werken volgens het diesel principe. Bij motoren met vonkontsteking wordt een verder onderscheid gemaakt tussen ‘stoichiometrische’ motoren met drieweg katalysator en ‘lean-burn’ of arm-mengsel motoren met oxidatiekatalysator. Bij het eerste type, wordt precies voldoende lucht gedoseerd om het gas te kunnen verbranden. Daardoor is een driewegkatalysator in principe mogelijk en kunnen zeer lage NO_x, CO- en HC-emissies gerealiseerd worden. Bij vrachtwagens is de dual-fuel motor populair. Deze werkt volgens het diesel principe, waardoor het motorrendement hoger is.
Daarnaast kan gewoon op diesel gereden worden, mocht aardgas niet beschikbaar zijn. De NOx en fijnstofemissies van de dual-fuel motoren wijken doorgaans niet veel af van die van de 100% diesel versie. Fijnstofemissies kunnen iets lager zijn. Dual-fuel kan ook achteraf op een diesel voertuig geïnstalleerd worden, alhoewel het maximum bijmengpercentage dan doorgaans lager is.

Het "lean-burn" vonkontsteking motorconcept, van enkele jaren geleden, maakt het momenteel niet goed mogelijk om aan de emissie-eisen van Euro-V te voldoen, zowel voor stikstofoxides (NO_x) als voor methaan (CH_4). Dit waren vooral Euro-IV bussen. Het lean-burn motor concept werd geïntroduceerd om met aardgas de rendementen van een dieselmotor te halen.

Voor het dual-fuel concept dient diesel voor de ontsteking, en is er altijd een deel diesel dat verbruikt wordt. De Europese methaan emissie-eisen zijn met dit concept moeilijk te halen. Amerika heeft geen methaan emissie limiet, en zo is er weinig bekend over deze in Amerika wijdverbreide technologie wat betreft de uitstoot van methaan. In Amerika wordt de directe LNG injectie met een pilot diesel injectie algemeen toegepast. Dit motor-concept is in Europa nog niet beschikbaar. Voor de andere gereglementeerde emissies: NO_x, CO, NMHC (NonMethane HydroCarbons), is een dual-fuel concept van de fabrikant vergelijkbaar, of iets beter dan diesel alleen. Maar gezien de complexiteit is het risico op hoge emissies in bepaalde situaties wellicht hoger. Voor dual fuel als retrofit zal het onder de huidige normen moeilijk zijn de limieten van Euro-V en zeker Euro-VI te halen.

De vrijheid in motormanagement voor een dual fuel concept heeft als nadeel de complexiteit, en bijhorende risico's. Maar dat is ook een kans voor de ontwikkeling van motorconcepten die nu nog in de kinderschoenen staan, met het voordeel van een energie-efficiënte dieselcyclus, mogelijk zonder de noodzakelijke nabehandeling in de vorm van een SCR voor het terugbrengen van de NOx-uitstoot. Deze technologie zal niet spoedig beschikbaar komen.

1.2 Emissies van aardgasmotoren

Aardgas wordt al jaren gebruikt in bussen. De strenge EEV eisen, die al ten tijde van Euro-IV als milieuvriendelijke variant bestonden, konden alleen met aardgas gehaald worden: de deeltjesemissie was lager, en de eisen aan stikstofoxides waren met een driewegkatalysator (vonkontsteking) geen probleem.

Tegenwoordig kan het diesel concept, wat in dual-fuel motoren gebruikt wordt, ook de lage EEV emissies halen. De normen voor de methaan emissies blijven één van de strengere eisen in de wetgeving. Plannen om de methaan emissie niet als vervuilende emissie maar als broeikasgas te behandelen kunnen tot een lichte verruiming van de emissie-eisen leiden. Aardgas heeft per kilogram, en per energie-eenheid, minder koolstof dan diesel, en geeft minder CO_2 uitstoot. Van diesel is 86% van het gewicht koolstof, van aardgas is dat 75%, dat is 13% minder. Daarnaast is de verbrandingswarmte, van aardgas, afhankelijk van de samenstelling, ongeveer 10% hoger. (IPCC gebruikt respectievelijk 74.1 kg/MJ en 56.1 kg/MJ CO_2 emissiefactoren op energiebasis voor diesel en aardgas.) Maar methaan is 25 keer zo effectief als broeikasgas. Dus een procent onverbrande methaan (methaan slip) doet het theoretische voordeel van aardgas op de broeikasgasuitstoot teniet. Voor retrofit dual-fuel motoren is het risico op methaanslip groter, omdat ze niet voor verbranding van aardgas zijn ontwikkeld. Aan de andere kant wordt er meer diesel en minder gas verbruikt. Per saldo blijft echter de mogelijkheid van methaanslip aanwezig.

Samenvattend: de motor met vonkontsteking wordt over het algemeen gebruikt vanwege de lage uitstoot van luchtverontreinigende emissies, terwijl voor de dual-fuel motor het accent ligt op lagere brandstofkosten en minder CO2-uitstoot. In de toekomst zal na verdere doorontwikkeling het onderscheid tussen enerzijds het diesel en dual-fuel concept en anderzijds het driewegkatalysator, vonkontsteking, concept vermoedelijk afnemen: Met Euro-VI, waarbij de testprocedure en de controle worden aangescherpt, wordt de eerste schoner en de tweede wordt de komende jaren naar verwachting een stuk zuiniger. De ontwikkelingen bij personenauto's met driewegkatalysator op het gebied van efficiëntie zijn met beperkte moeite te vertalen naar vrachtwagenmotoren.

Tabel 1 Emissiefactoren voor bussen (12 meter bus). De NO_2 fractie is laag: minder dan 10%, behalve voor de diesel EEV bus. Fijnstof slijtage emissies (71 mg/km) zijn niet meegenomen. CO_2 uitstoot typisch 1000 g/km voor een stadsbus, dual-fuel bussen mogelijk iets lager. Methaan (CH_4) emissies zijn indicatief. Voor dual-fuel Euro-VI zijn de eisen vergelijkbaar aan diesel en aardgas.

	stadsbussen emissies tijdens standaard lijnbus ritten	NO_x [g/km]	fijnstof [mg/km]	CH_4 [g/km]
Euro-IV	Diesel + SCR	7.7	113	0.0
	Aardgas lean burn	7.9	66	1-7
Euro-V	**Diesel + SCR (referentie)**	**4.5**	**113**	**0**
EEV	Diesel + SCR + DPF	4.5	29	0.0
	Aardgas stoichiometrisch	2.2	39	0.1
	Aardgas lean burn	5.6	39	1-7
Euro VI	Diesel + SCR + DPF	0.7-1.4	25	0.0
	Aardgas stoichiometrisch	0.7-1.4	25	0.0
	Dual fuel	0.7-1.4	25	0.5

1.3 Bedrijfsvoering met een aardgas voertuig

Het stoichiometrische (driewegkatalysator) motorconcept heeft in de bedrijfsvoering het nadeel dat het brandstofverbruik hoger ligt. Ondanks de lagere CO_2 uitstoot per stookwaarde, leveren stoichiometrische motoren momenteel geen CO_2 winst. Maar daarentegen is er geen diesel nodig, in tegenstelling tot dual-fuel motoren, en is het systeem van de motor en de uitlaatgasnabehandeling schoon en robuust. Doordat er geen diesel in de gasmotor komt, slechts een beetje motorolie, is het onderhoud vergelijkbaar met dat van een dieselmotor, en niet met dat van een benzinemotor wat over het algemeen meer onderhoud vraagt. Een ander voordeel is dat de motor stil is, en indien gewenst, extra lage emissies kan hebben. Dit maakt dat ze in sommige gemeentes buiten de venstertijden gebruikt mogen worden voor winkelbevoorrading. Het hogere brandstofverbruik wordt wellicht in de toekomst lager, door de technologie die voor personenauto's is ontwikkeld toe te passen op deze vrachtwagenmotoren. Zowel motorfabrikanten, zoals Iveco als onafhankelijke ontwikkelaars, zoals NONOx zijn hier mee bezig. Het (piek)vermogen van een stoichiometrische motor is momenteel wat lager, wat vooral te merken is bij het trekken van een zware last. De chauffeur zal voor “drivability” eerder voor diesel kiezen.

1.4 LNG: koud en vloeibaar aardgas

Naast motorconcepten is de LNG tank een nieuw aspect. LNG wordt gekoeld meegenomen, zodat de druk bij deze dichtheden van 430 - 350 g/liter beperkt is. De temperatuur varieert van -163 tot typisch -110 graden Celsius. De tanks zijn daarom dubbelwandig, voor de isolatie, en van austeniet roestvrij staal. De prijs van een LNG tank is een substantieel deel van de noodzakelijke investering om op LNG te rijden. Dit materiaal wordt bij deze extreem lage temperaturen niet bros. De technologische ontwikkelingen zijn niet afgelopen.
Het LNG kookt in de tank, hierdoor wordt de druk hoger, en ontstaat er het risico dat bij onvoldoende gebruik de druk verlaagd moet worden door een

veiligheidsventiel. Dit kan een substantiële methaan emissie geven. Daarnaast functioneren verschillende motoren bij verschillende temperaturen en, bijbehorende, drukken. Dat staat een standaardisatie en de ingebruikname van openbare tankstations in de weg. In principe kunnen alle druk-temperatuur combinaties geleverd worden, met behulp van warmtewisselaars, op basis van het koudste LNG, bij atmosferische druk.

De focus van LNG tankregelgeving ligt op een eis van een tijdsduur. Dat maakt dat de methaan emissies vooral optreden bij onregelmatig gebruik van het voertuig. Het "boil-off-gas", afgeblazen door een veiligheidsventiel, kan een significante contributie zijn aan de broeikasgasemissies, omdat het 25 keer effectiever is als broeikasgas dan CO_2. Een brander op het veiligheidsventiel is niet meer toegestaan.

In Amerika zijn er eisen aan de samenstelling van de LNG. De zwaardere koolwaterstoffen, beginnende bij ethaan (C_2H_6) mag slechts 1.5% van de LNG zijn. Er is een ECE richtlijn (brandstof G_{20} als onderdeel van R49 richtlijn) in ontwikkeling die deze eis overneemt. De reden is dat bij het onttrekken van het gas aan de tank, vooral de zwaardere componenten achterblijven in de vloeistof. Op den duur verandert de samenstelling van het LNG in de tank zodanig dat de motor niet meer functioneert vanwege het grote aandeel ethaan en propaan. In dat geval moet de tank afgeblazen worden. In Nederland zijn er nog geen eisen aan de samenstelling van LNG. Het LNG uit het Midden-Oosten bevat veel ethaan en propaan (typisch meer dan 10%) zodat de hierboven beschreven problemen reëel zijn. In Zweden wordt in een testprogramma de samenstelling van de tankinhoud bijgehouden, en wordt er indien noodzakelijk LBG (Liquid Bio Gas) getankt dat aan nauwe specificaties voldoet met nagenoeg alleen methaan, zodat de overgebleven zwaardere fracties verdund worden en een kleiner aandeel hebben in de totale tankinhoud.

De kansen en risico’s van CNG en LNG liggen in een verschuiving van diesel naar aardgas. Aardgas heeft grote leverzekerheid en prijsvastheid, naar verwachting. Voor schoon en stil is stoichiometrische verbranding met een driewegkatalysator de oplossing, voor zuinig de dual-fuel motor beter geschikt, waarbij de risico’s beide voor NO_x en methaan emissies beheerst moeten worden. De methaan emissies uit de tank, zogenaamde boil-off, vraagt om het gebruik van LNG in voertuigen die dagelijks gebruikt worden, en binnen één aan twee dagen een tank leegrijden.

De beschikbaarheid van LNG voor wegtransport is een struikelblok voor introductie. Regionale distributie en voertuigen in de stad hebben slechts een enkel tankstation nodig, en daar kan de introductie van LNG eenvoudiger dan voor nationaal transport. Ook speelt de lagere actieradius bij LNG en zeker CNG hier minder een rol.

1.5 Emissie limieten en regelingen

Diesel en aardgas motor-emissies zijn gereguleerd door de verschillende Europese normen (Euro-IV/V/VI/EEV). Dual-fuel motoren vallen hier (nog) niet onder. In het bijzonder zijn de methaan emissie limieten een onderwerp van discussie voor dual-fuel motoren.

Tabel 2 Emissie limieten, met onderscheid in methaan (CH_4), nonmethaan (NMHC), en alle koolwaterstoffen (THC). De testprocedure varieert tussen ESC, ETC, en WHTC (Euro-VI). Sommige limieten gelden voor diesel concept (C.I), andere voor vonkontsteking (S.I.).

g/kWh	THC	NMHC	Methaan (CH_4)	NOx
Euro-V	$0.46^{(ESC)}$	$0.55^{(ETC)}$	$1.1^{(ETC)}$	2.0
EEV	$0.25^{(ESC)}$	$0.4^{(ETC)}$	$0.65^{(ETC)}$	2.0
Euro-VI	$0.16^{(WHTC, C.I.)}$	$0.160^{(WHTC)}$	$0.50^{(WHTC, S.I.)}$	$0.46^{(WHTC)}$

Een limiet van 0.5, 0,65 en 1.1 gram CH_4 per kWh, oftewel 0.27%, 0.36% en 0.6% methaanslip kan beschouwd worden als extra broeikasgas emissies. Eén kWh mechanische energie geeft, bij diesel, ongeveer 650 gram CO_2. De consequentie is dat 0.5, 0.65 en 1.1 gram CH_4 per kWh overeenkomt met respectievelijk: 1.6%, 2.1% en 3.6% extra broeikasgas emissies. Een methaanslip van drie keer de emissielimiet is niet onwaarschijnlijk voor inbouwinstallaties. Dergelijke waarden, zeker in combinatie met een beperkte gas bijmenging doen de voordelen voor het verminderen van de broeikasgasemissies volledig teniet, en 10% tot 15% additionele broeikasgasemissies zijn mogelijk.

De globale formule voor dezelfde hoeveelheid geleverde arbeid in ideale omstandigheden is, bij volledige vervanging van diesel door aardgas:

$$1 \text{ kWh} = 650 \text{ g } CO_2 \text{ bij diesel} = 500 \text{ g } CO_2 \text{ bij methaan}$$

Dit correspondeert met 245 gram diesel, en 182 gram methaan. In de praktijk is de hoeveelheid geleverde arbeid wat minder, bijvoorbeeld bij stationair draaien wordt er geen arbeid geleverd maar wel brandstof verbruikt. De hoeveelheid CO_2, en brandstof zijn typisch 10%-15% hoger in praktijkomstandigheden. De extra uitstoot van methaan als gevolg van slip kan 6 gram (3.3% methaanslip) zijn per kWh. Dit geeft een extra uitstoot van 25 x 6 = 150 gram CO_2-equivalenten, waardoor het voordeel ten aanzien van broeikasgas emissies van 500 g/kWh t.o.v. 650 g/kWh verloren gaat.

Een vrachtwagen op de snelweg heeft een hoger motorrendement dan in de stad, en verbruikt dus minder brandstof per kWh en per kilometer. De emissielimieten per kWh zeggen daarom minder voor de praktijk. In plaats daarvan wordt de emissies per hoeveelheid brandstof, of per CO_2 vaak gebruikt. De lagere CO_2 uitstoot per stookenergie van aardgas compliceert die vergelijking: minder CO_2 bij aardgas geeft een hogere methaan emissies per CO_2. Daarnaast is het moeilijk te bepalen wat de verhouding diesel en aardgas is in een dual-fuel motor. Een directe bepaling van de broeikasgas reductie is uit de meeste metingen niet mogelijk, zonder aannames en correcties.

Metingen aan vier verschillende dual fuel aardgas vrachtwagens in Nederland laten een grote variatie aan methaan emissies zien. Uitgedrukt in de CO_2 emissies ligt de waarde van de methaan emissie tussen 1.3 en 17.5 g/kg CO_2. De hoogste waarde is voor specifieke omstandigheden. Dit voertuig had een gemiddelde methaan emissie van rond de 8 g/kg CO_2. De metingen zijn uitgevoerd in het kader van het testprogramma voor dual fuel voertuigen en het steekproefprogramma van het ministerie van IenM. De prototypen zijn niet allemaal op de weg toegelaten door de RDW. De meeste voertuigen hadden een emissie rond de 2 g/kg CO_2 in gecontroleerde omstandigheden. Maar de vervangingsgraad van diesel door aardgas blijft beperkt in de gevallen dat het gemeten is. Allen bij hoge last is de vervangingsgraad substantieel. Dit komt typisch voor bij volle belading, en op de snelweg.

Optimistische waarden van 50% vervanging van diesel door aardgas zou betekenen er een CO_2 voordeel van 11.5% wordt gehaald. Een methaanslip van 2 g/kg CO_2 zal een beperkt voordeel van 7% van verminderde broeikasgas emissies geven. De 8 g/kg CO_2 komt overeen, bij een 50% vervanging, met een 6.2% toename van de broeikasgas emissies. De voordelen lijken beperkt en de risico's zijn vergelijkbaar bij huidige dual fuel voertuigen. Ter vergelijking, de metingen aan een Euro-V stoichiometrische aardgas vrachtwagen, met driewegkatalysator, geeft 0.3% additionele broeikasgas emissies via de methaan emissies.

De uitstoot van fijnstof is bij dual fuel operatie van de motor vergelijkbaar of iets lager. De uitstoot van NO_x is in sommige gevallen lager, in andere gevallen hoger. Op deze gereguleerde componenten is er geen uniform beeld van de effecten van dual fuel operatie. Er zijn geen extreem hoge of lage waarden gemeten.

De emissies van koolwaterstoffen is gereguleerd vanwege de irriterende werking op de longen en de rol in ozon vorming. Verschillende koolwaterstoffen dragen daar verschillend aan bij. Methaan heeft slechts een kleine rol in de lokale luchtkwaliteit.

Indien methaan emissies alleen als broeikasgas beschouwd worden, omdat de bijdrage aan binnenstedelijke ozon productie beperkt is, dan wordt een CO_2 reductie van 10% door het gebruik van aardgas volledig gecompenseerd door 3.1 g/kWh methaan emissies. Dit komt overeen met 1.7% methaanslip. Alleen als de methaan emissies onder controle zijn bij dual-fuel motoren, kunnen deze motoren een substantiële bijdrage leveren aan de reductie van broeikasgassen.

1.6 Emissie wetgeving dual-fuel motoren

Voor dual-fuel motoren is er "world-harmonized" regelgeving in de maak. Deze maakt onderscheid tussen verschillende gradaties van dual-fuel werking, en van verschillende kwaliteiten van LNG en CNG. Zowel de calorische waarde, als het aandeel ethaan en andere zwaardere koolwaterstoffen worden hierin meegenomen.

Voor de methaan emissielimieten voor Euro-VI dual fuel motoren wordt er afhankelijk van het aandeel vervanging van diesel door gas geïnterpoleerd tussen de diesel limiet van 200 mg/kWh en de gasmotor limiet van 500 mg/kWh. Deze eisen zijn uniform, de testprocedure kan verschillen afhankelijk van de motorwerkingen. Euro-V eisen worden nog besproken. Regelgeving voor retrofit installaties komt in een later stadium.

In de afgelopen twee jaar heeft er een Nederlands Dual Fuel test programma gelopen bij de RDW en het ministerie van IenM. In dat kader zijn individuele vrachtwagens toegelaten op dual fuel, aardgas en LPG. Dit programma eindigt in januari 2013. De resultaten worden meegenomen in internationaal overleg, in Brussel en Geneve. De stakeholders zijn verdeeld of dual-fuel systemen voor vrachtwagens een toekomst hebben in Nederland, met de aankomende Euro-VI wetgeving in relatie tot de resterende economische bedrijfsduur op de bestaande Euro-V vrachtwagens. Met andere woorden, in principe zou een nieuwe vrachtwagen uitgevoerd moeten worden met dual fuel installatie, en Euro-VI staat dat niet toe (zonder dat het voertuig opnieuw de uitgebreide eisen van de Euro-VI wetgeving doorstaat) en van Euro-V worden er nog maar een beperkt aantal verkocht.

1.7 Conclusie

De emissies van aardgas vrachtauto’s en bussen laten een wisselend beeld zien. Stoichiometrische Euro-V gasmotoren zijn erg schoon en stiller. Met dit motortype kan nu al aan de Euro-VI eisen worden voldaan. De uitstoot van NO_x en fijnstof ligt op een lager niveau dan van huidige Euro-V dieselmotoren. Doordat dieselmotoren met de introductie van Euro-VI nog flink schoner worden, komt het NO_x en fijn stof voordeel van stoichiometrische gasmotoren t.o.v. Euro VI diesel grotendeels te vervallen. Door het lagere rendement hebben stoichiometrische gasmotoren nauwelijks een CO_2-voordeel t.o.v. diesel. In de toekomst kan het rendement van stoichiometrische gasmotoren worden verbeterd met van personenauto’s afgeleide techniek, waarbij opgemerkt dat het rendement van dieselmotoren ook verder zal verbeteren.

Lean burn en dual fuel motoren zijn minder schoon dan stoichiometrische motoren en ook minder stil. De NO_x emissie van lean burn motoren is vergelijkbaar met die van diesel. Voor fijn stof is er wel een klein voordeel. Lean burn en dual fuel motoren hebben een hogere efficiëntie en daardoor een lager uitstoot van CO_2. Lean burn en dual fuel motoren worden gekenmerkt door methaanslip: onverbrande brandstof die door de uitlaat weer vrijkomt. Doordat methaan een sterk broeikasgas is (GWP-waarde recentelijk op 25 gesteld door het IPCC) gaat met de huidige technologie het potentiële broeikasgassenvoordeel van lean burn en dual fuel motoren als gevolg van het hogere rendement weer gemakkelijk verloren. I.v.m. de strenge methaaneis kunnen lean burn en dual fuel gasmotoren met de huidige Euro-V technologie niet voldoen aan Euro-VI, alleen met stoichiometrische gasmotoren kan momenteel aan Euro-VI worden voldaan. Met Euro-VI in zicht zijn enkele fabrikanten van mono fuel aardgas trucks reeds overgeschakeld van lean burn naar stoichiometrische motoren.

Huidige dual fuel motoren zijn gebaseerd op Euro-V. Het gaat hierbij om zowel semi-affabriek als om retrofit systemen. Het is onduidelijk of deze motoren wel aan de emissienorm voor methaan voldoen. De Euro-V emissienorm voor methaan bedraagt 1.1 g/kWh, oftewel 0.6% methaanslip. Bij 6 g/kWh of 3.3% methaanslip gaat het potentiële voordeel van 24% voor de uitstoot van broeikasgassen verloren. Gegeven de lagere vervangingsratio’s van dual fuel motoren is 3 g/kWh, de emissielimiet waarbij dual fuel motoren broeikasgas neutraal zijn ten opzichte van de diesel-uitvoering. Twee van de vier geteste voertuigen hebben gemiddeld een hogere uitstoot van methaan. Bovenop de methaanuitstoot als gevolg van slip komen bij LNG-voertuigen nog mogelijke methaanverliezen als gevolg van boil-off effecten. Met de huidige Euro-V technologie kunnen dual fuel motoren niet aan Euro VI voldoen. Om aan Euro VI te voldoen is de toepassingvan nieuwe of doorontwikkelde motor- en aftertreatmenttechnologie noodzakelijk. Er zijn tekenen dat Europese OEM’s investeren in deze technologie.

2 Introduction

With the growth of the LNG and CNG market and availability, the use in heavy goods vehicles (HGV) seems only natural. The potential of these fuels and the potential risks are summarized in this report.

Liquid natural gas (LNG) is methane cooled to -163^o, so it turned liquid at atmospheric pressures. LNG has been the mode for transporting natural gas across the sea since the 1960s, mainly from Quatar, Algeria, and, in the near future, Australia. Regasification is done in Europe, Japan, and Korea. It was part of the transport chain, not a product as is. Only recently LNG is being sold as fuel, both North America and the Far-East (Japan, Korea) are ahead with the use of LNG.

The abundance of natural gas, such that it is still flared by 100 to 150 billion m^3 a year in many producing countries, makes it an interesting product. No longer flaring or releasing natural gas, but putting it to proper use will reduce greenhouse gas (GHG) emissions doubly: less methane emission as it becomes a viable commodity, and reduction of oil usage. Price and production stability is another positive feature of natural gas. Countries as the USA and Australia are entering as exporting countries.

Biogas, when properly upgraded can be used as CNG and LNG. In the UK a landfill side is combined with a LNG liquefaction plant for the use in trucks. In that case the GHG benefit is even larger.

LNG has a higher density than compressed gas, around 450 grams per litre. For the same amount of energy as diesel, LNG requires 1.8 times the volume. It is therefore interesting as fuel for vehicles which typically carry a lot of fuel: long-haul trucks, locomotives, and ships. Compressed natural gas at 200 bar requires 5 times the volume of diesel, which makes is unfeasible for long-operating, high-powered transport, generating vehicle autonomy.

LNG is boiling as it is heated up by the surroundings at ambient temperatures. Therefore the pressure increases in a closed tank. In part this may be used to have the LNG tank at the appropriate pressure for the operation of the attached installation. On the other hand it forms both a risk in terms of unwanted venting, and incompatible installations, all operating LNG but at a variety of pressures and temperatures.

LNG has a higher percentage of methane than the typical low-caloric gas found in Dutch households. In part this is due to the origin and in part due to the liquefaction process: CO_2 cannot be in LNG as it solidifies and usually heavier hydrocarbons are, in part, removed. However, some heavier hydrocarbons, like ethane and propane are still present, in 90% to 99% methane. They affect the methane number and the combustion characteristics. When boil-off gas is used in the combustion engine, the risk exists that heavier components remain in the tank, and a variation of composition, in particular methane number, which is a combustion characteristic, affects the operation.

Cummins-Westport is leader in LNG technology for HGVs. The combined diesel LNG operation in truck engines is commonly used in America. They expect to fulfil also the methane emission limit in Euro-VI technology. However, there are not yet engines demonstrated for the European market. Lean-burn and dual fuel will move toward this technology with some variation in the gas injection. Diesel serves as (small) pilot injection to the main gas combustion. Lean-burn has the advantage of a lower fuel consumption, but all problems as normal diesel operation, such as high engine-out NO_x emissions. Possible, the dual-fuel technology and operation will make the handling of the after treatment (SCR, DPF) more complex, and prone to failures in particular circumstances. The MethaneDiesel concept of Volvo is at the moment the only European OEM that explores similar concept to Cummins-Westport.

Low load operation of a compression-ignition natural gas engine is troublesome. Hence the dual fuel operation is not just a flexibility feature, but also needed for proper operation. Not enough fuel in the cylinder will cause high methane slip, of the unburned gas, in the corners of the cylinder. For the same reason is EGR useful in a gas-operating engine. Minimizing the methane slip requires an expensive oxidation catalyst. This catalyst may have a limited lifetime, especially in dual-fuel operation, with diesel exhaust gas passing through it. The placement of this catalyst is crucial, as it requires a high temperature. This makes retrofitting a gas system on a diesel engine unlikely to satisfy the methane emission limits.

Most European engine manufacturers choose stoichiometric, spark-ignition operation, also for heavy duty vehicles. In energy efficiency it is lacking. However, if the leap-forward in light-duty vehicle engines of the last years is any indication of the technological potential, the gap between compression ignition and spark ignition will decrease. The advantages of spark ignition is the easy, almost off-the-shelf, technology to fulfil Euro-VI emission limits, with very limited risks of failing operation under particular usage. The power and drivability of stoichiometric engine is less than that of a diesel engine. On the other hand, a stoichiometric engine produces less noise than a diesel engine, making it more suited for urban distribution.

3 Existing technologies

3.1 Engine technology

The technology used for new sold natural gas vehicles can roughly be divided in dedicated gas engines (spark ignition) and gas-diesel (dual-fuel, compression ignition) engines. In the sub chapters below these technologies will be discussed for trucks mainly, followed by a short bus discussion. Also a little insight in trends outside Europe is discussed.

3.1.1 Trucks dedicated gas

The table below shows the OEM HD vehicles using spark ignition currently on the market and their typical characteristics including advertised emissions if available. Main difference in used engine technology is stoichiometric versus lean-burn: Mercedes-Benz is the only supplier delivering lean burn engines in the Econic platform. Scania has supplied lean-burn CNG busses. Main advantages of lean-burn engines are the thermal behaviour and fuel efficiency. Disadvantages are the more complex aftertreatment system and higher NO_x emissions.

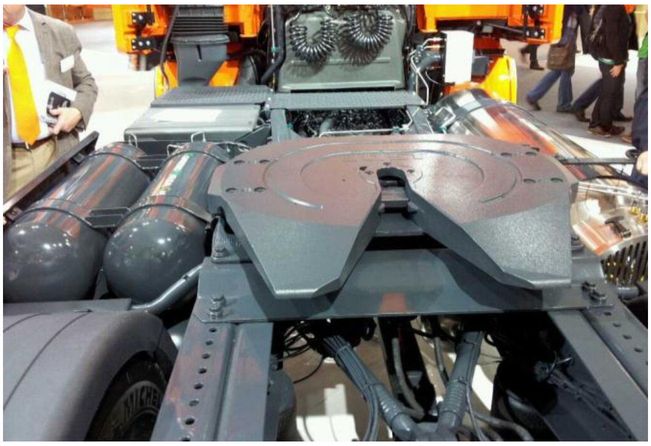
Suppliers of stoichiometric engine technology use EGR to influence both thermal behaviour and fuel efficiency (less throttling of air flow) to compensate for the disadvantages towards lean-burn. Significant advantage of stoichiometric engines is the simple and cheap 3-way-catalyst to control the exhaust emissions, wellknown from gasoline engine technology.

Note that Scania recently introduced their new Euro VI natural gas engine on the IAA in Hannover. The engine operates in stoichiometric mode, where the Euro V / EEV engines in the Scania program operate in lean-burn mode. It is expected that all manufacturers will change to stoichiometric for Euro VI legislation, see next chapter.

Brand	*MB*	*Scania*	*Iveco*	*Iveco*
Type	Econic NGT	P310 CNG	EuroCarco CNG	Stralis CNG / LNG
Emission legislation	EEV	Euro VI	EEV	EEV (Euro VI compliant)
Gas storage	CNG / LNG	CNG / LNG	CNG	CNG / LNG
Displacement [liter]	6,9	9,3	5,9	7,8
Max power [kW]	205	206-250	147	243
Max torque [Nm]	1000	1350-1600	650	1300
Combustion	SI lean-burn	SI stoich	SI Stoich	SI stoich
Catalyst	Special oxicat (methane)	3 way	3 way	3 way

Advertised emissions				
NOx [g/kWh]	1,94			0,43
CO [g/kWh]				
NMHC [g/kWh]				0,004
CH4 [g/kWh]				0,015
PM [g/kWh]	0,004			0,003

Most vehicles are available with both CNG and LNG storage capacity. It is interesting to see that some vehicles are even equipped with both on one vehicle, to have back-up CNG storage capacity in case LNG is not available. See the picture below as an example (Iveco Stralis), with CNG cylinders on the left and LNG cryogenic tank on the right.



CNG and LNG storage on one vehicle

The reason for the increased attention for the use of LNG in HD vehicles is the energy density of the stored fuel and thus the increased range of the vehicles, although the cryogenic LNG tanks are more expensive.

In case of LNG, vehicles require different refuelling pressures. Not every refuelling station can handle these pressure ranges.

- “Cold”: 3 bar (e.g. vehicles using Westport technology)
- “Saturated”: 8 bar (e.g. Iveco, Volvo dual-fuel)
- “Super saturated”: 18 bar (e.g. Mercedes, Scania)

It is expected that most or even all manufacturers will comply with saturated pressures in the near future.

The emissions of dedicated gas vehicles comply with Euro V or EEV. The only Euro VI compliant vehicle presented until now is the Scania P series CNG. The three way catalysts of stoichiometric engines control the regulated emissions to levels well below the limits.

Three way catalysts cannot handle lean-burn operation and the oxidation catalyst on lean-burn engines especially reduce hydro carbons. NO_x emissions of lean-burn engines are therefore closer to the limit.

3.1.2 Trucks dual-fuel

Dual-fuel engines operate with a mixture of gas and diesel. The engine technology is based on the diesel principle, meaning that the combustion is started by compression ignition. Depending on various parameters and engine operating point, a part of the diesel injection is replaced by gas, ignited by the diesel combustion. The origin of the dual-fuel systems in Europe can be found in price-driven LPG substitution, given the widely available infrastructure for this fuel in a number of European countries. With CNG or LNG, a higher substitution of up to 75% for OEM systems (90% for direct injection) and up to 60% for retrofit systems is reached with dual-fuel technology.

Two dual-fuel technologies can be recognized: manifold injection and direct injection. The latter technology uses a dual-fuel injector, injecting a small diesel pilot and up to 90% of natural gas. This technology is used in North America by Westport.

The aftertreatment system of dual-fuel engines is also diesel based, meaning the use of SCR for Euro V compliant engine technology. In some cases an additional oxidation catalyst is added to handle methane emissions.

Currently there is one supplier of an OEM dual-fuel system, being Volvo with their MethaneDiesel FM truck. All other vehicles currently on the road are equipped with so-called retrofit systems. These systems can be installed without the need for formal co-operation with engine manufacturers. Examples of retrofit dual-fuel system suppliers are Clean Air Power and the Hardstaff Group from the UK and Prins in the Netherlands.. Clean Air Power is the supplier of the Volvo Methane-Diesel system, but supplies retrofit systems for more brands and types of vehicles (see 2.3).

The challenge of retrofit systems is the compliance with emission legislation. In Euro IV and V emission legislation, dual-fuel engines are not recognized. Vehicles with retrofit dual-fuel systems are therefore regarded as diesel vehicles according to their base emission level. To cope with this, both in Europe and in the Netherlands task forces are set-up to suggest intermediate regulations, before Euro VI legislation comes into place, which includes dual-fuel operation.

Since dual-fuel engines operate with the diesel combustion principle, the valve timing is not optimized for gas/diesel operation. Due to the significant valve overlap in diesel engines, the natural gas in the inlet manifold easily slips to the exhaust manifold, resulting in high methane emissions.

3.1.3 Busses

The engine technology used in busses is primarily dedicated gas and CNG storage and comparable to the technology used for dedicated gas trucks. Both lean-burn (e.g. Scania, Mercedes, Volvo) and stoichiometric engine technology (e.g. Iveco, MAN) is used for Euro V / EEV emission legislation. As for trucks, it is expected that all manufacturers will use stoichiometric engine technology for Euro VI to comply with the NO_x and methane legislation.

3.1.4 *Real-world emission data*

The availability of real-world emission data, especially of trucks on CNG/LNG, is rather limited. The data which is available and can be used for further work is summarized below.

Dedicated gas trucks:
PEMS measurements of an Iveco Stralis Euro V with a stoichiometric LNG engine were reported in [Van Mensch 2011]. The used fuel was liquefied biogas with a CH_4 percentage of approx. 99% and representative for LNG. Both representative and reference routes were driven and the emission results were compared with type approval limits. NO_x, NO_2, THC, CO and CO2 were measured. CH_4 and NMHC could not be measured, as well as PM (which is expected to be well below the limit). NO_x is well below the type approval limit, but is depending strongly on the vehicle application (motorway, urban). The measured THC is very low, which allows the conclusion that CH_4 and thus the CH_4 contribution to the GHG is very low too.
The measurements are useful for further analysis and representative for a typical truck application using LNG in spark-ignited engines.

Dedicated gas busses:
Emission data is available of six representative busses in the EEV emission class, both lean-burn and stoichiometric. This data is available in the TNO database and in no public reports and it can be used for further analysis. Real-world emission behaviour is measured using the Braunschweig cycle, which is representative for urban bus application. Data is available for NO_x, NO_2, PM10, CO, HC and CO_2. Main conclusion is that the real-world regulated emissions are low. NO_x, NO_2 and HC (mainly CH_4) are depending on used technology.
For dedicated gas EEV busses, both lean-burn and stoichiometric, emission factors for 2015 are available:

Tabel 3 emission factors for busses (12 meter bus). Methane emissions are preliminary estimates.

	Urban busses emissions (in urban service, e.g. Braunscweig cycle)	NO_x [g/km]	PM10 [mg/km]	CH_4 [g/km]
Euro-IV	Diesel + SCR	7.7	113	0.0
	CNG lean burn	7.9	66	1-5
Euro-V	**Diesel + SCR (reference)**	**4.5**	**113**	**0**
EEV	Diesel + SCR + DPF	4.5	29	0.0
	CNG stoichiometric	2.2	39	0.1
	CNG lean burn	5.6	39	1-5
Euro VI	CNG/Diesel	0.7-1.4	25	0.0
	Dual fuel	0.7-1.4	25	0.5

Dual-fuel trucks:
The determination of the GHG benefit or penalty for dual fuel operation of engines is complicated by two factors:

1. It is difficult to determine the replacement fraction accurately.
2. The reduced CO_2 emission would yield a higher methane emission per CO_2 for the same amount of engine work.

The general formula for the same quantity of work for complete replacement of diesel by natural gas is:

1 kWh = 650 g CO2 from diesel = 500 g CO2 to methane

In practice, the amount of work is less, for example, at idle, no work done but fuel is used. The amount of CO_2 is typically 10% -15% higher in normal usage. The additional amount of methane, so that the greenhouse gas emissions remain stable, is 6 grams (3.3% methane slip) per kWh (25 x 6 = 150 grams difference).

To correct for the differences in vehicle deployment, or test conditions, the methane emission can be normalized on CO2 emissions: g/kg CO2. The additional GHG emissions ΔGHG[%] can be expressed in the specific methane emissions [g CH4/kg CO2] and replacement rate [% NG] of diesel fuel by natural gas:

$$\Delta \text{GHG [\%]} = 2.5 * [\text{g CH4/kg CO2}] - 0.23 * [\text{\%NG}] - 0.00575 * [\text{g CH4/kg CO2}] * [\text{\%NG}]$$

The last term in the equation follows from the fact that less CO_2 is emitted for the same amount of energy in natural gas combustion.

For example, with a replacement rate of 50% the CO_2 benefit of natural gas is 11.5% and the same absolute CH_4 emission, will, measured in g per kg CO_2, be 100%/88.5% = 13% higher. The last term in the equation above compensates for this effect in the total GHG emission.

Representative data of dual-fuel technology in real-world applications is only limited available. What can be concluded is that for the retrofit of dual-fuel systems the compliance with HC / CH_4 legislation is challenging.

Measurements on four different dual fuel natural gas trucks in the Netherlands show a large variation of methane emissions. Expressed in CO_2 emissions, the value of the methane emission vary between 1.3 and 17.5 g/kg of CO_2. The highest value is for specific conditions. This vehicle had an average methane emission of around 8 g/kg of CO_2. The measurements were performed in the framework of the testing program for dual fuel vehicles. The prototypes are not all allowed on the road by the RDW. Most vehicles had an emission around 2 g/kg of CO_2 in controlled conditions. But the degree of substitution of diesel by natural gas appears to be limited in cases where it was actually measured.

Optimistic values of 50% substitution of diesel by natural gas would mean a CO_2 advantage of 11.5% is achieved. A methane slip of 2 g/kg CO_2 leads to a limited benefit of 11.5% - 4.4% = 7% of greenhouse gas emissions. The 8 g/kg of CO_2 corresponds, at a 50% replacement, with a 6.2% increase of the greenhouse gas emissions. The benefits and risks appear to be similar for dual fuel vehicles. For comparison, the measurements on Euro V stoichiometric gas truck, with three-way catalyst, gives 0.3% additional greenhouse gas emissions through the methane emissions

Boil off LNG

Not taken into account in the emission legislation is the CH_4 boil-off when using LNG. This boil-off can either be in the atmosphere, re-used or burned. In The

Netherlands a burner on the boil-off gas is prohibited in view of safety. The emission as methane is a 25 times more effective GHG. Hence from that perspective burning the boil-off gas would be preferable. There is no representative data available of boil-off effects on emissions in practice. In the USA the concern regarding boil-off gas is raised. Tanks, both on the vehicles and at the tank stations, are typically designed to retain gas a week or ten days. This does require a constant 6-7 days a week operation. Different European stakeholders propose such limits, which, however, means that in limited operation substantial boil-off can still occur.

3.1.5 Trends outside Europe

In North America the demand for CNG and LNG fuelled vehicles is rapidly increasing. Main drivers are local air quality and the low natural gas prices: because of the increased natural gas production in North America, the price difference with diesel is increasing.

Trucks and busses are sold with both dedicated gas and dual-fuel technology. Canada based Westport, in collaboration with Cummins, is an important player in gas-fuelled engines with their HPDI system: diesel based engine technology with a fuel injector delivering a small diesel pilot and a gaseous fuel flow. The diesel pilot ignites the fuel mixture and the gaseous fuel quantity is delivering up to 90% of the power. There is no possibility for 100% diesel fall-back. Westport engines are sold in e.g. Peterbilt and Kenworth trucks.

LNG is required for long range vehicles. In the US, fuel suppliers are currently investing in LNG infrastructure in the main transport corridors.

3.2 Vehicle usage

Today natural gas in heavy-duty vehicles is mainly used in urban busses. In the total public bus fleet in the Netherlands in spring 2012, 481 of 5114 busses use natural gas or biogas [KPVV 2012]. Busses for public transport use either CNG or compressed biogas.

Heavy-duty trucks on CNG are primarily used for city distribution because of the limited range. For this reason, LNG receives increased attention because of the higher energy density. As an indication, a range of 1000 km is possible with a 300 kg LNG tank. Current tanks have a range of 700-800 km, a CNG tank for an additional 100 km is sometimes used as a fall-back option.

Dual-fuel technology is less linked to the vehicle application and availability of fuel infrastructure, because of the diesel fall-back option. However, to optimally use the cost benefit by natural gas substitution, the same arguments for LNG are valid to increase range. Diesel fall-back is standard for retrofit systems, which large fractions of diesel, however, may not exist for OEM solutions, where the diesel injection is limited.

3.3 Current operations

In Europe the introduction of LNG has been performed in some countries as part of trial programs where truck companies, public organisations, LNG suppliers, equipment suppliers and truck manufacturers are involved. With these programs the introduction of natural gas as fuel option for long haul operations is intended to be stimulated. In Europe some 200 trucks currently use LNG, following the information included in NGVA Europe (2012).

In NGVA Europe (2011) the number of stations[1] supplying LNG is indicated:

Table 4 Number of LNG stations in the EU (by the end of 2011)
Source: NGVA Europe (2011); NGVG (2011); Vilches, (2011).

EU Countries	Number of LNG stations (by the end of 2011)
Belgium	1
Estonia	2
The Netherlands	0
Poland	1
Spain	6
Sweden	2
United Kingdom	13
Total	**18**
USA	***74***

Due to recent investments some countries may have in the meantime a higher number of LNG stations. As an example, in the Netherlands the first semi-public LNG station was put in service last September 6th. However, some companies have their own LNG stations, like Vos Logistics and Simon Loos.

If the previous data is compared with the number of CNG stations one can conclude that the implementation of LNG is, in comparison, far behind.

Table 5 Number of CNG stations in the EU (by the end of 2011)
Source: NGVA Europe (2011)

EU Countries	Number of CNG stations (total)	Number of CNG stations (public)
Austria	202	172
Belgium	14	9
Bulgaria	102	101
Czech Republic	49	37
Denmark	1	1
Estonia	2	2
Finland	18	17
France	177	37
Germany	903	839
Greece	3	0

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[1] No indication is given about the type of accessibility (public or private)

Hungary	3	3
Ireland	1	0
Italy	858	811
Lithuania	3	3
Luxembourg	8	6
The Netherlands	150	85
Poland	46	32
Portugal	5	1
Slovakia	13	9
Slovenia	2	1
Spain	57	14
Sweden	179	132
United Kingdom	9	1
Total	2805	2313

On a European level the trend is to redefine the application of Natural Gas in Road Transport. While the Compressed Natural Gas (CNG) has the municipal use (garbage trucks and urban busses) as main focus, the LNG trucks will be introduced for services where a larger autonomy is an important pre-requisite. Following NGVA in Cadena (2012) there are for now 52 fuel stations planned for Europe. The European Commission in the revision of the trans-European energy network policy (TEN-E, 2010) indicates that a further investment in LNG terminals is needed to meet future demand. From this policy objective and assuming the further development of LNG Terminals one can foresee a development in the implementation of LNG. The steadiness of the development curve will depend of the policy options that individual countries follow, which result of the weighting of the different pros and cons. The most relevant of these are described and analysed in this report.

The organization Natural & Biogas Vehicle Association (NGVA) has been awarded with a 8 million € funding to execute a European based project that involves 23 partners of 13 European countries, the “Blue Corridor” project. Here 400 carriers will change from Diesel to LNG and with the conclusions of the project an input is expected to be given for the infra-structure organization of LNG European-based routes (Cadena, 2012).

Until now the introduction of LNG in Europe has been mainly performed as a result of trial programs. These programs will be described in more detail in the following sections.

3.3.1 *Sweden*

The project “BiMe Trucks” involves the energy suppliers (Fordons Gas, Aga, E-on and Energigas Sverige) and Volvo. This project aims to introduce 100 heavy-duty vehicles and construct LNG service stations, in a first phase, in Malmö, Gothenburg, Jönköping, Stockholm and Örebro. The service station of Göteborg is already in use since October 2010 as a supplier of Liquid and Compresses Natural Gas. In November 2011 a second service station opened, this time near Stockholm. (NGVG, 2011; BiMe, 2012; BiMe_truck, 2012)

The trucks used in the project are the Volvo FM / FMX equipped with a 13 litre motor and with an output of 460 hp. For a regional/long haul route a blending of 75% gas and 25% diesel is applied. (Volvo, 2011). The project includes an investment assistance of SEK 175,000 (20,555 €[2]) for the first 100 participants, which aims to reduce the pay-back time of the total investment[3] (BiMe, 2012; BiMe_truck, 2012).

The BiMe project is coordinated by Business Region Göteborg and is expected to run until 2013, as indicated in NGVG (2011). The co-financers are the Swedish Energy Agency and the Region Västra Götaland (BiMe, 2012).

3.3.2 *United Kingdom*

A LNG fuelling system has been installed in the United Kingdom by Chive Fuels along the two main south-north motorways (M5/M6 and M1), as indicated in Chive (2012). Recently a £23 million (28,89 million €[4]) trial programme involving 300 “low-carbon commercial vehicles was launched. The investment includes the construction of 11 new refuelling stations (TSB, 2012). The UK is following a natural gas strategy where it is standing at the forefront of the introduction of LNG but simultaneously has a relatively low CNG service station network (as shown in tables 1 and 2).

The project is to be managed by the Technology Strategy Board (TSB) in partnership with the Department for Transport (DfT) and the Office for Low Emission Vehicles. As indicated in TSB, 2012, it involves twelve companies covering different sectors such as retailers (Tesco, John Lewis Partnership plc), logistics (Ascot Transport, Brit European Transport Ltd, Howard Tenens Associates Ltd, J. B. Wheaton and Sons Ltd), energetic services (CNG Services, Ltd), alternative fuel technology development (G-Volution Ltd and T Baden Hardstaff Ltd), snack producers (United Biscuits), IT development tools (BOC Group) and milk producers and distributers (Robert Wiseman Diaries),

During two years the real use data related to the trials at these companies will be gathered and analysed by the DfT. A specific description of the technologies used in the different trials is not publicly available by TSB. However some technological description of the trials is provided:

- Application of the G-volution “Optimiser” dual-fuel technology fuelled with biomethane in ten 44 ton Heavy-Duty vehicles.
- Research on combined CO_2 reduction measures, such as application of dual-fuel engines with aerodynamic technologies. A 70% CO_2 reduction is expected to be achieved in this trial, which will take place at John Lewis Partnership plc.
- Analysis of the CO_2 reduction due to the use of cooking oil at 44 ton Heavy-Duty vehicles (trial involving the snack producer United Biscuits).
- Trial of 28 CNG or LNG retrofitted dual-fuel trucks blended with renewable biomethane.
- Trial of 40 ton dual-fuel trucks Volvo FM by Robert Wiseman Diaries.

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[2] Currency at the 24th September: 1 € = 8.49540 SEK

[3] Cost of a dual-fuel LNG truck, Volvo FM is estimated to be SEK 400,000 or 47,028 €.

[4] Currency at the 26th September: 1 € = £0,79

Before these trials the LNG dual-fuel engines were already introduced in pilot projects as a result of the development of the retrofit system of Clean Air Power. This system, named ‘Genesis’, was firstly introduced in 2006 at trucks of Tesco (Mercedes Axor, Euro III) and Warburtons Bakers (DAF CF85, Euro III), as described in Clean Air (2006) In the following years other companies requested the installment of these systems. In Clean Air (2007) an annual fuel saving of £10.000 (or 12.564€[5]) per vehicle is indicated as the driving motive for the market development of this technology.

Some of the fleets and models on which the Clean Air Power dual fuel technology is applied can be found in the table below. Some of them already run on biomethane[6]

Table 6 Number and type of vehicles in the UK fleet.

Fleet	Models	Quantity
J. Sainsburys plc	Mercedes Axor 6x2 tractor	5
Robert Wiseman Diaries	DAF CF85 340 4x2 tractor	22
Warburtons Family Bakers	Foden Alpha 385 hp 4 x 2 tractor DAF CF 85 430 hp 4 x 2 tractor ERF 380 hp 4x2 tractor DAF 18 ton 4x2	18 2 14 6
United Utilities	Mercedes Axor 6x2 tractor	1
Wheatons Transport	Mercedes Axor 6x2 tractor	1

Clean Air has received several new orders for the new ‘Genesis EDGE[7]’ system, such as a 49 order from the Sainsbury/s supermarkets, 27 systems for a major logistics company in the United Kingdom or a further order of 10 dual-fuel truck systems, as indicated in Clean Air (2011) and Clean Air (2012b). The Clean Air dual fuel systems installed in factory produced trucks (Volvo FM) comply with the Euro V norm

As indicated there are also other dual fuel technology providers such as the Hardstaff or G-Volution, that can adapt existing trucks to dual-fuel operations. The first one has developed the OIGI Gas Technologies, while the latter has developed the Optimiser dual fuel system. Both providers and companies are included in the recent trial promoted by TSB.

The Hardstaff Group has developed its dual fuel technology and has simultaneously applied it in existing dual-fuel versions of manufacturers, such as Mercedes (Econic, Axor and Actros) or Volvo (FE and FL). Within the group there is also a service of development of service stations, through the Portal Gas Service business branch.

The development of LNG has been done in cooperation with Chive Fuels, Ltd, which has been installing the fuel service stations.

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[5] Using the currency at the 26th September: 1 € = £0,79

[6] As an example, the Sainsbury’s supermarket chain has its dual fuel trucks running on gas produced from waste (Sainsbury’s, 2008).

[7] An upgrade of the first ‘Genesis’ system, with an increased control of the timing of the diesel injection, as indicated in Clean_Air (2010).

3.3.3 *Spain*

The application of LNG on road transport has been essentially performed in Spain by Transportes Monfort (logistic/transport services) and HAM Group (LNG installations designer and constructor).

HAM Group runs a retrofitted Mercedes Axor installed with a Clean Air Power ‘Genesis’ dual-fuel system. It also has other 10 Volvo FM13 fitted with Clean Air Power ‘Genesis EDGE’ dual-fuel technology, as indicated in Clean Air (2010). In fact, the HAM Group was a pioneer already in 2000 by importing 10 LNG vehicles from the United States, the half of which were dual-fuel technology (Vilches, 2011).

The firma Transportes Monfort retrofitted initially three Renault Premium 385/400 to install dual-fuel systems (NGVJournal, 2011). Some nine vehicles of the total fleet of one-hundred will be further submitted to a retrofitting for the installation of a dual-fuel system (El Mundo, 2012). Alcotral, a logistic company, has introduced in 2009 the first Mercedes Econic, with a full LNG engine

Transportes Monfort and the HAM group own their L-CNG filling stations, which were partially financed by state agencies (Vilches, 2011). Although some companies with the core business in Natural Gas distribution have already opened some filling stations, the majority is still oriented (but not exclusively) for the supply of fleets (like for the HAM Group or Transportes Monfort). Nevertheless it is expected that the current number of filling stations will be expanded in the coming years. With this development the logistic operators may have a more positive view on the LNG option for their fleets.

3.3.4 *The Netherlands*

In 2010 the first LNG filling station was opened in The Netherlands. This station is situated in the city of Oss and was promoted by the company Vos Logistics in a project with Mercedes-Benz, van Gansewinkel (waste logistics) and Indox CryoEnergySpain (turn-key construction partner of natural gas fueling stations). Vos Logistics expects to have until the end of 2012 a fleet of fourteen fully LNG trucks Mercedes Econics (Truck en Milieu, 2012).

Simon Loos, a logistic distributor is using 30 Mercedes Econic fully operating on LNG (Truck, 2011). The leading supermarket chain Albert Heijn has indicated that it will work with Simon Loos to assure a distribution based on LNG for the city of Amsterdam (Amsterdam, 2012).

Another ongoing project is the introduction of CNG dual-fuel (40% CNG; 60% Diesel) systems in MAN TGS/TGX trucks (also TGM or TGL are indicated). These trucks are retrofitted with the Prins DualFuel systems, and have been approved for use by MAN (Prins, 2012). The chain of convenience stores, Lekkerland, the distribution company Wim Bosman, or the logistics provider 3PL are some of the companies that use these MAN dual-fuel CNG trucks (Vilches, 2011).

The introduction of the Iveco Stralis LNG in the Netherlands roads was announced last April 2012. These trucks are factory made and include the dual fuel system developed by the Dutch company Rolande LNG B.V.. Peter Appel, a transport company is already using 4 of these trucks (Ecomobiel, 2012). The first truck of this Iveco model runs for Chr., Vermeer Transport B.V. a demonstration trial that started in January 2010 (NGVG, 2010).

The first semi-public LNG filling station was unveiled in September 2012 in the city of Zwolle. The market introduction of NG vehicles is being monitored. Also the "Dual-fuel test programme", initiated by RDW (Department of Road Transport) and involving the Ministry of Infrastructure and Environment (IenM) and the Netherlands Organization of Applied Scientific Research (TNO).

3.3.5 *Summary of Technology*

The technology that is currently applied in the different CNG/LNG projects is described in the following table:

Table 7 Summary of the CNG/LNG technologies applied in Long Haul/Distribution programmes.

Models	**Engine concept**	**Type of Service**
Mercedes Axor 6x2 tractor	Dual-Fuel retrofit	Long Haul
DAF CF85 340 4x2 tractor	Dual-Fuel retrofit	Long Haul
Foden Alpha 385 hp 4 x 2 tractor	Dual-Fuel retrofit	Long Haul
DAF CF 85 430 hp 4 x 2 tractor	Dual-Fuel retrofit	Long Haul
ERF 380hp	Dedicated	Long Haul
DAF 18 ton	Dedicated	Long Haul
Volvo FM / FMX	Dual-Fuel OEM assembled	Long Haul
Renault Premium 385/400	Dual-Fuel retrofit	Long Haul
Mercedes Econic	SI lean-burn	Long Haul / Distribution
Iveco Stralis	SI stoichiometric	Long Haul
MAN TGS/TGX	Dual-fuel retrofit	Long Haul / Distribution

3.4 Economic considerations

Equipment suppliers are currently the parties which present most business cases for operators. The price gap gas diesel is central in most business cases. Long-term trends are not considered guarantees for future developments. Hence only a small fraction of adapters exists. In many cases local communities play a role in the trials and transition to LNG usage.

4 Technologies in development

4.1 Engine technology

4.1.1 Dedicated gas technology

At present, the technologies used for Euro V / EEV are both lean-burn and stoichiometric with EGR. Because of the reduced NO_x limit for Euro VI, it is expected that it is not possible to reach these limits with lean-burn technology in combination with an oxidation catalyst. The first change to stoichiometric engines for Euro VI is already introduced (Scania) and it is expected that this will be the dominant technology.

It is uncertain what will happen after Euro VI. This is obviously depending on the market demand for natural gas engines and the investments vehicle manufacturers are willing to do. Furthermore, the price of SCR systems plays a role. Since these systems are widely adopted for Euro IV and V and are even used in North America, the prices of SCR technology might compete with the prices of 3-way catalysts for HD. This will enhance the chances for relatively efficient and simple lean-burn engines again, allowed to have a high engine-out NO_x level, converted by the SCR system. An additional advantage is the high exhaust gas temperatures, allowing a high efficiency of SCR catalysts in real-world conditions. It is possible that before 2020, lean-burn engines using SCR technology enter the market.

Emissions will be regulated by emission legislation and are expected to be very low. In Use Compliance legislation will enforce low real-world emissions as well. Meeting the Euro-VI legislation is an extensive and demanding requirement.

A point of attention is the combination of LNG and dedicated gas engines. Since the quality of LNG can vary significantly, the emissions might be influenced by LNG composition. Detailed information for this influence is not available yet.

4.1.2 Dual fuel technology:

First challenge for dual-fuel technology is to comply with Euro VI emission legislation, in which dual-fuel engines are recognized:

- A gas/diesel ratio (cycle energy based) < 10% is regarded as compression ignition engine: THC limits are applicable
- A gas/diesel ratio > 90% is regarded as positive (spark) ignition engine: NMHC and CH_4 limits are applicable
- A gas/diesel ratio between 10 and 90%, typical for dual-fuel: the THC limit shall be proportional to the gas/diesel ratio, but shall never exceed the CH_4 limit for gas engines.

It is expected that the diesel aftertreatment is not capable of dealing with these strict hydro carbon limits and an additional dedicated oxidation catalyst is required to deal with the methane emissions, increasing the system price.

For LD vehicles is in discussion to change the future CH_4 legislation, counting the CH_4 as green-house gas and thus adding it to the CO_2 emission. It is uncertain whether this will be adopted or not. In case it will, it is likely this methodology will be used for HD vehicles as well, easing the need for expensive aftertreatment systems.

Another point of attention is the combination of LNG and dual-fuel technology. Since the quality of LNG can vary significantly, the emissions of dual-fuel vehicles might be influenced by LNG composition. Detailed information for this influence is not available yet.

Although dual-fuel technology has the attention of vehicle OEM's, it is uncertain whether the example of Volvo to deliver an OEM dual-fuel solution will be followed.

4.1.3 Future combustion concepts

Next step in the engine development using gaseous fuels will be the development of combustion concepts aiming at very high efficiency and low NO_x to avoid expensive aftertreatment systems. An promising technology is premixed charge compression ignition (PCCI), where fuel, air and exhaust gas is partially mixed before auto-ignition. The conditions for auto-ignition need to be controlled by e.g. air management. A variable fuel composition can also play a significant role by using both natural gas and diesel.

It is not expected that this technology will be used in the market before 2020.

4.2 Vehicle usage

Fuel-efficiency of dual fuel makes it the technology of choice of haulage companies, if LNG station form a proper network. Stoichiometric engine concepts, with low emission, low noise and a reduced fuel efficiency, is often the choice for urban distribution, busses, and refuse trucks.

4.3 Fuel and tanks

Both LNG tanks and CNG tanks are still in development. The handling of liquid gas and its insulation technology arrives from other branches of industry. New polymer CNG tanks are lighter than the traditional steel tanks. LNG is expected to be safer to handle than LPG, as it is a lighter gas, diffusing more quickly and leaving no trace at the spillage location.

4.4 Economic considerations

Gas and LNG prices have an increasing gap with diesel. Making operation on CNG and LNG, despite the initial investment, viable. However, fuel-tax developments, with non-transparent rules, are a concern for many operators.

5 Standardisation

5.1 Engine technology

Euro-V and Euro-VI legislation set the standard for current and future engines of HGV. The important difference between Europe and the American regulations of EPA and CARB is the presence of a methane emission limit in the European emission limits (both inclusive in total hydrocarbons (THC), and exclusive as a methane limit). In the USA methane is excluded from the hydrocarbons.
The emission limit of 1.1 g/kWh (Euro-V), 0.65 g/kWh (EEV), and 0.5 (spark ignition)/0.16 (compression ignition) g/kWh Euro-VI, is strict for the fulfilment with an aftermarket (retrofit) installation. Dual-fuel engines (adapted diesel engines) are not fully covered by the current legislation, which create the current sense of a loophole for retrofitting, both properly tested installations with emissions close to the limit and other systems. Especially the latter group of installation outside the vision of regulating bodies might have high emissions.

Table 8 Emission limits, with disctinctions in total, methane, and nonmethane hydrocarbons, and spark and compression ignition.

g/kWh	THC	NMHC	Methane	NOx
Euro-V	$0.46^{(ESC)}$	$0.55^{(ETC)}$	$1.1^{(ETC)}$	2.0
EEV	$0.25^{(ESC)}$	$0.4^{(ETC)}$	$0.65^{(ETC)}$	2.0
Euro-VI	$0.16^{(WHTC, C.I.)}$	$0.160^{(WHTC)}$	$0.50^{(WHTC, S.I.)}$	$0.46^{(WHTC)}$

The CO_2 equivalent of methane is currently set at 25. With the current limits, the maximal additional GHG emission would be between 4% and 2%. However, if the real-world emission is triple the emission limit, which is not unlikely, with a retrofit installation, 10% to 15% additional green-house gas is possible.

The exclusion of the methane from the emission limits, or a shift of methane to GHG legislation, grouping it together with CO_2 emissions, is proposed by parties favouring dual-fuel and lean-burn engine concepts. For stoichiometric engines the Euro-VI methane limit poses less problems.

New world-harmonized legislation for dual-fuel engines handles both the variety in engine concepts and fuel qualities, both caloric and composition. The methane emission limits are interpolated between the diesel limits (0.2 g/kWh and 0.5 g/kWh) depending on the energy ratio of both fuel supplies to the engine.

5.2 Vehicle usage

Diesel engines, and the related natural gas compression ignition engine concepts, yield high power and high efficiency. The concept is therefore ideally suited for haulage companies with HGV on the motorway. The concepts are typically ill-suited for low-load distribution usage. In some cases, engines have to switch to diesel-only operation, with the same problems posed by diesel HGV: poor functioning of SCR after-treatment in urban situations. The WHTC test should match these conditions better, however, risks remain.

The stoichiometric spark-ignition concept with the three-way catalyst is old and proven technology with little low-load risk, except for cold-start. Apart from low emission, the engine produces less noise. The efficiency is lower, however, if the usage is (urban) distribution, this is less of an issue compared with the high load long-distance haulage.

5.3 Existing programmes

National and industry-led initiatives seem to take the lead in augmenting existing legislation with LNG specific requirements. This ranges from tank design, filling stations, and boil-off gas limits. Both the specifications of the filling nozzle and the filling pressure ranges from truck to truck. Treatment of tank vapour, pressure and temperature is currently by far from uniform. The engines expect gas of different pressures and the design of the LNG tank is set to match that.

5.4 Fuel and tanks

LNG fuel tanks for vehicles have no appropriate certification yet. The materials for cold temperature, the temperature range, the lack of controllability, and the pressure build-up are all unlike for other fuels. The LNG is boiling inside the tank, at temperatures between -162^o and -110^o Celsius. The arising problem is the boil-off gas (BOG), or venting, to prevent pressure above the design level. There are no viable alternatives to prevent bursts due to this autonomous process.

	Pressure	temperature	Usage
LNG	1 bar	-163^o	Transport
LCNG (cold)	3 bar	-153^o	Westport
LCNG (satutared)	8 bar	-130^o	Volvo, Iveco
LCNG (super sat)	18 bar	-110^o	
CNG	200 bar	ambient	Light-duty vehicles

The aim of many stakeholders is to have minimal holding time requirement of several days, typically 7 or 10. This is not necessarily a simple and uniform requirement, as minimal operation may take some pressure of the system, but it does not stop the boiling. A combined minimal holding time, and a minimal time between refuelling can cover more aspects of a day-to-day operation of a HGV.

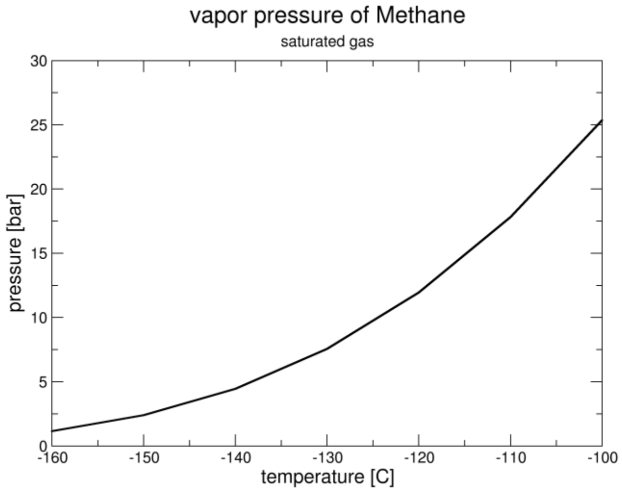

Figure 1 The vapour pressure above liquid methane is a function of the temperature only.

In the USA LNG is used on a large scale for some years. Their concern for boil-off is growing. Furthermore, they have more experience, both with boil-off of vehicle tanks and of fuelling stations. The design size of both have usually other considerations than limiting the size to limit boil-off.

5.5 Economic considerations

Participating in the standardisation, by specifications and regulations, have a clear economic benefit in the current market. Products are already available. Furthermore, different poorly compatible products exist side by side. Adopting USA or Japan standards have three clear advantages: 1) world-harmonization is afterwards easier, 2) more producers and products will be available for European market, 3) it will take the sting out of competing over the adoption to particular standards.

6 Risks

6.1 Engine technology

Complex technology, with after treatment controlled by the engine management always has the risk that the actual usage is covered by the design as prescribed in the test procedure. Dual fuel diesel-natural gas is a complex engine technology. If diesel control is already hard, the dual fuel concept takes this to another level. Hence, the problems foreseen with diesel Euro-V and Euro-V also exists for dual fuel. On-road testing, on-board diagnostics, and in-use compliance are needed to ensure all conditions encountered on the road are covered properly in the emission reduction strategies.

However, dual fuel also offers opportunities. Dual-fuel technology, in principle, allows for better heat management, and it is more flexibility in managing the combustion process. Although, Euro-VI emission limit in the diesel, or related, cycle can likely only be reached by a OEM solution. Furthermore, it is not likely that this is a gas-only engine. Therefore, low-load usage vehicles (i.e. refuse vehicles and busses) are not likely to have many benefits of gas, but the trouble of a complex system with more risks of failure.

For stoichiometric engine the story is different. There is little risk in the case of emission limits, and the presence of a cold start in the Euro-VI WHTC test will further reduce these risks. Once GHG emissions will be legislated for HD vehicles, it may serve as a driver for technological improvements on the engines. However, the stoichiometric engine will remain less efficient than a lean-burn engine.

6.2 Vehicle usage

The table summarizes the risk and opportunities of technologies in combination with their usage:

Vehicle	Engine concept	Risk	Opportunities
Long-haul	OEM dual fuel	CH_4, NO_x emissions	GHG reduction
Distribution	Stoichiometric	Higher CO_2 emission	Low pollutants, quiet
Busses	Stoichiometric	Higher CO_2 emission	Low pollutants, quiet
LCV on CNG	stoichiometric.	Higher CO_2 emission	Replace diesel LD

6.3 Existing trials

Methane slip is not commonly measured. Indications are it is high in dual-fuel concepts, such that it takes away part of the GHG benefits in lower CO_2 emission. For stoichiometric engines emissions are under control, but trials show no GHG benefit, unless biogas is brought to LNG quality, which requires quite a lot of effort, in processing.

7 Conclusions

Emissions from natural gas trucks and buses show a mixed picture. Stoichiometric gas engines are very clean and quiet. This type of engine can already meet the Euro VI requirements. The emissions of NO_x and particulates are at a lower level than current Euro V diesel engines. Because with the introduction of Euro VI diesel engines will become considerably cleaner, the NO_x and particulates emission advantage of stoichiometric gas engines compared with Euro VI diesel will disappear. Due to the lower yield stoichiometric gas engines have barely a CO_2 advantage over diesel. In the future, the efficiency of stoichiometric gas engines will improve with the technology already adapted in passenger cars (and so will diesel engines).

Lean burn and dual fuel Euro-V engines have higher emissions than stoichiometric engines with Euro-V technology and are also less quiet. The NO_x emissions from lean burn gas engines is similar to that of diesel. For particulate matter, there is anadvantage in using natural gas. On the other hand, lean burn and dual fuel engines have higher efficiency and therefore lower CO_2 emissions. The problem of lean burn and dual fuel engines lies with the methane slip: unburned fuel is released through the exhaust gas.

Because methane is a strong greenhouse gas (GWP value was 21, but recently at 25 provided by the IPCC) the current technology potential benefit of lean burn gas and dual fuel engines can be easily lost. The strict requirement of methane emissions are not met by lean burn gas engines and dual fuel with current technology. The Euro VI limits can only be met with stoichiometric gas engines. With Euro VI in sight, some manufacturers of mono fuel gas trucks already switched from lean to stoichiometric engines.

Current dual fuel engines are based on Euro-V. These are both OEM supported as to retrofit. It is unclear whether these engines have to meet the emission of methane. The Euro V emission standard for methane is 1.1 g/kWh, or 0.6% methane slip. At 6 g/kWh or 3.3% methane slip the potential benefit of 24% of greenhouse gas emissions is lost. Given the lower replacement rates, of diesel by gas, of dual fuel engines, the 3 g/kWh emission limit will on average mean an GHG emission neutral operation at 50% replacement compared to the diesel version. Two of the four vehicles tested have on average higher emissions of methane than this 3 g/kWh. In addition to the methane emissions from the exhaust, the evaporation and boil-off in LNG vehicles are also possible. With current Euro-V technology, dual fuel engines will not meet Euro VI standards. In order to meet Euro VI the development of new or further developed engine technology is required. There are signs that European OEM’s are investing in this technology development.

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9 Signature

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