Slide 1

Light Duty Diesel Engine Technology to Meet Future Emissions & Performance Requirements of the US Market

10th Diesel Engine Emissions Reduction (DEER) Conference

29th August – 2nd September 2004

Coronado, California

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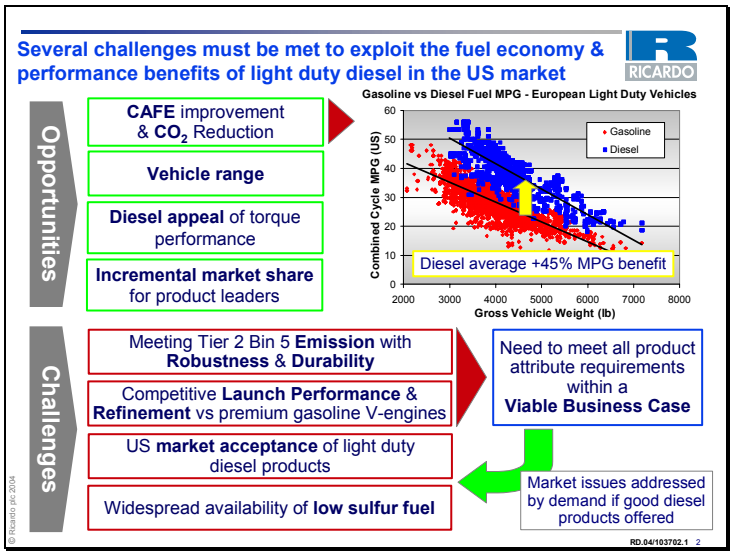
Slide 2



The success of diesels in Europe is well known, and with the huge progress made in light duty diesel technology over recent years, there are now real opportunities for light duty diesel in the US market.

Average diesel fuel economy benefit over gasoline in European light vehicle market is approximately 45% as shown by the upper right plot.

The improved performance of diesel products has been a major driver for growth of diesel sales in the European market, and diesels can now compete and surpass gasoline on performance attributes, as well as offering fuel economy and vehicle range benefits.

But there are some significant challenges to be overcome:

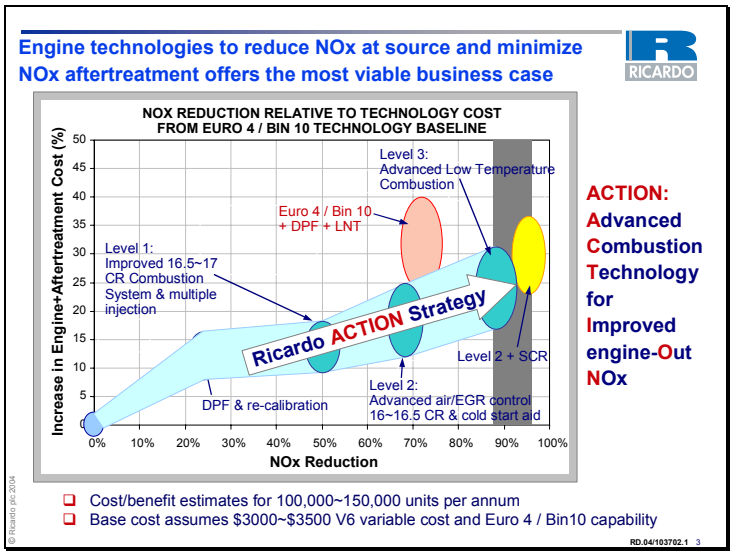
NOx emission reduction for Tier 2 Bin 5 is the most significant technical issue, and in particular, achieving Bin 5 with production robustness and durability.

Launch performance is a more significant issue for the US than Europe. Consumer expectations in the US are based on large gasoline V engines.

Emissions, performance, refinement and fuel economy attribute targets for competitive US light duty diesel product can be met, but the biggest challenge is now delivering these within a viable business case.

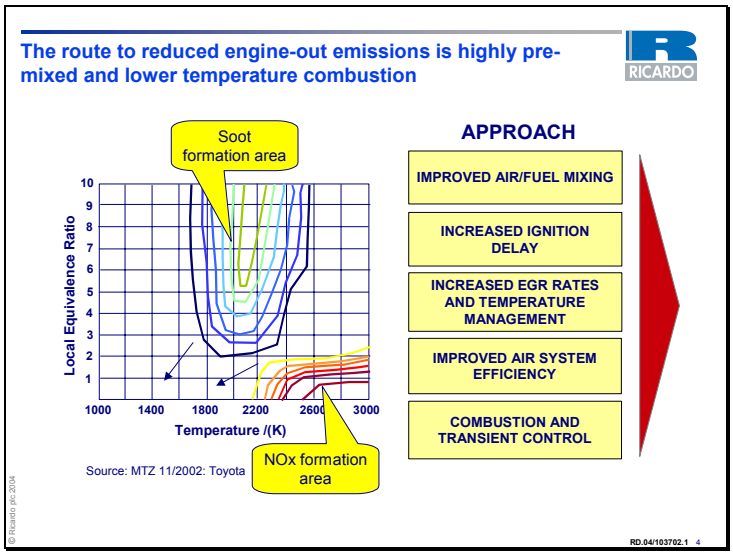
It is expected that other consumer perceptions and infrastructure issues will be addressed in time by demand, if good diesel products are offered.

Slide 3



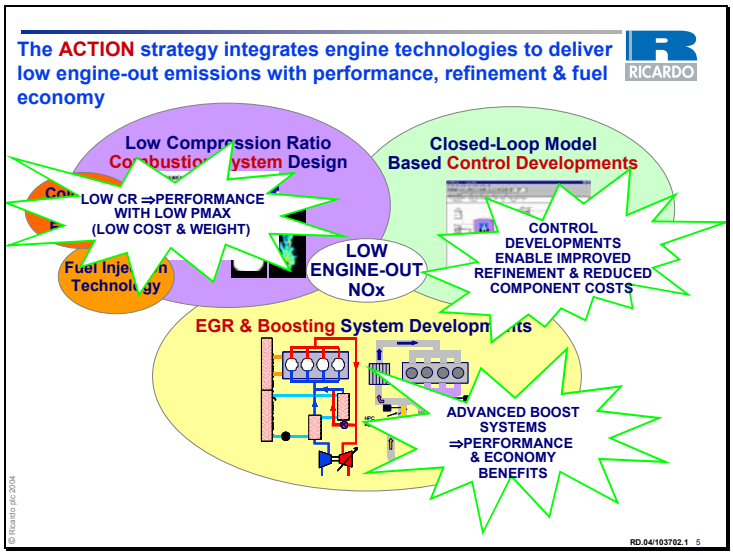
Achieving a viable business case for light duty diesel in the US depends on finding the lowest total system cost solution for Tier 2 Bin 5 emissions.
This slide compares estimated total system costs for engine and aftertreatment versus full life NOx reduction for 2 alternative routes:
Euro 4 baseline engine+oxidation catalyst technology, with addition of a DPF and LNT as represented by the red oval
Ricardo approach (ACTION strategy) for reduction of engine-out NOx emissions which delivers greater NOx reduction potential at lower total system cost.
The grey band around 90% NOx reduction from Euro 4 / Bin 10 level technology represents the typical requirement for light duty applications to meet Tier 2 Bin 5.
Further details of the ACTION strategy will be given in later slides.

Slide 4



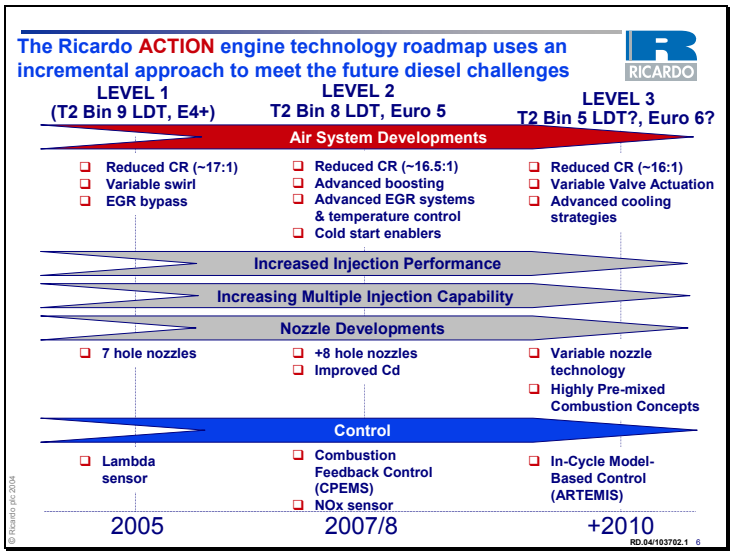
The desired changes in combustion conditions for low NOx and soot emissions are well recognized and characterized by the familiar NOx/Soot formation island plot.
The approach taken by Ricardo involves incremental steps in technology to progressively increase the degree of pre-mixing and promote lower temperature combustion.
The elements of the approach described above are achieved by integration of technology developments in 3 major areas as shown on the following slide…..

Slide 5



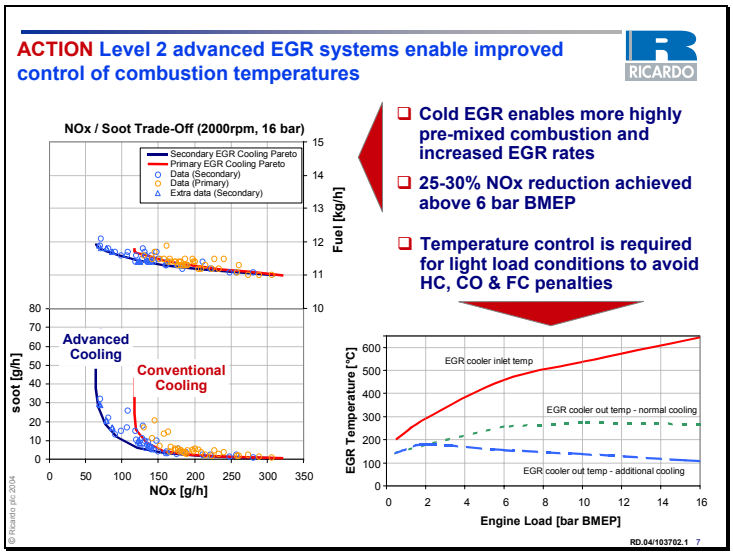
Integration of incremental developments in the areas of combustion system, air handling system and control are used to deliver low engine-out emissions.
Reduction of compression ratio directionally reduces NOx emissions and can also provide net fuel consumption benefits through the reduction of frictional losses. Compression ratio reduction is however limited by cold start and drive capability. Hence cold start/drive enabling technologies have been evaluated by Ricardo to validate the limit of compression ratio reduction.
Advances in fuel injection technology are also a key part of the strategy as a fundamental component of the combustion system.
The overlayed comments on the above slide illustrate some of the key additional benefits, beyond emissions reduction, that technology developments in these areas provide. Investing in technologies which enhance performance, refinement and fuel economy, as well as meeting future emissions requirements, supports premium product positioning of diesels in the market. This in turn supports a more viable business case for introduction of light duty diesels.

Slide 6



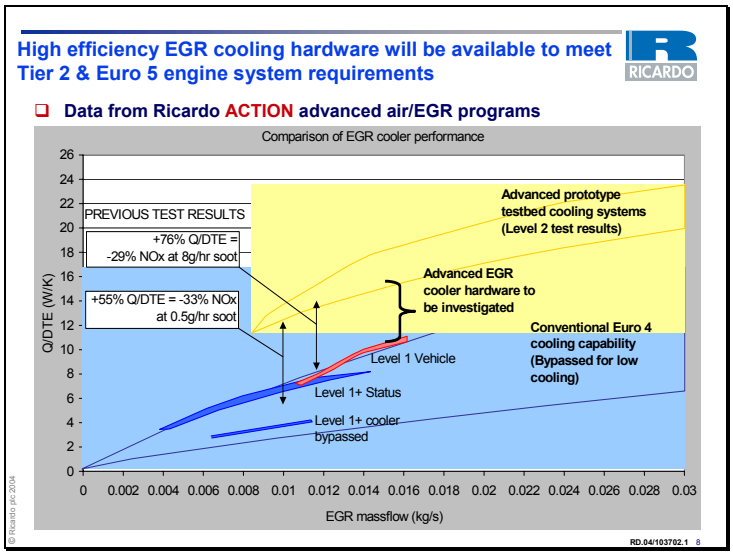
The above slide shows the roadmap of technologies which make up the ACTION strategy for engine-out NOx reduction, to support both European and US light duty diesel markets.
The technologies described cover the 3 main subsystem areas described on the previous slide.
The emissions levels along the top of the slide reflect engine-out NOx emission targets at each level. Hence Tier 2 Bin 5 can be support at Level 2 by the addition of minimum NOx aftertreatment to reduce tailpipe emissions from Bin 8 engine-out NOx levels.
The timescale along the bottom of the slide reflects the anticipated first introductions to market at each technology level.
All hardware specifications at Level 1 are in fact already in production in Europe on some light duty applications. However, the distinction here is that further optimization of the combustion system by Ricardo at this hardware level has demonstrated in vehicel >50% reduction in engine-out NOx from current Euro 4 levels.
Further description and example results for elements of the above roadmap are provided on subsequent slides.

Slide 7



Air handling system development is a key part of the ACTION strategy and can deliver significant NOx emissions reduction with low incremental hardware cost.
The plots on the left of the slide show multi-cylinder engine results with enhanced EGR cooling, at 2000rpm, 16 bar BMEP. The scattered points are results from DoE testing to optimize all calibration variables with conventional and advanced EGR cooling systems. The solid lines are pareto optimum trade-off curves for each hardware configuration.
25%-30% NOx reduction from enhanced EGR cooling has been demonstrated with negligible impact on fuel consumption at this relatively high load point.
Although not shown, application of highly cooled EGR at light loads improves NOx, but results in HC, CO and fuel consumption penalties, as well as increased risk of system fouling. Hence, the ACTION strategy applies modulated cooling of EGR across the load range as shown in the lower right plot.

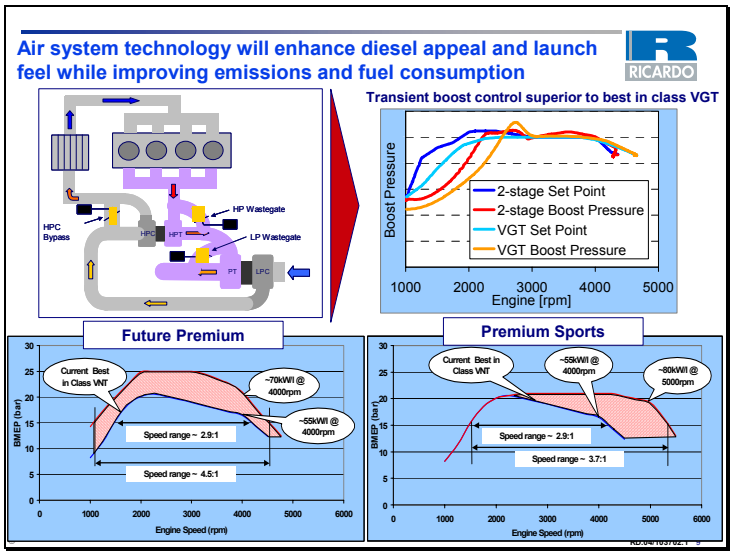
Slide 8



To achieve the increased levels of EGR cooling required, developments in EGR cooler hardware are in progress. This plot shows EGR cooler effectiveness versus EGR mass flowrate. The blue region represents typical performance of Euro 4 EGR coolers with and without bypass activated.

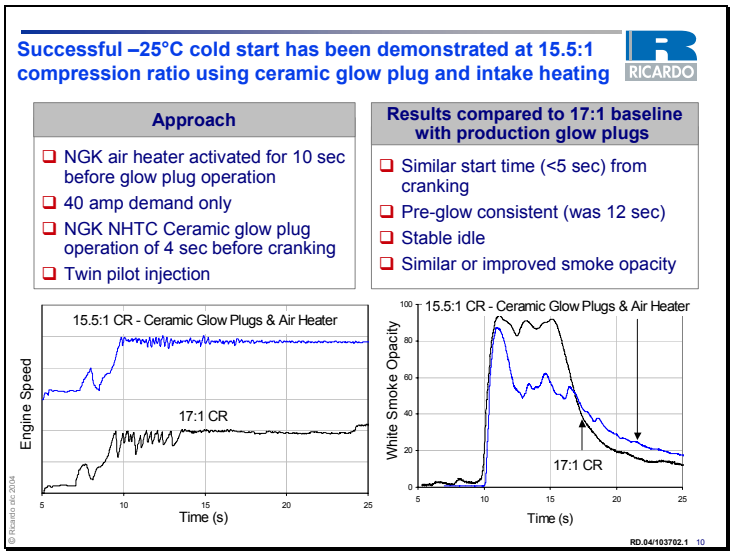
Ricardo has applied enhanced prototype EGR cooler systems represented by the yellow region in ACTION strategy development. As shown, a range of production intent hardware options are available from the Tier 1 supply base, spanning the gap between current Euro 4 and future system requirements.

Slide 9



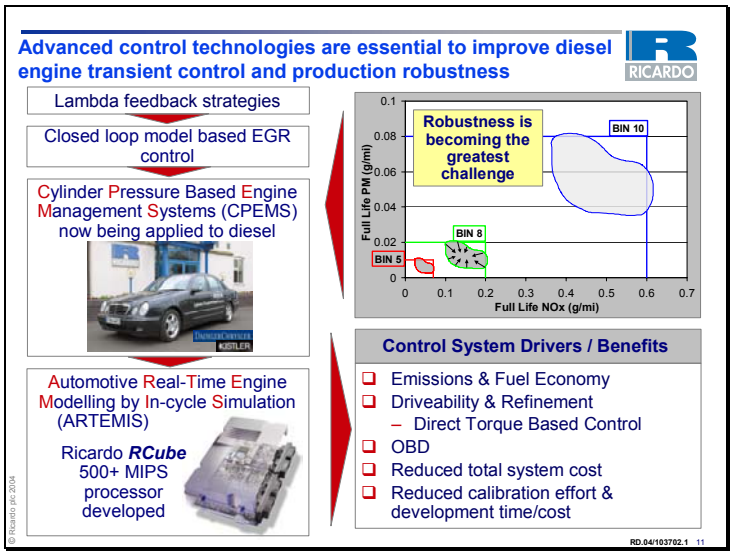
There are a wide range of advanced boosting system concepts in development and coming to market. One example shown here is the sequential 2 stage system, which applies 2 fixed geometry turbochargers to expand the air system capability across the speed/load range. This can be applied to deliver a range of exciting new premium product attributes as shown by the 2 alternative enhanced torque curve profiles.
In addition, the reduced size of the high pressure turbocharger allows improved transient boost response compared to a single VGT, as shown in the upper right plot. This characteristic could be particularly applicable in the US market, where diesel powertrains typically fall short of competitive large V-engine gasoline launch performance.
Furthermore, Ricardo development of sequential 2 stage systems has demonstrated both emissions and fuel economy benefits over transient emissions cycles.

Slide 10



As previously described, the ACTION strategy incorporates reduction in compression ratio to support reduced NOx and emissions and enhanced performance at miminal base engine cost and weight.
The above slide shows validation of cold start and drive capability at 15.5:1 compression ratio with additional cold start/drive enablers applied.
The example results above were achieved using European specification diesel fuel, and hence an increase in the minimum practical compression ratio should be expected for current US fuel at lower Cetane numbers.

Slide 11



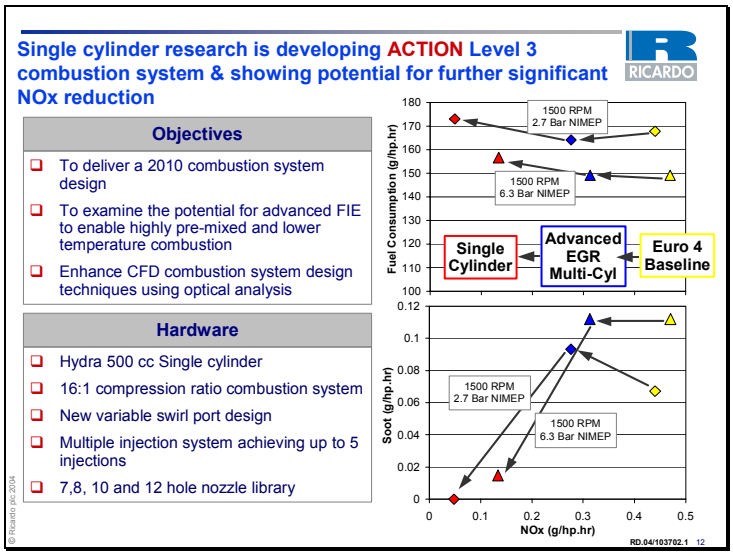
Robustness and conformity of production is now becoming the most significant challenge in meeting future US and European emissions legislation, and developments in control system technology are essential to meet this challenge. The magnitude of the robustness challenge in moving from Bin 10 to Bin 5 emissions is illustrated by the upper right figure.

The Ricardo ACTION strategy includes a number of incremental steps in control technology which progressively improve the accuracy of closed loop combustion control, as shown by the flow diagram on the left.

Lambda sensors are well established existing technology which are now becoming more widely applied in diesel applications for EGR and aftertreatment feedback control. Model based elements are also being increasingly applied, particularly for EGR and air system control. Initially model based controls will take a 'mean value' or cycle averaged approach.

Ricardo are developing cylinder pressure based control technology for diesels which will then further enhance closed loop feedback on a cycle-by-cycle basis. Ricardo ARTEMIS software then provides the potential for real-time model based cycle-by-cycle elements within control strategies. In addition to providing improve control and robustness, more accurate representation of the engine physics within the control strategies will reduce the amount of map based elements which are calibration intensive. This will reduce development time and costs of these increasingly complex systems.

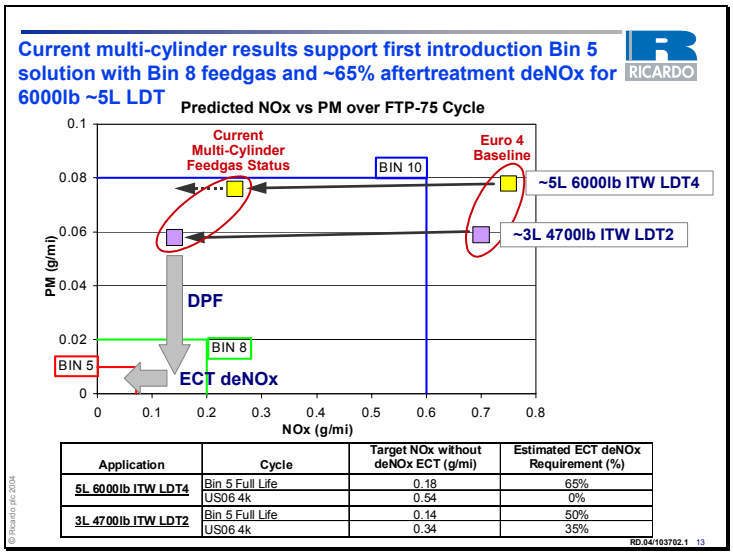
Slide 12



To deliver Level 3 of the ACTION strategy, Ricardo have a single cylinder development program running in parallel to vehicle and multi-cylinder activities for Levels 1 and 2. The objective of the single cylinder work is to develop a light duty diesel combustion system for ~2010. The preliminary results shown reflect the potential already identified to further reduce engine-out NOx, and hence further reduce or eliminate NOx aftertreatment in future systems.

Clearly significant challenges still exist to translate this very low NOx capability to multi-cylinder and vehicle with robust transient emissions and competitive driveability.

Slide 13



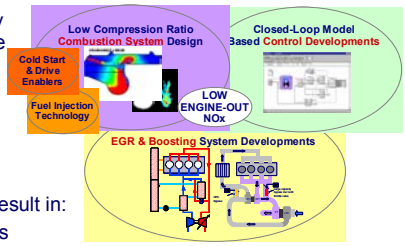
Application	Cycle	Target NOx without deNOx ECT (g/mi)	Estimated ECT deNOx Requirement (%)
5L 6000lb ITW LDT4	Bin 5 Full Life	0.18	65%
	US06 4k	0.54	0%
3L 4700lb ITW LDT2	Bin 5 Full Life	0.14	50%
	US06 4k	0.34	35%

The above plot and table shows predicted vehicle emissions results from cycle simulation for 2 generic US vehicle specifications over FTP-75 (plot) and US06 (see table) cycles. The squares on the plot reflect feedgas NOx and PM before application of DPF and deNOx aftertreatment, represented by the wide arrows.
The predicted engine out results to the left of the plot are based on currently achieved multi-cylinder engine emissions performance for Level 2 of the ACTION strategy.
It is proposed that this approach of ~Bin 8 engine out NOx emissions, leaving an aftertreatment deNOx requirement of ~65% for a 6000lb 5 liter LDT4 to meet Bin 5, provides the optimum, practically achieveable strategy for first introduction of Bin 5 diesel LDTs to the US market in the 2007-2008 timeframe.

Slide 14

Summary: ACTION technologies offer an integrated approach to deliver competitive US diesels within a viable business case

- The operating range of highly pre-mixed combustion can be enhanced
  - Practical solutions are under development
  - Robustness is becoming the most critical challenge



- An integrated approach will result in:
  - Aftertreatment cost savings
  - Improved engine performance
  - Optimized the trade-off between fuel consumption, NOx and cost
  - Improved refinement (transient control and combustion noise)
- Engine out NOx reduction combined with minimum NOx aftertreatment offers the best potential to achieve Bin 5 and US06 emissions for '07/'08 first Tier 2 introductions

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