Looking Back

Timothy V. Johnson
Corning Incorporated

All too often we get immersed in the details of making progress without looking back to gain perspective on how far we have actually travelled. Not only can retrospective views be satisfying and provide proud moments, but many times a look back can help guide us forward. In this regard, the editors thought the first CLEERS newsletter preface ought to recall the status of emissions during the early days of CLEERS. As such, a "broad snapshot" of the status of vehicular emissions regulations, engines, and emissions control in the five-year period from 1997 to 2001 is provided here.

Regulations

The regulatory framework for criteria pollutants through 2015 was largely determined in the 1997-2000 timeframe. CLEERS was formed to help the technical community meet these very tight regulations. In the US LD sector, Tier 1 and LEV1 regulations were in effect in 1997, and CARB had their first public workshop on LEV2 direction. Within two years, US LD Tier 2 and CARB LEV2 were finalized, calling for about 90+% emissions reductions by 2007, and 30 ppm sulfur gasoline. These regulations were groundbreaking. They added LD trucks and SUVs to the car regulations, introduced the fleet average NOx requirement, and brought in the SULEV certification level. After a brief transitional period (NLEV), implementation began in 2004, with full phase-in for the lighter class by 2007 and heavier LD vehicles (>6000 lbs.) by 2009. In 1997, almost all OEMs expressed deep concern about hitting the pollution standards. The 1996 California EV mandate for 10% EVs by 2003 later morphed into requiring ~30% SULEV vehicles instead. This spurred work on ICE emissions. This ultimately led to the new Tier 3 and LEV3 being implemented now, requiring an additional 80% emissions reduction from Tier 2 and LEV2.

Europe was implementing LD Euro 3 in 2000 (~2.5-3X the emissions of Euro 6), and finalized Euro 4 (2005) and Euro 5 (2008) in this timeframe. The particle number (PN) discussion was starting to gain momentum with Peugeot's implementation of DPFs in 1999. The German regulators were proposing a PN test program in 1999 to gain knowledge. A PN regulation for LDDs was eventually added to Euro 5.

The US2007 HD regulations (and the US2010 subset) were finalized in late 2000. As with Tier 2, they called for 90+% PM and NOx reductions and 15 ppm sulfur. To help ensure that in-use emissions are lined up with those measured on the dynamometer, the first in-use regulations in any sector, NTE (Not-to-Exceed), were part of this. Europe also finalized the Euro IV (2005) and Euro V (2008) regulations with the intent of implementing DPFs (80% PM reductions) and SCR (60% NOx reductions). It called for 50 ppm sulfur fuel going to Euro IV and then 10 ppm for Euro V.

In the non-road sector Stage 1 and Tier 1 regulations were in force, with allowable emissions roughly 20X of those today. Talk of inevitable tightening further was occurring in this period.

Engines

In 1997, common-rail direct injection LD diesel engines were just emerging, with injection pressures less than half of what we have today. The flexibility of injection timing and quantity enabled active DPF regeneration. European LDD market share subsequently grew from about 15% through the 90's to about 30% in 2000. Some credible projections showed 50% penetration by 2010. This was met five years earlier due to performance enhancements offered by DI and turbocharging. US LDD penetration was projected at <0.5% by 2010, but up to 20% if they were clean. US penetration today is <5%. A 1.3 liter, 3-cylinder diesel car was projected to deliver 60 MPG (~4 liter/100 km) and would need 95% NOx control and 80% PM control to hit Tier 2 Bin 5 (fleet average emissions). Such a car today might need only 75-80% NOx control. One engineering company was projecting a large diesel pick-up truck would need 90% NOx control to meet SULEV targets. Delivering such NOx reduction efficiencies was thought to be very difficult, but LD SCR systems surpassed this efficiency in 2009. However, the projection had pick-up truck engine-out NOx levels at half of where we are today, so today's big pick-ups might require 95% NOx reductions to meet SULEV requirements.

On the gasoline side, direct fuel injection was also emerging, with the first mass-produced engine being a lean-burn engine from Mitsubishi introduced in 1996. By 2001 a half-dozen other manufacturers had at least one GDI engine, with all but one (Renault) being lean. Technologies to drop SULEV emissions by an order of magnitude (exhaust cleaner than city air) included low-mass exhaust manifolds, lean cold-start with ignition delay to 8° ATDC, cylinder-by-cylinder air-fuel control enabled by a 32-bit ECU, UEGO oxygen sensors, VVT, and a 1200-csi palladium close-coupled catalyst (plus a large under-body catalyst). In 1997, full gasoline hybrids were very much in discussion, and projected to deliver 60 to 80 MPG (3 to 4 l/100km) in a mid-size car.

Almost all projected technologies from this timeframe for CO_2 reductions have been implemented: VVT, cylinder de-activation, variable compression ratio, electric-assist turbocharging, GDI, full-HEV, and a 48 volt starter-generator (coming now). There was no discussion on cooled-EGR, increasing specific power ratios (downsizing as we know it today), nor mild hybrids, all of which are leading approaches for fuel consumption reductions today.

Heavy-duty diesel engines of fifteen years ago used electronic unit injectors and turbocharging, but had no aftertreatment or EGR. In 2001, projections were emerging showing that Euro IV and V emissions might be met without DPFs but needed 65 and 80% efficient SCR accordingly. One projection showed that with some effort Euro V (2.0 g/kW-hr NOx, 20 mg/kW-hr PM) might be met without any NOx aftertreatment. This never happened, perhaps not even in the lab, as aftertreatment technology quickly emerged as a better route. In the US, projections for US2007 called for both NOx and PM aftertreatment. The EPA started a big demonstration program on LNTs to meet this need. EGR engines eventually evolved, cutting NOx about 50% from their first introduction in 2002, enough to meet US2007 needs. HD DPFs were first applied in October 2005 in Japan and then in 2007 in the US. Europe implemented SCR a couple years ahead of Euro IV, and Japan followed in 2005.

Aftertreatment

The most significant aftertreatment distinction of the 1997-2001 period was the major shift from gasoline emission control to diesel. Gasoline pathways to meet the tight emissions regulations were available – close-couple catalyst, high-cell density and/or low-mass substrates, and feasible engine control strategies. In 1997, conference sessions on gasoline emission control were packed, but diesel emissions conferences were emerging. That all changed in 1999 when Peugeot introduced LD DPFs and European and US HD regulations were emerging, requiring lean NOx control.

Much of the early work on lean NOx control in this period was aimed at lean-burn gasoline. Iridium NSCR catalyst, as used in the first lean-burn GDI engines, were achieving 60% deNOx at 200-400C and a 45,000/hr space velocity, but required a very high 14:1 HC:NOx ratio. They had terrible durability. LNTs were reported at 80 and even 95% efficiency at SVs 30-35,000/hr over 250-450C, but 60 seconds of rich operation was needed for every 60-120 second lean. More realistic rich/lean modulations dropped deNOx efficiency to 35-50%. Desulfation at 650C was required for about 3 minutes to remove 80-90% of the sulfur, and staged desulfation events using lambda and temperature, and even sulfur traps, emerged in 2000. By 2001, LNTs were being integrated with DPFs and went commercial in Europe in 2003. This was the first-ever diesel vehicle application to use NOx aftertreatment. SCR catalysts were almost all vanadia-based, and achieving 70% deNOx efficiency on vehicles and 80% in laboratories at 200-500C and 60,000/hr space velocity. The pesky on-board urea requirements stifled much work on them until maybe 2000, when one of the European engineering companies declared that a 65% efficient SCR-only system could save ~5% of fuel versus alternative approaches to meeting Euro IV. Urea appeared not to be as bad as thought. Zeolite SCR catalysts first emerged in the engineering literature at this time in a LDD application. Finally, non-thermal plasma work was of some interest in this period for NOx control, coming in at up to 80% deNOx efficiency at a 5% fuel penalty in the 100-500C temperature range.

DPFs and particulate measurement methods quickly evolved in this period, primarily due the market need for them in the LDD sector, but also because of the HD regulatory requirements coming in 2005+. Throughout the 90's cordierite was the main filter material and used only in retrofit applications. SiC emerged for the LDD sector in this period, but cordierite remained the leading HD DPF material. However, through 2001 much of the effort was on DPF regeneration. The concept of balance-point temperature was first reported at 325-375°C with catalyzed filters. The effect of EGR on the "CRT effect", which uses NO_2 to burn soot, was described. (The first commercial CRT application went into bus retrofits in 1995.) Refinement of how particles are measured in the tailpipe was needed to quantify DPFs, and government labs validated a COV of 10% at 10 mg/kW-hr PM and 30% at 1.5 g/kW-hr. Two reports in 2000 showed that although DOCs and SCR dropped PM, they had no effect on particle number. PN experiments reported in 2000 showed consistency in measuring solid ultrafine particles, but the small nucleation mode particles (<30 nm) showed significant variability with time, ambient temperature, and dilution rates. A few years later Europe added a LDD PN regulation on solid particles >23 nm to Euro 5.

Although there was a clear shift to diesel emissions technologies in this period, gasoline emissions control was advancing quickly. In 1997 and 1998, to support the need for clean fuels in the upcoming regulations, numerous reports showed the deleterious effects of fuel sulfur on advanced catalysts and sensors. Catalysts were being optimized for various applications in terms of Pt, Pd, and Rh balance. In 1999 the first technology reports surfaced on Pd/Rh TWCs, with Pt removed altogether. This is the period when exotic rare earths were being doped into the OSC. Substrates also evolved quickly, with a major competition occurring between metal and ceramic substrates. The trade-offs between surface area (high cell-density), thermal mass (thin walls), positioning, volumes, and catalyst loadings dominated the literature in this period. The first reports on gasoline PN emissions came in 1999, with a commercial engine of the period showing levels similar to unfiltered diesel. PFI had generally low PN emissions, but spikes on acceleration were approaching diesel levels. It took 18 years to get this into European regulation on GDI engines that will force emissions technologies (engine or aftertreatment). California lags, wherein their PM regulation doesn't become effective until 26 years after this initial discovery. By this time, half of the car parc could be GDIs. In this period there were reports about an air separation membrane for vehicle applications, a vacuum-insulated can that dropped real-world emissions but had little impact in certification testing, and a substrate with a cone-shaped inlet face to help exhaust gas distribution. None of these technologies made it into the market, yet.

Wrap-Up

Since the start of CLEERS, the automotive industry has faced a total tightening of emissions standards of about 97%. HD trucks and non-road equipment faced similar reductions over the same time period. The challenges are continuing as the LEVIII and US Tier 3 implementation proceeds through 2025, the EU shifts to an emphasis on LD real-driving emissions (RDE), and the California HD and European NR sectors tighten further. This progress occurred simultaneously with fuel consumption reductions: LD GHG emissions have dropped about 25-30%, with further reductions being required on the order of 25-30% through 2021; and HD engine fuel consumption has dropped about 10% with further reductions coming, perhaps another 10% through 2025. The research community played a key role in these remarkable developments, and the engineering community will increase their reliance on them going into the future. Keep up the impressive work!