NGVs Past & Prologue

Lessons Learned to Create Deployment Strategies for Commercializing NGVs

Webinar 2

NGV Technology

Dr. Jeffrey Seisler, CEO

Clean Fuels Consulting

20 November 2014

Presented by:

Acknowledgements

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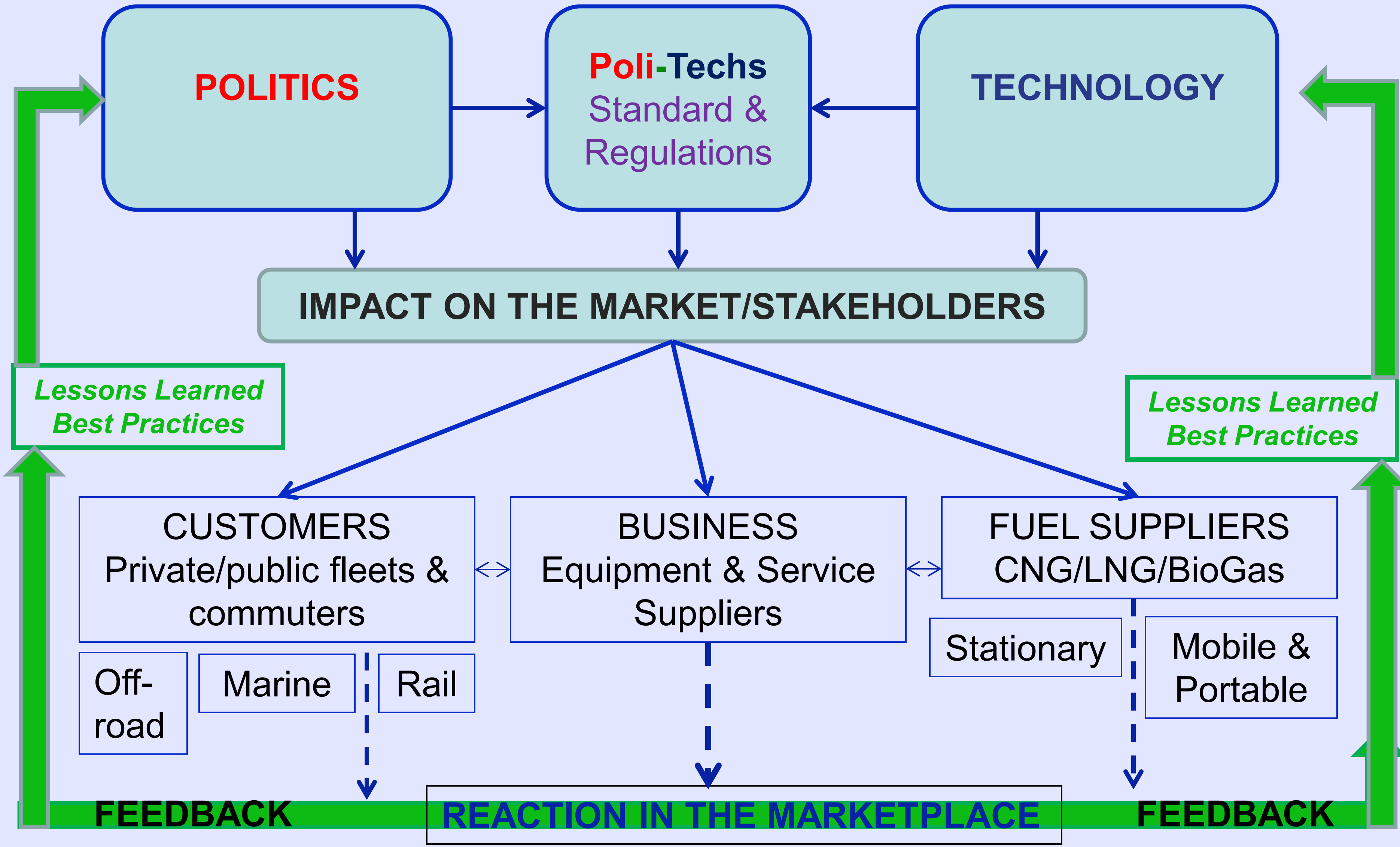
  - Clean Cities
  - International DOE
- Thanks to Marcy Rood-Werpy & Dan Santini for their personal support and enthusiasm for this work
- Special thanks to Dan Santini for his rigorous, dedicated and intellectually challenging involvement in refining this presentation.

Structure & Dynamics
Framework for this presentation



Overview of the Webinars

Webinar 1: 6 Oct 2014

- Background to success in NGV markets
  - *NGVs by the numbers: Looking Back-Looking Forward*
- Poli-techs: NGV Standards and Regulations

Webinar 2: 20 November 2014

- NGV Technology, Best Strategies & Lessons Learned

Webinar 3: 15 December 2014

- Role of Government: *Policy making & Strategy Process*
- Infrastructure Concepts & Strategies
- Best Strategies: Institutional Lessons Learned

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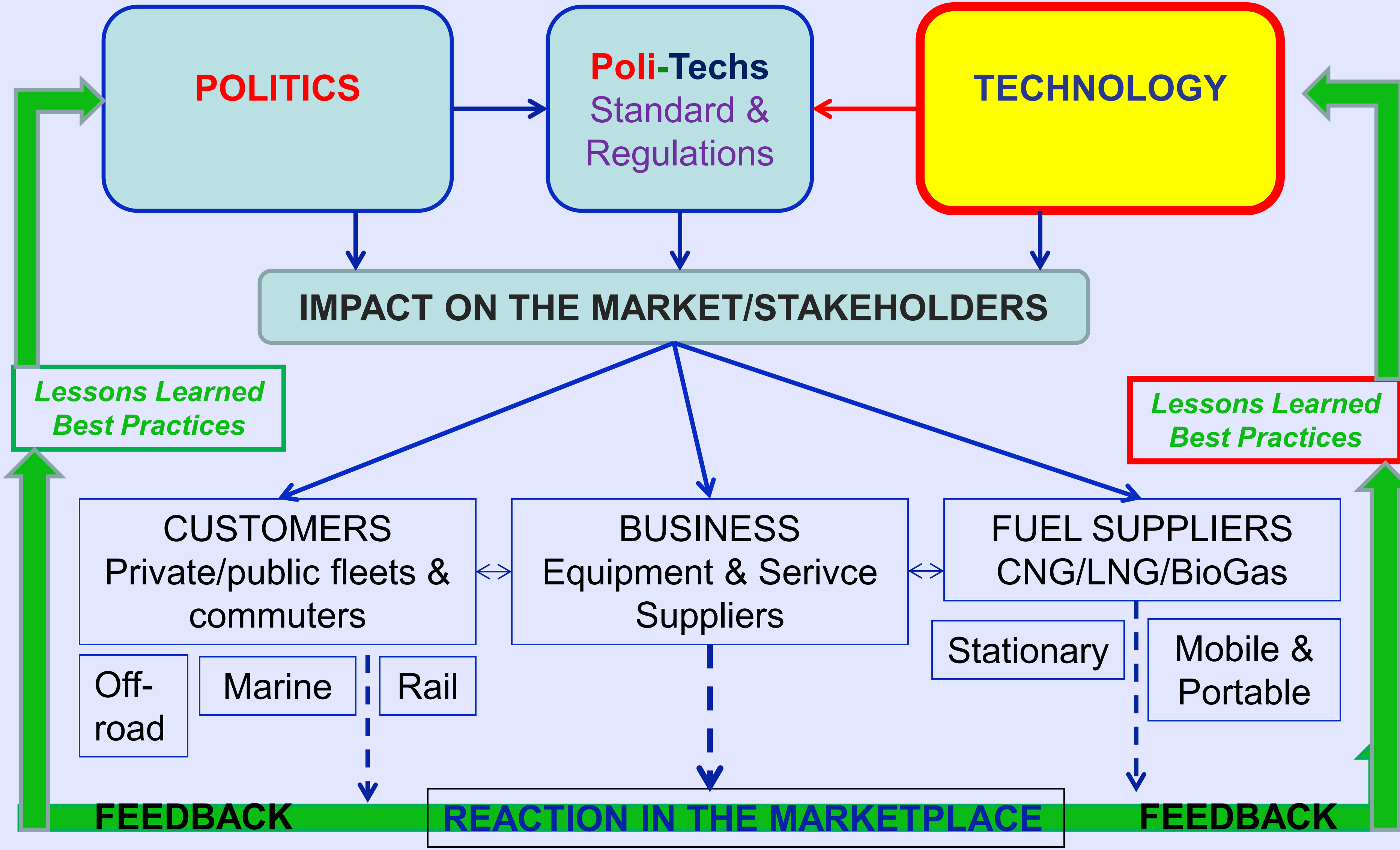

Technology availability and transparency with petroleum-fuelled vehicles is a *requirement for success*

Adler-Diplomat – 1939
Coal Gas Conversion

1983: Ford NGV Concept

1st internal combustion engine vehicle, a single cylinder, 2-stroke engine running on coal gas (methane). Inventor: French/Belgian engineer Jean Joseph Etienne Lenoir 1860

1992: Dedicated Ford Crown Victoria: 40 field test units leased to NGV stakeholders for 2 yr. trial

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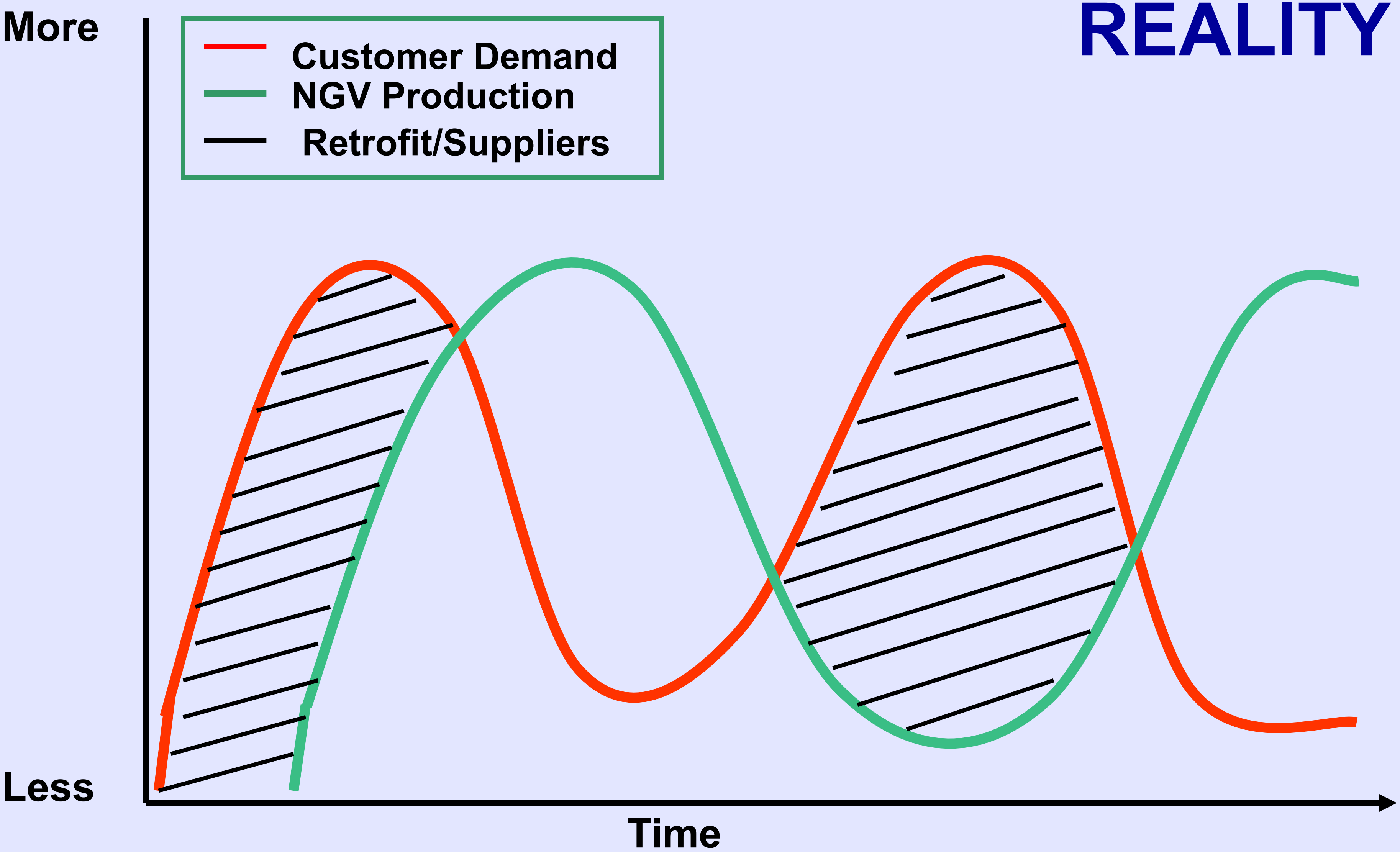
OEM NGV Models Produced Worldwide
(including Qualified Vehicle Modifiers - QVMs)

COUNTRY	OEM	LDV/MDV	HD Truck	Bus
TOTAL WORLD	152	274	128	192
EUROPE	37	115	36	51
CHINA	44	28	17	77
USA	40	68	66	29
JAPAN	11	35	7	4
GERMANY	8	46	9	18
ITALY	6	36	7	5
INDIA	5	11	2	4
FRANCE	5	14	4	
SOUTH KOREA	3	18	2	3
OTHERS	76	64	33	131

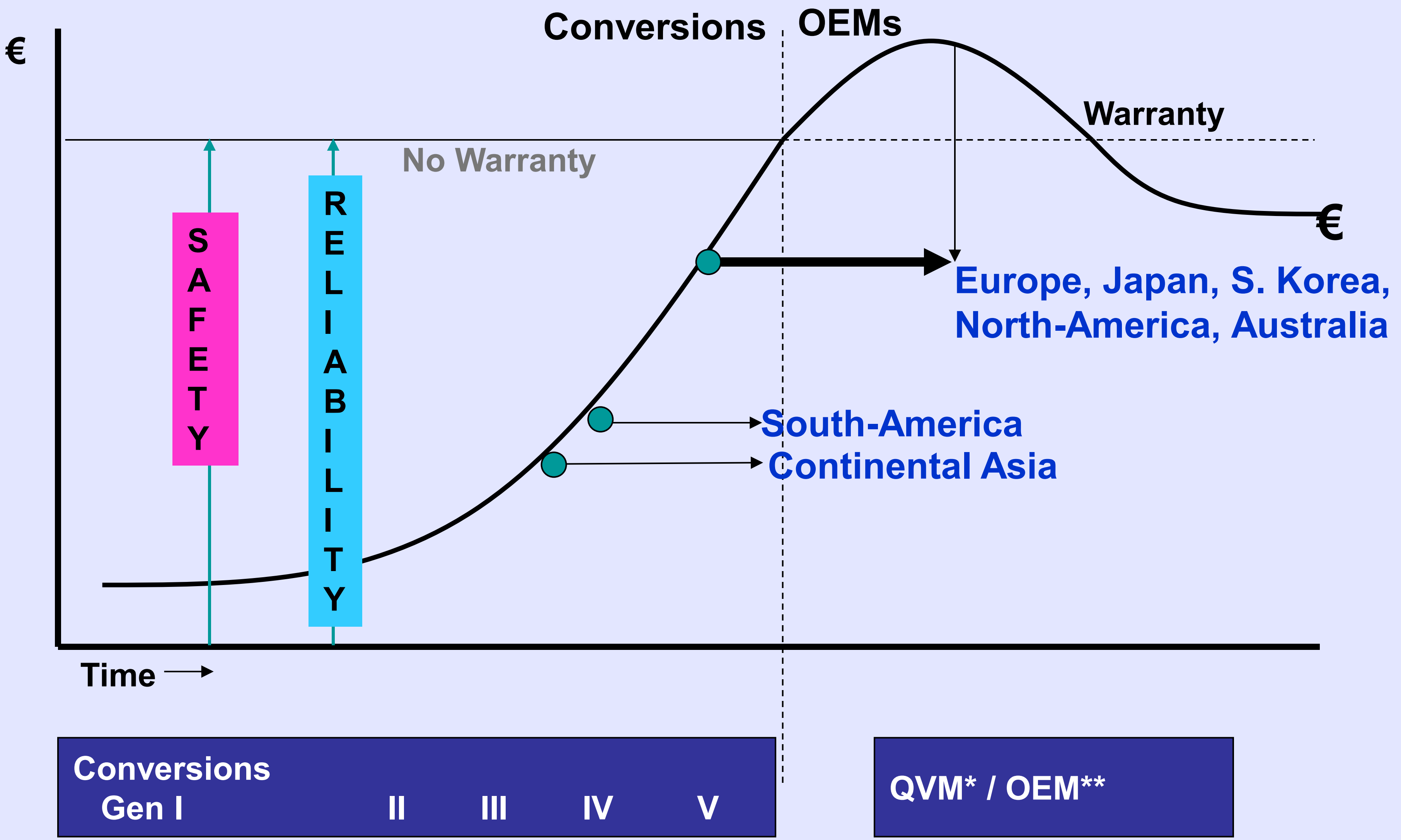
Source: CATARC, Liikennebiokaasu.fi, NGVA Europe & Erdgas Mobil, Clean Fuels Consulting, June 2013

NGV PRODUCTION vs CUSTOMER DEMAND: SYNCHRONISING A MARKET REALITY



The shift from retrofit to OEM

2000-2010+



*Qualified Vehicle Modifier
**Original Equipment Manufacturer

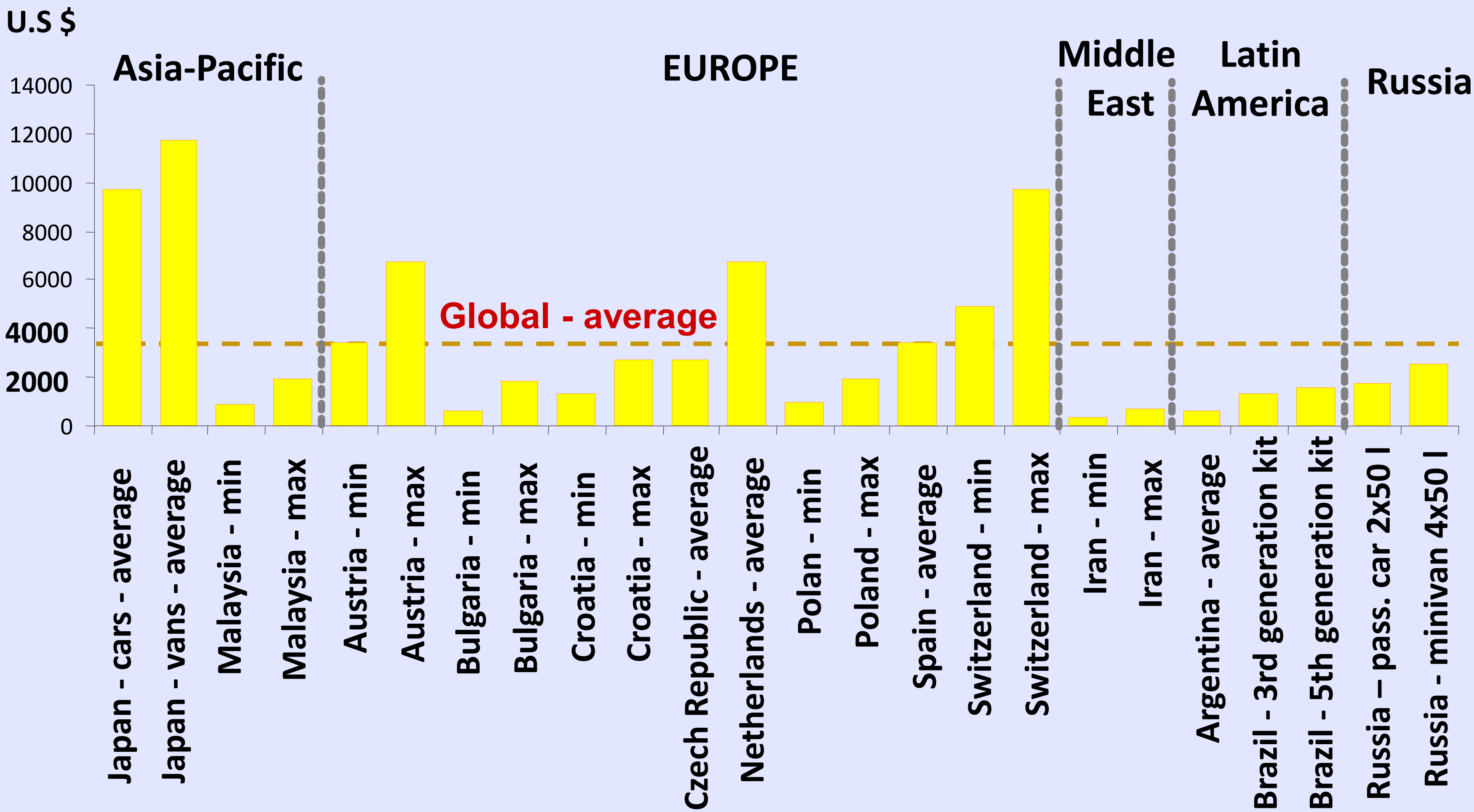
RETROFIT SYSTEMS MANUFACTURERS

(independent & aligned with OEMs)

- Italy = 14 LDV
- Brazil = 3 LDV
- Netherlands = 2 LDV; 1 HDV
- US = 6 LDV; 4 HDV
- Canada = 2 LDV; 2 HDV
- UK = 2 HDV
- Australia = 4 LDV 1 HDV
- Argentina = 71(retrofitters or manuf.?)
- Bangladesh = 350 (only 192 *'authorized'*)
- Russia, Asia, = multiple hundreds (?)

Clean Fuels Consulting survey January 2011 & 2013

Worldwide (outside USA) Average* NGV conversion costs - LDVs



***NOTE: Highly dependant on type of equipment; cylinder volume, type and number; new or recycled components; approvals and certification etc.**

Which is best?

Reduce fuel variation to enable optimized engines?

or….

Adapt engines to fuel variation?

The answer is: Yes!

- In areas where fuel composition is widely varied, adaptive engine technology would be useful.
- In areas with a relatively stable and high quality gas, engines can be optimized for local conditions (and so long as they are not driving into areas with lower quality gas).

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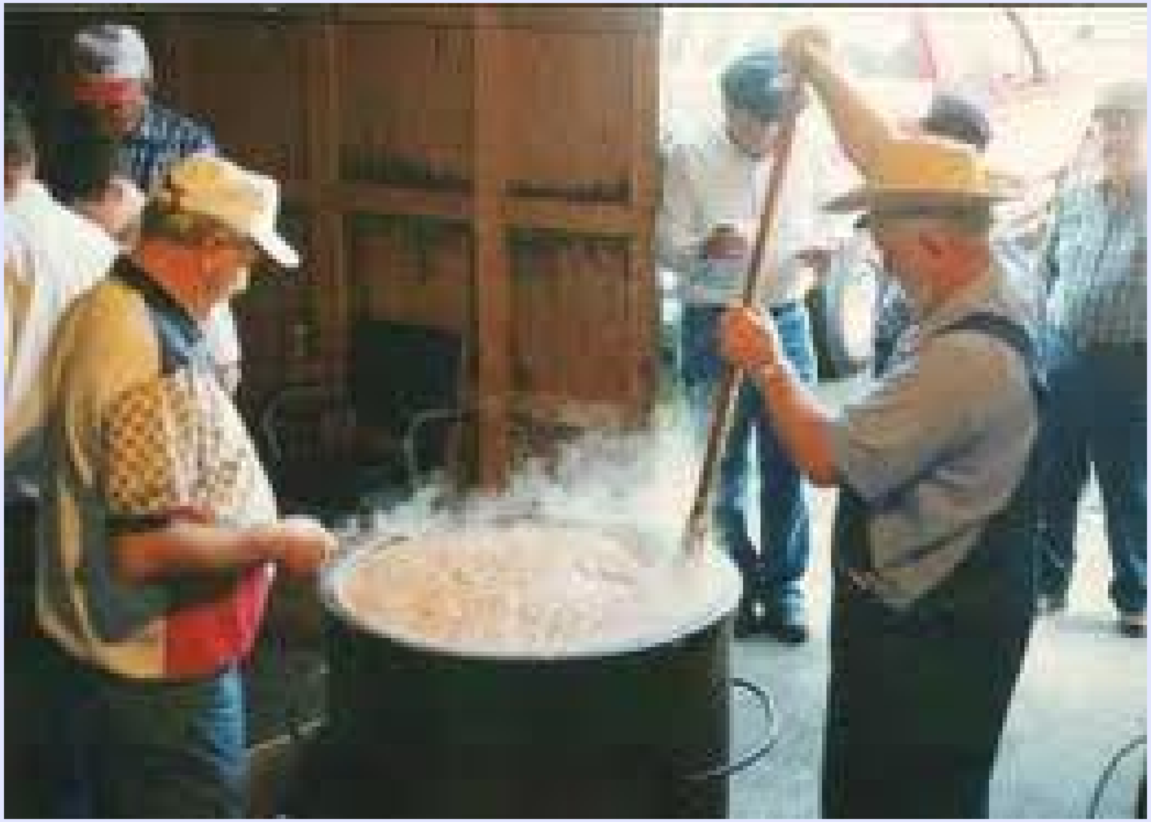
NGV Technology: Overview of Topical Issues & Lessons Learned

- **Gas composition**/quality
- **Engines & vehicles** (bi-fuel, dedicated & dual-fuel)
- **CNG fuel storage technology & 'systems'** (cylinders & peripherals)
- **Fuelling Systems** (CNG/LNG/L-CNG)

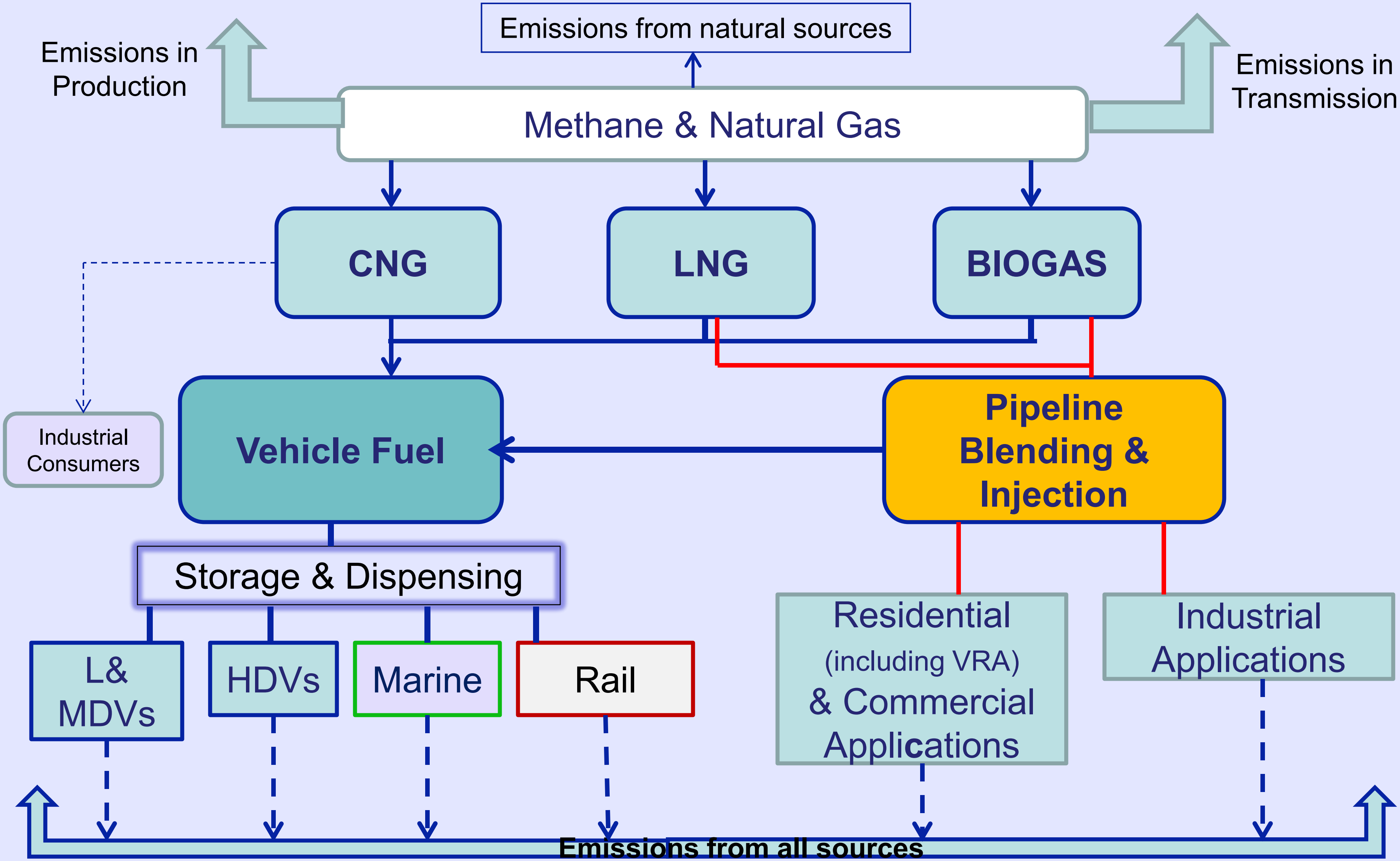
Gas Composition



CNG -- LNG -- Biomethane
(Ethanol?)

Framework for CH4 & Natural Gas

Emphasis on composition & quality



Requirements (and potential) for gas composition is very different for different stakeholders

- Energy distribution companies
  - *'pipeline quality'*
- Retailers of automotive methane fuels
  - *No water or oil pass-through (or 'other stuff')*
- Needs of the vehicle manufacturers
  - *Consistency, clean & 'high quality'*
- Driving customers
  - *Hgas/Lgas = range concerns*

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Components in natural gas can have a variety of effects on engines & compressors

Gross WI (MJ/m^3)	Power, fuel injection duration, OBD
Sulfur	Deterioration of exhaust emission treatment device, deposit. Use of odorants have been taken into account.
HC	Liquefaction
Methane Number	Anti-knock property
Water (dew point)	Water condensation under certain conditions of usage.
Lubricant contamination	Function deterioration caused by compressor oil
O_2, H_2, CO	Flammability, hydrogen embrittlement, attack on plastic and rubber, health effect
CO_2	Liquefaction, attack on plastic and rubber, lowered WI
Metal, Particulate Contaminants	Malfunction caused by metallic and particulate contaminant

Source: Masato Matsuki (Honda R&D Co.),'Study on Required CNG Qualities as an Automotive Fuel, as presented at ANGVA Conference, 28 November 2013

Natural Gas Composition Issues CNG

- Wobbe index: in broad terms, energy value at the 'burner tip'
- Methane content which, for heavy vehicles should be ~87% or higher
- Methane number: anti-knock value, i.e. octane, which auto industry advocates prefer at least MN 70
  - Determining the Methane Number (MN) is complex.
  - The most notably used methodology has been developed by AVL in the 1970s. Shell International is advocating the development of a new, publically available method for determining MN.
- Non-methane components affect engines, aftertreatment
  - Water content: can affect cylinder valves; fuel injectors
  - Contaminants (H_2S, sulfur [including odorant])
  - Other components: propane, H_2, oil, dust, etc.

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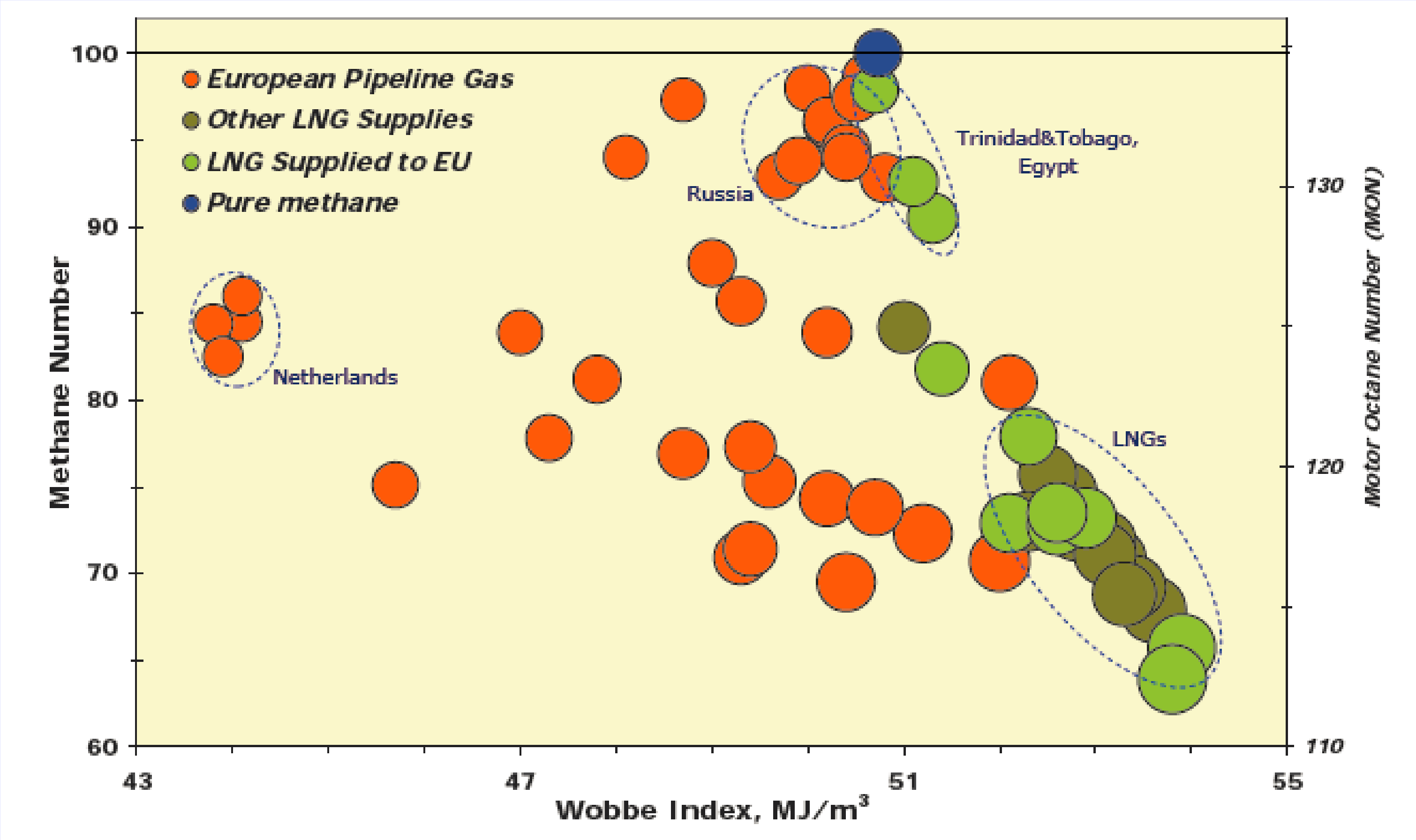
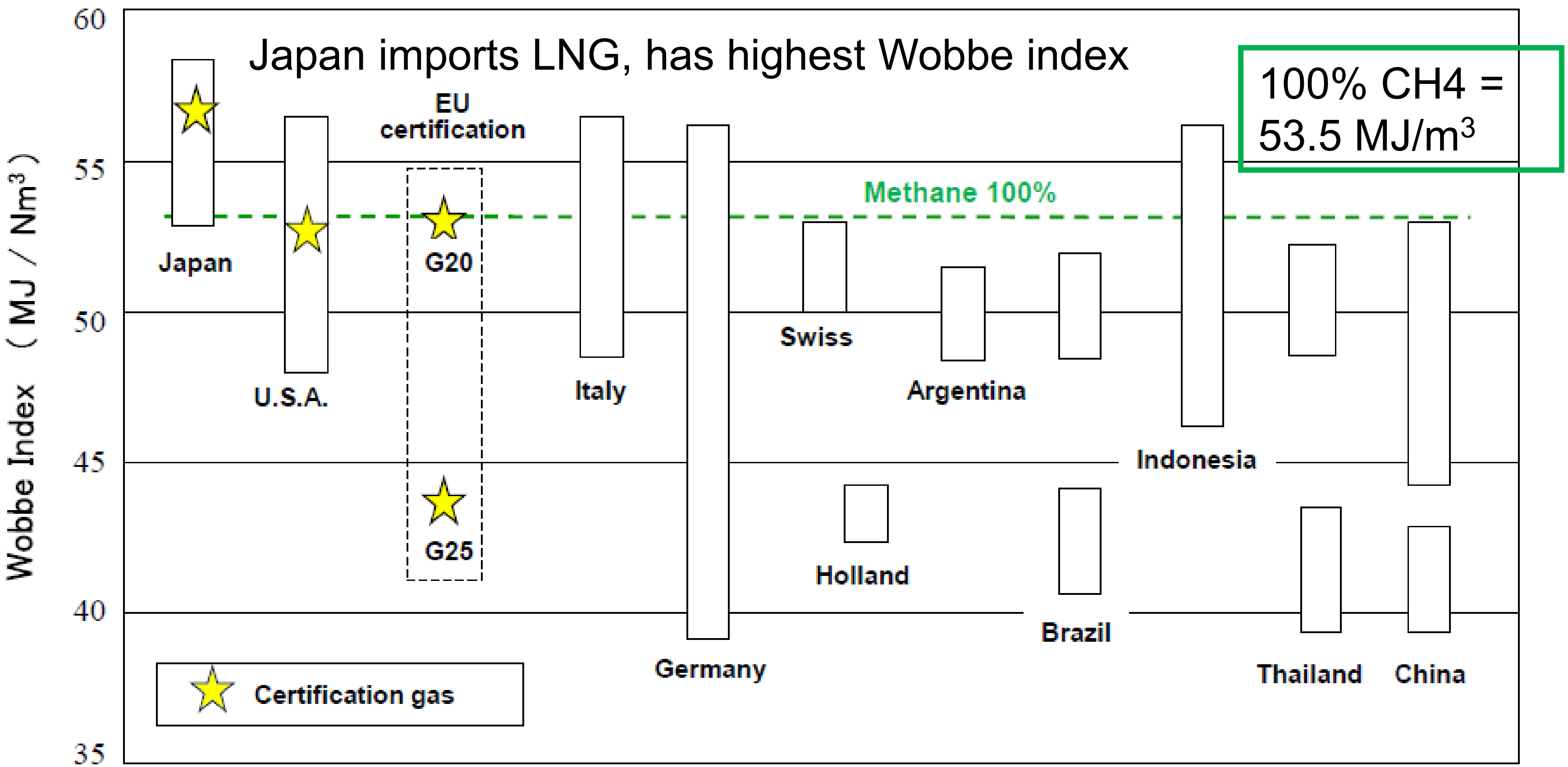
Engines using LNG sourced gas can rely on higher Wobbe # than from pipelines

Size of the bubbles expresses the variations in Gross Calorific Value [GCV]



Source: LNG for Europe: Some important considerations, Joint Research Center, uropean Commission, 2009.

Wobbe index (i.e. energy value) will affect combustion & engine power. U.S. is high



WI=H / √S

H: High calorific value (MJ/Nm³)

S: Specific gravity (Air=1)

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Source: Masato Matsuki (Honda R&D Co.),'Study on Required CNG Qualities as an Automotive Fuel, as presented at ANGVA Conference, 28 November 2013

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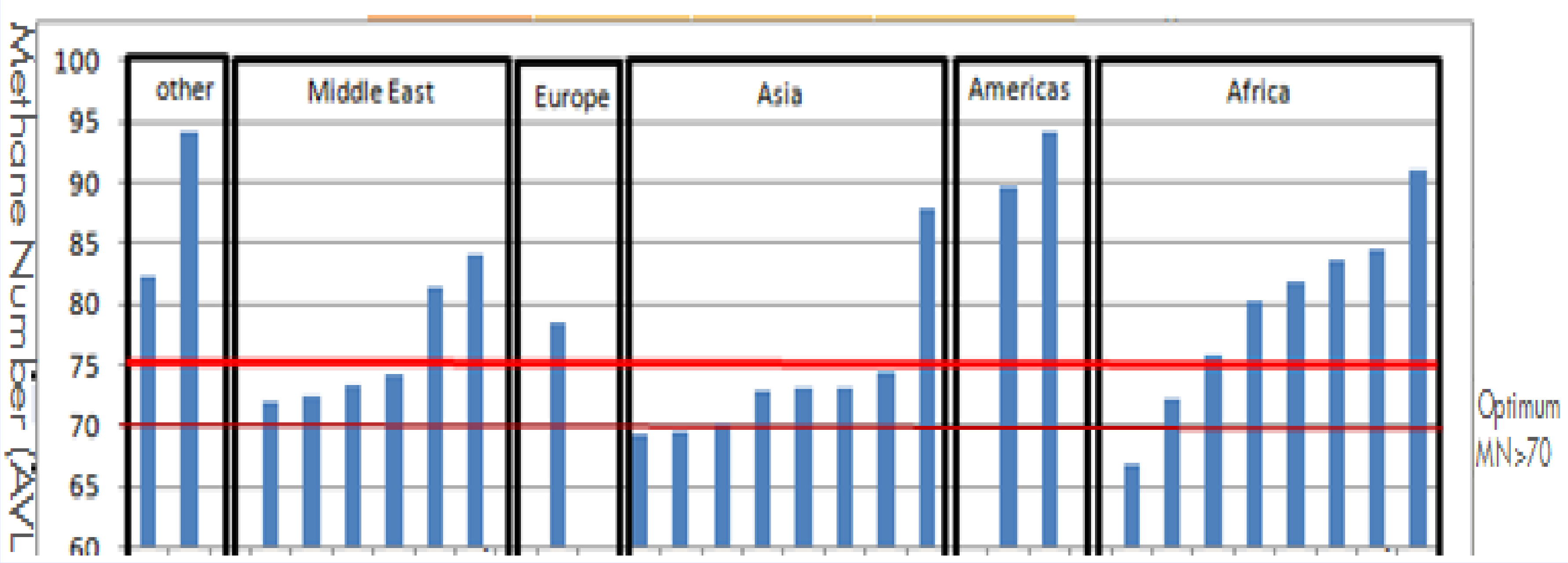
Methane Number of gas worldwide should be sufficient to meet the demands of regional NGVs: Americas are high



Source: *Gas Quality: Leadership as a Driver for LNG in Transport Markets*, Stuart McDonald, Shell International, as presented at Clean Fuels Consulting Poli-techs workshop, 27 March 2013, Brussels.

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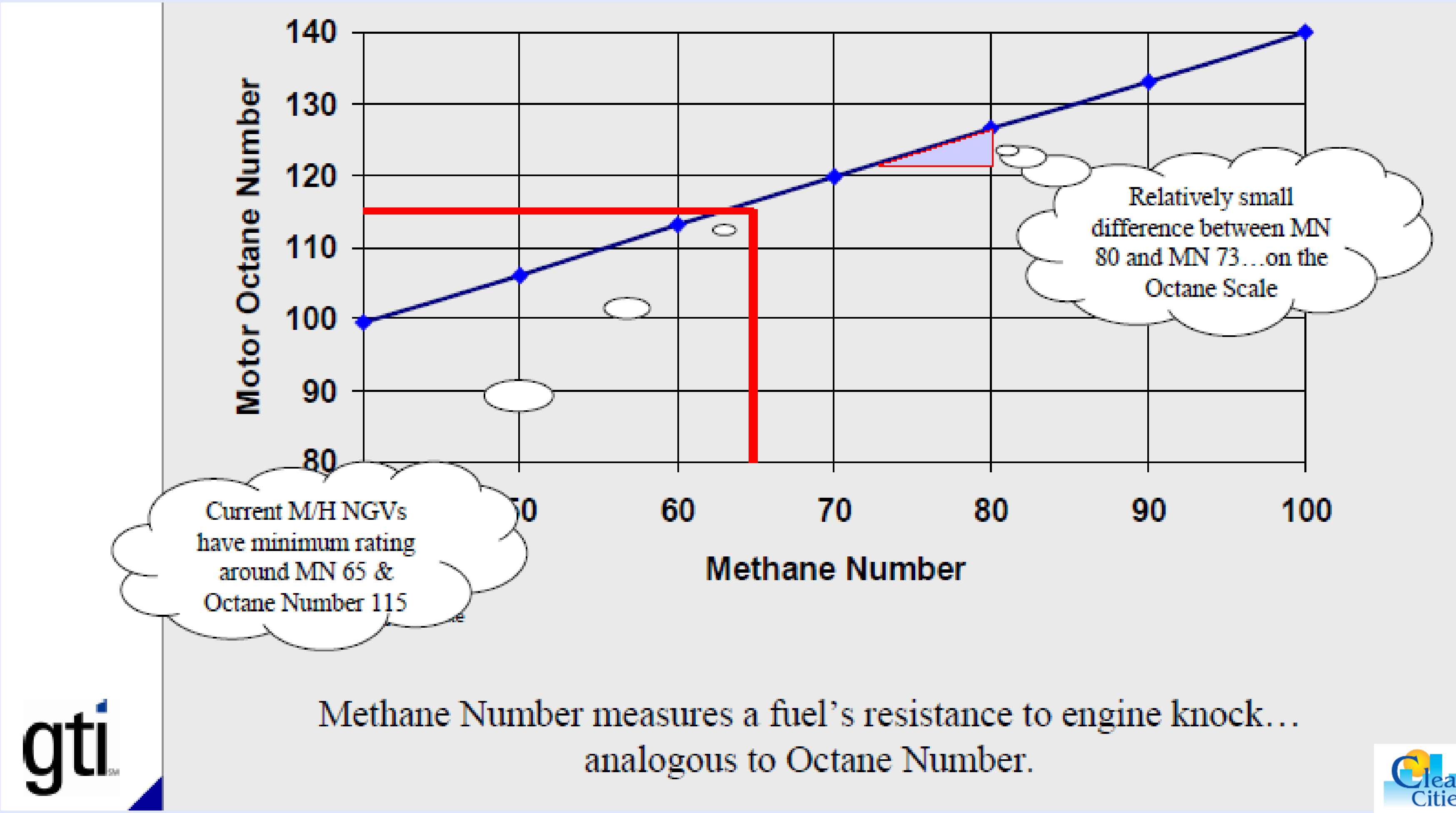
Natural gas has excellent knock resistance



Source: Bill Liss, Natural Gas Composition for NGVs, Gas Technology Institute.

Samples of natural gas specifications show different requirements and realities in different world regions

① USA EPA (Federal)

Item		ASTM test method No.	Value
Methane	min. mole pct.	D1945	89.0
Ethane	max. mole pct.	D1945	4.5
C_3 and higher	max. mole pct.	D1945	2.3
C_6 and higher	max. mole pct.	D1945	0.2
Oxygen	max. mole pct.	D1945	0.6
Inert gases:			
Sum of CO_2 and N_2.	max. mole pct.	D1945	4.0
Odorant [1]			

② USA CARB

Specification	Limit
Compressed Natural Gas Certification Test Fuel	
Methane	90.0 ± 1.0 mole percent
Ethane	4.0 ± 0.5 mole percent
C_3 and higher hydrocarbon content	2.0 ± 0.3 mole percent
Oxygen	0.5 mole percent maximum
Inert gases ($CO_2 + N_2$)	3.5 ± 0.5 vol. percent

③ Japan

Methane	(% mole)	85.0 over
Ethane	(% mole)	10.0 under
Propane	(% mole)	6.0 under
Butane	(% mole)	4.0 under
$C_3 + C_4$	(% mole)	8.0 under
C_5 upper	(% mole)	0.1 under
Others	(% mole)	1.0 under
High heating value	($Kcal/Nm^3$)	10410～11050
Wobbe Index	($Kcal/Nm^3$)	13260～13730
Sulfur	(mg/m^3)	10.0 under

④ Europe ※1 CH4 cert fuel = 86-100%

Characteristics	Units	Basis	Limits minimum	Limits maximum
Reference fuel G20				
Composition:				
Methane	% mole	100	99	100
Balance (1)	% mole	—	—	1
N_2	% mole			
Sulphur content	mg/m^3 (2)	—	—	10
Wobbe Index (net) ※2	MJ/m^3 (3)	48,2	47,2	49,2

※1 G20 and G25(Methane86%, Nitrogen14%)

※2 Wobbe Index is calculated using low calorific value

Source: Masato Matsuki (Honda R&D Co.),'Study on Required CNG Qualities as an Automotive Fuel, as presented at ANGVA Conference, 28 November 2013

LNG compositions vary depending on it source

Properties at bubblepoint at normal pressure		LNG Example 1	LNG Example 2	LNG Example 3
Molar content (%)				
N_2	Nitrogen	0,5	1,79	0,36
CH_4	Methane	97,5	93,9	87,20
C_2H_6	Dimethyl Ether (Ethanol)	1,8	3,26	8,61
C_3H_8	Propane	0,2	0,69	2,74
i C_4H_{10}	Iso Butane	—	0,12	0,42
n C_4H_{10}	Butane	—	0,15	0,65
C_5H_{12}	Pentane	—	0,09	0,02
Molecular weight (kg/kmol)		16,41	17,07	18,52
Bubble point temperature (°C)		– 162,6	– 165,3	– 161,3
Density (kg/m^3)		431,6	448,8	468,7
Volume of gas measured at 0 °C and 101 325 Pa/volume of liquid (m^3/m^3)		590	590	568
Volume of gas measured at 0 °C and 101 325 Pa/mass of liquid (m^3/10^3 kg)		1 367	1 314	1 211

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Fuel Composition ‘Decisions’ from CEN TC 408* (Bio-&-NG Composition)

- **Methane Number:** discussed 80 for non-grid (i.e. vehicles); (65 for gas into the grid– TC 234)
- **Wobbe Index**: Proposed range from Volvo is 47.2 – 50.3 MJ/Nm3. Issue under discussion.
- **Sulphur limits**: Proposed limit in order to assure proper operation of NGVs should be 10 mg/Nm3 due to poisoning effect on the after-treatment equipment. (Values being discussed within CEN/TC 234 WG 11 for non-odorised and odorised gas).
- **H_2S + COS** (carbonyl sulfide)**:** proposed limit for is 5 mg/Nm3

*CEN TC 408 communication: Expert Group discussion 2013,

Fuel Composition 'Decisions' from CEN TC 408* (Bio-&-NG Composition)

- **Siloxanes**: CEN TC/408 discussing various preliminary limits:
  - <0,1mg/Nm3 (also *0,06 mgSi/kg) for the vehicle fuel application*
  - *2 mgSi/m3; for pipeline injection*
- **Other contaminants**: filter out the rest of the 'nasties' (1 micron filter for dust; coalescing filters in fuel stream, etc.)

*CEN TC 408 communication: Expert Group discussion, 2013,

Fuel Composition
Lessons *being* learned
(The jury is still out)

- Gas composition should be identified: all applications
- Natural gas fuel composition *standards* must allow for *natural* and regional variations while achieving levels of energy content and combustion characteristics to satisfy the needs of regional gas consuming technologies.
- Regulations on sulfur could cause a re-think of gas odorization (big change for a small market)
- LNG standard challenging: *pipeline quality* needed
- Biomethane (upgraded from biogas) = *pipeline quality*, with potential for high methane content
- Compressor stations (public/private/VRAs) should have gas dryers on inlet side & filters (oil/dirt/metallics) on outlet side

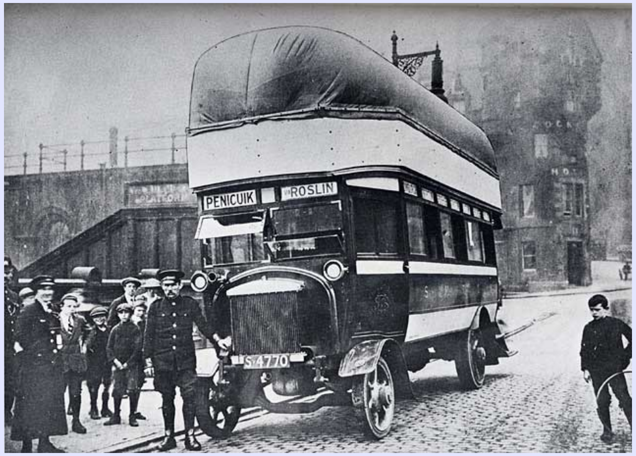
Natural gas vehicles have benefited from improvements in engine technology developments over the years

- Fuel injection
- Multiport fuel injection
- OBD: compatibility with 'master-slave' provides simpler solution for CNG 'fit' to gasoline
- OBD (future) for HDVs (?)
- Emissions strategies: i.e. Exhaust Gas Recirculation (EGR)
- Turbo charging: good for more complete methane combustion & power
- Multiair electro-hydraulic valve timing
- Etc.

NGV Engine Technology Lessons Learned

- The better performing the petroleum fuelled engines become, generally, the better it is for NGVs.
- Challenge for NGV system & equipment suppliers to move to Tier 1 level.
- Enforcing quality control of retrofits and for 'new entry' OEMs, particularly from developing economy countries, is essential.

CNG Storage Technology



Scottish Motor Traction Bus, Edinburgh 1914-1918

Citroen 1941

Dedicated Ford Ranger: 1st Type II Cylinder- 1983

Chinese buses 1988

The Wikov NGV, Czechoslovakia 1936

CNG Cylinder Severe Abuse Test 1983

U.S. DOT study systematically characterized NGV/CNG accidents, equipment failures & fires from 1976-2010

- **138 incidents:** 56% U.S.; 44% Europe, Asia, S.America
- **All vehicles included:** 51% LDV/Trucks; 38% buses; 11% other commercial vehicles
- Most problems were with individual NGVs
- Some systemic problems identified, especially with Pressure Relief Devices (PRDs)
- 12% involved fire but most not attributed to CNG systems or NGVs (leaking petroleum liquids)

Natural Gas Systems: Suggested Changes to Truck & Motorcoach Regulations & Inspection Procedures, U.S. Dept. Transportation (FMCSA), March 2013, findings based on data from Clean Vehicle & Education Foundation

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135 CNG incidents characterized

Type of Incident	Number of Incidents	Percentage of Total (135)
Cylinder ruptures	50	37%
PRD release (no fire)	14	10%
Vehicle fire (no cylinder rupture)	17	13%
Accident w/another vehicle	12	9%
Single vehicle accident	6*	4%
Cylinder or fuel tank leak	14	10%
Other	7**	5%
Unknown cause	15[+]	11%

*5 of these were at low underpasses
** 5 related to operational/maintenance
[+]12 outside the U.S.

Source: Natural Gas Systems: Suggested Changes to Truck & Motorcoach Regulations & Inspection Procedures, U.S. Dept. Transportation (FMCSA), March 2013, findings based on data from Clean Vehicle & Education Foundation

Many PRD-related incidents but many were not design-related or due to failures

- PRDs worked properly in 42% of incidents involving fire
- In half of these the gas ignited but was attributed to poor installation or PRD
- 35% of fires PRDs did not release but mostly because fire did not reach location of PRD so storage system was compromised
- Two-thirds of NGV accidents w/vehicles no gas was released.

Natural Gas Systems: Suggested Changes to Truck & Motorcoach Regulations & Inspection Procedures, U.S. Dept. Transportation (FMCSA), March 2013, findings based on data from Clean Vehicle & Education Foundation

CNG cylinders have been a source of accidents not so much because of the cylinders but due to human error, ignorance, neglect or mis-handling

Lessons Learned: *Inspection*

- Adopt inspection policies (at a minimum 36,000 miles or every three years, whichever comes first) (UNECE = 4 year inspection)
- Visually inspect the CNG fuel systems (at this time, the best method of monitoring the overall safety of NGV fuel systems)
- Create a pool of certified cylinder inspectors
- In-situ cylinder inspection method?

Source: Clean Vehicle Education Foundation

Clean Cities U.S. Department of Energy

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CNG retrofit installation Issues

- With NGV market growth conversions of CNG vehicles by independent, untrained mechanics have presented safety concerns

Lessons Learned: Training & Certification

- Certification programs needed to train/test/certify conversion shops and technicians (& shops)
- Must provide basic standards & regulatory information (i.e. U.S. Automotive Service Excellence [ASE] certification) on a country-specific basis

Source: Clean Vehicle Education Foundation w/ediits

Example of improper installation and failure to take proper action from an after-accident inspection

Lessons Learned: Enforcement

- Develop enforcement program for periodic and after-incident cylinder inspections
- Training needed for inspectors, mechanics, fleet managers, and first responders (fire marshals)

Source: Clean Vehicle Education Foundation

Clean Cities U.S. Department of Energy

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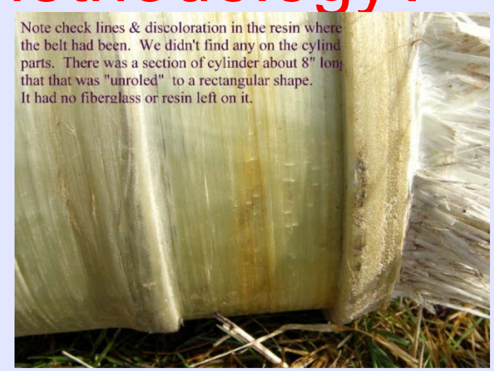
Cylinders removed from service or at *end of life* should be destroyed using proven methods based on standards and best practices.

Lessons Learned: Use common sense!

- Train NGV service providers & inspectors
- Develop cylinder/vehicle tracking methodology?
- Radio Frequency Identification?

Ukraine 2007: Cylinder was shortened to fit into the trunk of the car – exploded when refuelled



Cylinder useful life date had expired; 'sour gas' from a farm was used to fuel the vehicle.

 Source: Adapted from Clean Vehicle Education Foundation

Lessons learned (and still learning) about PRDs

- Venting system should not be restricted below design level
- PRDs should be ice and dirt free
- Direction of the venting gas should :

- Not enter a passenger compartment or any other compartment

- Not block an emergency exit on a vehicle

- Be designed with a defuser to avoid 'flame thrower' effect, in case of fire

Wassanaar, NL Oct.2012

Natural Gas Systems: Suggested Changes to Truck & Motorcoach Regulations & Inspection Procedures, U.S. Dept. Transportation (FMCSA), March 2013, findings based on data from Clean Vehicle & Education Foundation; private communication Nov 2012, J.Dimmick, CVEF.

Lessons Learned….& challenges CNG cylinders & NGV accidents

- (Transparent) Forensic investigation of cylinder incidents (and accidents) is essential to identify root cause
- Establishing incident history (done by industry and/or government) allows lessons to be learned and corrections made
- Implementation and enforcement of standards and regulations is essential to maintain the highest level of safety. (US-FMVSS 304; International ISO 11439 or UNECE R.110)
- Safety standards and regulations should be assured throughout the entire equipment supply chain via documentation or, as necessary, direct inspection of the manufacturing facility.
- 3 essential things: training, training and training

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Natural Gas Fueling Technologies & Systems

CNG

L-CNG

LNG

Mobile Fueller:
Mother Daughter
Australian Truck Train

Vehicular refuelling appliance (VRA)

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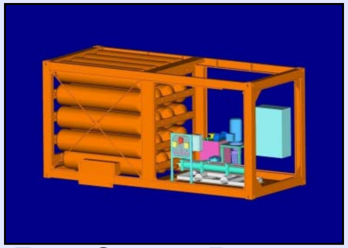
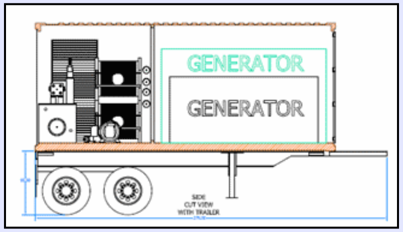
A variety of mobile fuel systems are available for CNG & LNG that allow the market to grow beyond the pipeline

Proof of Concept Systems	Packaged CNG Systems	Emergency Breakdown Systems	Packaged LNG Systems	Mother Daughter & Mobile Storage Systems



Raufoss: Power Gen & nobile fuelling

Varieties of Chinese-built mobile fuellers



Pinnacle (U.S.)

Chart (US)

Xperion CNG truck

Korean All-in-one modular unit

IMW (U.S.A) mobile fuel dispenser

Tokyo Gas compressor truck

Gazprom L-CNG fuel truck

Dynetek portable fueller

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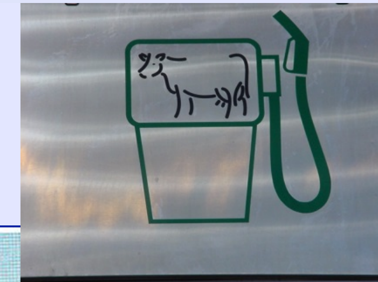
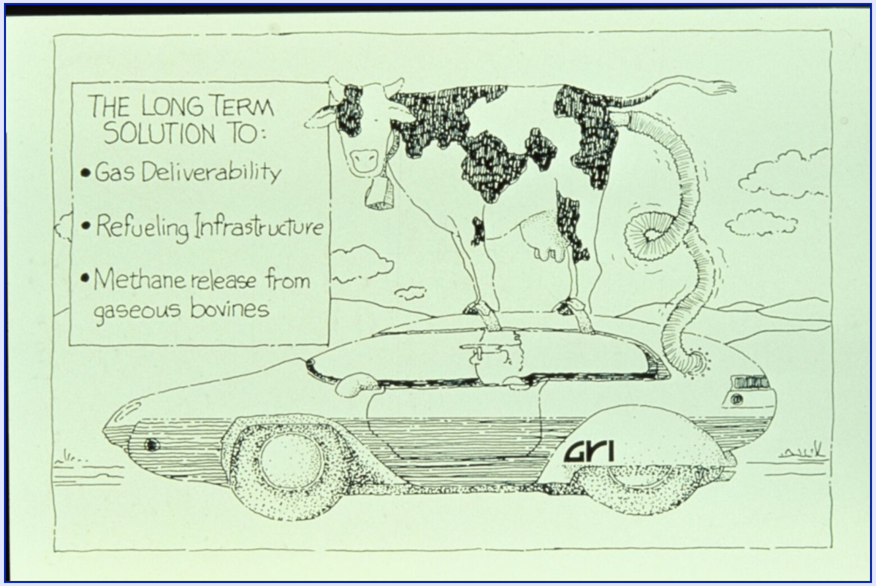
BIOGAS DELIVERY CONCEPTS





U.S.: Gas Research Institute

Volvo, Sweden

The Netherlands

Switzerland

Listening to the Suppliers & Customers

- Develop an understanding of cost reduction opportunities and 'best practices' for the installation and operation of fuelling stations serving natural gas vehicles.

- **60 experts from 5 continents worldwide surveyed**
- **Suppliers** of NGV fuelling stations; installers; consulting engineers. (48% response rate and 14 reviewers of draft report)
- **Operators and customers** of NGV fuelling stations (50% response rate and 15 reviewers of draft report)
- Some were in both categories (i.e. gas company installers who also run NGV fleets)

Source: *"Natural Gas for Vehicles,"* IGU/UNECE 2012, section 7.2, J. Seisler & P. Seidinger, survey of 60 fuel station installers & customers worldwide,.

Lessons Learned

Possible cost reduction & best practices at the design stage

- Modular design of compressor systems (to extent possible)
- Provide ‘adequate’ compressor capacity. Don’t over-or-undersize stations. Design for expansion.
- Reduce size of ‘footprint’ (compressor & storage)
- Adaptive designs: LDVs vs HDVs vs mixture of both have to be considered for different markets in different countries
- Reduce electrical costs due to ‘powering up’ (peak demand)
- Gas dryers on the inlet side; oil filters on the outlet side

Source: *“Natural Gas for Vehicles,”* IGU/UNECE 2012, section 7.2, J. Seisler & P. Seidinger, survey of 60 fuel station installers & customers worldwide,.

Lessons Learned

Opportunities to reduce the 'hidden' cost of filling stations

Grid Issues for gas distribution consideration

- Connection fees: universally still very high
- Inlet pressures need to be as high as possible
- Shortest distance to hook-up station to grid
- **'Educate' local code officials** who will inspect & certify fuel stations in advance about fuelling systems, and particularly safety.

Source: *"Natural Gas for Vehicles,"* IGU/UNECE 2012, section 7.2, J. Seisler & P. Seidinger, survey of 60 fuel station installers & customers worldwide,.

Lessons Learned

Possible cost reduction & best practices during operations

- **Remote metering & controls** is desired by many station operators to ensure better reliability and provide quicker response to problems in order to reduce station down-time.

- **On-site monitoring is possible**
- **Off-site monitoring** provides centralized control for the fuel station service provider and/or for the owner of multiple stations monitoring their own facilities

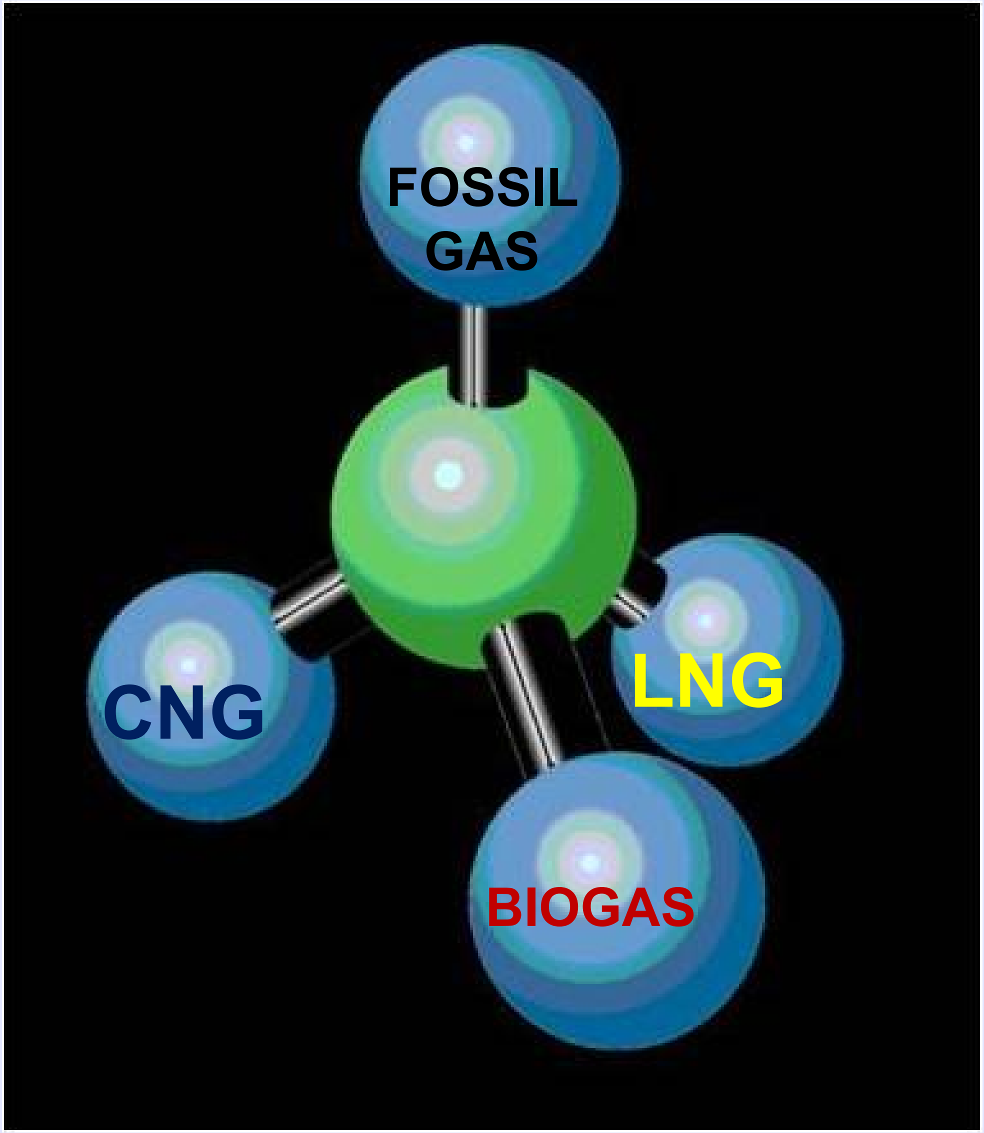
Source: *"Natural Gas for Vehicles,"* IGU/UNECE 2012, section 7.2, J. Seisler & P. Seidinger, survey of 60 fuel station installers & customers worldwide,.

Lessons Learned Fuelling Stations & Systems (suppliers' perspective)

- **Lack of harmonization** is seen as the single most important factor increasing costs system producers/installers.
- **Adopting the best practices** for safety can reduce costs by as much as 30%.
- **GOOD NEWS**: ISO CNG/LNG fuel station standards DIS adopted in March 2014! Likely in-force 2015.
- Result of voting DIS 16923 (CNG) had a positive vote 13 out of 15 = 87%; and ISO 16924 (LNG): 9 votes in favor out of 12 = 75%.

Source: *"Natural Gas for Vehicles,"* IGU/UNECE 2012, section 7.2, J. Seisler & P. Seidinger, survey of 60 fuel station installers & customers worldwide,.

METHANE IS A DIVERSE & FLEXIBLE FUEL FOR THE TRANSPORT SECTOR



Keep your eyes focused on the road ahead and make good policy today that gets us where we want to go!

The future is a big place. It's going to take a long time to get there.

NGVs Past & Prologue

Lessons Learned to Create Deployment Strategies for Commercializing NGVs

Dr. Jeffrey Seisler, CEO

Clean Fuels Consulting

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Presented by: