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ANALYTICAL TOOL DEVELOPMENT FOR AFTERTREATMENT SUB-SYSTEMS INTEGRATION

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ABSTRACT

The stringent emissions standards of 2007 and beyond require complex engine, aftertreatment and vehicle systems with a high degree of sub-system interaction and flexible control solutions. This necessitates a system-based approach to technology development, in addition to individual sub-system optimization. Analytical tools can provide an effective means to evaluate and develop such complex technology interactions as well as understand phenomena that is either too expensive or impossible to study with conventional experimental means. The analytical effort can also guide experimental development and thus lead to efficient utilization of available experimental resources.

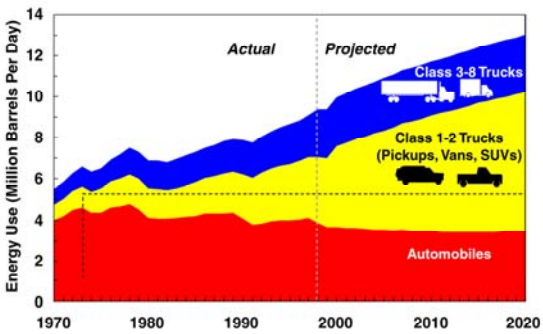
A suite of analytical models has been developed to represent PM and NOx aftertreatment sub-systems. These models range from computationally inexpensive zero-dimensional models for real-time control applications to CFD-based, multi-dimensional models with detailed temporal and spatial resolution. Such models in conjunction with well established engine modeling tools such as engine cycle simulation, engine controls modeling, CFD models of non-combusting and combusting flow, and vehicle models provide a comprehensive analytical toolbox for complete engine, aftertreatment and vehicle sub-systems development and system integration applications. However, the fidelity of aftertreatment models and application going forward is limited by the lack of fundamental kinetic data.

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

A proven concept and methodology of combining experiments with analytical tools has been developed (Figure 2), pursuing an integrated engine, aftertreatment and vehicle development roadmap. As can be seen from Figure 2, 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.

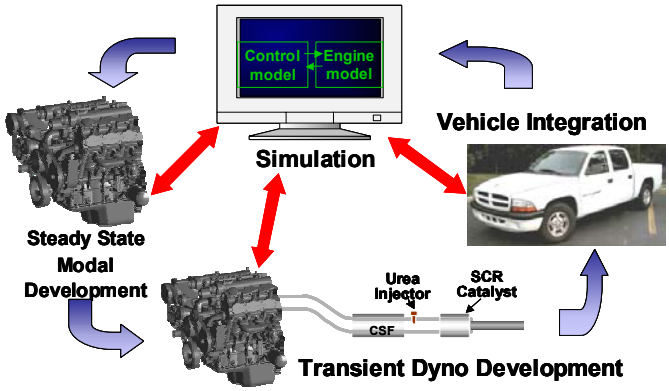


Figure 2: System Development Methodology

Following the 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.

Figure 3: DAKOTA Light Truck Platform

As shown in Figure 3, the platform used in the program for the Tier 2 demonstration included a DaimlerChrysler Dodge Dakota light truck platform, in addition to the DCX Neon. 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.

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.

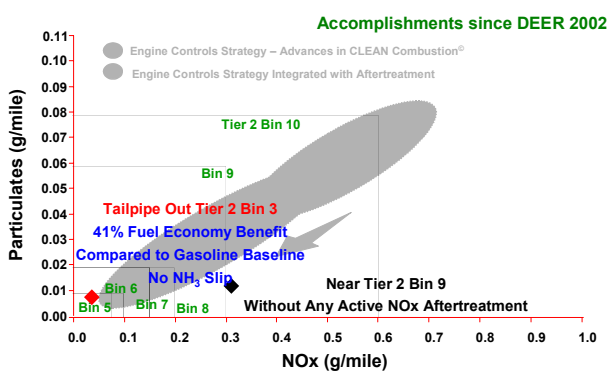


Figure 4: NOx Reduction Via Combustion and Aftertreatment Development Light Truck / SUV Platform

The more detailed results in 2003 can be seen in Reference [6], and other historic and accomplishments can be viewed from References [7,8,9].

MODEL APPLICATIONS TO SYSTEM INTEGRATION AND CONTROL STRATEGY DEVELOPMENT

It should be pointed out that analytical simulations plays a significant role in all major testing stages shown in the previous section. The analytical toolbox consists of engine, vehicle and aftertreatment models that have been developed, validated and widely used for many real life driving situations [10].

Two cases will be presented in this section in order to demonstrate how analytical tools can help system integration and control strategy developments.

The first case is the urea injection mixing and spray development using 3D CFD program combined with flow bench testing results on a given urea injection system. Figure 5 shows the bench testing results for hole-to-hole flow rate variation before and after optimization. The use of these urea flow boundary conditions for 3D CFD of urea injection, vaporization and mixing is made to optimize the urea doses and exhaust system design. Figure 6 shows the detailed flow structures and demonstrates why non-uniform injection profile can deliver poor SCR performance.

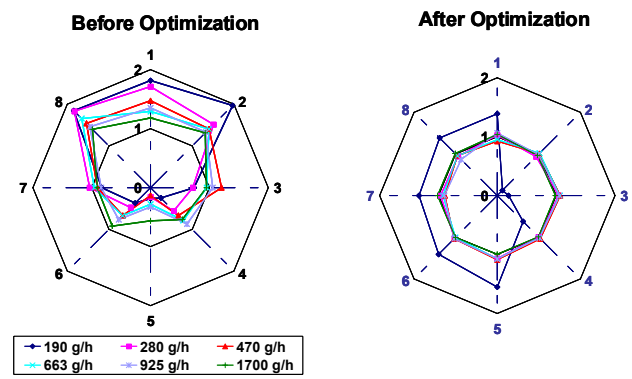


Figure 5: Urea Injection Control Issue - Hole-to-Hole Flow Rate Variation

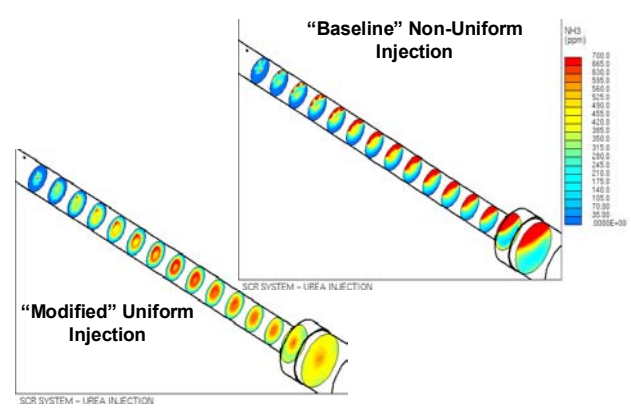


Figure 6: 3D CFD for NH3 Distribution

The second case is the use of 1D SCR model to develop urea control strategies over FTP transient cycles. Figure 7 shows

that NOx emission traces over a Hot 505 transient cycle. In addition to baseline SCR out NOx trace, other two urea injection control strategies denoted as X and Y were applied, showing significant NOx reduction improvement compared to the baseline. The values of 1D SCR tool can be further demonstrated by looking into the trade-off of the ammonia slip and NOx reduction efficiency, shown in Figure 8.

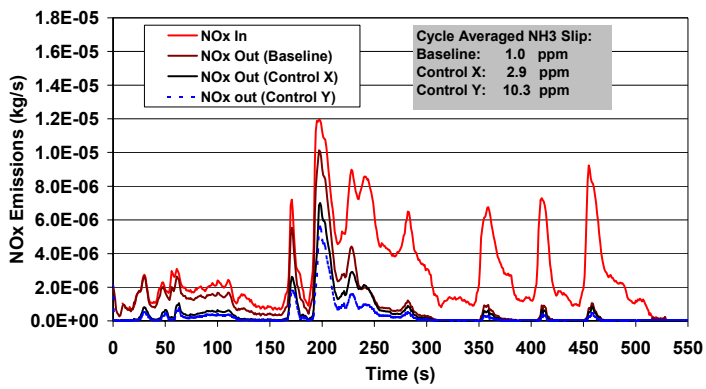


Figure 7: Urea Control Strategies over Hot 505 Transient Cycle Using 1D SCR Model

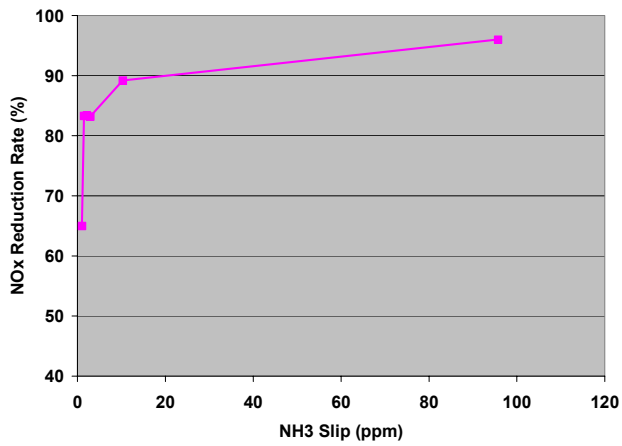


Figure 8: Urea Injection Control Strategies on SCR Performance for a Hot 505 Cycle Using 1D SCR Model

This ultimate end results from simulations greatly help the achievements of Bin 3 emission level as discussed in Figure 4 and further demonstrated in Figure 9.

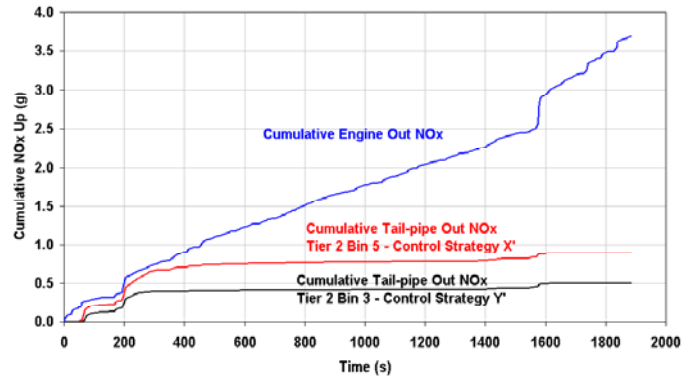


Figure 9: System Integration Experimental Validation Urea Injection Control Strategy Development

SUMMARY AND CONCLUSIONS

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. During this project, advanced analytical tools play a significant role in optimizing the engine/vehicle/aftertreatment systems. It is shown that the use of advanced analytical tools combining with hardware tests can provide detailed development directions, design parameters and control strategies, thus reducing developmental cycle.

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. Through engine and aftertreatment integration which actively controls species at the inlet of the SCR, this results in a very high fidelity mixing design inherent in the doser and into the system itself. During this process, 3D CFD tool provides detailed understanding on the urea mixing, thus yielding a better urea injection mixing system. It is shown that 1D SCR model can quickly investigate different urea control strategies by looking into the trade-off between the ammonia slip and NOx reduction efficiency. The optimized 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.

While achieving significant progress in both testing and simulations, numerous technical challenges and issues in modeling still need to be addressed: the use of analytical tools to assist the aftertreatment system simplifications, the development of sophisticated control technology integration related to soot filter regeneration, urea injection and mixing; virtual sensors to effectively investigate the aging effect on aftertreatment performance, etc. Ultimately, more and better kinetics data is needed. This requires industry, catalyst suppliers, National Laboratories and universities to work together to fill this pre-competitive void.

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