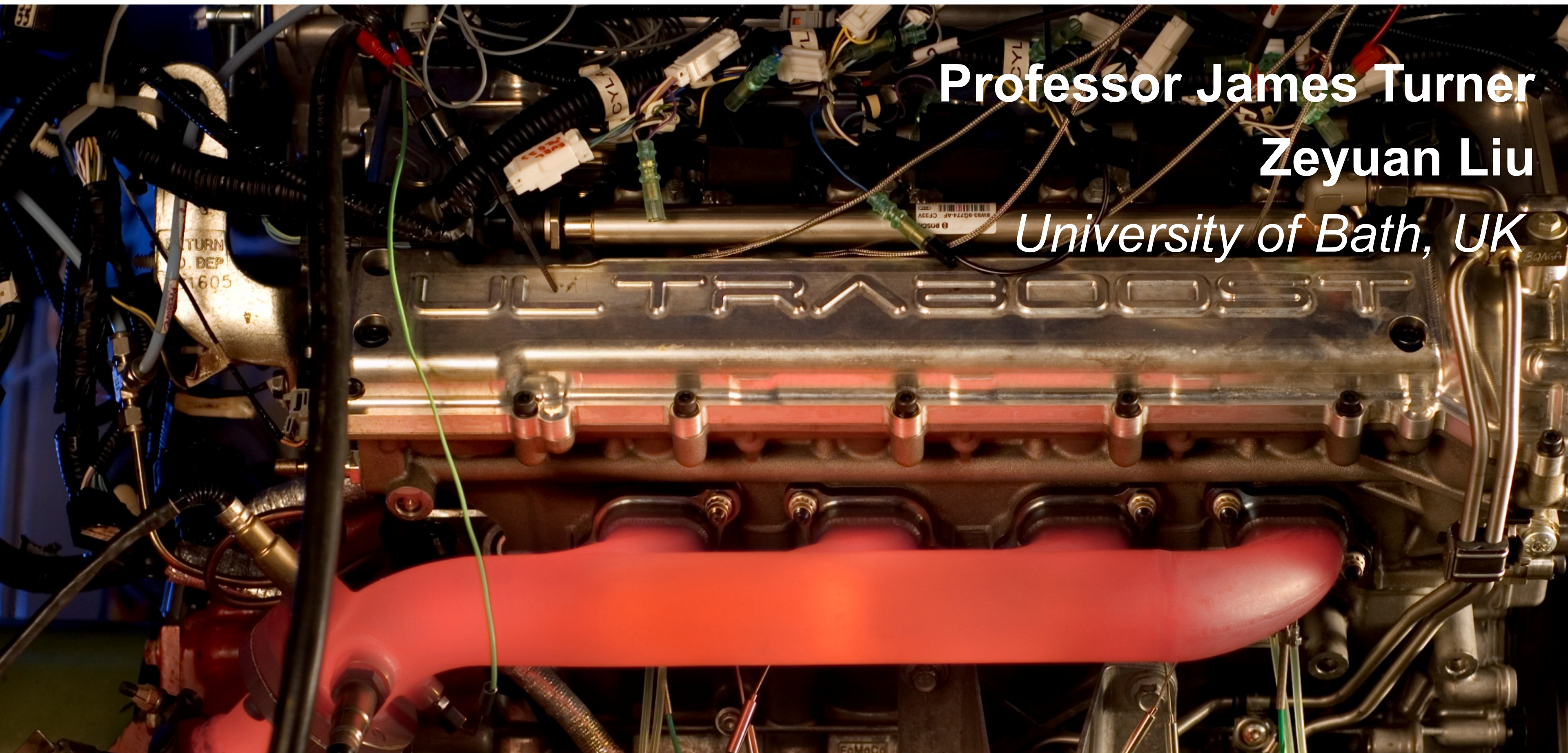
Department of Mechanical Engineering

Powertrain & Vehicle Research Centre

GEM Fuels Development – New Ways of Introducing Methanol into Transport Fuel



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Zeyuan Liu

University of Bath, UK

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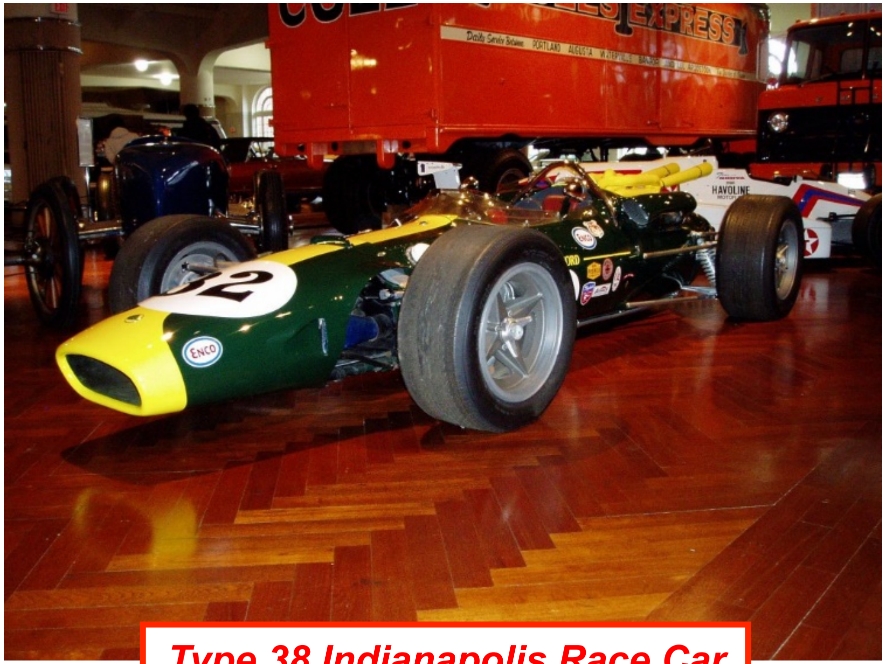
- **Paul Wuebben** – CRI
- **Edward Goossens** – GUTTS Motorsport
- **Kjell ac Bergström** and **Kenth Johansson** – Saab Automobile

- *…And all of the many others who have embraced the concept of methanol and GEM fuels as an evolutionary enabler towards a practical and affordable transport energy economy*

OVERVIEW OF THE INITIAL TERNARY BLENDS WORK CONDUCTED AT LOTUS

Exige 270E Tri-Flex-Fuel Car

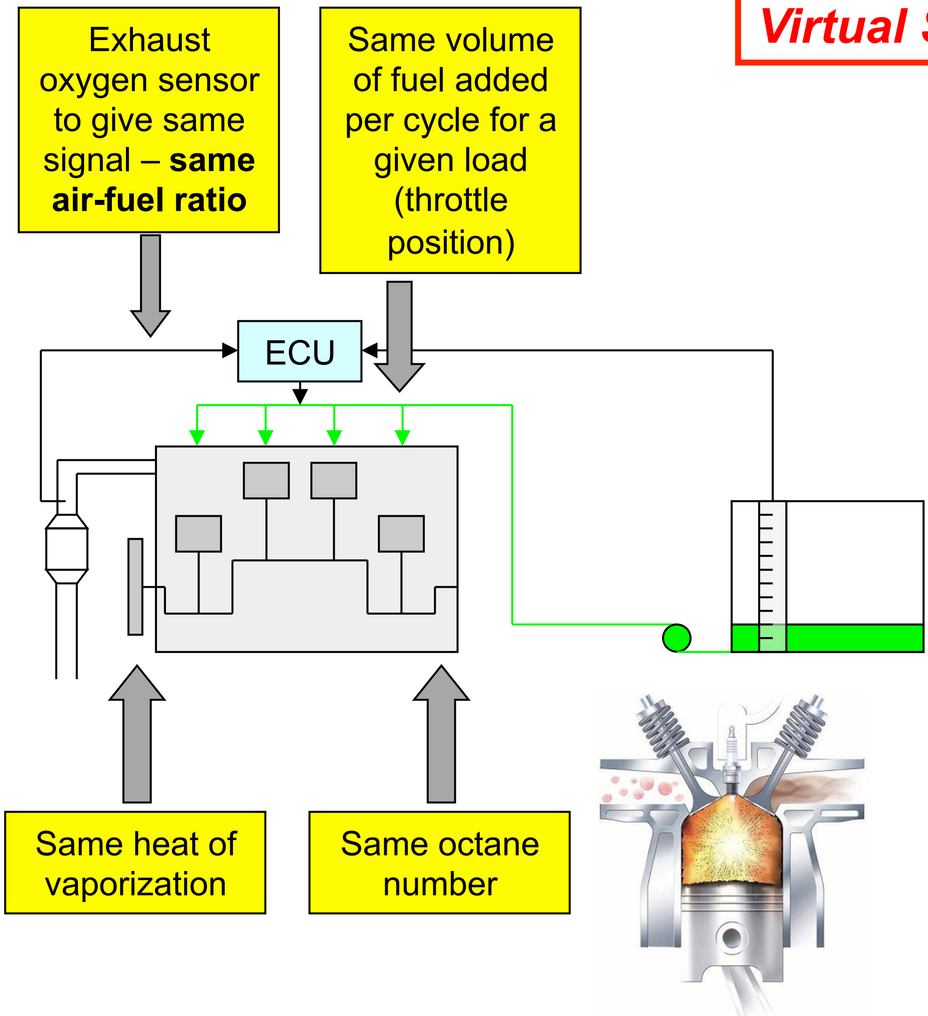


Type 38 Indianapolis Race Car

Pathways to a Low Carbon Fuel Future

- One can achieve a low-fossil-carbon future for the fuel path via two primary routes:
- The fuel (by producing a multi-component blend which is a **drop-in alternative** to an existing formulation)
- The vehicles (by making changes to them to accommodate the use of *any* proportions of the different fuel components)
- This presentation will discuss the first approach, and how methanol might be applied to enable an evolution towards a zero-net-carbon future without a requirement for a revolution on the part of any stakeholder in transport
  - *Governments – OEMs – Fuel suppliers – Owners/users*
- *Since it can be synthesized from any carbonaceous feed stock, **methanol does not suffer from the biomass limit of bioethanol**, meaning that, if it can be incorporated in a practical fuel, it can be used to **break its biomass limit***
  - *The comingling potential of gasoline, ethanol and methanol is key*
- The approach could therefore provide an evolutionary path to full decarbonization of transport under the current economic model

Requirements for 'Drop-In Fuels'



Virtual Sensor Car

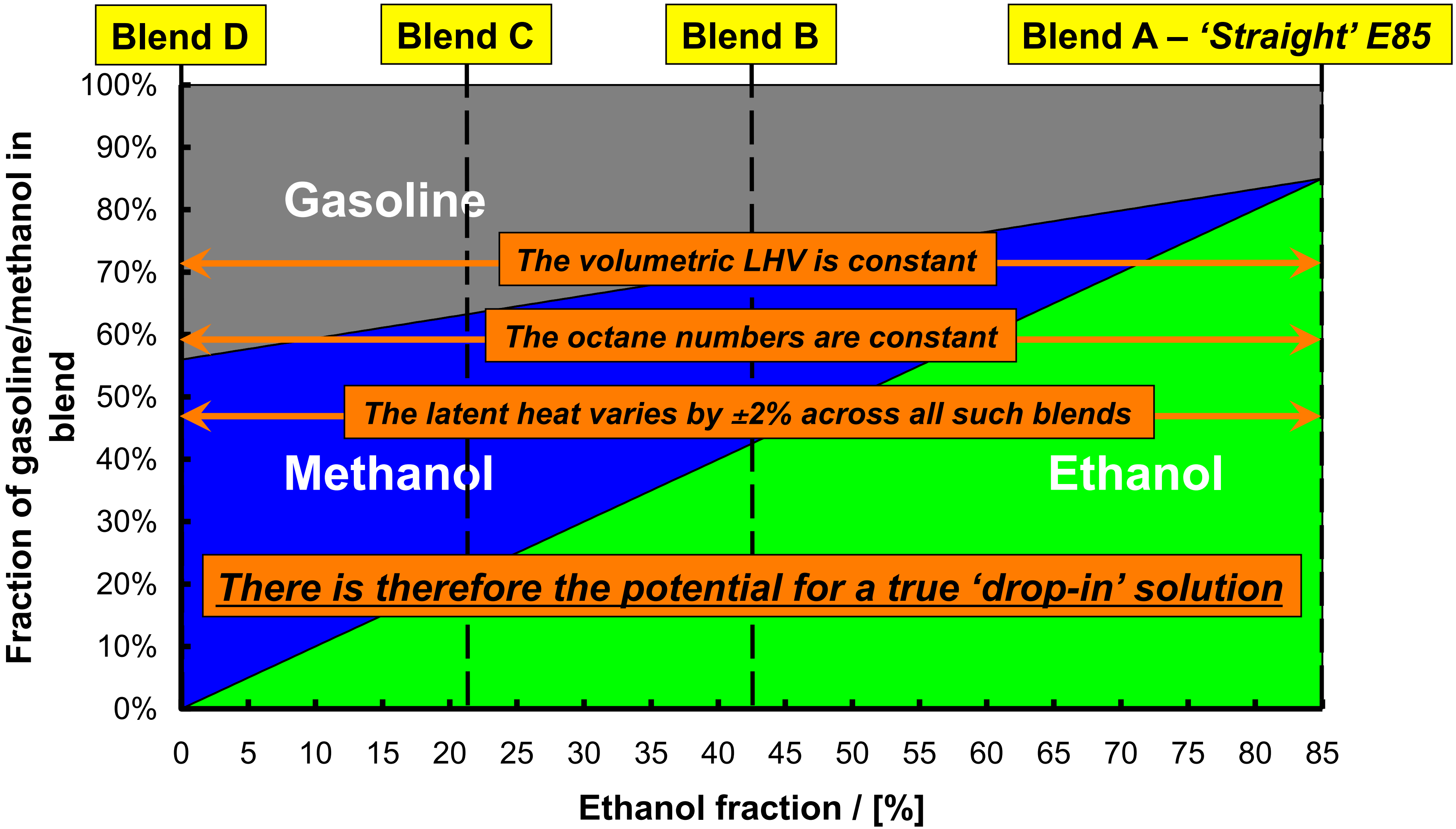
Physical Sensor Car

‘GEM’ Ternary Blends

- In the context of this presentation, the phrase ‘ternary blends’ relates to blends comprising gasoline, ethanol and methanol – *‘GEM’*
  - *They can also be formulated with other alcohols and with other individual hydrocarbon components*
- The GEM blends in the vehicle tests reported here were formulated based on having equal stoichiometric air-fuel ratio, <u>equivalent to E85</u>
  - *Making them ‘**iso-stoichiometric**’*
- This work was a result of some initial calculations by Lotus which showed that for equal AFR, <u>all iso-stoichiometric GEM blends have the same volumetric lower heating value</u>, to ±0.25%
- It was postulated that this could enable ‘drop-in’ fuels to be formulated for existing E85/gasoline flex-fuel vehicles, which could then be used to <u>extend the biomass limit of ethanol</u>
  - *The initial work tested this hypothesis on cold and hot NEDC cycles*
- This initial ternary blend work was supported and enabled by BioMCN, Methanex, the Methanol Institute, Saab and Inspectorate
  - *Since then, distillation curves and Reid vapour pressures have also been investigated*

GEM Blend Concentrations at 9.7:1 AFR

Straight E85 is 'dry' and has a stoichiometric AFR of 9.7:1

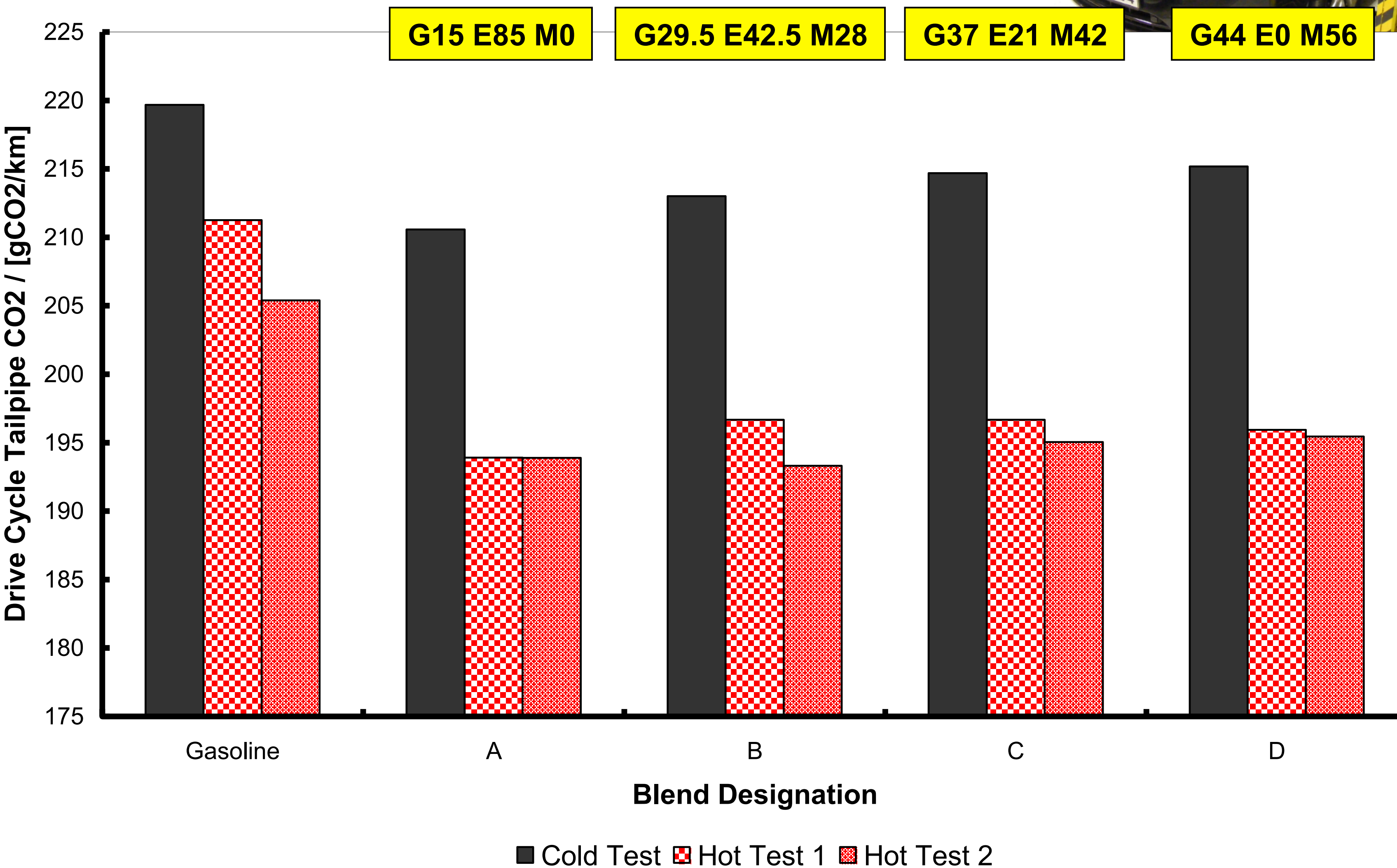


Rationale for the Chosen Test Blends

- After the initial calculation phase, two series of tests were conducted at Lotus using production Saab 9-3 flex-fuel vehicles with different emissions levels and alcohol sensing technologies
- A control gasoline was analyzed first and used to specify the blends:
- **Blend A – *G15 E85 M0***
  - *Test fuel representing 'Straight E85'*
- **Blend B – *G29.5 E42.5 M28***
  - *Splits the ethanol available for E85 across twice the total volume of fuel*
- **Blend C – *G37 E21 M42***
  - *Splits the ethanol in for E85 across four times the total volume of fuel*
  - *Methanol is twice the volume of ethanol; total alcohol is approximately twice the volume of gasoline*
- **Blend D – *G44 E0 M56***
  - *Binary methanol-gasoline equivalent of Straight E85*
  - *Extreme of the range of ternary blends at 9.7:1 stoichiometric AFR*
- **Blend D4 – *G40 E10 M50***
  - *A 'later' blend to avoid low-temperature phase separation*

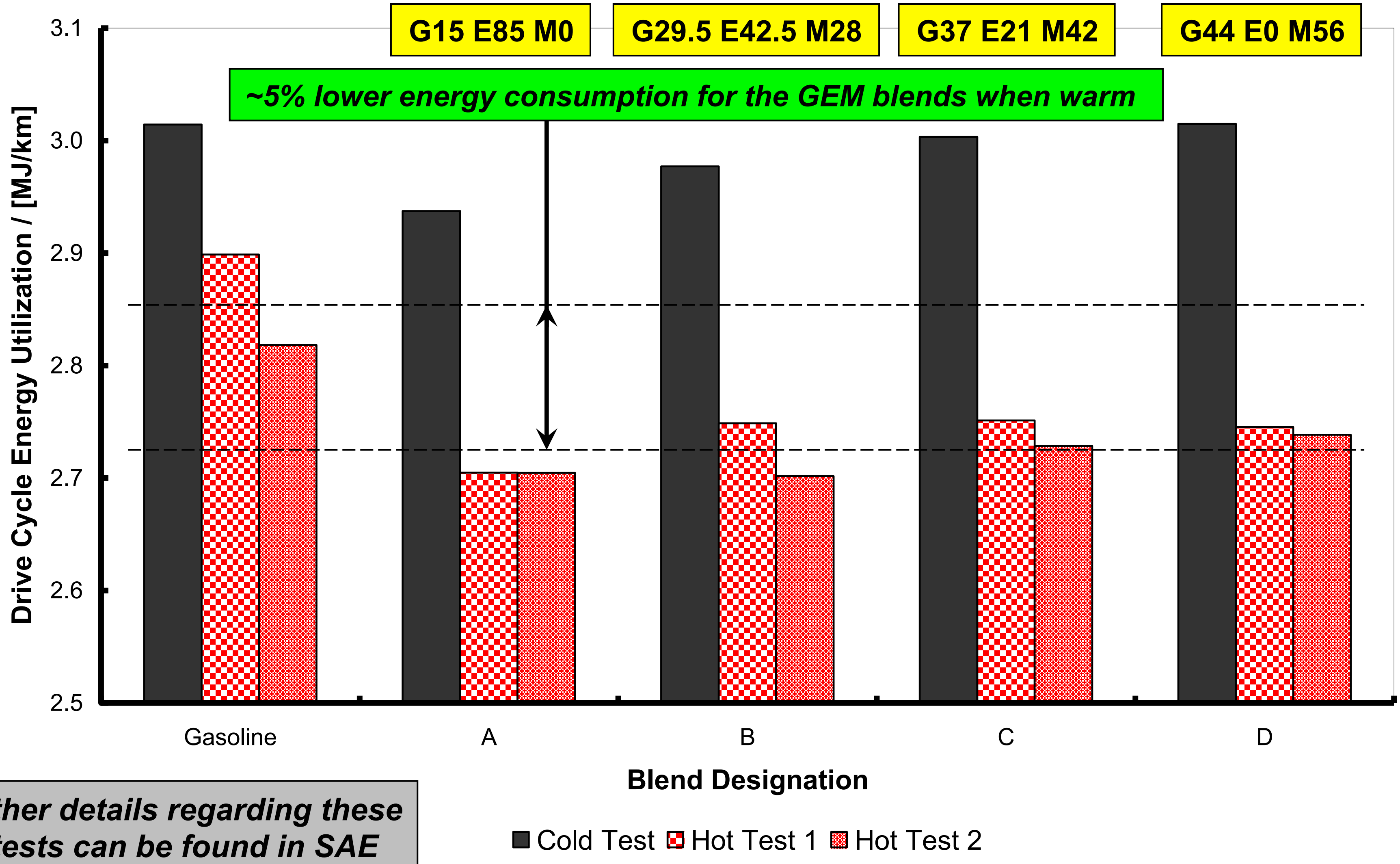
Drive Cycle CO_2 – *Cold and Hot Tests*

Virtual Sensor Car



Drive Cycle Energy – *Cold and Hot Tests*

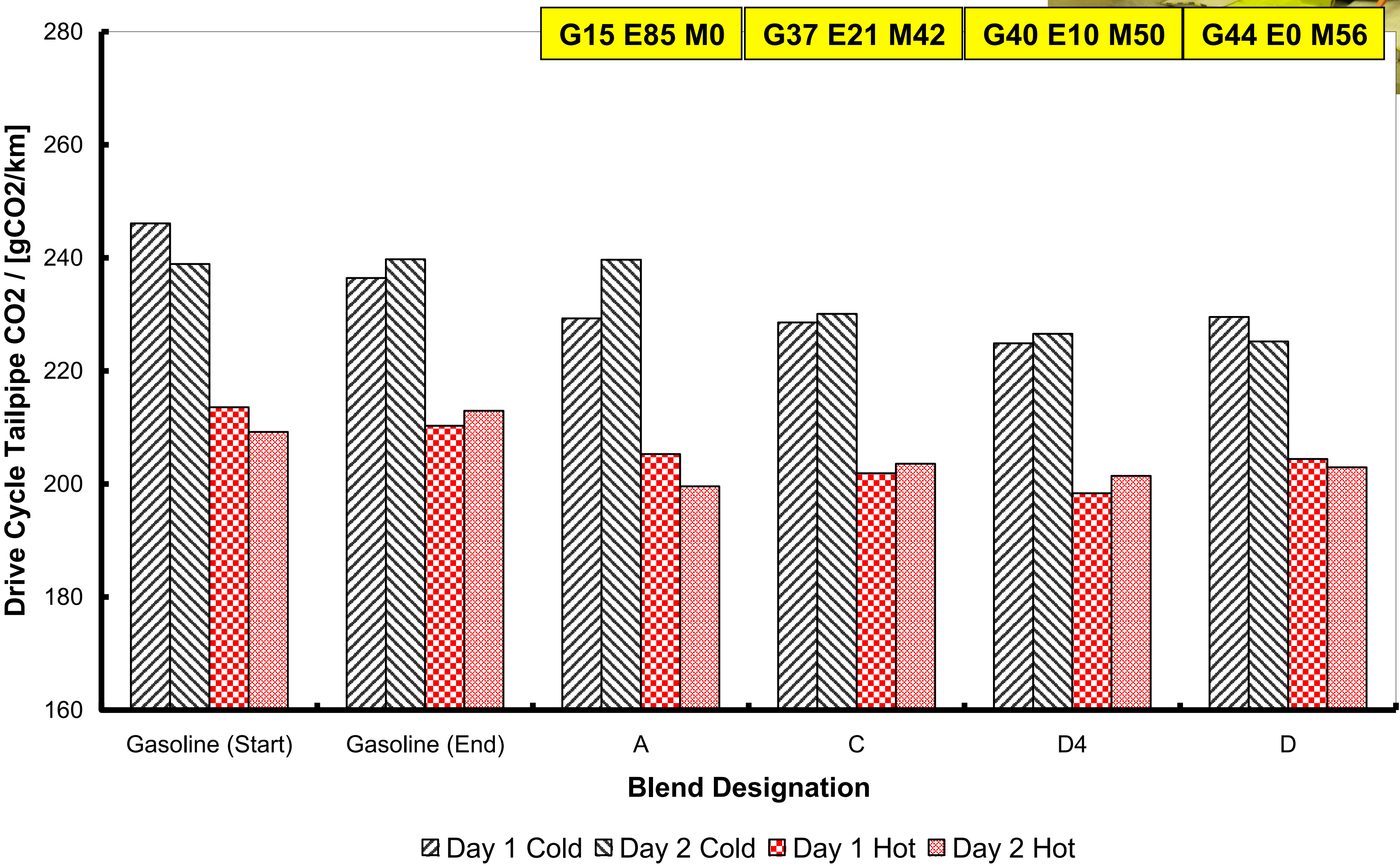
Virtual Sensor Car



Other details regarding these tests can be found in SAE 2011-24-0113

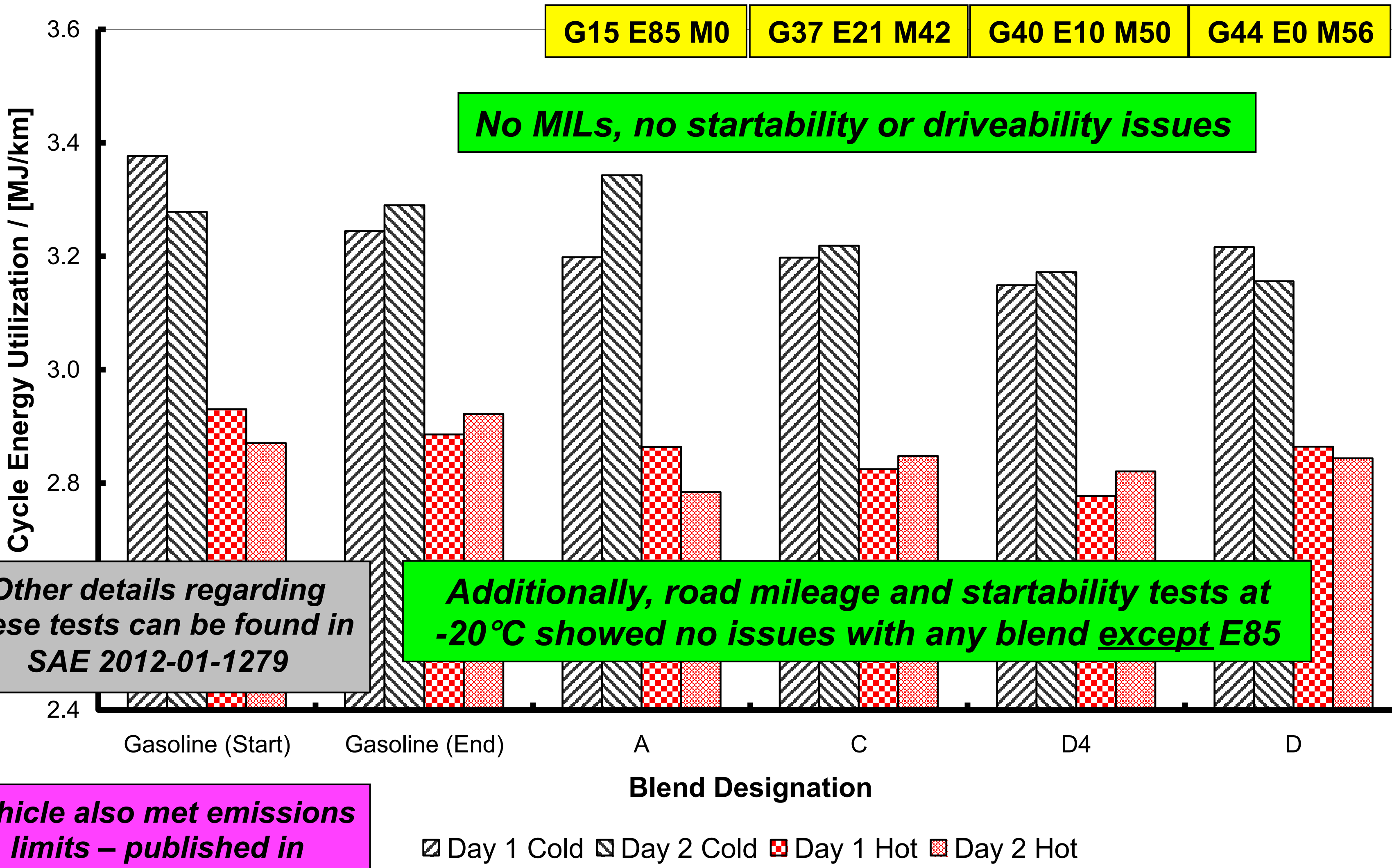
Drive Cycle CO_2 – *Cold and Hot Tests*

Physical Sensor Car



Drive Cycle Energy – *Cold and Hot Tests*

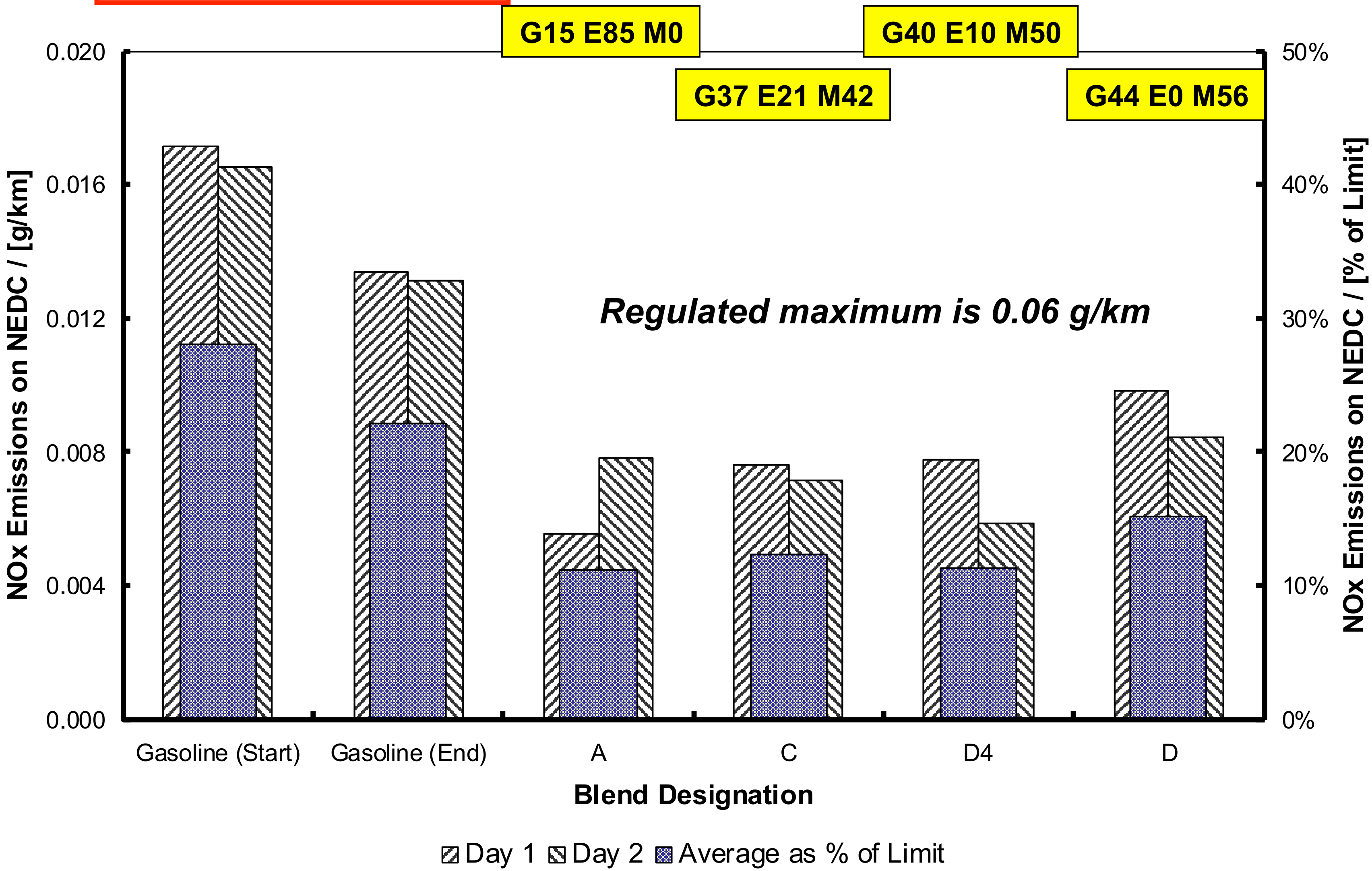
Physical Sensor Car



Vehicle also met emissions limits – published in SAE 2012-01-1586

NOx Emissions – *Cold Tests Only*

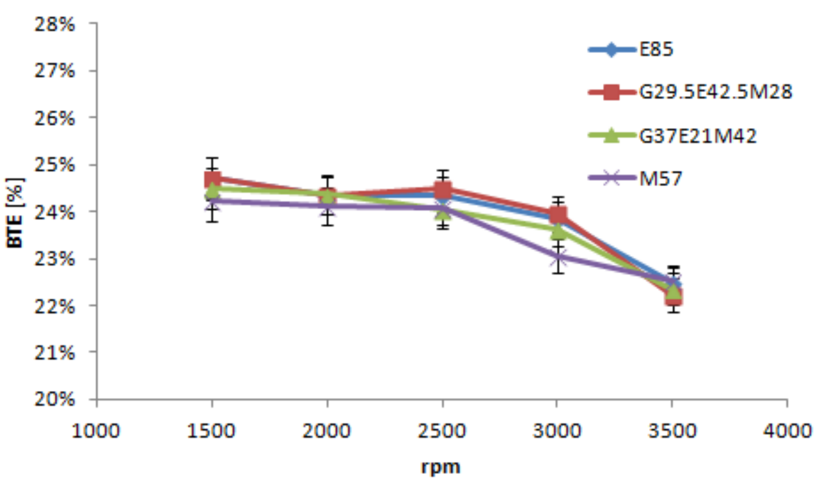
Physical Sensor Car

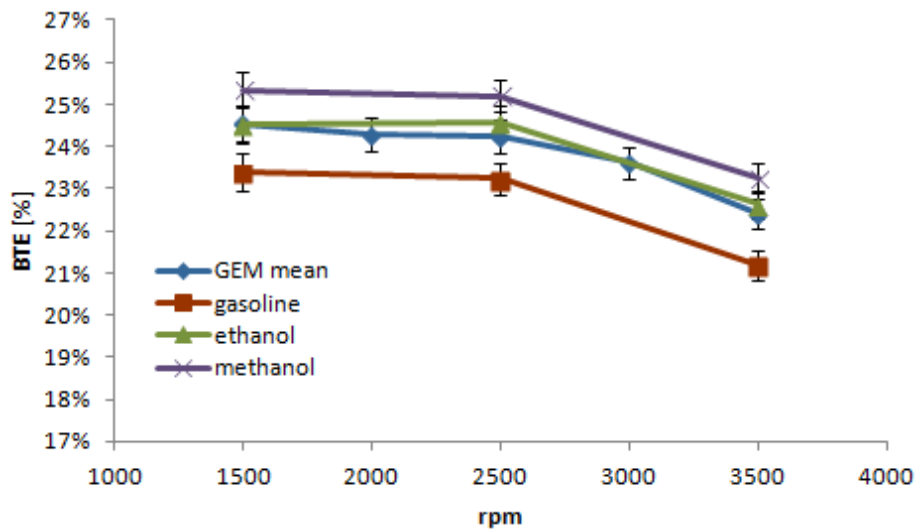


GHENT UNIVERSITY ENGINE TEST BED RESULTS

Engine Measurements on GEM Fuels (PFI)

- 4 cylinder PFI production engine, fuelled with 4 different GEM blends
  - *E85 (Blend A), G29.5E42.5M28 (Blend B), G37E21M42 (Blend C) and M57 (~ Blend D)*
- Steady state operating conditions at various engine speeds
  - *Stoichiometric operation (λ = 1) and MBT timing*
- Effect of different GEM blends on performance and emissions was investigated to check the 'drop-in' potential of GEM fuels





- Confirmation of similar BTE, volumetric efficiency, BSFC and knock behaviour was reported for the tested operating points

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UNIVERSITEIT GENT

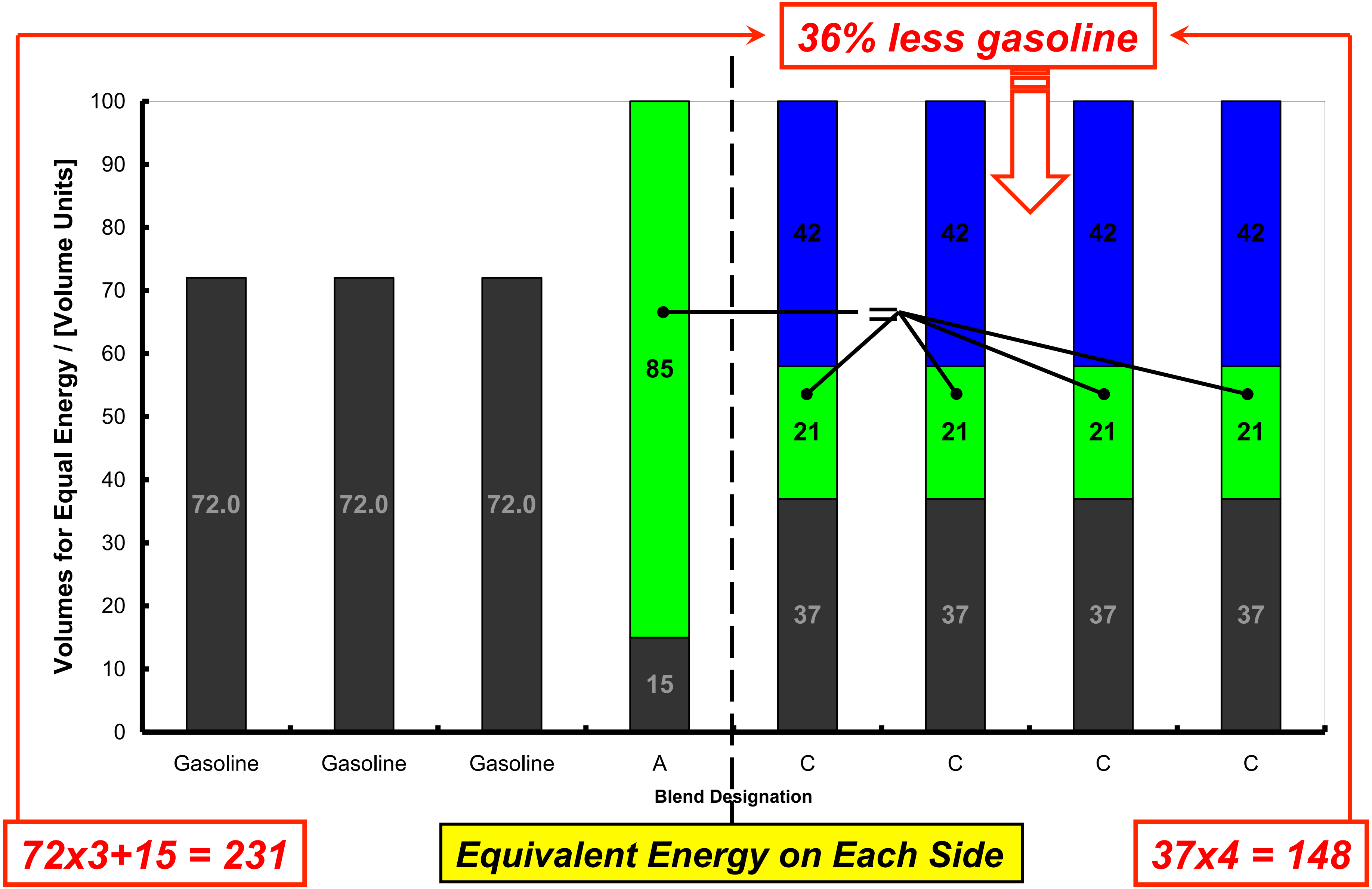
Engine Measurements on GEM Fuels (DI)

- 4 cylinder DI production engine fuelled with 2 different GEM blends
  - *E85 (Blend A) and M56 (Blend D)*
- Steady-state operating conditions at various engine speeds
  - *Stoichiometric operation ($\lambda = 1$) and MBT timing*
- Measurements were done for E85 at fixed loads of 50, 75 and 150 Nm for a range of engine speeds
- All parameters regarding injection (start of injection and injection pressure) and ignition were kept the same for the measurements on M56 to investigate the effect on injection and burn duration
  - *Only very small adjustments of the throttle valve were necessary to maintain the same torque output*
- This work again reinforced that GEM fuels configured for the same stoichiometry can indeed function as drop-in alternatives in direct-injection engines.

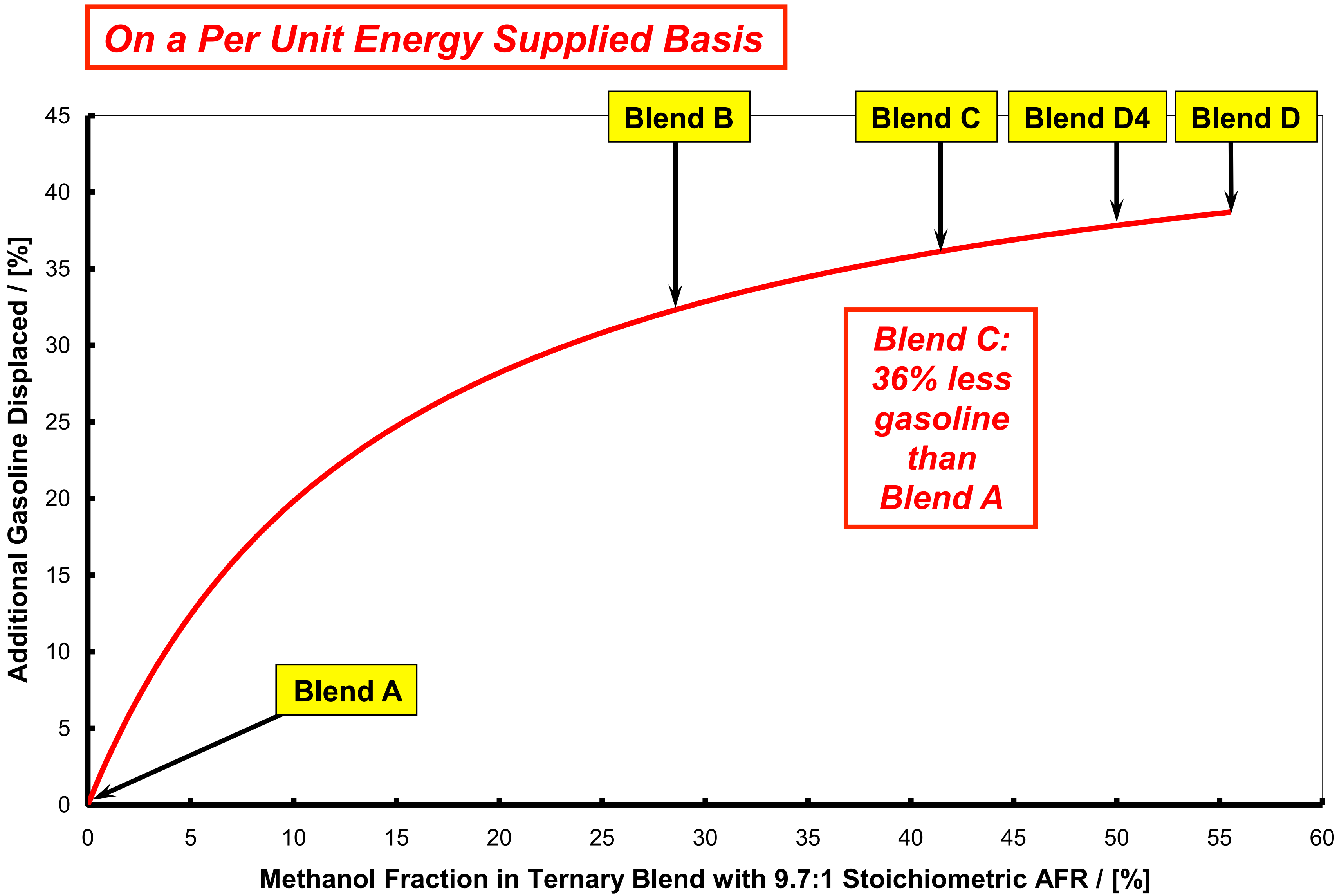
SAE 2015-01-0768

INCREASING THE GASOLINE DISPLACEMENT EFFECT OF ETHANOL WITH GEM BLENDS

Gasoline Displacement: Blend C versus A



Gasoline Displacement Curve



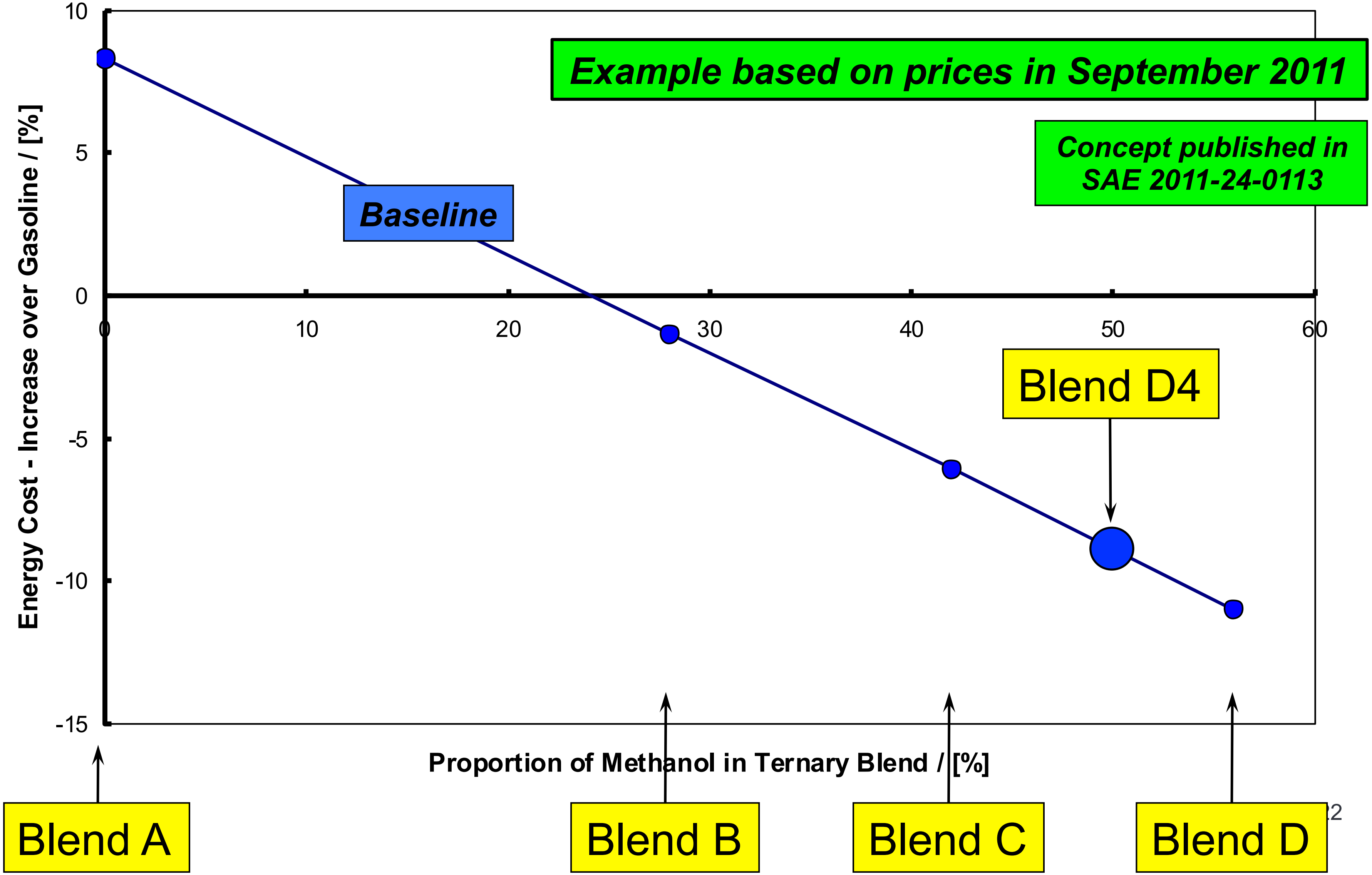
ECONOMIC CONSIDERATIONS OF GEM BLENDS: MAKING THEM “CHEAPER THAN GASOLINE”

Price Calculations Based on Energy

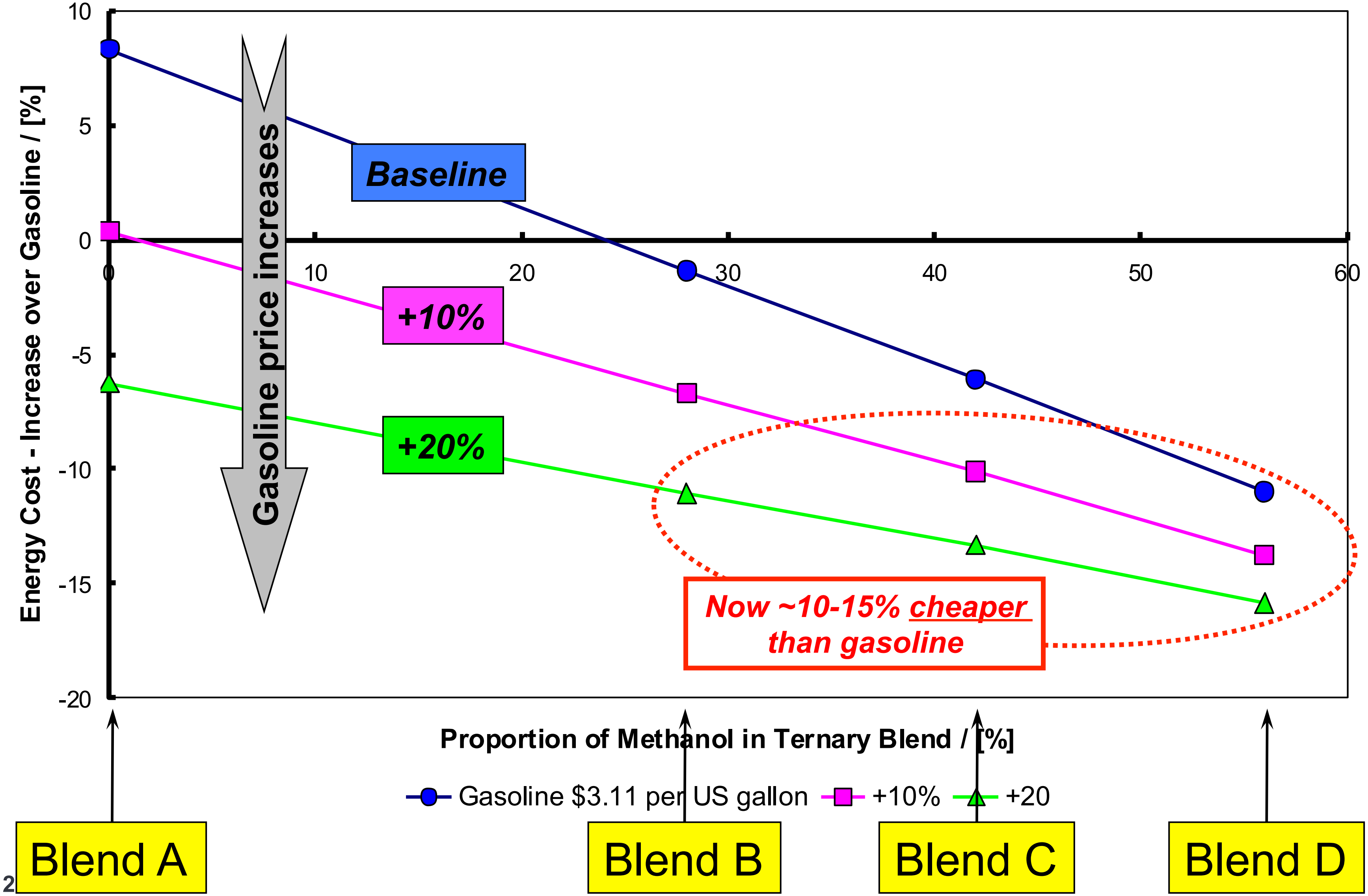
- In a previous publication, calculations were performed based on the wholesale prices of the individual components in September 2011
  - *Based on the volume percentage of the different components*
  - *Methanol price is that of fossil-gas-manufactured form*
  - *Arithmetic still applies*
  - *Benefit depends on taxation regime*
- All iso-stoichiometric GEM blends could be taxed based on the energy they contain and this used to incentivize them versus gasoline
  - *Because all have the same volumetric energy content*
  - *Perhaps based on fossil CO_2 avoided or energy security considerations*
- The sensitivity of the different blends to price fluctuations can be shown
  - *The blends with higher alcohol content can be cheaper than gasoline* <u>based on units of energy sold</u>
  - *Energy is, after all, what moves the vehicle, not the volume the fuel occupies in the fuel tank*
- ***In the future, all fuels should be taxed based on the energy that they contain, with a factor applied for fossil carbon intensity***

Calculations Using Wholesale Prices

G $3.11 / US gal., E $2.30 / US gal., M $1.11 / US gal.



If the Gasoline Price Increases…

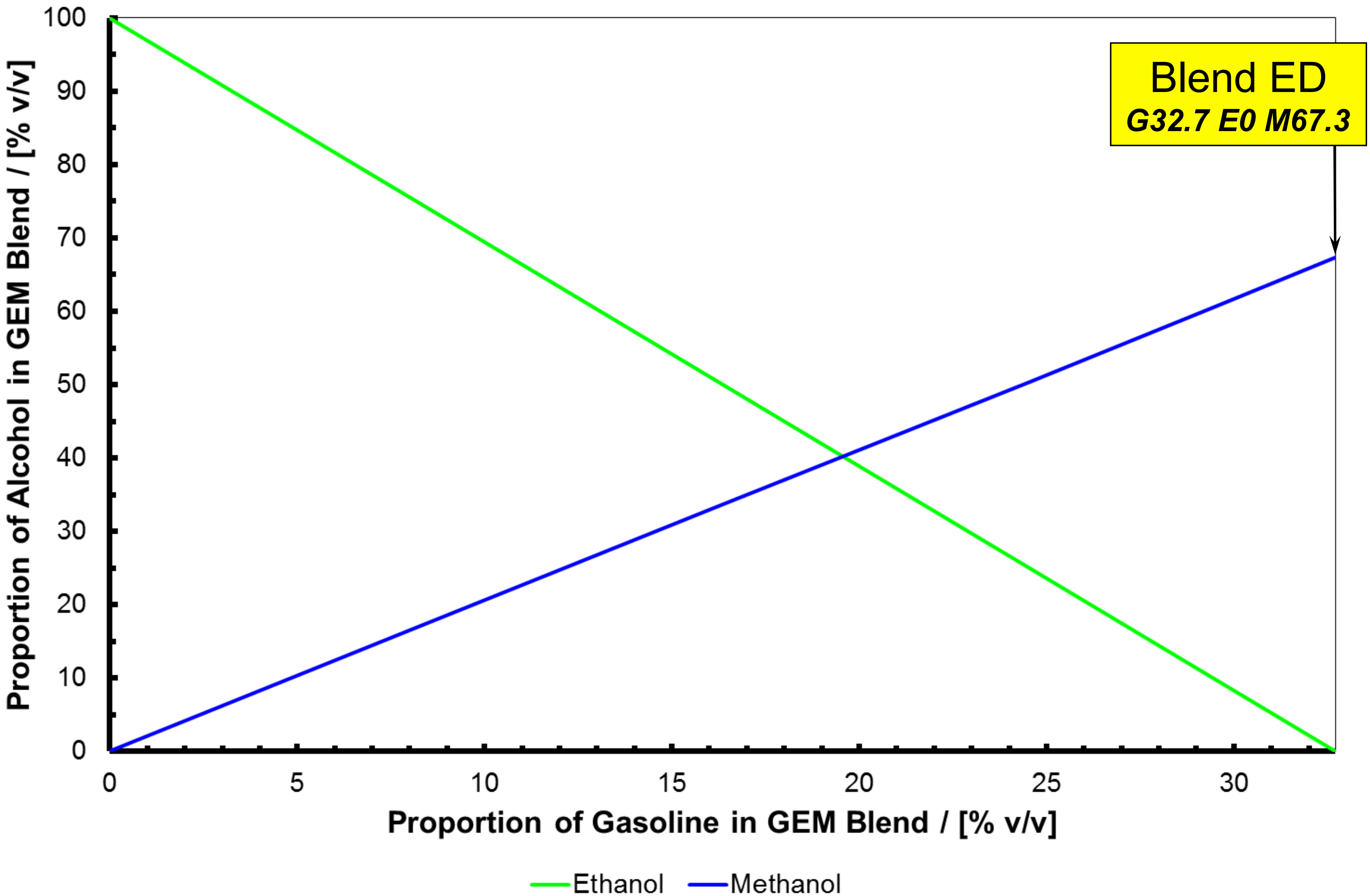


AN IDEA FOR DISPLACEMENT OF THE IGNITION ENHANCER IN ED95

GEM Blends Equivalent to Ethanol

- Iso-stoichiometric GEM blends equivalent to ethanol can be configured
  - *Actually, this is at the root of all of the calculations already discussed – 100% ethanol is equivalent to a gasoline:methanol mixture of 32.7:67.3 % v/v*
- One can therefore imagine replacing the ethanol in ED95 with GEM equivalents
  - *This could have an interesting potential effect on price: the higher autoignitivity of the gasoline (or diesel) component may allow the removal of some of the ignition enhancer (currently as expensive as ethanol, despite being only 5% of the mixture volume)*
- Some engine-based research would definitely be necessary
  - *The autoignivity may not be suitable*
  - *The flash boiling of the alcohol component in the diesel combustion system might cause particulate matter to rise too high*
  - *Nevertheless, this could be a worthwhile approach based on price*
- The blend relationship is shown on the next slide

GEM Blends Equivalent to Ethanol



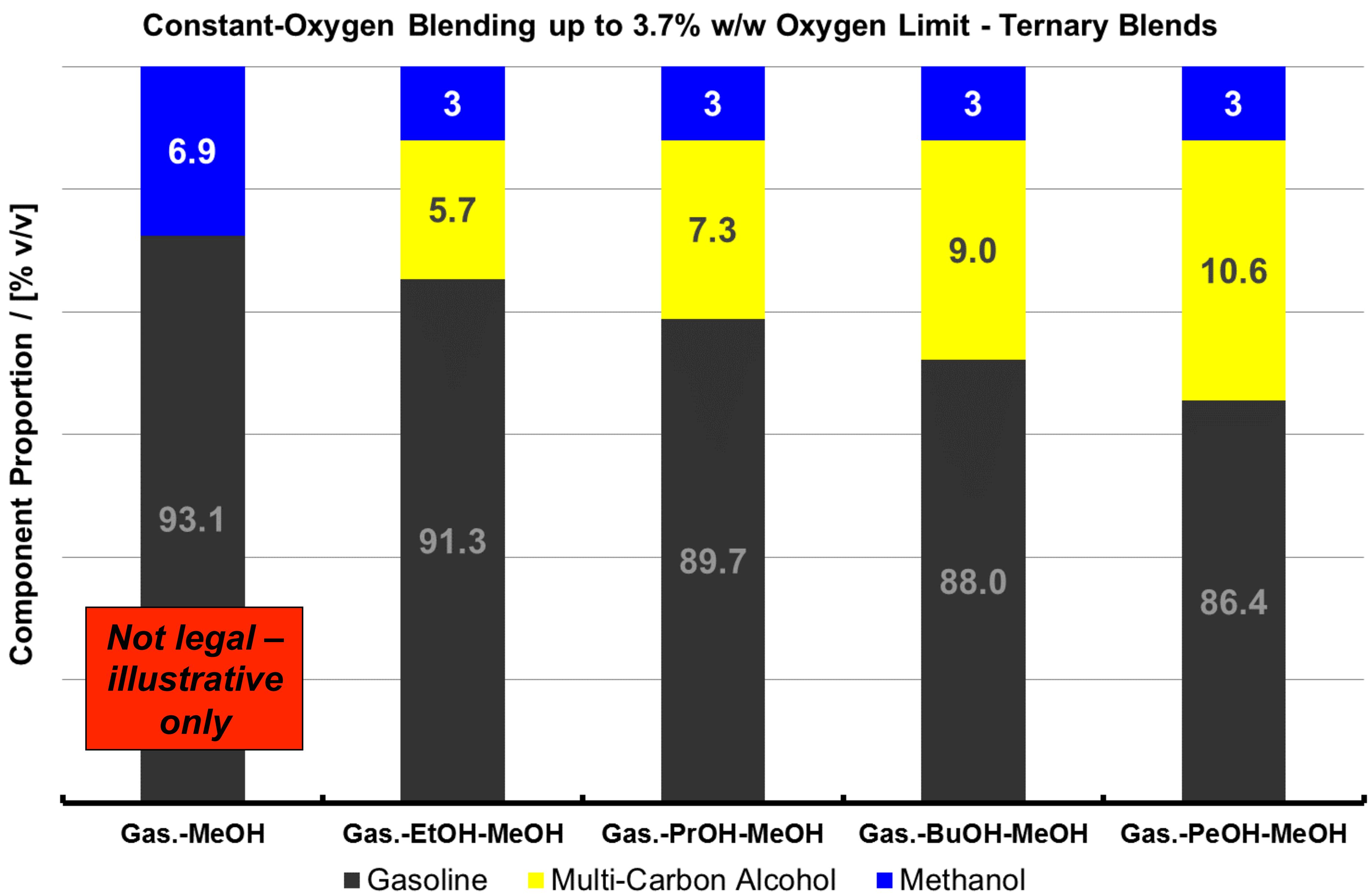
THE UNIVERSITY OF BATH
FUEL PROPERTIES CALCULATOR

The Bath Fuel Properties Calculator

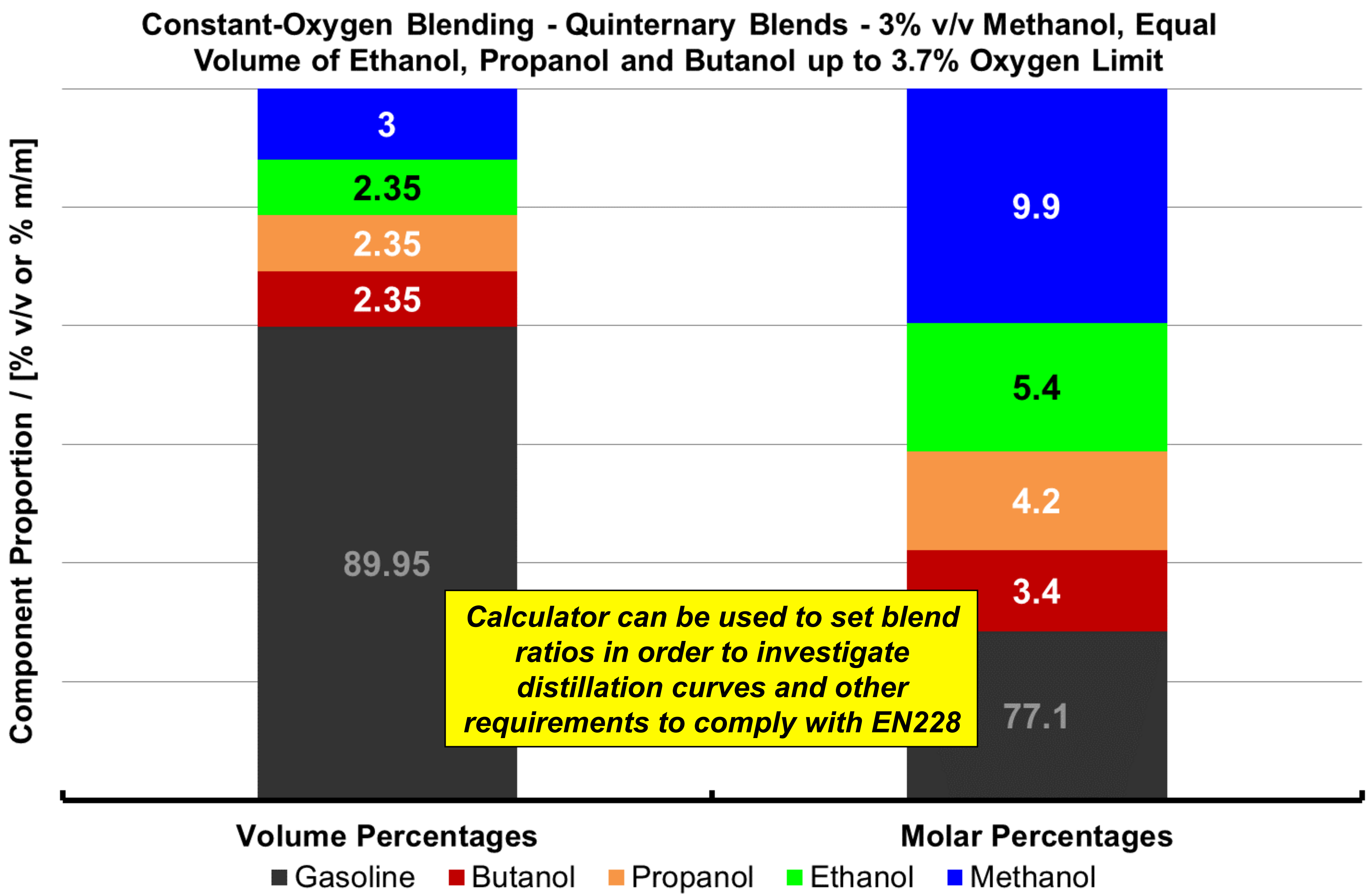
- An MSc student project has been run this year to create a University of Bath Fuel Properties Calculator
  - *With much acknowledgement to the student, Zeyuan Liu*
- The intention was to replicate and improve upon the Lotus Fuel Properties Calculator, used in the Lotus-published data to date
- This new calculator uses improved mathematical approaches, as outlined in a publication by the University *(see ref. [1] at end)*
- There is improved functionality over the original Lotus calculator:
  - *Has an increased number of alcohol types*
  - *Can now accommodate up to quinternary blends*
  - *Has some functionality for estimating laminar flame speeds with hydrocarbon-alcohol mixtures*
  - *Can accommodate user-inputted fuel properties*
  - *Can solve for constant gravimetric energy in blends directly*
  - *Can solve for constant oxygen mass in blends directly*
- Will be made available on the web and updated in a follow-on project

Liu, Z. and Turner, J.W.G., "University of Bath Fuel Properties Calculator"

The Bath Fuel Properties Calculator



The Bath Fuel Properties Calculator



Potential for an EN228-Compliant Blend

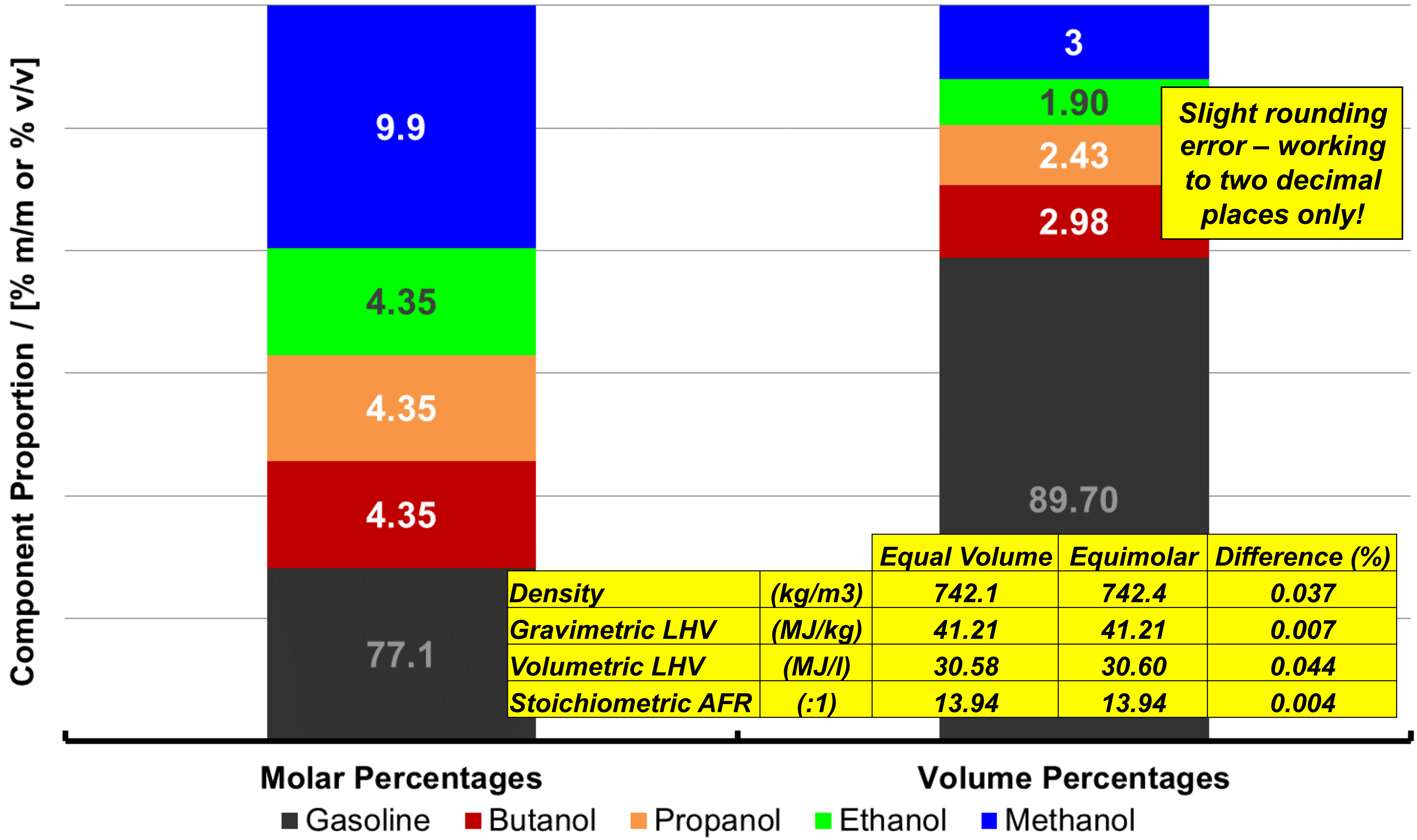
- A new initiative by University of Bath and GUTTS has been started to use the calculator as a first step in understanding how to create an EN228 E10-compliant blend
- The 'equal-volume' blend has been assessed using UNIFAC
  - *Assessment carried out by Othmar Popken at GUTTS using a Euro BOB*
- It seems entirely possible to configure a fully-legal blend
  - *The forced restriction of methanol to 3% will hopefully allow sufficient other heavier oxygenated species to be employed to counteract its effect on vapour pressure (to be assessed soon)*

	EN228 Specs ISO 3405		Baseline EN228	M-EN228 Preliminary Values
% Evaporated at 70°C ('E70')	% (V/V), min	**22%**	40%	**48,9%**
	% (V/V), max	**50%**		
% Evaporated at 100°C ('E100')	% (V/V), min	**46%**	52%	**67,4%**
	% (V/V), max	**72%**		
% Evaporated at 150°C ('E150')	% (V/V), min	**>75%**	85%	**91,6%**
Final Boiling point FBP	°C, max	**<210 °C**	125 °C	**174 °C**

- But there is further flexibility in the application…

The Bath Fuel Properties Calculator

Constant-Oxygen Blending - Quinternary Blends - 3% v/v Methanol, Equal Number of Moles of Ethanol, Propanol and Butanol up to 3.7% Oxygen Limit



		Equal Volume	Equimolar	Difference (%)
Density	*(kg/m3)*	*742.1*	*742.4*	*0.037*
Gravimetric LHV	*(MJ/kg)*	*41.21*	*41.21*	*0.007*
Volumetric LHV	*(MJ/l)*	*30.58*	*30.60*	*0.044*
Stoichiometric AFR	*(:1)*	*13.94*	*13.94*	*0.004*

CONCLUSIONS AND RECOMMENDATIONS

Conclusions and Recommendations (1)

- If one can find a way to bypass the biomass limit, alcohols are effectively ‘ruled in’ as a future transport energy vector
- GEM blends provide an evolutionary route to do this
  - *With existing technology and <u>under the current economic model</u>*
- Vehicle tests show that it is possible to produce GEM blends which are invisible to the control system of E85/gasoline flex-fuel vehicles
- Engine tests have shown that iso-stoichiometric blends all behave essentially identically and with similar efficiency
  - *In both DI and PFI in multi-cylinder engines*
  - *Single-cylinder engine tests (not reported here) have shown potential for significant efficiency increase, and spray morphology tests have also shown the same behaviour in DI engine combustion systems*
- The economics of ternary blends need to be investigated further
  - *They may be very attractive in terms of cost and LCA*
- It may be possible to make GEM blends cheaper than gasoline
- <u>In addition to further lab tests, a wider fleet trial is considered to be justified to begin adding real-world data</u>
  - *Best begun with a captive fleet?*

Conclusions and Recommendations (2)

- There is some opportunity to introduce methanol into existing ED95 buses
  - *Preliminary testing needs to be conducted*
- A new University of Bath Fuel Properties Calculator has been written and used to produce new blends at the EN228 oxygen limit
  - *Some example blends have been shown with the maximum methanol concentration and the other alcohols adjusted by different blending rules (e.g. equimolar or equal volume)*
- This tool can form the basis for an investigation into complying with EN228 with the maximum alcohol concentration
  - *It is recommended that this study be done as a next step*

Thank You for Listening

1. *Pearson, R.J., Turner, J.W.G., Bell, A., de Goede, S., Woolard, C. and Davy, M., "Iso-stoichiometric fuel blends: characterization of physicochemical properties for mixtures of gasoline, ethanol, methanol and water", Proc IMechE Part D: J Automobile Engineering 2015, Vol. 229(1) 111-139, doi: 10.1177/0954407014529424*

   http://pid.sagepub.com/content/229/1/111.full.pdf+html

2. *Liu, Z. and Turner, J.W.G., "University of Bath Fuel Properties Calculator"*