industry: diesel
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Meeting Tighter Emissions Limits While Improving Diesel Engine Efficiency

New environmental legislation has created an engineering challenge for heavy-duty diesel engines. CO2 and NOx emissions must fall below stricter standards; at the same time, greater engine efficiency has resulted in a corresponding loss of exhaust gas temperature, leading to lower catalytic activity. This is particularly concerning when it comes to NOx emissions for Cold Start and Low Load Cycles, as there is a lot of thermal inertia in the aftertreatment system.

Many of the solutions put forward to meet these stricter standards are engine-based. While they have been import contributions, it might be that we are reaching the limit of what these can do in terms of NOx emissions reduction. To achieve the newer, stricter standards, automobiles and trucks will need to look at other elements of the system—specifically, adding heat to exhaust to increase catalytic activity.

Such an advanced heating strategy has already been shown to be the most efficient means of meeting these NOx emissions standards. In fact, a small heater placed at the intake of the aftertreatment system enables its rapid and efficient heating, even during cold start and low load operating conditions. Having a practical means to power and control such a heater has been a barrier for implementation, however.

More recent testing has shown that a small heating element, using only conventional alternator or battery power, can be effectively used to heat the exhaust and meet emissions standards in vehicles typically operated in a city (road sweeper and city bus). Integrating these heaters into new designs might be the final piece of the puzzle in bringing diesel engines into compliance with the current laws—and an innovative way to make them more efficient as well.

Heat tends to make things less efficient, not more. While this statement is a good starting point (and something engineers would agree with), it is not always true—indeed, heat might be the key to more fuel-efficient, environmentally friendly diesel engines for tomorrow's heavy-duty vehicles.

Specifically, using a small electric heater in the aftertreatment system of a heavy-duty diesel vehicle might be the key to solving a lurking engineering problem brought on by environmental legislation in both Europe and the United States.

Granted, government regulation of vehicle emissions is nothing new. Various pieces of legislation have addressed CO2, NOx, volatile organic compounds, and particulate matter levels in emissions, as well as other pollutants, both in the U.S. [1] and Europe. It is not surprising, then, that there should be regulations affecting heavy-duty diesel vehicles.

What is new and surprising is the dramatic decline in emissions that is required by more recent rounds of legislation on heavy-duty vehicles. Whereas in the past, manufacturers of heavy-duty vehicles have been able to meet emissions standards by making small, incremental improvements in the engines themselves, these newer, stricter standards will require more of a "systems" approach because of the engineering challenges involved.

The data being generated are beginning to prove the success of this systems approach, including the counterintuitive idea of drawing power from the engine to heat engine exhaust.

Legislative Limits, Engineering Challenges

Before looking at the technology involved, it would help to understand the legislative context in which these technologies are being developed. Newer environmental legislation, passed both in Europe and in the U.S., has created a particular engineering challenge for diesel engines, especially those used in heavy-duty vehicles (such as trucks and buses).

In Europe, emissions regulations began in 1992, with the latest round—Euro 7—set to go into effect in September of 2020. (The most recent round, Euro 6, went into effect in 2015.) The new Euro 7 standards set a CO2 emissions target of 95 g/km, a 27% lower standard than the existing Euro 6 standard. Emissions limits are based on the mass of the vehicle, using a limit value curve. The new law states that all vehicles operating in Europe must be compliant (in accordance with the limit value curve) by 2021. Manufacturers that do not meet that deadline will have to pay a penalty for excess emissions.

Stage	Date	CO	NOx
		Measured in g/kWh	
Euro I	1992, ≤ 85 kW	4.5	8.0
	1992, > 85 kW	4.5	8.0
Euro II	1996.10	4.0	7.0
	1998.10	4.0	7.0
Euro III	1999.10 EEV only	1.5	2.0
	2000.10	2.1	5.0
Euro IV	2005.10	1.5	3.5
Euro V	2008.10	1.5	2.0
Euro VI	2013.01	1.5	0.40

PM = 0.13 g/kWh for engines < 0.75 dm3 swept volume per cylinder and a rated power speed > 3000 min-1

Table A: EU Emissions Standards for CO and NOx for heavy-duty CI (diesel) engines. From https://www.dieselnet.com/standards/eu/hd.php

In the U.S., the California Air Resources Board (CARB) has mandated that any heavy-duty diesel vehicle operating in the state of California needs to meet strict requirements for toxic air contaminants coming from their exhaust systems. Specifically, heavy-duty vehicles will be limited in their NOx emissions to just 0.05 – 0.08 g/bhp-hr starting in 2024, and eventually 0.02 g/bhp-hr by 2027. This is a particularly ambitious emissions standard, as it can easily be exceeded by vehicles in the initial phases of the Cold Start Cycle. This, the first 300 seconds of the Cold Start Cycle, will be critical in achieving the standard.

It is currently unclear whether the U.S. Environmental Protection Agency (EPA) will follow suit with similar standards—but it remains an open possibility.

Complicating both of these laws is the need to test diesel engines under real-world conditions. In 2016, the Commission Regulation (EU) amended their emissions standards to include Real Driving Emissions (RDE) tests. These tests are meant to prove that engines are meeting emissions standards, not only under laboratory conditions but also under “real-world” driving conditions. California, while not requiring such tests, has mandated that on-board controls on heavy-duty vehicles must, by 2022, be able to collect and store emissions data and thereby prove their ongoing compliance with emissions standards.

Governments regulating the amount of CO2 and NOx emissions from vehicles is nothing new. The industry has become accustomed to developing innovative new technologies to meet government standards, especially when it comes to the efficiency of engines themselves.

Unfortunately, manufacturers are beginning to reach the limit of what they can do with standard approaches. In fact, the new standards from Euro 7 and CARB have revealed an underlying engineering problem.

As engines have become more efficient, there has been a corresponding drop in the temperature of exhaust gas, leading to lower catalytic activity. This is particularly concerning when it comes to NOx emissions for Cold Start and Low Load Cycle, as there is a good deal of thermal inertia in aftertreatment systems. In other words, as engines themselves have become more efficient, aftertreatment systems have become worse at removing NOx from emissions.

Thus, to meet these new emissions standards, new aftertreatment architectures are needed. These will need to be incorporated into designs now to meet these stringent emissions standards in the near future.

Systems Approaches

Many of the solutions put forward to meet these stricter standards are engine-based. While many of these are import contributions, it might be that we are reaching the limit of what these can do in terms of NOx emissions reductions. Some engineers are thus exploring other elements of the system, particularly when it comes to increasing the catalytic activity in the aftertreatment system itself. The idea is that it will take many solutions, in combination, to achieve these strict standards.

The catalysts in question reside in the Selective Catalytic Reduction (SCR) filter in the aftertreatment system, downstream of the Diesel Oxidation Catalysts (DOC) and Diesel Particulate Filters (DPF). (Note, though, that a few diesel engines lack an SCR.) The DOC and DPF are thermal reservoirs, and thus tend to absorb a significant amount of heat until warmed up. It can take up to 300 seconds for the SCR to reach a temperature at which the catalyst will efficiently remove NOx from exhaust gas.

There have been several approaches to this problem using passive exhaust thermal management technologies, most notably insulating the downpipe, close-coupling the aftertreatment system, and reducing the thermal inertia of the DOC and DPF [2]. Of these, only the last has been shown to have any significant effect on SCR temperature and efficiency. This suggests that a more active approach is needed.

What kind of active approach? There are several that have been tested in combination with each other, including application of an electrically heated catalyst, mini-burners, fuel dosing, passive NOx absorbers (PNA), and ammonia injection [3]. These tests indicate that an advanced heating strategy that uses a pre-DOC electric heater (along with fuel-dosing) was shown to be the most fuel-efficient means of meeting the low NOx standards as set out by CARB.

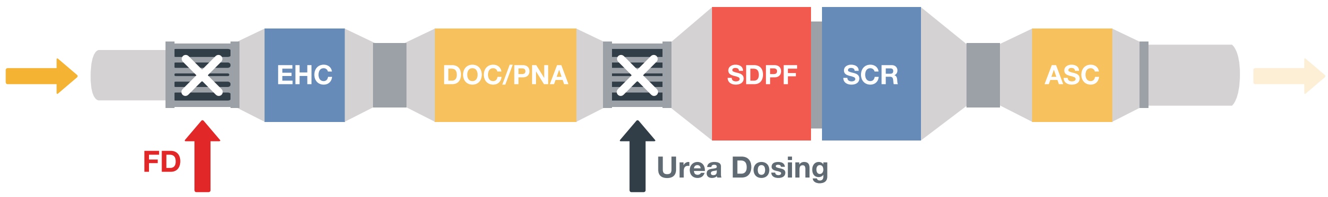

Figure 1: Setup of an Ideal Aftertreatment System with an Advanced Heating Strategy.

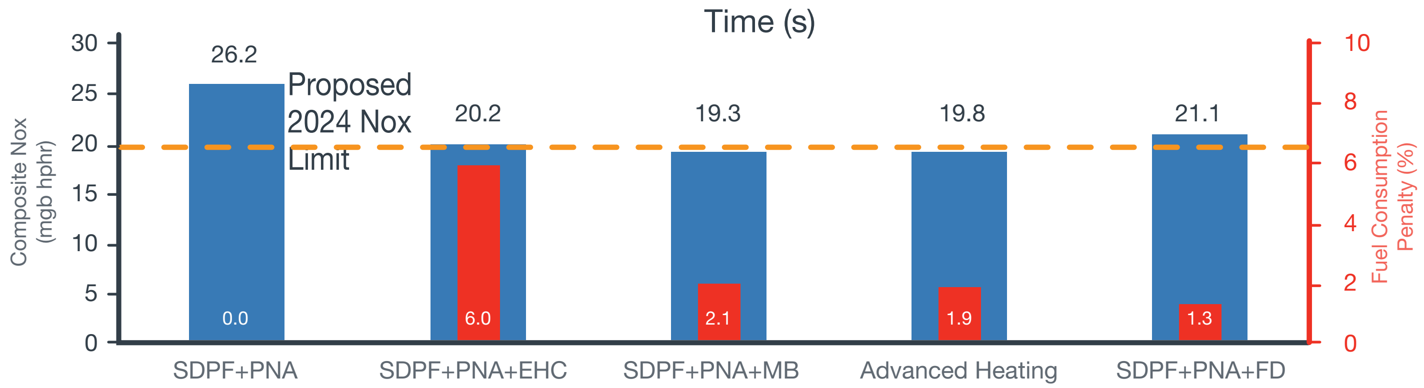

Figure 2: Emissions and Fuel Efficiency Results from Active Heating Measures. From [2]

Indeed, a joint project between CARB and the Southwest Research Institute (SwRI) has shown that approximately 10 kW of additional thermal energy is required to achieve Cold Start NOx emissions anywhere near the 2027 goal of 0.02 g/bhp-hr [4].

Road Testing Electric Heaters

Creating models to prove the benefits of using a pre-DOC electric heater are one thing. Actually proving that such a heater can reduce NOx emissions in road test (RDE) conditions is another. Not only must the effects of lowered emissions and better fuel efficiency have to be validated, but a practical means for controlling the heater and providing power must be provided as well. To date, these have been barriers to implementation.

Our research team set out to test such a system, using Watlow's ECO-HEAT Exhaust Heating System in a 2017 Cummins ISB 6.7L. Setup of the system is given in Figure 3. These tests included a Heavy-Duty Federal Test Procedure (FTP) Cycle (for setup and calibration only), a Partial City Bus Cycle, and a Road Sweeper Cycle [5].

Here, the ECO-HEAT is a 24V (or 48V) heater that draws power from the alternator to operate when exhaust gas temperatures are too low. As Figure 3 indicates, it fits easily within the aftertreatment system footprint. This heater was also coupled with a smart power switch to control the heater based on ECU information.

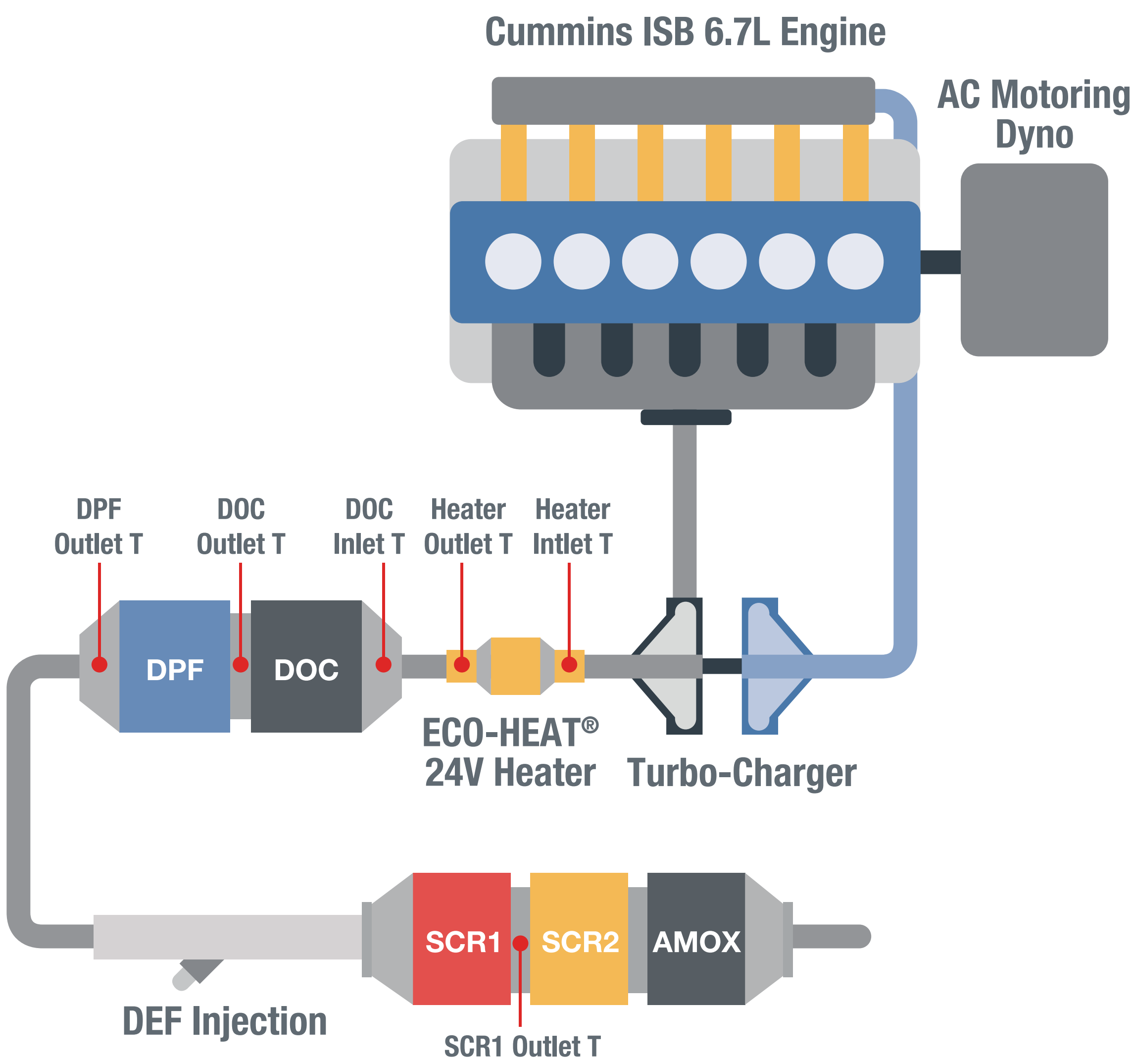

Figure 3: Diagram of Aftertreatment System Used in Testing.

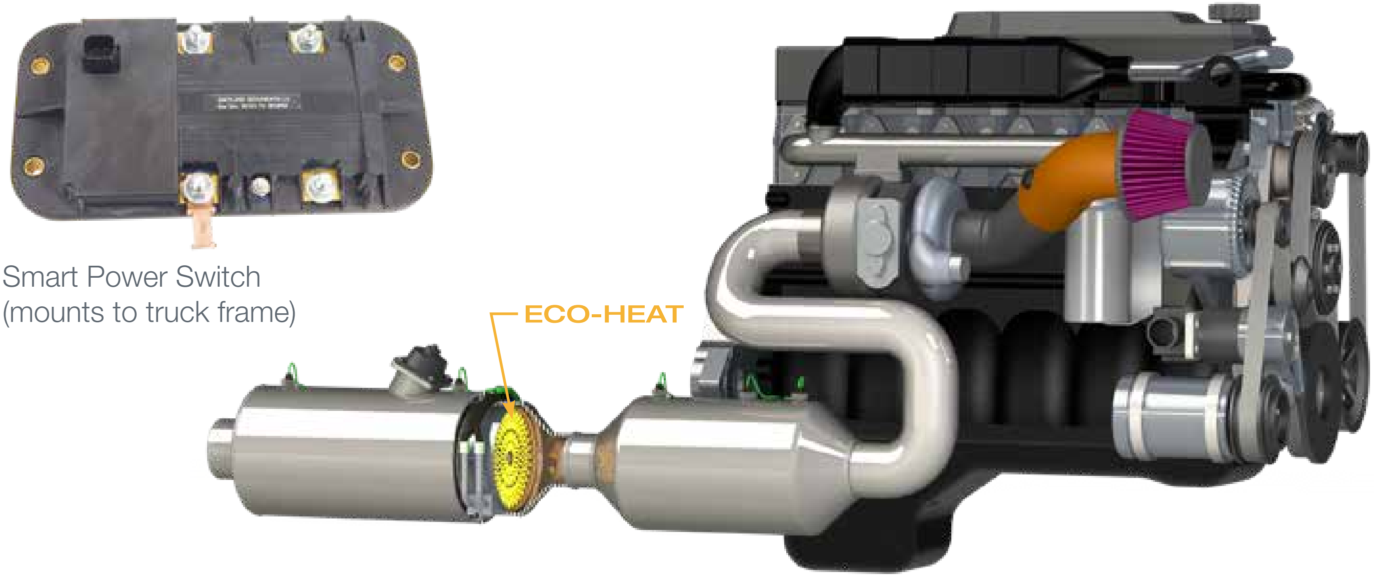

Figure 4: Engine with ECO-HEAT and Smart Power Switch.

Initial Heavy-Duty FTP Cycle

The initial Heavy-Duty FTP Cycle showed that the heater allowed the system to reach target temperature for DOC intake at about 260 seconds. Average heater power was 2.6kW for the first 410 seconds and 0.9kW for the entire cycle.

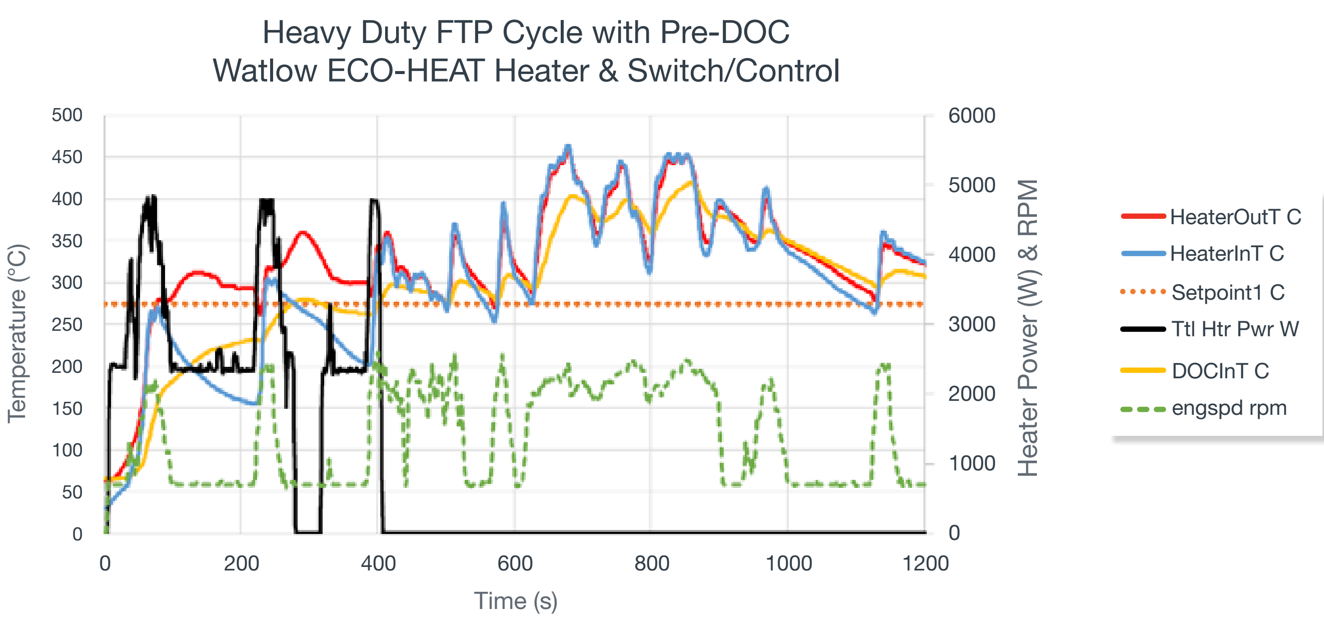

Figure 5: Heavy-Duty FTP Cycle.

City Bus Cycle

The City Bus Cycle differed in some key ways from the Heay-Duty FTP Cycle. Most importantly, the engine was subject to repeated starts and stops, to simulate the operation of an actual city bus. Engine speed ranged from 680 rpm to 2040 rpm in a cyclic pattern, with exhaust mass flow following a similar pattern.

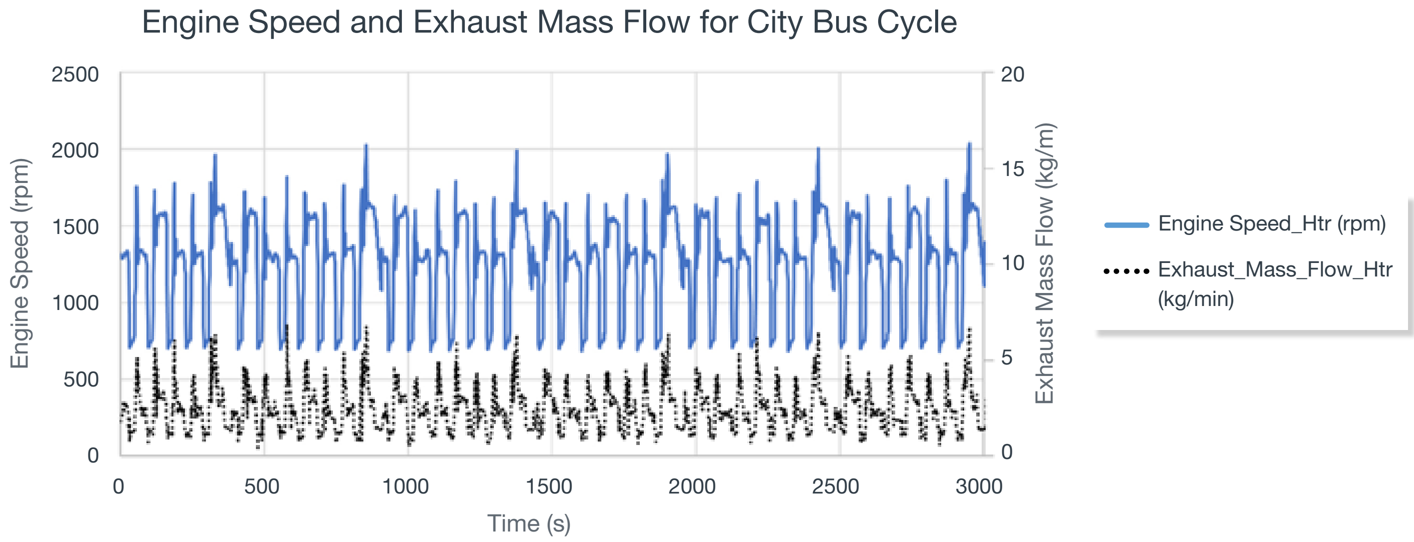

Figure 6: Simulating a City Bus, With Frequent Starts and Stops.

In this test, the average temperature of the exhaust entering the DOC without heating was 208˚C. The heater drew power in a way that was cyclic, ramping up when engine speed decreased. With the heater, exhaust entering the DOC was kept at a stable setpoint temperature of 275˚C. The important finding in this test was that the inlet temperature for the SCR was increased by approximately 45˚C while using the heater.

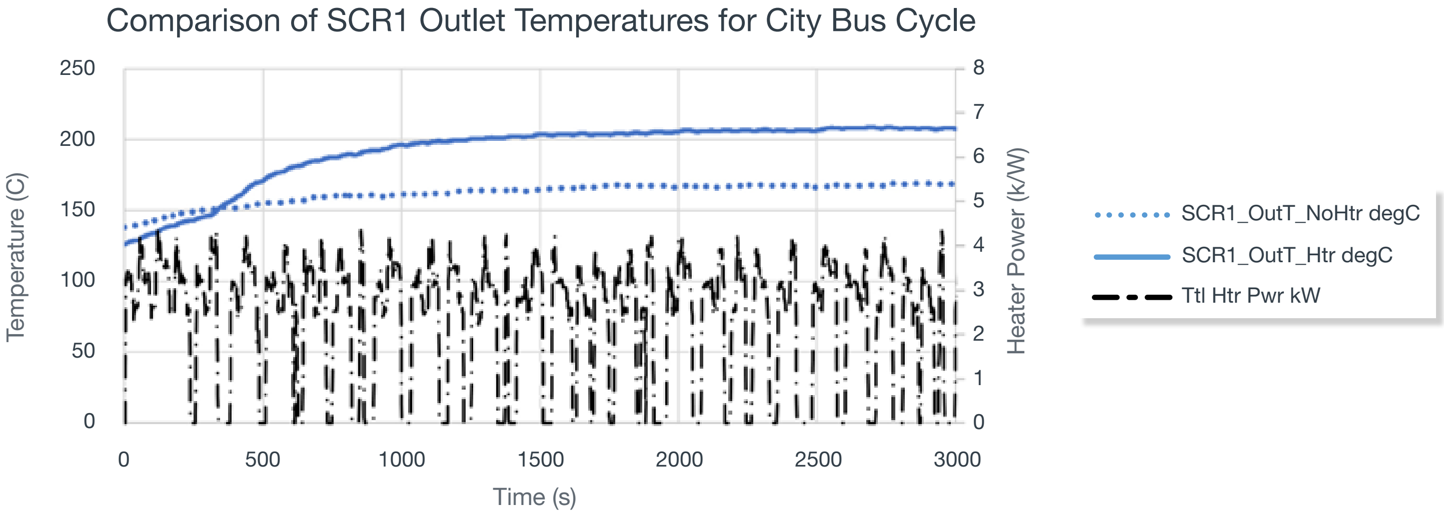

Figure 7: SCR Outlet Temperatures for City Bus Cycle.

Road Sweeper Cycle

In the Road Sweeper Cycle, engine speed and exhaust mass flow was much less cyclical. The goal was to simulate intermittent periods of higher load and extended idle. Engine speed ranged from 600 prm to 1920 rpm.

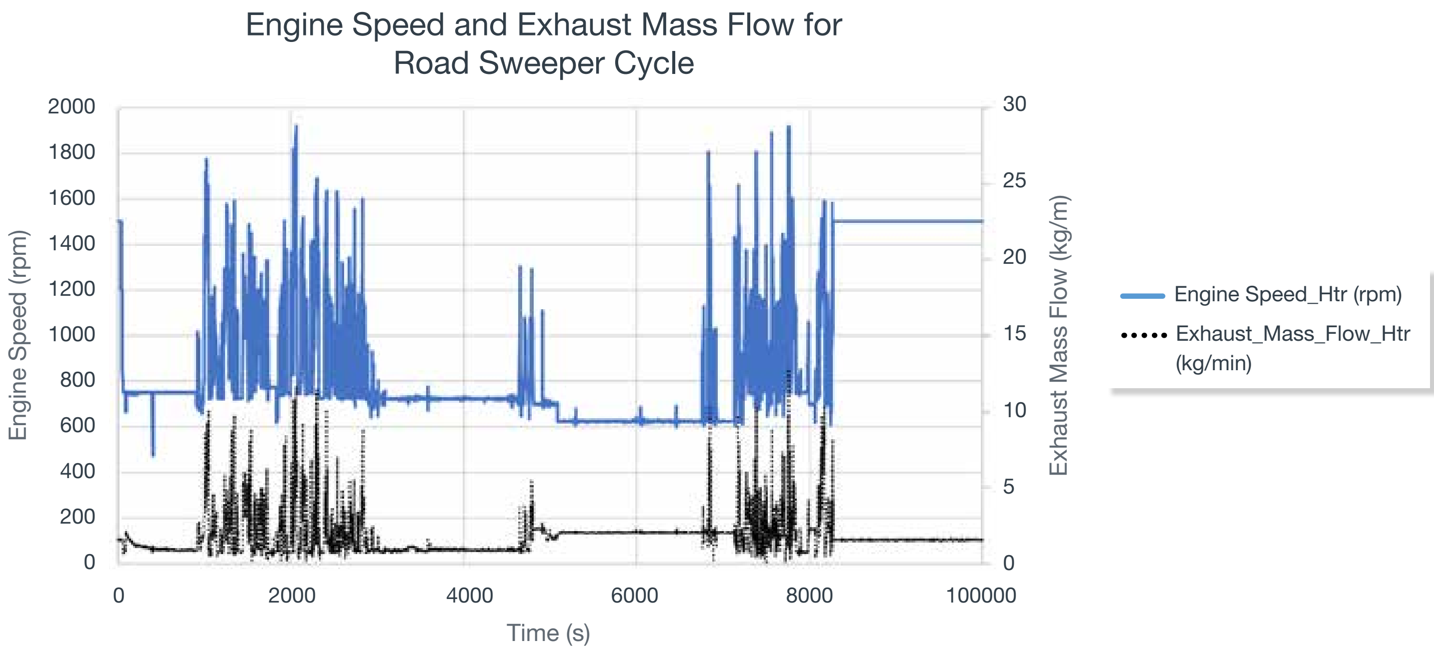

Figure 8: Simulating the Activity of a Typical Road Sweeper.

What we found in this test cycle was that, when the heater was not used, the system took much longer to reach the setpoint temperature during the Cold Start portion of the cycle, from 0 to 1000 seconds (which was expected). Additonal heat from the heater was also required between 3000 and 5000 seconds, a bit after the engine began to idle. At 2500 seconds, the DOC Inlet temperature began to drop; in the no-heater condition, that temperature crosses below the 275˚C setpoint at the 3000-second mark and reaches a low of approximately 12˚C at 4700 seconds.

In the heater condition, however, the temperature is maintained at no lower than 248˚C, and returns to the setpoint much more quickly than in the no-heater condition.

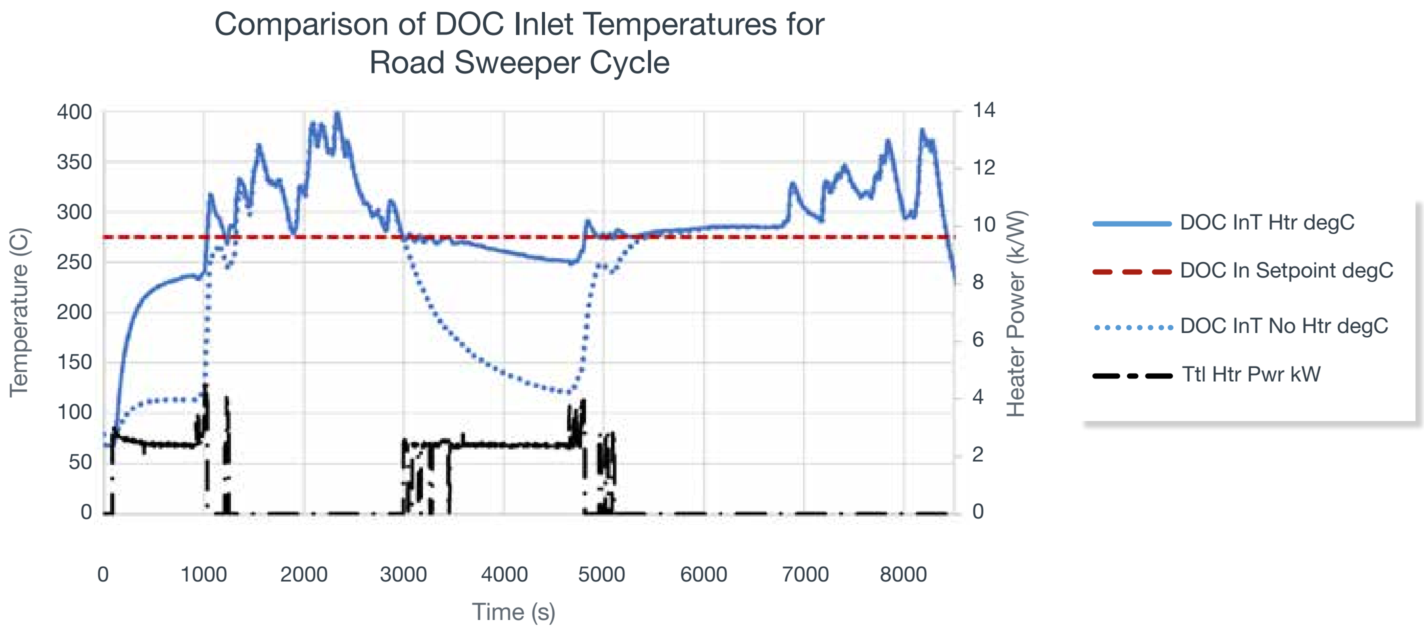

Figure 9: DOC Inlet Temperature With and Without Heater in the Road Sweeper Cycle.

We should note here that, in all test cycles, the increased load from the heater did lead to slightly higher Engine-Out (EO) NOx emissions. But this was more than compensated for by the improved conversion efficiency, leading to an overall reduction in System-Out (SO) emissions.

These tests prove several things. First, a small electric heater can draw power from the alternator when needed, adding heat directly to the exhaust in the aftertreatment system. Second, this method is an effective means of significantly raising the intake temperature to the SCR, a task that has been proven difficult by other means. Third, it is clear that this increase in exhaust temperature leads to lower SO NOx emissions, due to the increased catalytic activity in the SCR.

Addtionally, these tests show that it is possible to both power and control the heater in a straightforward way. Engine activity changes over time, especially for vehicles like buses and trucks. An efficient electric heater would need to add the appropriate amount of heat at the appropriate time in order to achieve the above effects in the most efficient way possible. The City Bus Cycle data and Road Sweeper Cycle data bear this out.

Conclusion and Outlook

Anyone designing a heavy-duty diesel vehicle for the European or U.S. markets needs to be aware of the strict standards imposed by recent environmental legislation. Meeting these strict standards will require more—much more—than simple tweaks to engine efficiency. As argued above, a systems approach is needed. Research strongly suggests that an integral part of this approach will be the addition of a small electric heater to aftertreatment systems, which will help boost catalytic activity in the SCR.

So what does this mean for engine developers? And what does it mean for auto industry leadership at large?

When the details of Euro 7 were announced, some environmental advocates expected that the new regulations would finally push diesel engines out of the market. While this downturn has been slower for heavy-duty vehicles, it is rapidly approaching as vehicle makers struggle to design engines that can meet the new stricter standards.

It is easy, then, to be pessimistic about the future of diesel. But innovation has a way of turning markets around, and companies that embrace innovation survive trying times better than their competitors. High-efficiency diesel engines will continue to serve as a bridge until cheaper electric alternatives are more widely available, and the profits on diesel vehicles easily justify the cost of innovation. Who would have guessed that the proof of this idea lie in a small electric heater?

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