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Challenges in Fuel Efficiency and Emissions Measurements for Hydrogen Vehicles

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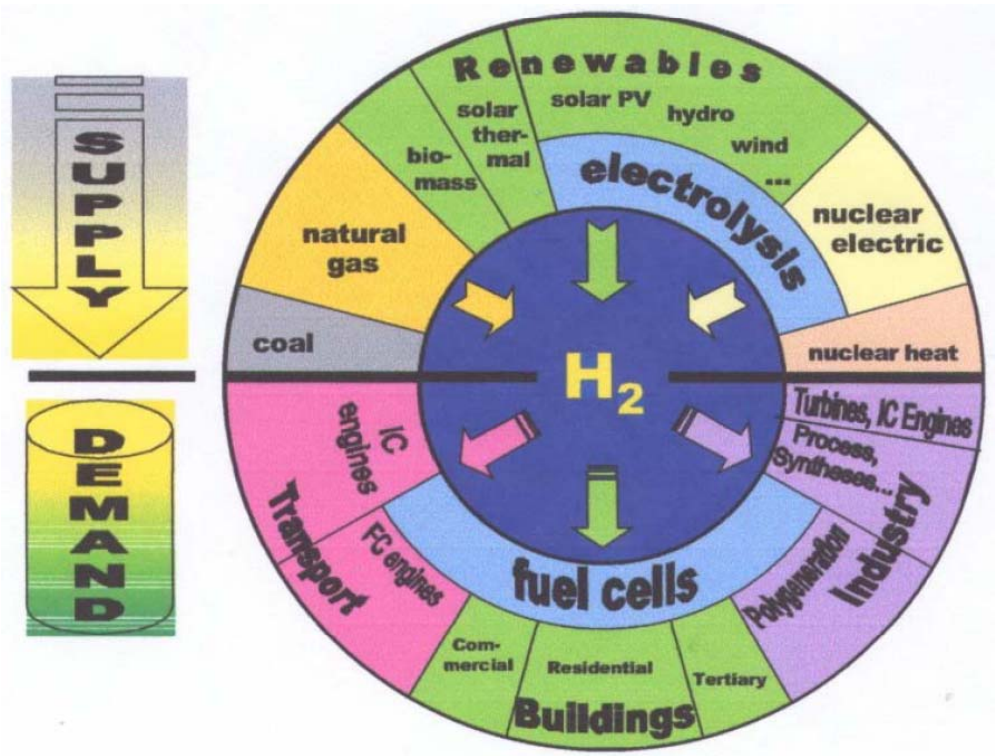
Outline

- Motivation for hydrogen combustion engine vehicle work
- Hydrogen as an engine fuel
- Comparison of test vehicles
- Experimental environment
  - Vehicle dynamometer
  - Safety equipment
  - Emissions equipment
- Results
  - Validation of fuel consumption measurements
  - Efficiency and emissions results
- Summary

President's Hydrogen Fuel Initiative
Why Hydrogen?



Source: APS Discussion Paper, March 2004

- H_2 can be produced from abundant domestic energy resources including fossil, nuclear, and renewable
- When burned in an engine, hydrogen produces effectively zero emissions; when powering a fuel cell, its only by-product is pure water
- Hydrogen engines can act as a bridging technology towards a wide-spread hydrogen infrastructure

Hydrogen as an engine fuel
Comparison of concepts

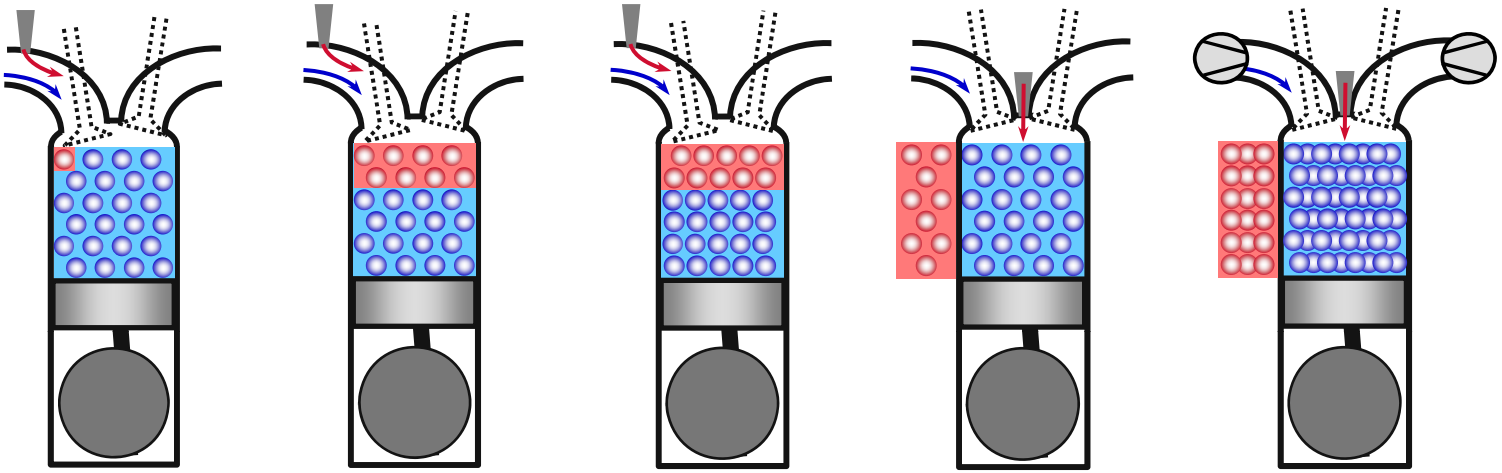
Conditions:

λ=1

η=const.

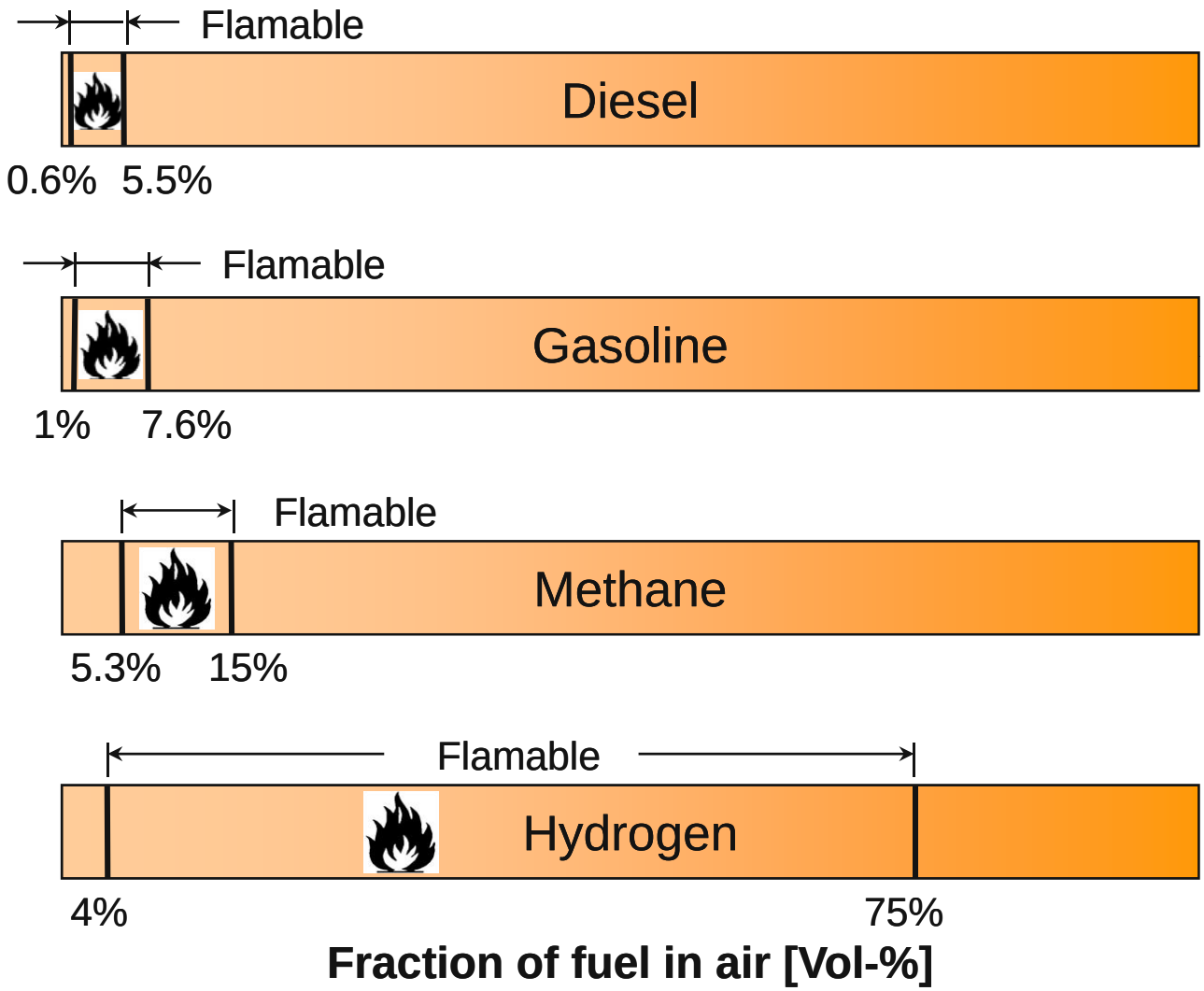
η_v=const.

T=const.



Fuel	Gasoline	Hydrogen	Hydrogen	Hydrogen	Hydrogen
Concept	Port injection	Port injection	Cryogenic Port injection	Direct injection	Supercharged Direct injection
Mixture calorific value [MJ/m³]	3.9	3.2	4.5	4.5	~7.8
Power output [%] (compared to gasoline)	**100**	**82**	**115**	**117**	**~200**

Hydrogen as an engine fuel
Properties of hydrogen



Program objectives
Durability of conversion vs. series development

Vehicle	eTec-Roush Hydrogen ICE Silverado Truck	BMW Hydrogen 7
Base vehicle	Chevrolet Silverado/ GMC Sierra	BMW 760Li
Hydrogen application by	eTec-Roush	BMW
Approach	Conversion	Series development
Number of vehicles	~10	~100
Argonne involvement	Semi-annual emissions testing	Benchmark testing
Program focus	Durability testing of conversion vehicle	Series development compliance

Comparison of test vehicles
Standard features

Vehicle	eTec-Roush Hydrogen ICE Silverado Truck	BMW Hydrogen 7
Seat positions	6	4
Engine	6.0 Liter V8	6.0 Liter V12
Transmission	4-speed automatic	6-speed automatic
Drive	2-wheel	2-wheel
Curb weight (est.)	2,858 kg (6,300 lb)	2,460 kg (5,420 lb)
Wheelbasis	3,886 mm (153 in)	3,124 mm (123 in)

Comparison of test vehicles
Vehicle modifications

Vehicle	eTec-Roush Hydrogen ICE Silverado Truck	BMW Hydrogen 7
On-board storage concept	Compressed Hydrogen	Liquid Hydrogen
Tank type	Type 3 – aluminum lined, carbon fiber reinforced	Vacuum isolated cryogenic tank
Number of tanks	3	1
Total volume	450 Liters	170 Liters
Maximum tank pressure	350 bar (5000 psi)	5.1 bar (74 psi)
Storage temperature	ambient	20K
Hydrogen storage capacity	10.5 kg (10.5 GGE)	8 kg (8 GGE)

Comparison of test vehicles
Vehicle modifications

Vehicle	eTec-Roush Hydrogen ICE Silverado Truck	BMW Hydrogen 7
Fuel nozzle	Standard 350 bar fueling nozzle (SAE J2600)	Generation II cryo nozzle
Fuel injection system	Gaseous port injection	Gaseous port injection
ECU modifications	Powertrain control system custom calibrated for H_2	Series development hydrogen vehicle
Engine configuration	Supercharged/intercooled	Naturally aspirated
Engine operation strategy	Lean burn	Lean burn/stoichiometric
Catalytic converter	None	3-way catalyst

Applicable emissions targets
Tier II Bin 5 versus SULEV

Vehicle	eTec-Roush Hydrogen ICE Silverado Truck	BMW Hydrogen 7
Emissions target	Tier II Bin 5	SULEV (NZEV)
Target set by	DOE	BMW
NMHC [g/mi]	0.09	0.01
NO_x [g/mi]	0.07	0.02
CO [g/mi]	4.2	1

Encountered challenges and mitigation measures

Vehicle	eTec-Roush Hydrogen ICE Silverado Truck	BMW Hydrogen 7
Properties of hydrogen	Integrated safety system/ sensors/ventilation	Integrated safety system/ sensors/ventilation
On-board storage/leakage	Ventilation	Ventilation/deer antlers
Vehicle fuel system	External gaseous hydrogen supply	Closed liquid/gaseous fuel system
Fuel consumption measurement	Coriolis meter & water balance	Water balance
Emissions measurement	Standard	Account for water cross sensitivity/water diffusion

Experimental environment
Vehicle dynamometer

- 2 x 48” rolls
- Variable wheel-base
- 250 HP each
- Gas warning system with hydrogen sensors in test cell and soak room
- Air exchange rate in purge mode more than 1 complete exchange/min
- Hydrogen rated with outdoor gaseous hydrogen supply

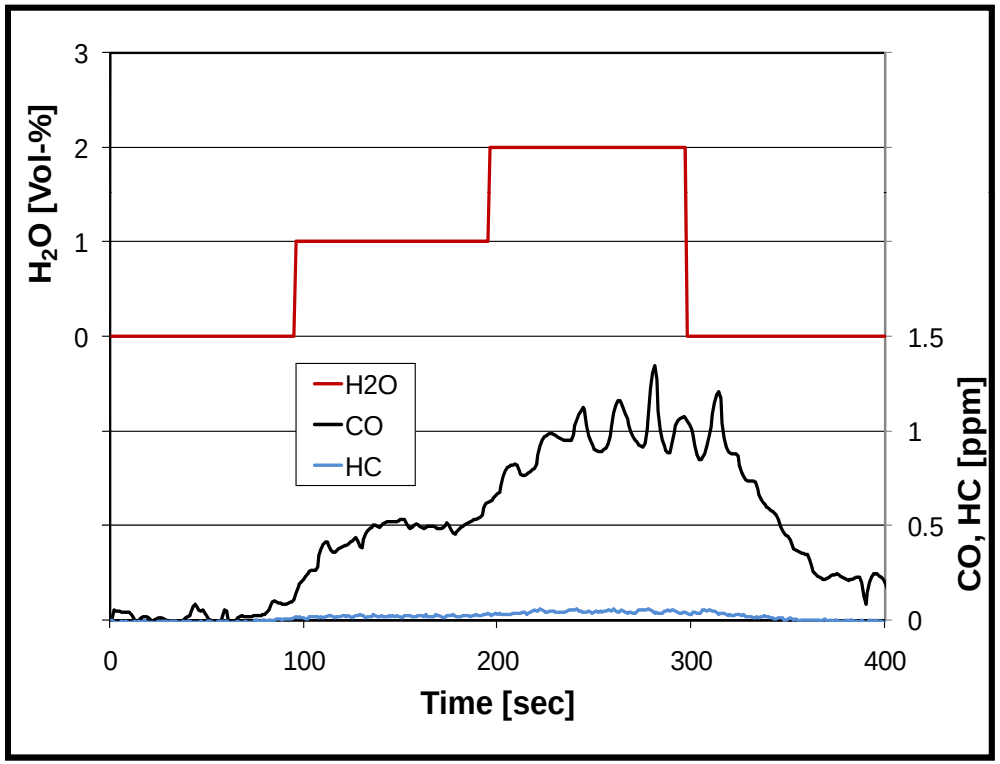
Experimental environment
Safety precautions

- Hydrogen purge lines (deer antlers) for emergency release of hydrogen in case of vacuum failure (due to lack of long-term experience with tanks)
- Detailed vehicle operating and handling instructions including
  - Tank pressure check
  - BMS (Boil-off management system check)

Experimental environment
Emissions equipment

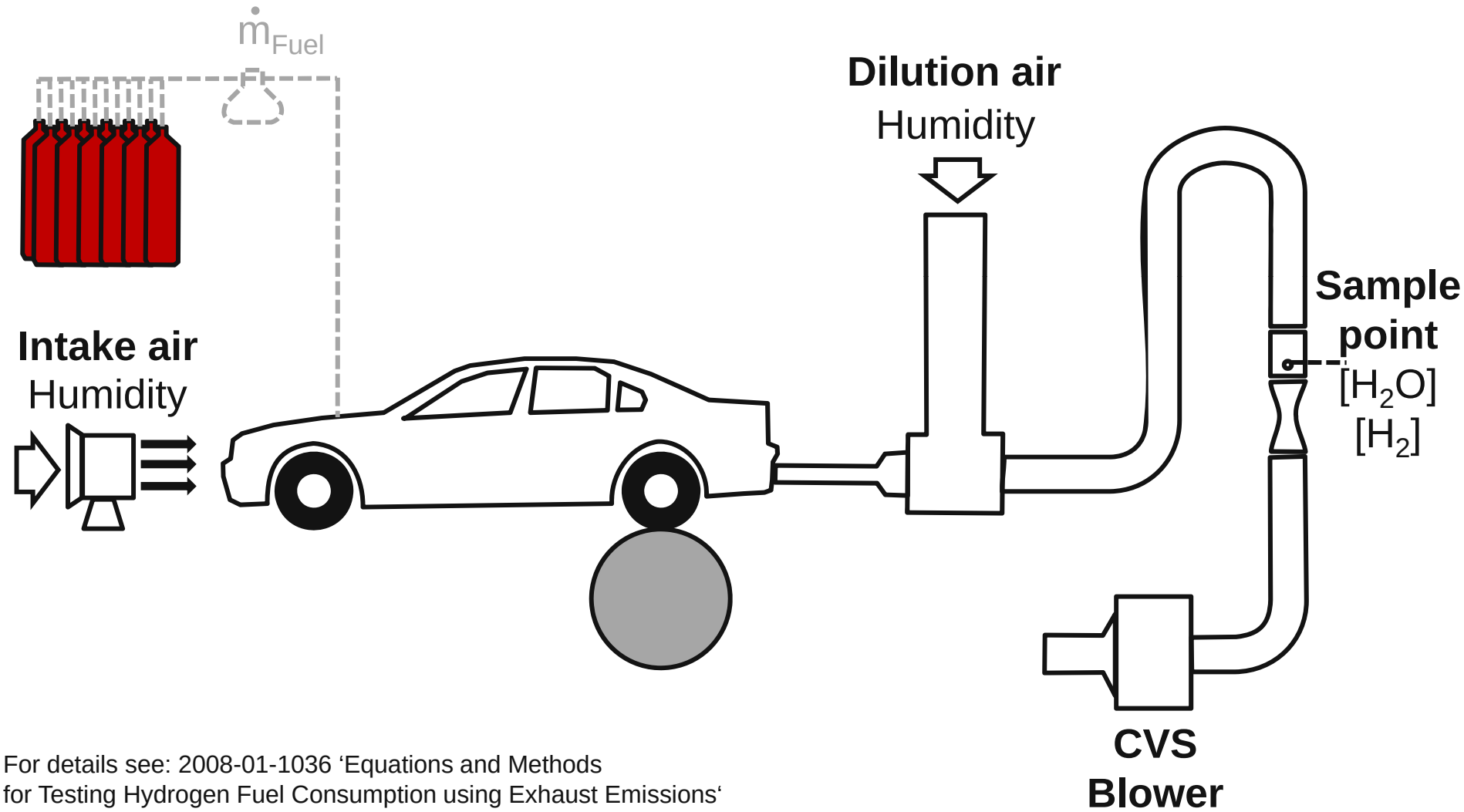
- Full dilution CVS
- AMA 4000 emissions bench
- Hydrogen analyzer (unburned fuel)
- Water analyzer

Experimental environment
Challenges of increased humidity



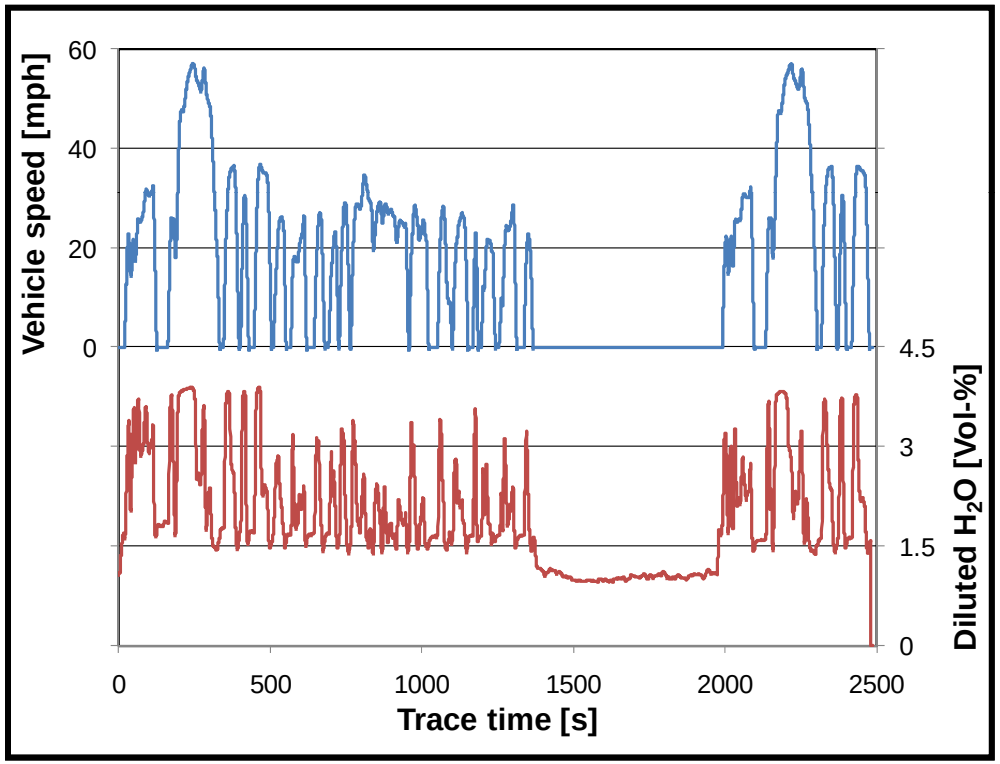
- Analyzers cross-sensitive to water
- Water correction required
  - CO_2
  - CO
- Diffusion of water through sample bags
  - Modal sample measurement
  - Ambient bags are bag-in-bag

Fuel consumption measurement
Approach



For details see: 2008-01-1036 'Equations and Methods for Testing Hydrogen Fuel Consumption using Exhaust Emissions'

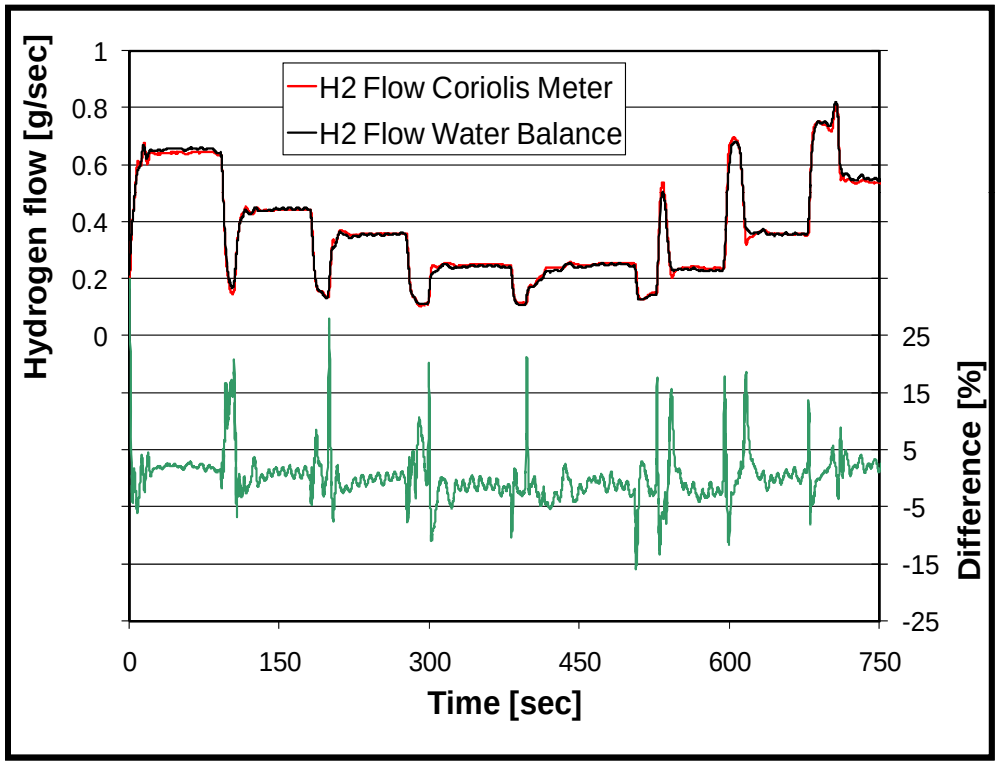
Experimental environment
Limitations



- Condensation in exhaust lines
  - Heated lines
- Range of water analyzer (5 Vol-%)
  - High dilution rates
- Dilution and ambient air humidity
  - Correction for ambient humidity
  - Measurement of dilution air humidity

For details see: 2008-01-1037 'Possible Influences on Fuel Consumption Calculations while using the Hydrogen-Balance Method'

Fuel consumption measurement
Validation



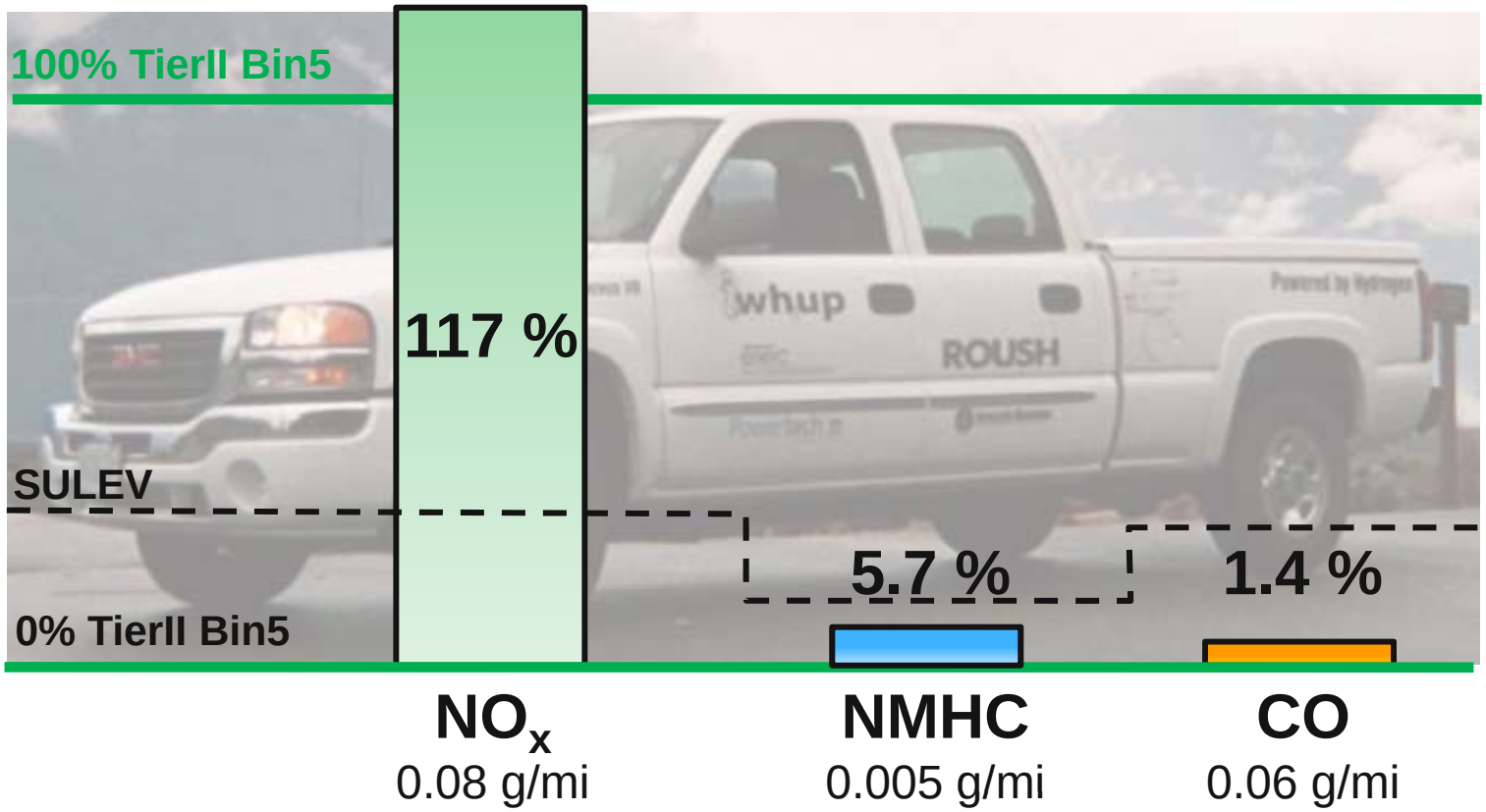
- Good correlation between coriolis meter and water balance for steady states at relevant flow rates
  - Deviation less than ±2%
  - Good dynamic reaction
- Difference in total fuel consumption on Japan 1015 cycle: > 2%

Comparison of Test Vehicles
*Fuel Economy**

Vehicle	eTec-Roush Hydrogen ICE Silverado Truck	BMW Hydrogen 7
FTP-75 [kg/100km]	4.6	3.7
FTP-75 [miles/GGE]	14	17
Highway [kg/100km]	3.1	2.1
Highway [miles/GGE]	20	30

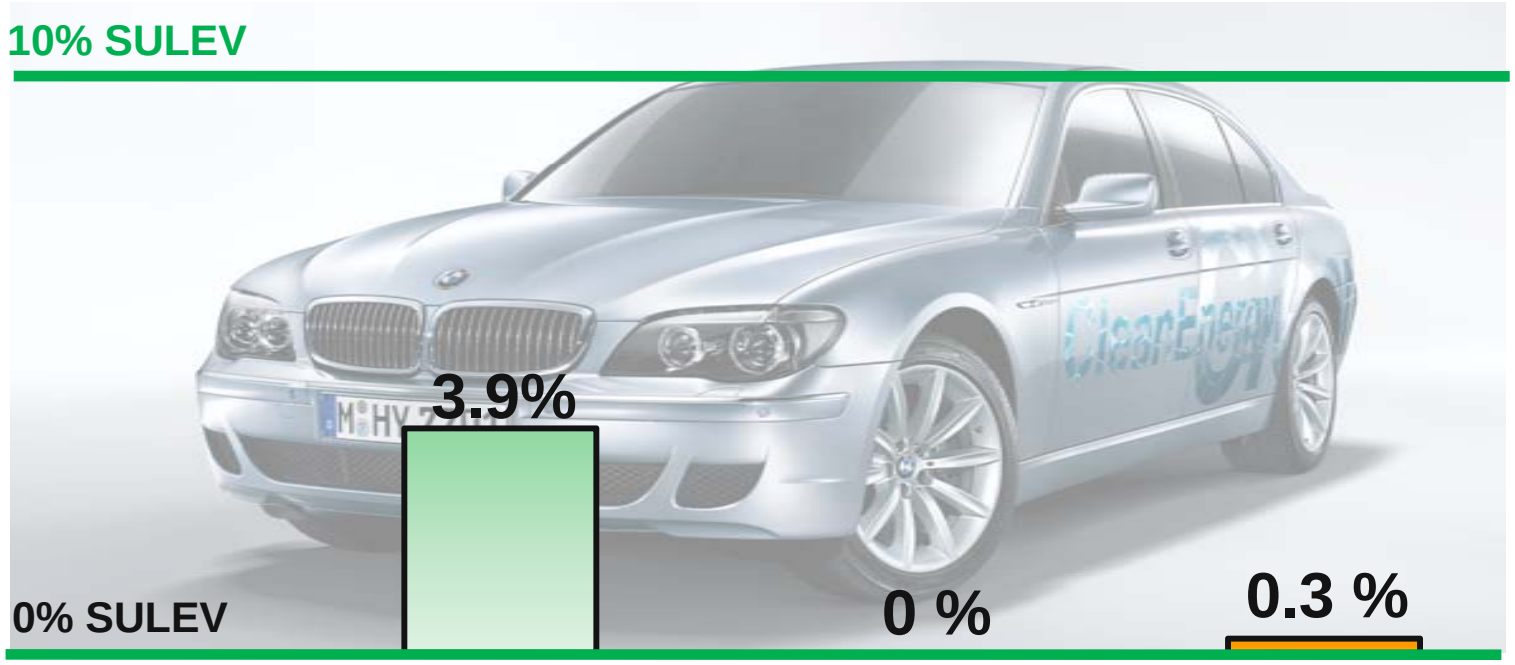
* Average values for several tests on two vehicles

*Emissions results**
eTec / Roush H_2 Silverado



* Average values for several FTP75 tests on two vehicles

*Emissions results**
BMW Hydrogen 7



NO_x	NMHC	CO
0.0008 g/mi	0 g/mi	0.003 g/mi

* Average values for several FTP75 tests on two vehicles

Conclusions

- Hydrogen shows very advantages properties for combustion engine application
- High water contents and low levels of emissions require additional measures that ensure accurate measurement of fuel consumption and emissions
- Water balance for fuel consumption measurement shows excellent correlation with direct consumption measurement
- Hydrogen combustion engine vehicles are capable of operating at emissions levels that are only a fraction of the most stringent emissions regulations