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ADVANCED DIESEL ENGINE AND AFTERTREATMENT TECHNOLOGY DEVELOPMENT FOR TIER 2 EMISSIONS

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ABSTRACT

Advanced diesel engine and aftertreatment technologies have been developed for multiple engine and vehicle platforms. Tier 2 (2007 and beyond) emissions levels have been demonstrated for a light truck vehicle over a FTP-75 test cycle on a vehicle chassis dynamometer. These low emissions levels are obtained while retaining the fuel economy advantage characteristic of diesel engines.

The performance and emissions results were achieved by integrating advanced combustion strategies (CLEAN Combustion©) with prototype aftertreatment systems. CLEAN Combustion© allows partial control of exhaust species for aftertreatment integration in addition to simultaneous NOx and PM reduction. Analytical tools enabled the engine and aftertreatment sub-systems development and system integration. The experimental technology development methodology utilized a range of facilities to streamline development of the eventual solution including utilization of steady state and transient dynamometer test-beds to simulate chassis dynamometer test cycles.

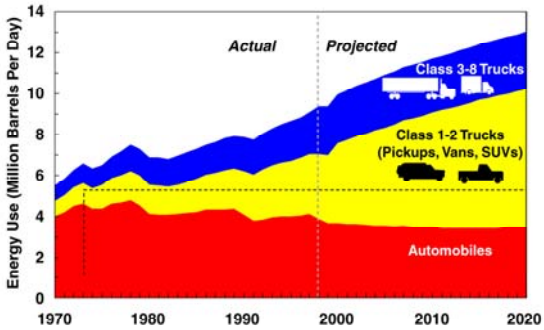
Key Words: diesel engine, Tier 2, SCR, aftertreatment, emissions, urea

INTRODUCTION

In the late 1990s, fuel use projections were prepared for future transportation requirements. Energy use among automobiles was shown to be fairly steady for the future outlook from 2000 to 2020, while Class 3 through Class 8 trucks (heavy-duty type vehicles) were predicted to increase marginally over that same twenty-year time frame. However, a significant increase was seen in the Class 1 to Class 2 trucks (pickups, vans and SUVs). In some cases, these are used commercially, but the primary source of increase was seen as a growing part of the passenger car market for use for personal transportation. This major increase in the use of these vehicles is subsequently increasing the energy use and thereby driving up total energy use in terms of millions of barrels per day of petroleum, from approximately 8 million barrels in the late 1990s up towards 12.5-13 million barrels in 2020 [1,2]. (See Figure 1.)

At that time, it was forecast that the dieselization of the vehicle fleet, primarily these Class 1 and Class 2 light trucks, would have a significant reduction on the U. S. transportation energy use; however, many people questioned whether the diesel engine's potential to achieve future Tier 2 emissions would make it a viable option. Those who considered that the emissions hurdle could be overcome, then questioned what the resulting fuel economy improvement would be after all of the NOx abatement technologies were applied and the fuel efficiency was reduced.

As a response to this, a series of collaborative projects with the Department of Energy were initiated including the DELTA program, and later, the LEADER program at Detroit Diesel Corporation. The purpose of these programs was to look at the technical viability of meeting Tier 2 emissions and also the fuel economy impact that that would have. The approach that was followed at Detroit Diesel was an integrated analytical and experimental approach that utilized simulation in the early stages of the program to develop the concepts required for engine design as well as strategy development.



Trucks account for increasing highway transportation energy use. [1,2]

In 1999, many questioned the diesel engine's potential to achieve future Tier 2 emissions and the resulting fuel economy improvement.

Figure 1: "Dieselization" of Vehicle Fleet Offers Significant Reduction to U.S. Transportation Energy Use

METHODOLOGY AND RESULTS

Control systems were integrated along with the engine control system in a fairly dynamic, yet effective way that led to significant advancements in the overall emissions characteristics of the engine while maintaining the inherent fuel economy advantage of the diesel engine over the baseline gasoline engine. Initially, extensive simulation was conducted to design a clean sheet engine. This simulation was validated by actually procuring and building the engine and doing the steady state modal development. This effort both validated the simulation and quantified the performance in the steady state mode. Once this activity established calibrations and a robust, repeatable engine performance level, it was used to forecast transient engine performance by characterizing transient cycles, again still in a steady state type of scenario. Integrating with analytical tools allowed for transient types of situations to be identified and then run in a steady state test cell environment which is highly controlled. This allowed for critical answers to questions such as tradeoffs between air systems, EGR systems and combustion systems to allow an improved engine development scheme to be worked out.

Following the steady state development, the work and theories were validated in a transient engine dynamometer setting where the engine could run transient engine-type of operations. Also, vehicle integration was forecast and vehicle emission types of driving cycles, such as the Federal Urban Drive Cycle, the FTP-75, the US06, and the Highway Fuel Economy Test Modes were programmed into the transient engine dynamometer. These could be run in a very controlled setting to allow for the control system and calibration to be refined.

Following development on this workhorse dynamometer system, the engine was used to repower a number of commercial light truck vehicles: Dodge Durango, Dodge Dakota, and also a Class 1 DaimlerChrysler Neon passenger car vehicle, and validate some of the control system development in calibrations that had been developed. This vehicle integration then led back into the simulation domain to develop higher fidelity control systems and calibration development. This path leads through an iterative network of engine and aftertreatment development. On the second, third and fourth iterations through this loop, aftertreatment was increasingly integrated.

2001 Dakota Quad Cab Sport 4 x 2
Re-powered with DDC DELTA 4.0L V6
Twin VG Turbocharged, Common Rail Injection
235 hp @ 4000 rpm

Figure 2: DAKOTA Light Truck Platform

As shown in Figure 2, the platform used in the program for the Tier 2 demonstration was a DaimlerChrysler Dodge Dakota light truck platform. It was repowered with a DELTA 4-Liter V6 engine [3,4]. This engine used variable geometry turbocharging, common rail fuel injection, unique high pressure loop, cooled EGR system, created 235 HP at 4000 rpm and has been shown at the 2002 DEER conference and participated in the 2002 Ride-and-Drive in San Diego. Early in the program, an integrated emission reduction roadmap was developed for the light truck and SUV platform, as shown in Figure 3. It was based on the FTP-75 emission performance and it looked at two domains. The first domain identified the emission performance targeted for engine out utilizing engine control strategy and advances in Clean Combustion©. The patented advanced combustion technique developed in the program allows significant reductions in engine out emissions without a significant impact on fuel economy; and, in fact, without any tangible impact on transient fuel economy.

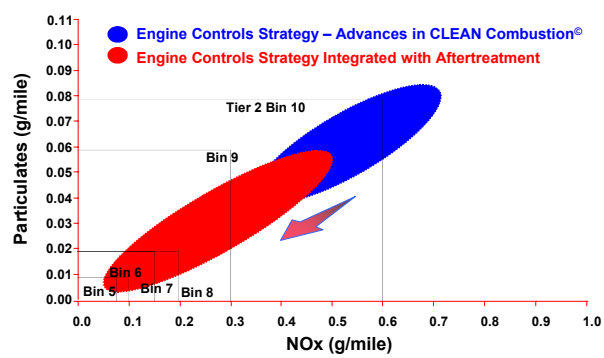


Figure 3: Integrated Emissions Reduction Roadmap Light Truck / SUV Platform

Once this engine out emission performance was established, then the second goal was identified: tailpipe out emissions, which showed the integration of this advanced engine control strategy with aftertreatment. The target for engine out emissions was essentially at a Tier 2 Bin 10 level and then going down very close to a Tier 2 Bin 9 level that was targeted, with the ultimate objective of reaching Tier 2 Bin 5 with the implementation of aftertreatment.

At the 2002 DEER Conference, preliminary results were presented that showed the demonstration of engine out FTP-75 emissions at the Tier 2 Bin 10 level without any aftertreatment [5]. This is significant in that it achieved very low engine out emissions while maintaining very high fuel economy, over 50% better than the gasoline engine that was the baseline powertrain in the vehicle. By adding a catalyzed soot filter, a urea-based SCR technology and related controls, a significant reduction in both NOx and PM was attained, and a Tier 2 Bin 6 level of emission performance was achieved without any ammonia slip over the FTP-75. This emission benefit was achieved with a 45% fuel economy benefit as compared to the baseline gasoline engine.

The accomplishments since the 2002 DEER conference have shown significant improvements in the engine out emissions and are shown in Figure 4. Without any active NOx aftertreatment, emissions very near the Tier 2 Bin 9 level were achieved: NOx of ~0.3 grams per mile with very low particulates. This exceeds the roadmap objectives established in the early stages of the program. Adding the urea-based SCR technology to this engine out baseline actually achieved Tier 2 Bin 3 levels over the FTP-75 while maintaining over a 40% fuel economy benefit as compared to the baseline gasoline engine. Again, these emissions levels were achieved without any ammonia slip throughout the FTP-75 cycle. Furthermore, US06 levels were also demonstrated at the Tier 2 level utilizing the catalyzed soot filter and the urea-based SCR technology.

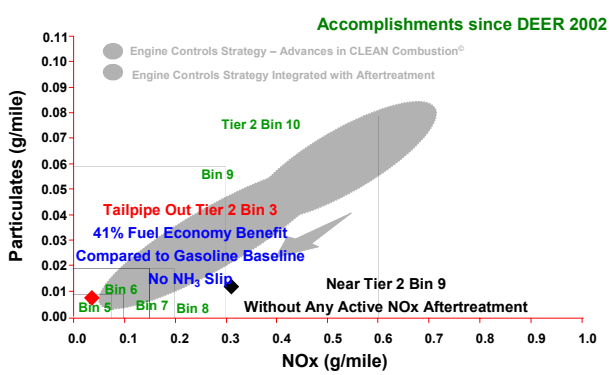


Figure 4: NOx Reduction Via Combustion and Aftertreatment Development Light Truck / SUV Platform

One way to show the benefit of advanced technologies employed is to categorize the NOx reduction by combustion or engine out as well as by the integration with aftertreatment by comparing the FTP-75 vehicle out NOx to the FTP-75 engine out NOx. This is shown in Figure 5. Aftertreatment efficiencies are usually between ~80 - 95% over the FTP-75 cycle. These are fairly high levels of NOx reduction for the low temperature FTP-75 cycle. What the program shows is that significant reductions were attained on the engine out NOx levels over the last year, further utilizing the CLEAN Combustion© technology and enhancing calibration and controls strategies. Over a 50% reduction in engine out NOx has been achieved. Furthermore, significant improvements in the NOx reduction over the FTP-75 cycle has occurred going from an 85% level shown last year, now upwards of 90% at this very low overall NOx level. This is achieved by fully utilizing the capabilities of the control system and the multi-mode advanced combustion. It essentially demonstrates the improved engine and aftertreatment integration that is inherent in this technology and this project approach, especially when you consider going over the iterative process starting with simulation, going through the steady state, the transient engine and then finally the vehicle validation step. The more times that we go through that iterative loop, the more we are able to integrate the aftertreatment and engine through engine design, through engine controls and through advanced capabilities.

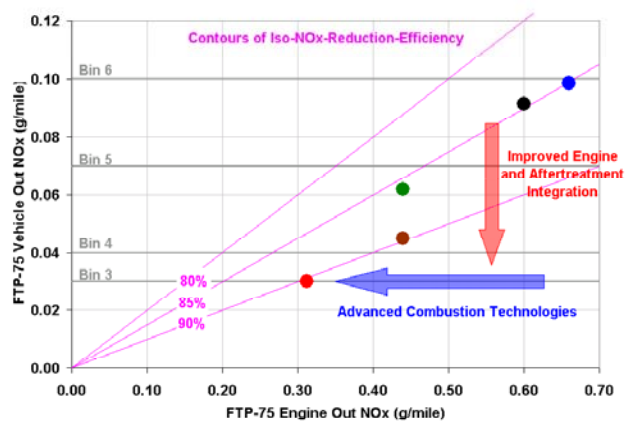


Figure 5: NOx Reduction Via Combustion and Aftertreatment Development Light Truck / SUV Platform

While achieving Tier 2 Bin 3, essentially significantly breaking the traditional NOx/PM tradeoff curve, it is important to identify that that NOx/PM tradeoff curve still remains at each of these individual milestones. In the same way, the NOx/Fuel Economy tradeoff curve also remains. We can plot the tradeoff curve for the range of NOx emissions from a Bin 7 to a Bin 3 showing that as NOx is reduced, the fuel economy for the FTP-75 is also reduced at some level. What is important to identify is the fuel economy recovery potential that is inherent in the methodology used in this project in terms of using the analytical-based approach. At each individual step of the development methodology, the causes of the fuel economy degradation is identified and can be addressed in the following iteration.

So, for the 2002 Tier 2 Bin 6 level, the fuel economy for the FTP-75 was ~20 miles per gallon for this light truck. In

2003, although we still have this tradeoff with fuel economy and NOx, we can now achieve a Tier 2 Bin 5 level of NOx at the same miles per gallon. This shows ~55% reduction in NOx from the previous level at the same fuel economy. Alternatively, if we maintain the same NOx, we can increase the fuel economy to a 20.5 mpg with the 2003 level emissions performance identified. Or, we can reduce the NOx significantly to the Tier 2 Bin 3 level which is more of a 70% reduction in total NOx with minimal degradation in fuel economy. But, the message is that through subsequent iterations of engine development, the fuel economy can be recovered so that there is no significant fuel economy penalty with further reductions in NOx.

These results are further demonstrated and prior results have been previously presented, if we compare the results on the passenger car platform [6-8]. We had a similar roadmap as the light truck, again, identifying two regimes: one with engine out NOx and PM targets over the FTP-75 and one integrated with aftertreatment looking at Tier 2 Bin 5 level. In this case, the engine out baseline was refined early on to a much cleaner level down to a 0.4 g/mi NOx and a .05 g/mi particulate engine out without any aftertreatment applied. Including a catalyzed soot filter, over the FTP-75 a Tier 2 Bin 8 result was achieved, again without any active NOx aftertreatment (0.2 g/mi NOx with a very low particulate level). Adding urea-based SCR technology allowed a significant reduction in NOx, again down to a Tier 2 Bin 3 level, both NOx and particulate, again without any ammonia slip. These results are shown in Figure 6.

This project showed a significant improvement in fuel economy with each progressive iteration of the development methodology, where there is essentially a horizontal reduction in NOx without a fuel economy penalty. Tier 2 Bin 5 results were obtained with ~67 mpg combined fuel economy, which is the combination of a FTP-75 and Highway Fuel Economy for this Neon mule vehicle. It clearly shows how the fuel economy can be recovered, or even improved, with successive R&D when utilizing an integrated analytical and experimental approach.

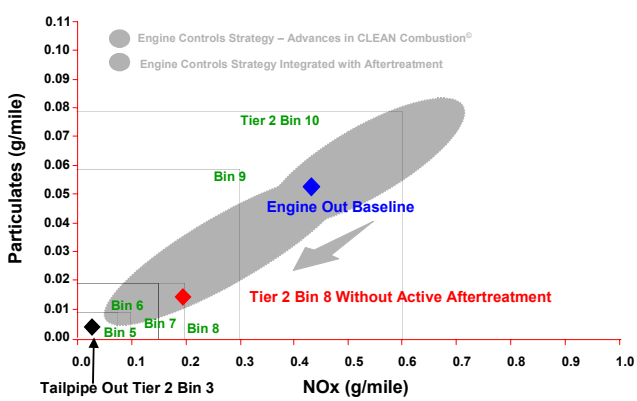


Figure 6: Integrated Emissions Reduction Roadmap Passenger Car Platform

SUMMARY AND CONCLUSIONS

In summary, this project demonstrated Tier 2 Bin 3 emissions for the light truck SUV applications, as well as for the passenger car platform, utilizing integrated diesel engine and aftertreatment technology, in this case, a catalyzed soot filter with a urea-based SCR system. Tier 2 is also demonstrated for the light truck platform over the US06 cycle and for the FTP-75 results (Tier 2 Bin 3). A 41% fuel economy advantage was demonstrated over the light truck gasoline baseline, again with the same vehicle running the tests. The emissions reductions are attributed to advanced combustion technology primarily, and this is shown by achieving a near Bin 9 engine out NOx and PM level without active NOx aftertreatment. Also, through engine and aftertreatment integration which actively controls species at the inlet of the SCR and has a very high fidelity mixing design inherent in the doser and into the system itself. The urea injection control strategy is also a primary reason for the excellent emissions results obtained which minimizes the risks of ammonia slip while maximizing the total NOx reduction.

Also, in summary, the development methodology emphasizing integrated testing and analysis was one of the core reasons that the Tier 2 Bin 3 emissions were demonstrated with both the light truck and passenger car platforms in a fairly efficient short time scale. Considering the drivers for commercialization potential of the technology, a reduction in aftertreatment system complexity by increased engine aftertreatment integration is required to make the technology more feasible for large scale implementation. In addition, a sophisticated controls technology integration is absolutely required considering the multi-mode combustion strategy employed and incorporating a urea reductant injection strategy and soot filter regeneration strategy in one control ECU fully integrated over the driving cycle. This is a significant hurdle left in the project development.

There are infrastructure needs including low sulfur fuel below the 15 ppm level that is absolutely required, and also a urea reductant for SCR. We believe that the urea reductant infrastructure will be led in the heavy-duty arena, which will lay a foundation from which the light duty infrastructure can then be subsequently developed. Significant concerns are the measurement techniques and the emissions variability that are seen at the Tier 2 levels. The effective aging and device variability on the aftertreatment performance and the combination of these two effects can play significant role in trying to predict long-term degradation or long-term emissions. A statistical type of analysis is required in post processing these types of results for future low emissions engines.

Finally, the integrated analytical and experimental test approach is valuable and absolutely required given the limited resources and these nearer-term, high-risk objectives. Fundamental aftertreatment kinetic data is also a key need, pacing the applications of these tools and methodologies and especially pacing the integration of engine and aftertreatment technology. Hence, the species at the inlet of the aftertreatment devices over the transient is critical to ultimately integrating these devices and further simplifying them.

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