THE ULTIMATE POWERSPORTS EXPERIENCE

BRP-Rotax GmbH & Co KG

Potential of Different Injection Systems for High Performance Two-Stroke Engines

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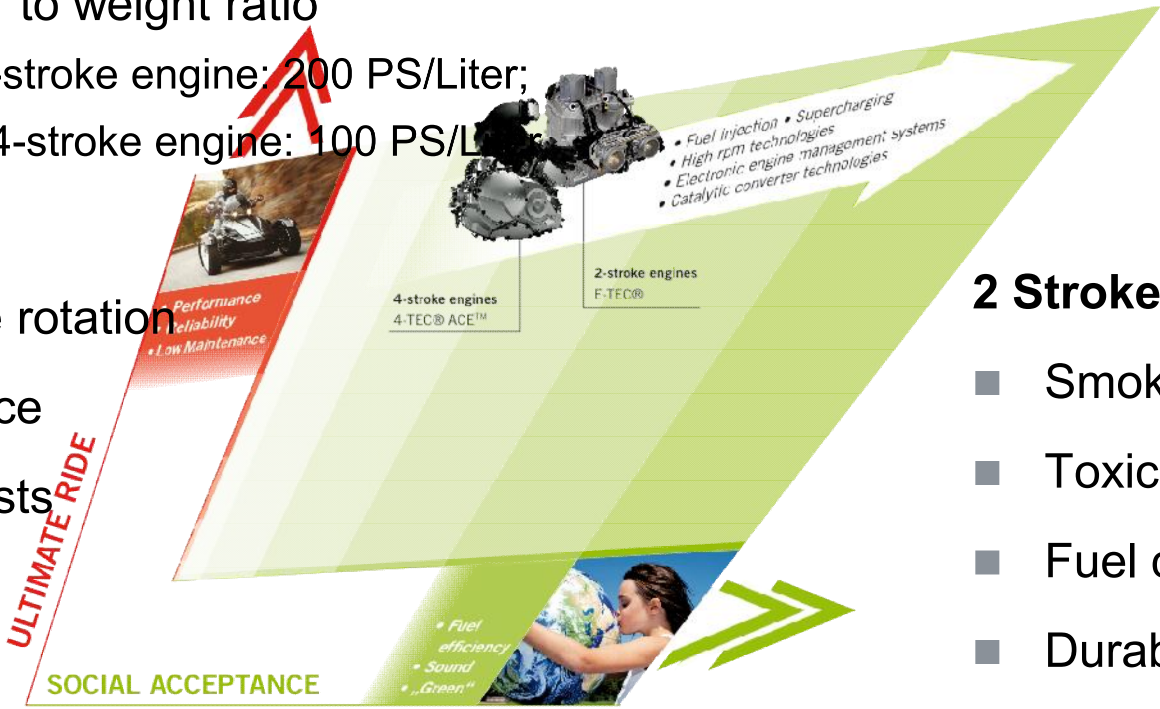
Content

1. **Motivation**
2. Injection System Descriptions
3. WMTC Steady State comparison
4. WMTC Chassis Roll comparison
5. Summary & Conclusions

Motivation : 2 stroke Powersports

2 Stroke Benefits

- Excellent power to weight ratio
  - 800 cc BRP 2-stroke engine: 200 PS/Liter;
  - 1000 cc BRP 4-stroke engine: 100 PS/Liter
- Small package
- Reverse engine rotation
- Low Maintenance
- Low System costs



2 Stroke Challenges

- Smoke / Smell
- Toxic Emissions
- Fuel consumption
- Durability

Motivation : 2 stroke Motorcycle Application

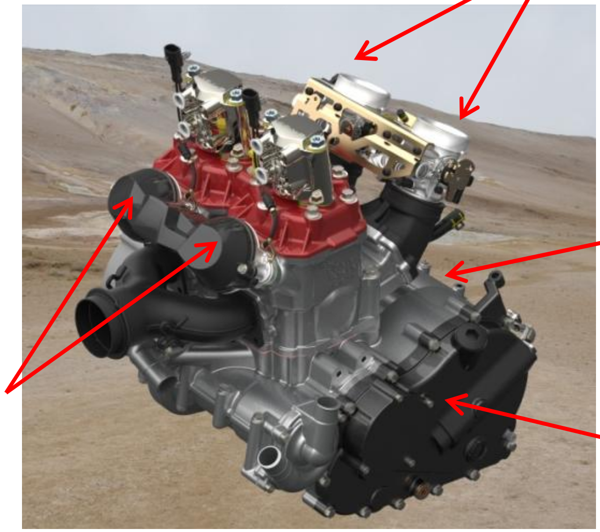
How does the latest Two-Stroke DI technology perform in a motorcycle application ?

Is there a future for large capacity 2stroke motorcycles after EUIV / V ?

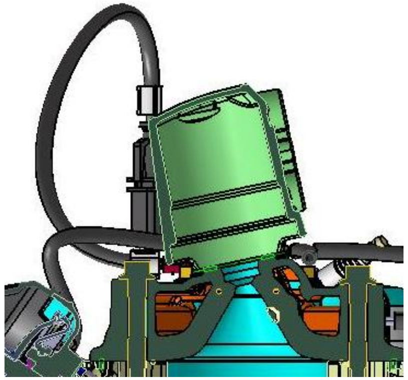
Content

System Descriptions – Base engine

- 593 cm³ two-stroke In Line two-cylinder
- Rated power 78 kW @ 8200 1/min
- Bore 72 mm / Stroke 73 mm

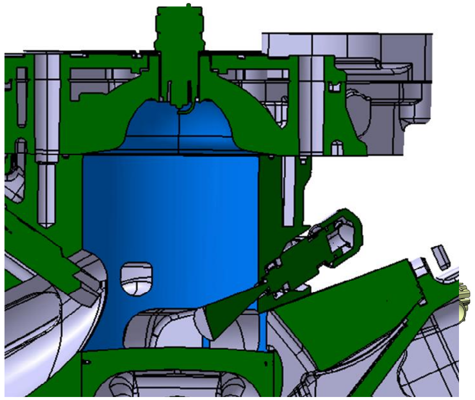


System Descriptions – ETEC & LPDI



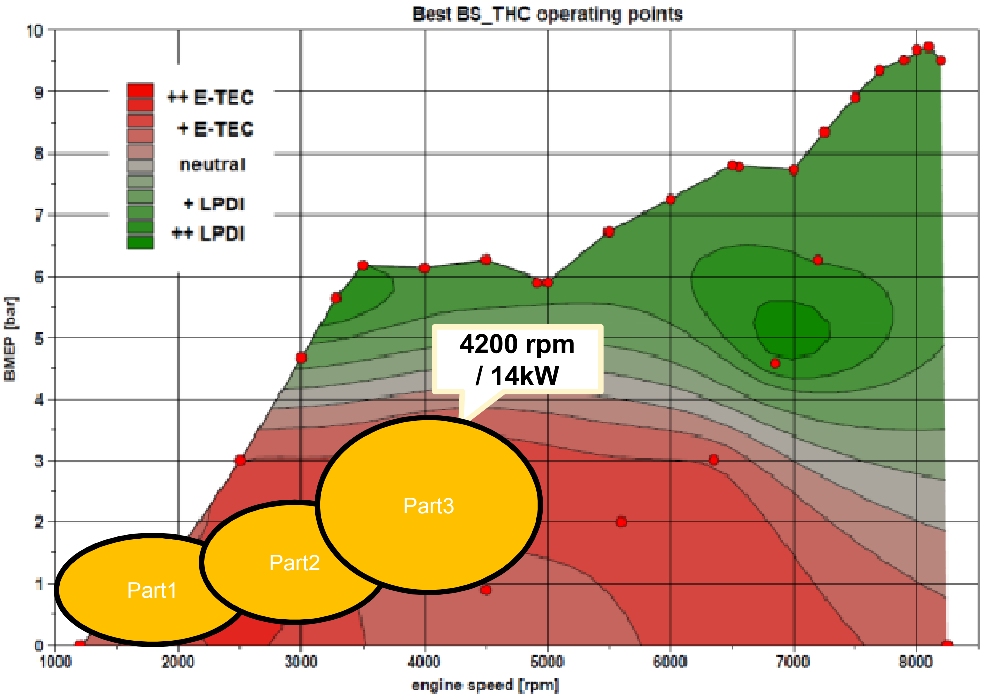
- Medium pressure direct injection 25-40 bar
- Injector location in centre of cylinder head
- Injection direct onto spark plug
- Pre pressure pump 2,5 bar
- Voltage supply for DI injector is 55 V
- Batteryless start to -30° C
- In production Evinrude Outboard since 2003
- In production in Skidoo since 2009
- Over 500,000 ETEC engines produced to date

- Low pressure direct injection 5 bar
- Injector location in cylinder wall, downwards towards cylinder center
- 2 standard 5 bar PFI injectors per cylinder
- In part load, injection alternates between the two injectors
- Modified E-TEC cylinder used for injection holes

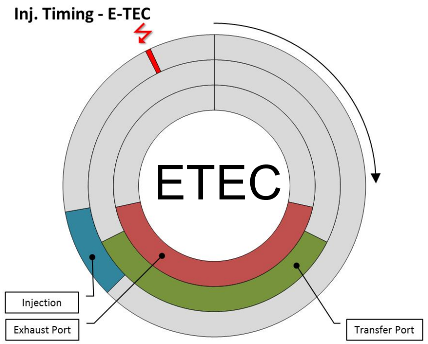


System Description : Overview of HC emissions performance

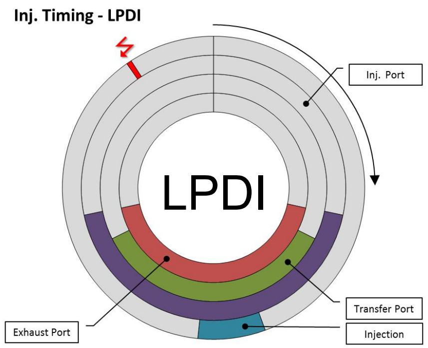
- A previous dynamometer study to compare the two injection systems steady state, showed the ETEC system to have benefits in low load & rpm conditions; whilst LPDI showed lower emissions at higher load & rpms.
- The key operating range of the engine during WMTC can be seen .
- Based on this it would be expected that ETEC would be beneficial in this 600cc motorcycle application
- The reason for the ETEC benefit can be seen by reference to the following 3D cfd investigation at the highlighted rpm / load point. The cfd calculation was carried out using the optimum calibration parameters determined from testing



System Descriptions : Selected Result @ 4200 rpm / 14kW

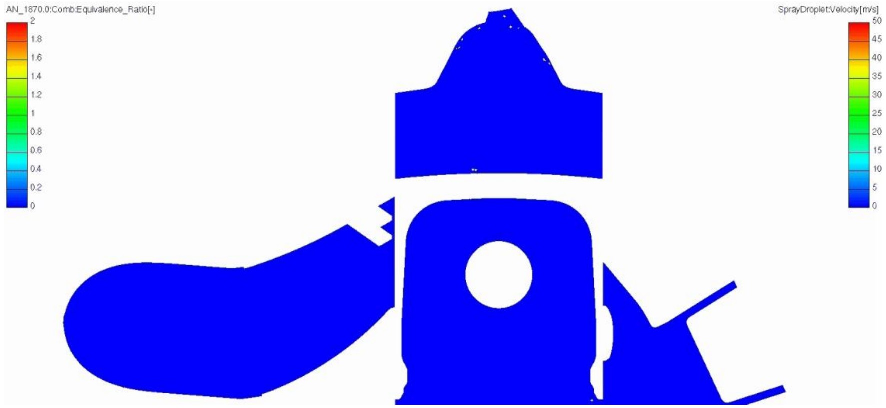


- Since injection begins shortly before the exhaust port closes there should be no loss of unburned fuel during scavenging
- A later injection would be possible, however this timing gave the best trade off between unburned fuel loss during scavenging and maximising residence time (mixture preparation).
- Dynamometer testing showed this calibration to be the best for HC emissions



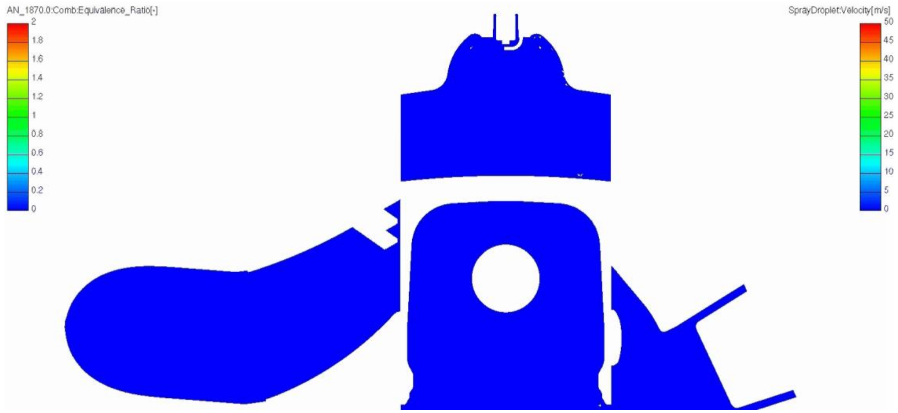
- An earlier injection compared to ETEC is required since mixture preparation is strongly influenced by flow through the transfer port
- This early injection leads to some loss of unburned fuel at the beginning and end of the injection event
- Start of Injection timing for LPDI typically does not vary significantly with rpm and load

E-TEC

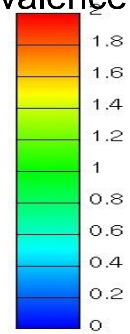


4200 rpm / 14 kW

LPDI



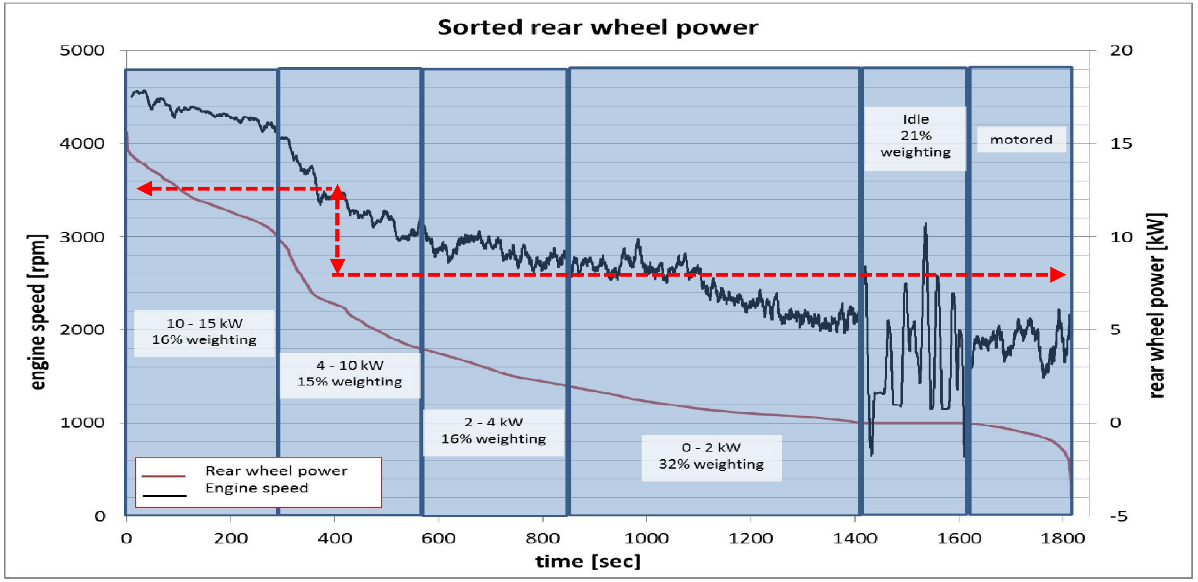
Equivalence Ratio



Content

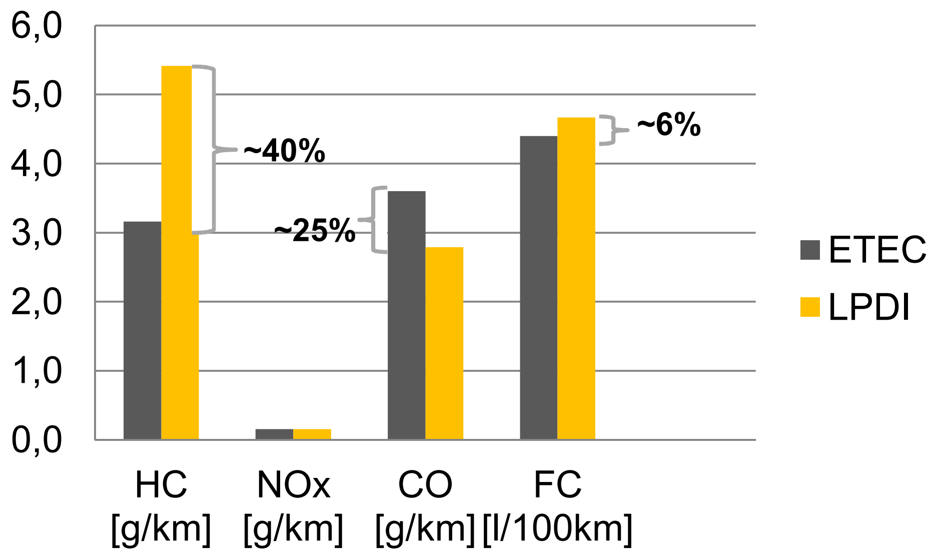
WMTC Steady State comparison

- Before WMTC testing took place, it was investigated whether Steady State points, looking at Raw Emissions, could offer a good estimate of the engine performance in vehicle
- Taking a histogram from WMTC rolls test, 5 Steady State test points were defined (and weighted) based on cumulative time at load.
  - 5 Chosen points :
  - 1200 rpm / 0 kW
  - 2500 rpm / 2,4kW
  - 2900 rpm/ 3,6kW
  - 3500 rpm / 7,5kW
  - 4200 rpm / 14kW



WMTC Steady State comparison – Raw Emissions

- Comparing Raw Emissions results for the 5 Steady State points :
  - HC - ETEC showed approx 40% reduction
  - NOx – similar results for ETEC & LPDI
  - CO – LPDI showed approx 25% reduction
  - FC – ETEC approx 6% better than LPDI
- The generally lower CO with LPDI is due to a more homogeneous mixture (injection timing and position)
- On the basis of these results with extremely low NOx levels; the decision was taken to apply oxidation only catalysts to the vehicle



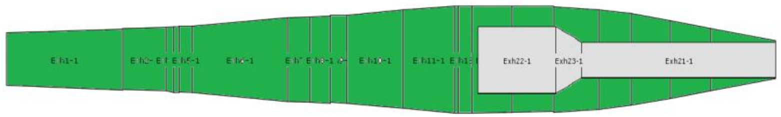
Content

WMTC Chassis Roll Comparison : Motorcycle Specification

Vehicle Setup:
Frame: BMW F800 GS
Engine: 593 with E-TEC injection
Gearbox: BMW F800 in prototype housing
Exhaust: 593 modified with pre- and main catalyst.

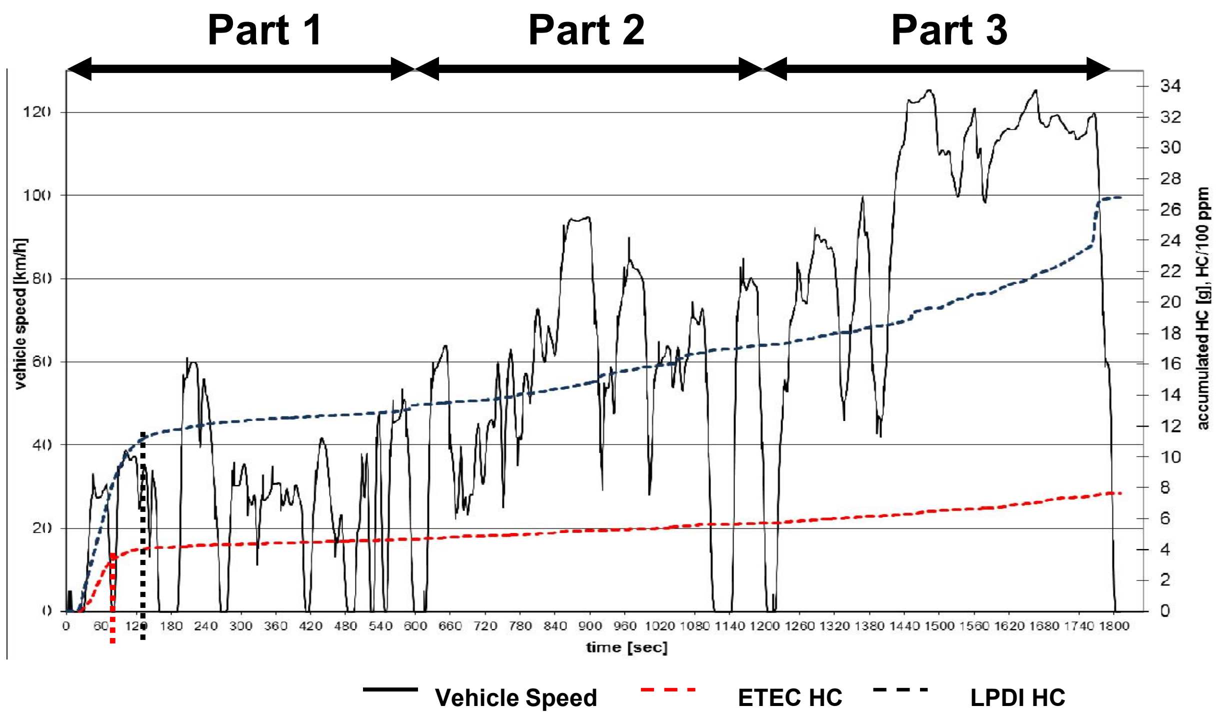
Pre cat:
- 2 x ∅60 x 40 100cpsi Pd/Rh:15/1

Main cat:
- ∅90 x 120 400cpsi Pd/Rh:15/1



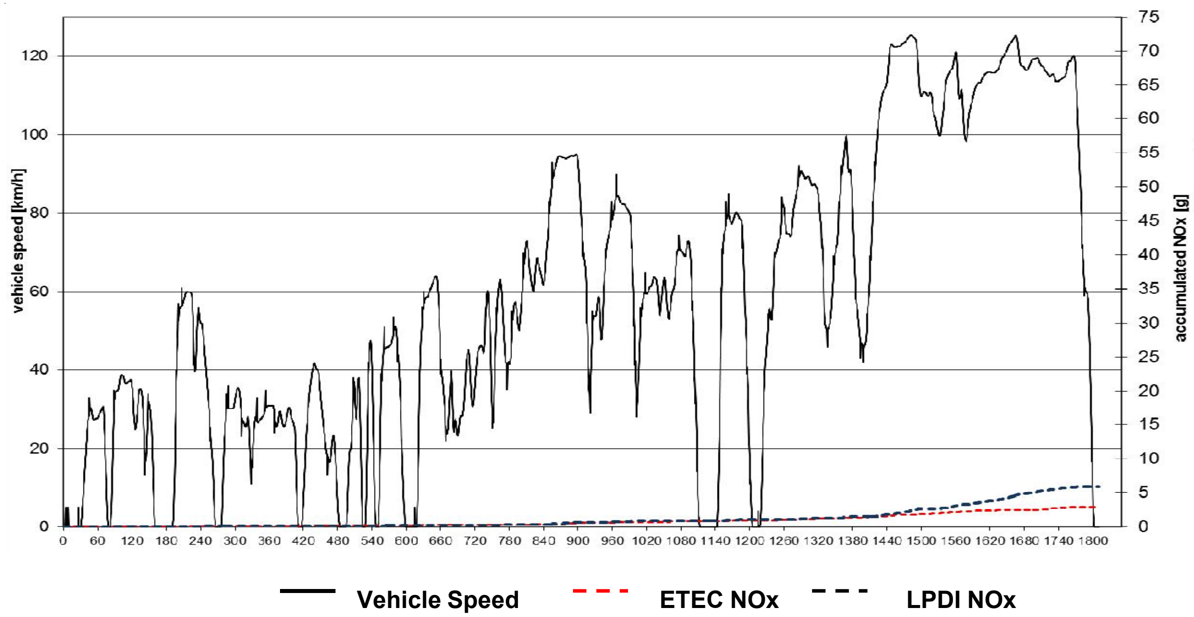
WMTC Chassis Roll Comparison : Results – Cumulative HC

- **Catalyst Light Off**
  - ETEC ~90 seconds
  - LPDI ~120 seconds
- Faster light Off with ETEC is achieved by using late injection timing in combination with late ignition
- Prior to light off ETEC produces approx 70% lower HC emissions compared to LPDI
  - This is a combination of lower ppm and reduced light off time
- After light off , HC accumulation is higher for LPDI than ETEC
  - This is due to higher fuel scavenge losses as seen in the cfd



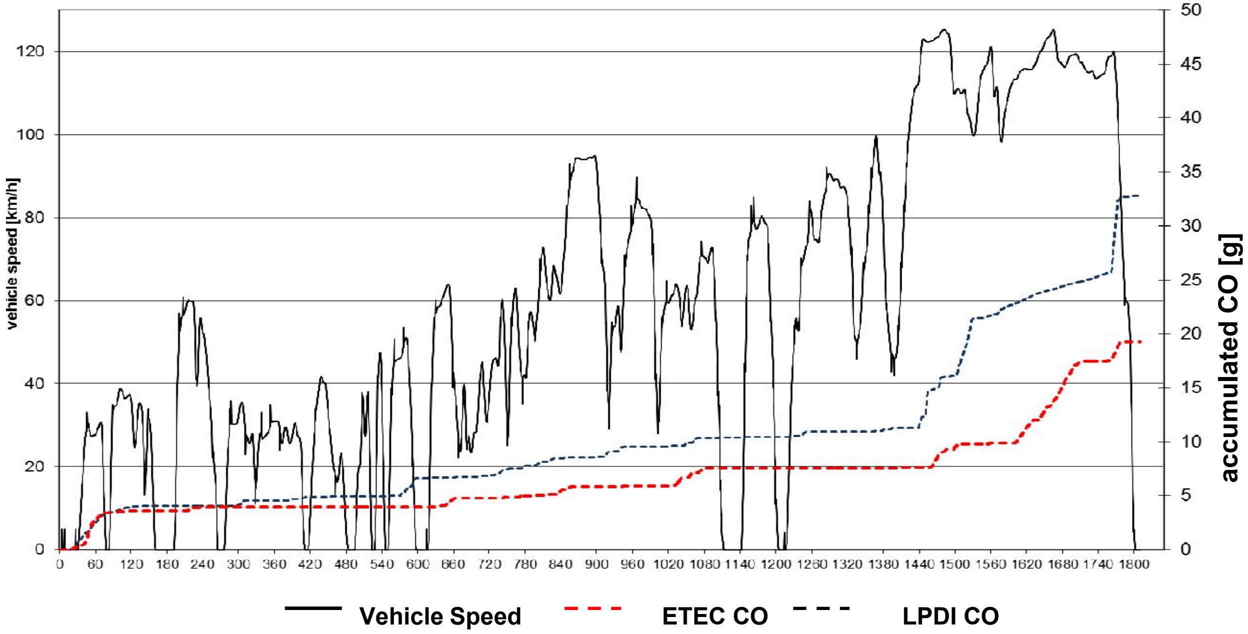
WMTC Chassis Roll Comparison : Results – Cumulative NOx

- Due to an oxidation only catalyst the tailpipe results are effectively raw emissons
- The trend is therefore as predicted by the Steady State points
  - Similar levels between ETEC and LPDI
  - Extremely low NOx during Part1 & Part2
  - Increasing NOx accumulation during higher loaded Part3
- The higher NOx levels with LPDI in Part3 are due to a leaner calibration compared to ETEC



WMTC Chassis Roll Comparison : Results – Cumulative CO

- **Catalyst Light Off**
  - No noticeable difference in light off time between ETEC and LPDI
  - Light Off at ~80 seconds
- After light off CO accumulation slightly higher for LPDI than ETEC
  - due to higher breakthrough during transients
- The generally lower CO levels expected for LPDI, from Steady State points, is offset by an immature transient calibration



WMTC Chassis Roll Comparison : Final Bag results – ETEC v LPDI

ETEC

WMTC Total Result

Measurement: E020

Emission		Limits EU 4
	CO [g/km]:	1,14
	HC [g/km]:	0,17
	NOx [g/km]:	0,09

Emission PART 1 cold			Weighting
	CO [g/km]	0,722	25
	HC [g/km]	0,836	
	NOx [g/km]	0,080	
	CO_2 [g/km]	159,910	

Emission PART 2 hot			
	CO [g/km]	0,638	50
	HC [g/km]	0,084	
	NOx [g/km]	0,081	
	CO_2 [g/km]	100,323	

Emission PART 3 hot			
	CO [g/km]	1,109	25
	HC [g/km]	0,113	
	NOx [g/km]	0,115	
	CO_2 [g/km]	112,893	

	Total Emission	% from limit
CO [g/km]	0,7770	68,16
HC [g/km]	0,2790	164,11
NOx [g/km]	0,0891	98,98
CO2 [g/km]	130,12	NO

F.C. km/l	
C.B. km/l	24,2

LPDI

Measurement: L015

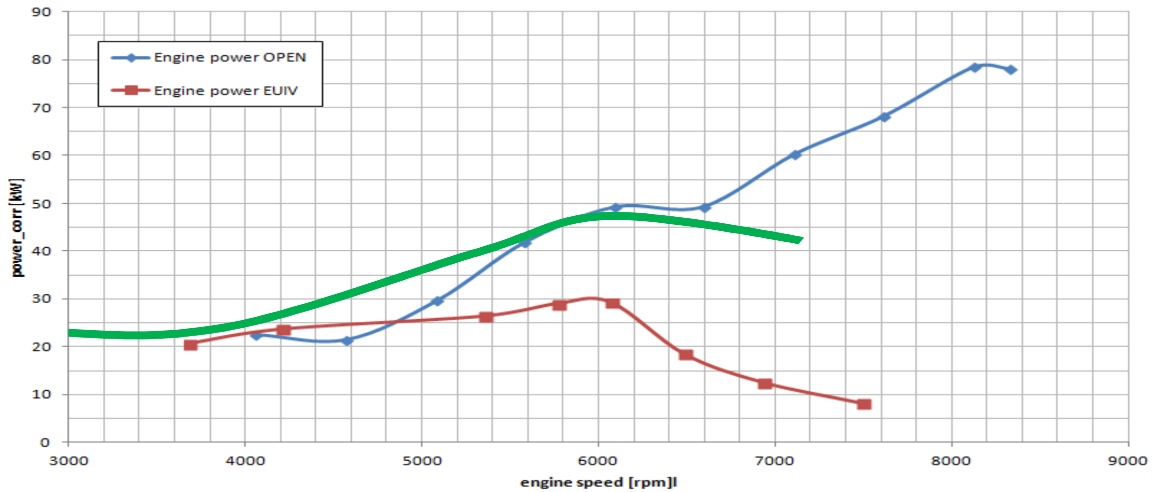
	Total Emission	% from limit
CO [g/km]	1,1464	100,56
HC [g/km]	1,1649	685,26
NOx [g/km]	0,1327	147,45
CO2 [g/km]	126,67	NO

F.C. km/l	
C.B. km/l	19,6

- ETEC : Final bag results showed NOx and CO within EUIV limits and HC still ~60% above (no DFs included)
- LPDI : NOx and CO above limits but calibration maturity (especially transient) should improve this. HC over 6 times above limits

WMTC Chassis Roll Comparison : Performance at EUIV

- Max power reduced from 78kW to 30kW due to aftertreatment
- Expansion chamber and ports no longer tuned for peak power at 6000 rpm
- By tuning for lower rpm it would be expected to win back some of the lost performance without further increasing emissions
- Realistic goal would be 45kW to 50kW (100 PS/l to 112 PS/l)



Content

Summary & Conclusions

How does current PowersportsTwo-Stroke DI technology perform in a motorcycle application ?

- The ETEC system currently in production in Snowmobile and Outboard engines, offers significant benefits in reduced raw emissions compared to alternative indirect and direct injection systems.
- These application as yet require no additional exhaust aftertreatment to meet their legislated emissions targets.
- For motorcycle applications, at EUIV and beyond, the impact of the aftertreatment system becomes increasingly significant.
- In this investigation 50% of final bag HC emissions (and almost 100% of legislated target) was released prior to catalyst light off. Light off time and cold start HC must be reduced.
- Late injection (using ETEC) to reduce catalyst light off time, coupled with retarded spark can be a significant advantage that requires further development.
- For a large capacity motorcycle, where a significant part of the WMTC cycle is at very low loads, ETEC's ability to inject fuel late to reduce unburned fuel scavenge losses brings advantages.

Summary & Conclusions

Is there a future for large capacity 2stroke motorcycles after EUIV / V ?

- With further optimization of hardware and calibration it is felt that EUIV emissions could be achieved using ETEC and current two stroke technology in this motorcycle application
  - A significant reduction in peak performance is to be expected compared to current applications (from 200PS/liter to 100PS / liter)
- Reduction in emissions limits from EUIV to EUV
  - HC : -41% NOx : -33% CO : -12%
  - HC is major challenge
  - Possible to use oxidation only catalyst but a low NOx strategy must be developed for Part3 of the cycle
- The application of Direct Injection technology alone is not enough for emissions limits after EUIV, additional technologies will be required
  - Reducing the sensitivity of exhaust tuning on performance
  - Improving catalyst light off time / HC trap
  - Reducing raw HC emissions at cold start and generally during the drive cycle
- Particulates and higher DFs must also be considered at EUV
- Further technologies are in development at BRP Rotax & IVT to address these challenges.

Thank you for your attention

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