HEAVY-DUTY DIESEL VEHICLE NO_X AFTERTREATMENT IN 2010: THE INFRASTRUCTURE AND COMPLIANCE CHALLENGES OF UREA-SCR

By

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Submitted to the Department of Mechanical Engineering
and the Engineering Systems Division
in Partial Fulfillment of the Requirements for the Degrees of
Master of Science in Mechanical Engineering
and Master of Science in Technology and Policy

at the
Massachusetts Institute of Technology

February, 2008

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ABSTRACT

Increasingly stringent heavy-duty vehicle emission regulations are prompting the use of PM and NO_X aftertreatment systems in the US, the EU and Japan. In the US, the EPA Highway Diesel Rule, which will be fully implemented in 2010, has stimulated debate over whether urea selective catalytic reduction (urea-SCR) or lean NO_X traps (LNT) are the better NO_X aftertreatment approach for meeting this new standard. And, if urea-SCR is indeed the preferred option, how can its compliance and infrastructure challenges be overcome during the relatively short window of time between now and 2010. This thesis begins by performing a comprehensive technical and economic assessment of urea-SCR and LNT aftertreatment to determine which technology is more appropriate for use in heavy-duty vehicles and how sensitive that judgment is to changes in key variables, such as the price of urea. The focus then shifts to an exploration of the various compliance and infrastructure challenges associated with urea-SCR, namely the need to have a replenishable supply of urea. In particular, the actions and policies necessary to surmount those obstacles are discussed. Next, the policies and market factors that played a role in the EU's successful introduction of urea-SCR are examined and assessed for their ability to be applied in the US context. Finally, the long-term viability of urea-SCR is appraised through an investigation of the potential for competing emission control technologies to emerge and the prospect that urea-SCR becomes adopted by the light-duty diesel market. This thesis concludes by offering both a prognosis for what can be expected to occur between now and 2010, given the current course of action, as well as policy recommendations for how that trajectory might be corrected, such that the introduction of urea-SCR in 2010 is achieved with the maximum air quality benefit at the lowest cost.

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CHAPTER 1: PROBLEM STATEMENT

1.1 Motivation

In recent years, the US, European Union (EU) and Japanese governments have implemented a series of increasingly stringent heavy-duty diesel engine emission regulations. These standards are focused primarily on reducing particulate matter (PM) and nitrogen oxide (NO_X) emissions. In the US, PM and NO_X emission thresholds will both be reduced by approximately 90 percent from 2004 levels within the 2007-2010 timeframe (US EPA 2001a).

Diesel emission regulations have historically been met through a combination of in-cylinder techniques, such as retarded fuel injection timing and cooled exhaust gas recirculation (EGR). It is generally accepted that further improvement in these and other in-cylinder technologies will no longer be sufficient and that post-combustion aftertreatment systems, like filters and catalytic converters, will be required to meet further reductions in emissions.

On January 2007, the first phase of the US EPA Highway Diesel Rule, referred to hereafter as the 2007 Highway Rule, was introduced. US engine manufacturers unanimously chose to meet its significantly lower PM threshold and moderately lower NO_X requirement by incorporating diesel particulate filters (DPFs) and more extensive use of EGR into their engine designs. The 2007 Highway Rule will become fully implemented in 2010, at which point the NO_X standard will be ratcheted down even further.

There are currently two candidate aftertreatment technologies that have the potential to comply with the challenging 2010 NO_X limit: urea-selective catalytic reduction (urea-SCR) and lean NO_X traps (LNT). Superior durability and lower projected lifetime costs make urea-SCR the favored technology among many heavy-duty engine manufacturers. Unlike LNT, however, urea-SCR requires the continuous injection of a urea and water mixture into the exhaust stream for the system to function properly.[1]

The need to carry urea on-board heavy-duty vehicles introduces significant compliance and infrastructure challenges. Compliance is a concern because the driver of a urea-SCR equipped vehicle has no inherent incentive to refill their vehicle's urea tank. Although an empty urea tank does not impact vehicle performance, it does cause vehicles to emit NO_X at a significantly higher rate.

Likewise, drivers will need to have a convenient way to locate urea and refill their tanks. Implementing an infrastructure for distributing urea is challenging because it cannot simply co-evolve with the introduction of urea-SCR vehicles. It must be robust and fully functional even before the first vehicles enter the market. The concern among potential urea retailers, such as truck stop owners, is that the demand for urea will be insufficient to pay back the capital investment required to install the requisite storage and dispensing equipment. This concern is exacerbated by the potential for alternative NO_X control strategies (i.e. ones that do not require a separate fluid like urea) to displace urea-SCR in the foreseeable future.

1.2 Objectives

This thesis has several objectives. The first objective is the completion of a comprehensive technical and economic assessment of the aftertreatment strategies that have the potential to meet the 2007 Diesel Rule's 2010 NO_X emission threshold. The second objective is to fully explore the compliance and infrastructure challenges associated with the currently favored technology, urea-SCR. The goal of this task is to understand what actions and policies need to occur, and by when, for urea-SCR to be

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[1] Throughout the remainder of this thesis, the word "urea" will be used to reference the 32.5 percent urea mixture (diluted with water) that is commonly used as a reagent in mobile SCR systems. When referencing urea in its distilled form, the term "pure urea" will be used.

successfully implemented by 2010. Lastly, emerging emission control technologies and the potential introduction of urea-SCR into the light-duty diesel vehicle market are examined to assess how future developments could impact the long-term viability of urea-SCR and therefore, the current decision of whether to invest in the infrastructure for distributing urea.

1.3 Thesis Overview

Chapter 2 provides the context within which the 2007 Highway Rule was introduced. It begins by defining the term "heavy-duty vehicle". Next, it discusses this class of vehicle's historical contribution to air pollutant emission levels in the US. Third, the current round of US, EU and Japanese heavy-duty vehicle emission regulations are described. The chapter closes by reviewing the industry's use of emission control defeat devices during the 1990s. In particular, it focuses on the repercussions this incident had on the relationship between engine manufacturers and EPA, as well as on the competitive strategies of engine manufacturers with respect to emission compliance.

Chapter 3 reviews the most recent literature on the aftertreatment technologies that are candidates for meeting the 2010 NO_X threshold, urea-SCR and LNT. This chapter also contains a section describing the production, current demand, specifications, and human health and environmental implications of urea. Finally, it concludes with a comprehensive lifetime cost comparison of urea-SCR versus LNT.

Chapter 4 examines the compliance and infrastructure challenges associated with introducing urea-SCR by 2010. It begins by discussing the various stakeholder positions, the ability of these groups to influence urea-SCR adoption, and the developments that have occurred to date. This chapter then considers the negotiations that have started to occur between the industry and EPA surrounding the specific urea-SCR compliance and infrastructure criteria that will be required for engine manufacturers to have their engines certified by EPA. It closes by reviewing the most recent study to investigate the business case for introducing a urea infrastructure, highlighting per gallon urea cost projections and potential models and modes of distribution (e.g. underground storage tanks, pre-packaged bottles, etc.).

Chapter 5 examines the recent introduction of urea-SCR equipped heavy-duty vehicles into the EU market. It reviews the policies and market factors that made it possible for urea-SCR to be introduced successfully. In particular, the industry's strategy for mobilizing urea stakeholders, EU regulatory policy, and country-level early-adoption incentives are analyzed.

Chapter 6 describes the influence that emerging and alternative NO_X control technologies, such as so-called "advanced combustion" and novel LNT/SCR combined configurations, are expected to have on the decision to introduce urea-SCR in 2010. This chapter also examines the effect that urea-SCR adoption by light-duty diesel vehicles could have on the viability of urea-SCR in the heavy-duty fleet.

Chapter 7 concludes by offering a prognosis for how the urea-SCR issue can be expected to unfold as 2010 approaches. It also provides several recommendations for facilitating successful implementation.

CHAPTER 2: HISTORICAL CONTEXT

2.1 Heavy-Duty Vehicle Definition

In the US, heavy-duty vehicles are defined as commercial vehicles having a gross vehicle weight rating (GVWR) over 8,500 lbs. in the federal jurisdiction and over 14,000 lbs. in California (Majewski and Khair 2006).[2] Heavy-duty vehicles are further subdivided into classes by weight, ranging from Class 2 (e.g. Ford F-350 Super Duty pickup) to Class 8 (e.g. 18-wheeler tractor-trailer).[3] Most heavy-duty vehicles are trucks with diesel engines. Accordingly, the eight weight classes are often aggregated by either truck or engine size categories. Table 1 depicts the various heavy-duty vehicle weight classes, aggregating schemes, and several relevant statistics on the US fleet. As the vehicle stock, annual travel and fuel economy figures reveal, heavy heavy-duty diesel (HHDD) vehicles have an important impact on both fuel use and emissions.

Table 1: Heavy-duty Vehicle Classifications and Statistics

Class	GVWR (lbs.)	Truck Category	Diesel Engine Category	Vehicle Stock	Average Annual Travel (mi.)	Average Fuel Economy
1	< 6,000	Light Trucks	Light and Medium Duty	51,941,389	11,882	17.6
2	6,001 - 10,000		Light Heavy-Duty (starting at 8,500 lbs)	28,041,234	12,684	14.3
3	10,001 - 14,000	Medium Trucks		691,342	14,094	10.5
4	14,001 - 16,000			290,980	15,441	8.5
5	16,001 - 19,500			166,472	11,645	7.9
6	19,501 - 26,000		Medium Heavy-Duty	1,709,754	12,671	7.0
7	26,001 - 33,000	Heavy Trucks		179,574	30,708	6.4
8	> 33,000		Heavy Heavy-Duty	2,153,996	45,739	5.7

Source: (Davis and Diegel 2006; Majewski and Khair 2006).

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[2] GVWR designates the maximum weight a vehicle is designed to carry. It includes the weight of the vehicle plus its load.

[3] Class 1 is used to designate passenger vehicles.

2.2 Contribution to US Criteria Pollutant Emissions

When the Clean Air Act was first passed in 1970, light-duty gasoline cars were responsible for the large majority of air pollutant emissions from highway vehicles. For example, light-duty cars contributed over 85 percent of highway vehicle NO_X emissions in 1970, which represented approximately 35 percent of national NO_X emissions from all sources (US EPA 2001b). As more stringent light-duty gasoline vehicle emission regulations were introduced, the relative contribution from light-duty gasoline vehicles to total highway vehicle emissions decreased significantly. Figure 1 and Figure 2 illustrate this trend for PM_{10} and NO_X, two important mobile-source air pollutants.[4] These figures show that heavy-duty vehicles, which did not come under regulation until 1988, eventually became the dominant source of highway vehicle PM and NO_X emissions. In fact, as of 2002, heavy-duty vehicles were responsible for approximately 55, 65 and 45 percent of highway vehicle PM_{10}, $PM_{2.5}$ and NO_X emissions, respectively (US EPA 2005). On a per kilometer basis, the average heavy-duty vehicle sold in the US in 2007 is allowed to produce 42 times more grams of NO_X and 1.6 times more grams of PM than an average light-duty vehicle (Majewski and Khair 2006; US EPA 1998b).

Emissions of PM and NO_X are undesirable because they impact human respiratory function. Rather than representing a single chemical species, PM consists of a wide variety of diverse substances that exist as discrete particles, either in solid or liquid droplet form over a range of sizes. PM affects breathing by becoming lodged inside lungs. Diesel exhaust, which has historically contained significant concentrations of PM, is considered a human carcinogen by the State of California (California Office of Environmental Health Hazard Assessment 2006). Nitrogen dioxide emissions, on the other hand, affect respiration indirectly. It is a precursor to ground-level ozone or smog, which reacts with and harms lung tissue. Several US and Canadian studies have shown that ground-level ozone is associated with 10 to 20 percent of all summertime respiratory-related hospital admissions (US EPA 2000).

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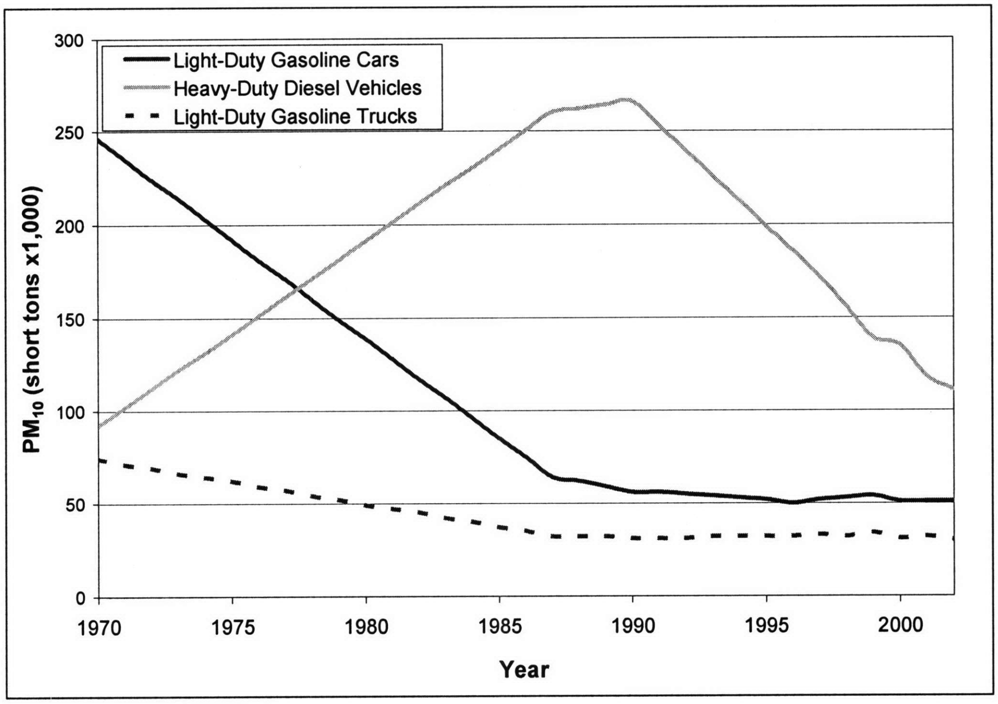
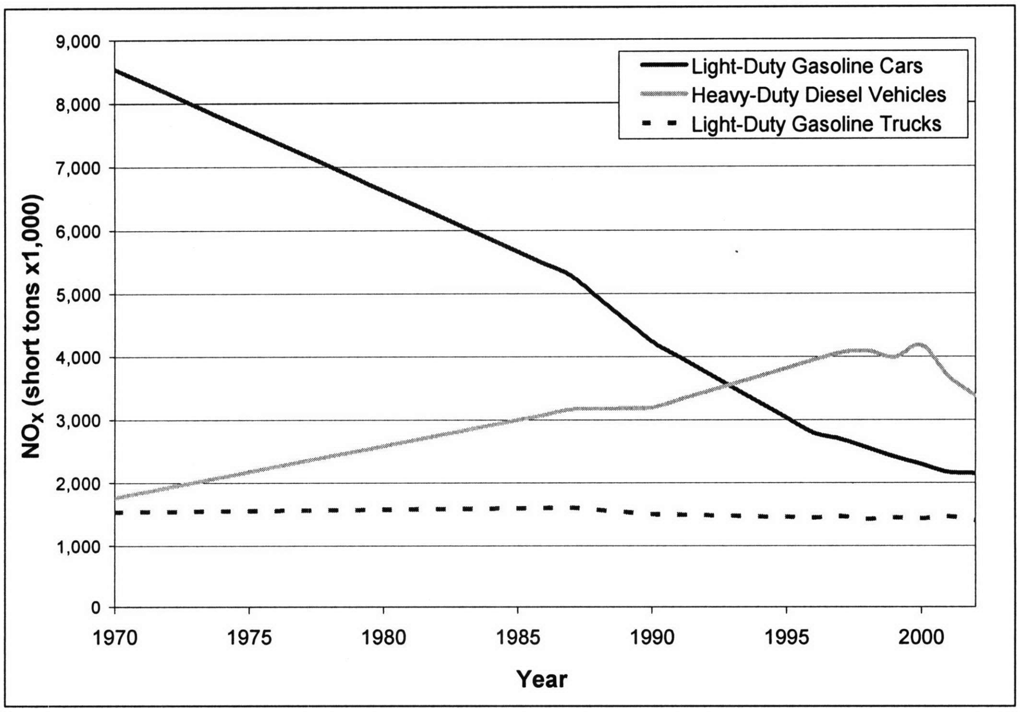
[4] NO_X is a collective term for nitric oxide (NO) and nitrogen dioxide (NO_2). PM_{10} is used to classify particulate matter whose diameter is below 10μm.

Figure 1: PM_{10} Emissions from On-Road Vehicles



Source: (US EPA 2005).

Figure 2: NOx Emissions from On-Road Vehicles



Source: (US EPA 2005).

2.3 Current and Future Emission Regulations

Emission regulations can be characterized by three important components: the emission threshold of the various pollutants; the test procedure that a vehicle or engine is subjected to while its emissions are being measured; and the durability requirements for emission compliance. The US, EU and Japan, are the three regions of the world that regulate vehicle emissions most stringently. It is often the case that other countries around the world choose to adopt one of these region's standards. For example, Australian emission standards are synchronized with Japan's standards, whereas China has chosen to adopt an earlier and less demanding version of the current EU regulations. The four pollutants that have traditionally been regulated from vehicles are PM, NO_X, hydrocarbons (HC) and carbon monoxide (CO).[5] Heavy-duty vehicle emission regulations are primarily geared towards reducing PM and NO_X because these vehicles contribute such a large share of total on-road vehicle PM and NO_X emissions, and because diesel engines, which power the majority of heavy-duty vehicles, do not produce much HC or CO emissions.

2.3.1 PM and NO_X Threshold Levels

The PM and NO_X levels that have been specified in the most recent rounds of US, EU and Japanese heavy-duty emission regulations are shown in Figure 3. The 2007 Highway Rule, which was discussed in Chapter 1, is depicted in Figure 3 as US 2007 and US 2010. First introduced in January 2007, the 2007 Highway Rule will become fully implemented in 2010, at which point the NO_X standard will be ratcheted down even further. By 2010, US heavy-duty vehicles will be required to meet a PM and NO_X threshold of 0.013 g/kWh and 0.27 g/kWh, respectively (DieselNet 2006c).[6] Compared to EU and Japanese emission regulations, the most striking feature about the US 2010 standard is its

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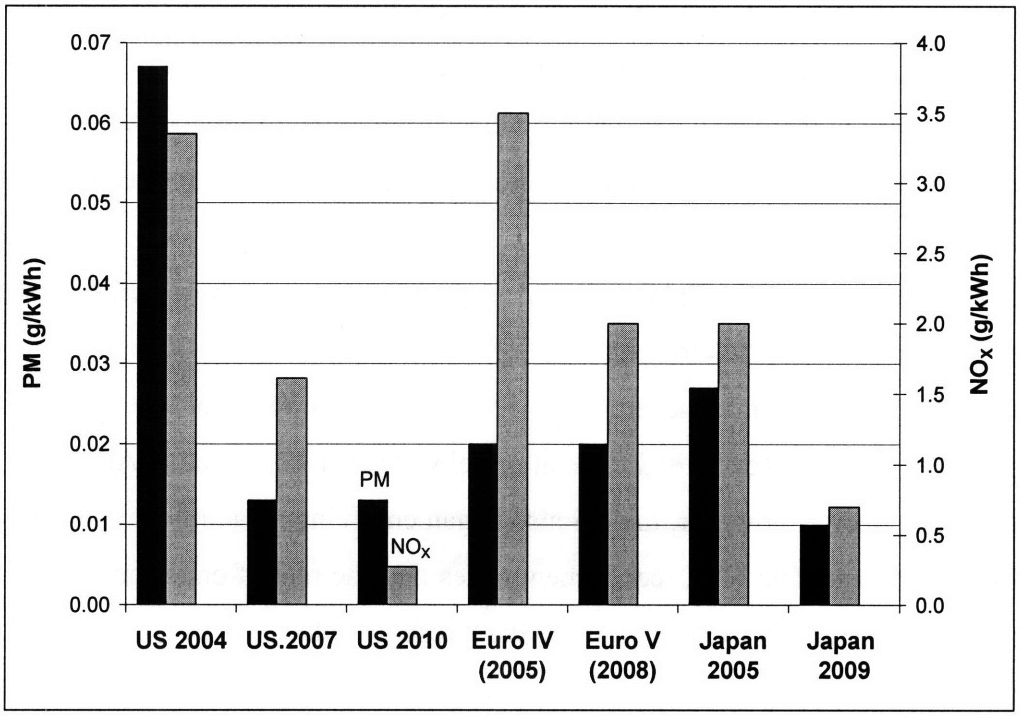
[5] Like NO_X emissions, hydrocarbons are a ground-level ozone precursor. CO is undesirable because it is a colorless and odorless toxic gas.

[6] It should be noted that the European Commission is expected to rule on proposed Euro VI standards, which could introduce emission levels that are on par with US 2010 and Japan 2009 requirements (Johnson 2006). There are many experts, however, who question whether the European Commission would institute considerably more stringent NO_X limits, given the increasing level of concern over CO_2 emissions, which could increase if a lower NO_X threshold were to be enforced (Bunting 2005).

significantly more stringent NO_X requirement. As will be discussed in subsequent chapters, this has important implications on the choice of emission control technology.

Figure 3: Worldwide Heavy-Duty PM and NO_X Emission Regulations



Source: (DieselNet 2006c).

2.3.2 Test Procedures

The second relevant component to an emission standard is its test procedure. It describes under what conditions a vehicle or its engine is required to demonstrate emission compliance to achieve EPA certification. In contrast to light-duty regulations, which specify that vehicles be chassis certified, heavy-duty regulations instead require that the engines themselves be certified using a dynamometer.[7]

Another important feature of an emission test procedure is its test cycle, which is the set of sequential speed and load conditions that an engine is subjected to while its emissions

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[7] A dynamometer is a device whose resistance can be varied to simulate changes in the load being placed on an engine. Its other function is to measure torque and rotational speed, which are then used to determine the power output of an engine. As a result, heavy-duty emissions thresholds are expressed in g/bhp-hr or g/kWh as opposed to g/mi or g/km. This explains why the units in Figure 3 are measured in g/kWh.

are being measured. Essentially, test cycles are designed to simulate the conditions that are typically encountered during real-world driving. In the US, the EU and Japan, engines are required to demonstrate compliance over both a transient and steady-state test. Transient tests are intended to represent urban driving, while steady-state tests simulate line-haul driving on a highway. In the US, the former is called the transient federal test procedure (FTP), whereas the latter is termed the supplemental emission test (SET). The SET gets its name from the fact that it was not introduced until 1998, following the defeat device consent decree, which will be discussed at greater detail in the following section.

A final relevant point on emission regulation test procedures is how emissions measurements are correlated to the threshold levels for individual pollutants. For most of recent history, US, EU and Japanese emission regulations required that the rate of emission averaged over the test cycle had to be at or below the threshold value. After the defeat device consent decree, however, the US also began enforcing an additional not-to-exceed (NTE) requirement. The NTE requirement states that the rate of emission at any point in the test cycle should not exceed 1.5 times the threshold value. As such, even if all three regions had similar threshold levels, the US regulations would still be significantly more challenging to meet.

2.3.3 Durability Requirements

The third important component of all emission regulations are their durability requirements. Durability requirements specify how long, usually expressed in distance or hours of operation, an engine is required to meet an emission threshold. In the US, EU and Japan, manufacturers of HHDD engines are required to guarantee emission compliance for 435,000 mi (696,000 km), 500,000 km, and 650,000 km, respectively. Like the emission threshold itself, durability requirements can impact the choice of emission control technology that is employed. For instance, durability is a particularly important factor when comparing catalytic aftertreatment devices, many of which have a tendency to become poisoned by components like sulfur, which are found in diesel fuel and engine lubricant.

2.3.4 Alternative Compliance Options

Besides meeting emission regulations by complying with the standards that were described above, engine manufacturers have the option of using emission averaging, banking and trading to generate compliance credits. These credits can either be used to meet current or future regulations. For example, an engine manufacturer could decide to introduce engines that comply with the 2010 standard in advance of 2010 to avoid having all of the engines that they sell in 2010 comply with the standard. In fact, Cummins announced in January 2007 that it would provide DaimlerChrysler with 2010 compliant engines for their model year (MY) 2007 Dodge Ram diesel trucks starting in March (DieselNet 2007a). It is anticipated that Cummins will use the credits that it generates to avoid having to certify some of their engine families to the 2010 standard during the first few years of the 2010 NO_X regulation.[8]

2.4 Emission Control Defeat Device

2.4.1 Defeat Devices and the Consent Decree

From 1987 to 1998, approximately 95 percent of all heavy-duty engines sold in the US were equipped with emission control defeat devices. These engines were manufactured by the nation's seven largest heavy-duty diesel engine manufacturers, which included Caterpillar, Cummins, Detroit Diesel, Mack Trucks, International, Renault, and Volvo Trucks (General Accounting Office 2004). These so-called "defeat devices" consisted of software built into the engine control unit, which would advance an engine's fuel injection timing under highway driving conditions. This action enabled more fuel efficient operation yet at an estimated NO_X emissions penalty of two to three times the existing regulatory limit, which in 1998 was 5.36 g/kWh (Majewski and Khair 2006).

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[8] The reason Cummins is able to certify its Dodge Ram engines to the heavy-duty standard as opposed to the light-duty standard is because these vehicles fall under a special weight class. According to the Federal Tier 2 emission standards, which govern light-duty vehicles, vehicles with a GVWR between 8,500 and 10,000 lbs that are used for personal transportation are classified as "medium-duty passenger vehicles." Therefore, if a diesel engine model is in the same weight category it may be classified as either light- or heavy-duty and therefore certified to either standard, depending upon the specific application (Majewski and Khair 2006).

EPA has estimated that, in total, defeat devices were responsible for 15.8 million tons of excess NO_X emissions between 1988 and 1998 (General Accounting Office 2004). This amount of emissions was equivalent to doubling the number of passenger cars to the nation's roadways in 1998 (US EPA 1998a).

Once EPA became aware of the use of defeat devices they responded by carrying out what in their words was "the largest Clean Air Act enforcement action in history" (General Accounting Office 2004). The primary reason EPA was not aware of the defeat devices earlier is that, at the time, the federal emission test procedure for heavy-duty engines consisted only of a transient test cycle. Therefore, EPA had no way of knowing that these engines were preprogrammed to increase their rate of emissions once they were being driven under steady-state, highway conditions. The engine manufacturer industry protested the agency's enforcement actions. Citing the lack of a steady-state test cycle, they argued that clearly the government's emission regulations were originally intended to address emissions in urban areas only.

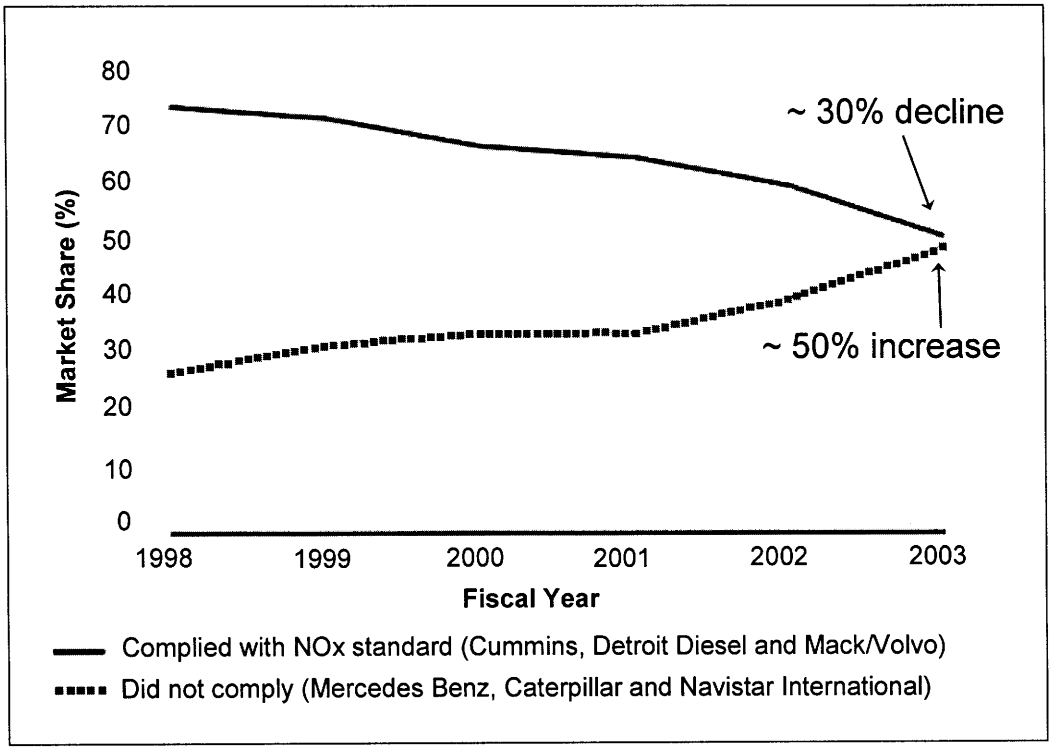
In 1998, EPA, US Department of Justice, and the engine manufacturers settled the cases that had been brought by EPA, agreeing to a consent decree. The decree stipulated the following requirements of engine manufacturers. They were obliged to pay civil penalties totaling \$83.4 million, while also agreeing to jointly invest \$109.5 million in R&D and other projects to lower NO_X emissions. Every engine manufacturer except for Navistar International was also required to comply with the upcoming 2004 standard 14 months early, beginning in October 2002. In meeting this goal, engine manufacturers were commanded to collectively spend at least \$850 million to produce engines that conformed to the 2004 standard ahead of schedule. As a concession, the industry was granted the following three non-compliance options: (1) pay nonconformance penalties equal to the cost of engines that met the standards; (2) sell MY2004 compliant engines prior to October 2002 to compensate for non-complying engines that were sold after October 2002; and/or (3), use emissions averaging, banking and trading to generate compliance credits. The final requirement of the consent decree was that engine manufacturers had to agree to supply kits that could be used to readjust the computer controls (a.k.a. "reflash") non-compliant engines when operators brought their engines in to be rebuilt.

2.4.2 Unintended Consequences of the Consent Decree

The consent decree, namely its pull-ahead provision, resulted in unanticipated consequences in engine sales rates, market structure and emissions. Engine production surged between January and October 2002, then fell precipitously through the end of the year, and only began to recover in 2003. According to representatives of the trucking industry, the 2002 "pre-buy" can be attributed to two factors. First, the accelerated compliance date interfered with engine manufacturers' product development cycles, which limited the opportunity for fleets to test prototype engines before they went into production. Fleet owners therefore deviated from their typical purchasing cycles in favor of buying engines that they were familiar with, as opposed to engines whose performance and durability were unproven. Secondly, fleet owners were concerned that the new engines would have a higher initial cost, as well suffer from a loss of fuel economy, which by itself could conceivable cost several millions of dollars in fuel. Many fleet owners who had chosen to pre-buy their vehicles estimated that the sticker price of the vehicles would have been between $1,500 and $6,000 higher and that their fuel economy would have suffered by 2 to 10 percent. In total, eight of the nation's ten largest trucking companies opted to pre-buy in advance of the October 2002 deadline. Econometric analysis, performed by the US Government Accounting Office, revealed that between 20 and 26 percent of the trucks that were purchased between 1998 and 2002 would not have been purchased were it not for the consent decree's pull-ahead requirement (General Accounting Office 2004).

The decision by fleet owners to purchase more familiar and less expensive engines proved crucial to the success or, in many cases, failure of the various engine manufacturers' pull-ahead compliance strategies. The combined market share of the three companies that chose to produce October 2002 compliant engines (Cummins, Detroit Diesel and Mack/Volvo) shrunk from 73 percent in 1998 to 50 percent in 2003, a loss of over 30 percent. In contrast, the companies that either did not have to meet the new standards until 2004 (Mercedes Benz) or that chose to continue selling older engines (Caterpillar and Navistar) increased their market share from 27 percent in 1998 to 50 percent in 2003 (General Accounting Office 2004). Sensing the advantage afforded to it by the consent decree, which it was not a signatory to, Mercedes Benz entered the US heavy-duty diesel engine market for the first time in 1999. Navistar International pursued other means of compensating for its excess emissions. Caterpillar, on the other hand, was the only company that decided to pay the nonconformance penalty. It continued to sell non-compliant engines through November 2003 (General Accounting Office 2004). Figure 4 illustrates the resulting shift in market share over time.

Figure 4: Consent Decree Impact on Market Share



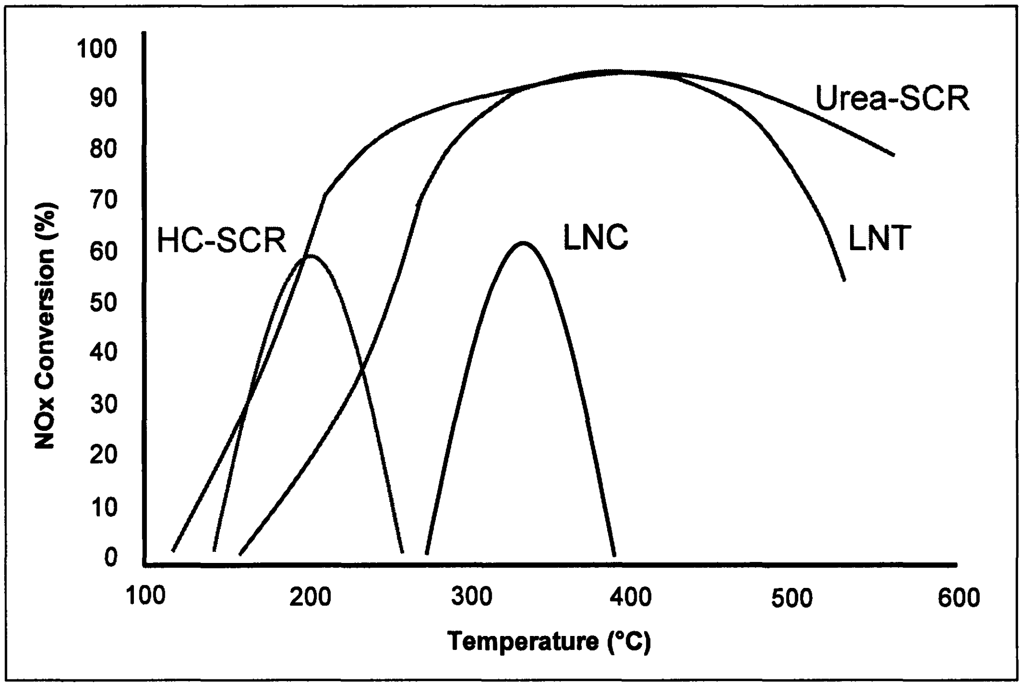
Source: (General Accounting Office 2004).

EPA estimated that the pull-ahead and reflashing provisions of the consent decree would have resulted in 1 million and 3 million fewer tons of NO_X emissions, respectively. However, only 148,000 out of an estimated 233,000 full or partially compliant engines were sold during the 15 month pull-ahead period. Also, as of September 2003, far fewer trucks than expected had been reflashed, due to the fact that fleet operators were running their engines longer than expected before replacing or rebuilding them. Thus, although EPA did not perform any formal cost-benefit analysis before-hand, the consent decree provisions clearly produced fewer benefits than anticipated, not to mention that it penalized those companies, like Cummins, that opted to meet the pull-ahead emission regulations on schedule (General Accounting Office 2004).

CHAPTER 3: NO_X EMISSION STRATEGIES FOR 2010

As discussed earlier, the most challenging aspect of the EPA 2007 Diesel Rule is the phased-in NO_X regulations, which get reduced from a 2004 level of 3.35 g/kWh to 1.61 g/kWh in 2007 and 0.27 g/kWh in 2010. It is believed that engine manufacturers will choose conservative internal engineering targets of 1.54 g/kWh and 0.2 g/kWh for 2007 and 2010, respectively. Assuming that no significant improvements in in-cylinder pollution control are achieved between now and then, this implies that 2010 NO_X aftertreatment technologies would need to achieve at least an 85 to 90 percent reduction in emissions to present a feasible pathway to compliance. Currently, there are four NO_X aftertreatment technologies that are either already on the market or that have the prospect of being commercialized in time for 2010: urea selective catalytic reduction (urea-SCR), lean NO_X traps (LNT), lean NO_X catalysts (LNC), and hydrocarbon SCR (HC-SCR). Figure 5 illustrates the relative NO_X conversion efficiencies of these technologies over the standard heavy-duty diesel exhaust gas temperature window. As shown in Figure 5, urea-SCR and LNT are the only two technologies that offer the 85 percent and higher NO_X reduction potential that will be required to meet the 2010 regulation. Both of these technologies are described in detail below. This chapter concludes by comparing the initial and lifetime costs of urea-SCR and LNT catalysts. It also includes a discussion of how cost, in conjunction with other attributes, make urea-SCR more suitable for medium to heavy-duty applications, while LNT catalysts are more appropriate for light-duty applications.

Figure 5: Potential NO_X Aftertreatment Technologies[9]



Sources: (Dou and Balland 2002; Johnson 2002; Johnson 2003; Johnson 2006; Lambert et al. 2004; Majewski 2002; Majewski 2004; Van Helden, Verbeek, and Willems 2004).

3.1 Urea-Selective Catalytic Reduction

Selective catalytic reduction (SCR) is a NO_X catalyst technology which was originally developed for industrial applications over 35 years ago. First implemented in Japanese thermal power plants in the late 1970s, SCR later spread to Europe in the mid 1980s and to the US in the 1990s. In the US, SCR was initially applied to gas turbines, followed by coal-fired cogeneration plants and other industrial applications, like coke ovens, municipal waste incinerators and refinery heaters. The earliest application of SCR to mobile engines occurred in the early 1990s on large marine diesel engines (Majewski and Khair 2006). Prompted by Japan 2005 and Euro IV regulations, SCR was first introduced in 2004 by Nissan Diesel in Japan and DaimlerChrysler in Europe for on-road heavy-duty diesel engines (Majewski and Khair 2006).

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[9] This graph was created by synthesizing NO_X conversion efficiency data obtained from several authors.

3.1.1 Catalytic Reactions and Catalysts

Like their much larger industrial and marine counterparts, mobile SCR catalysts eliminate NO_X from diesel exhaust by converting NO and NO_2 to N_2 and H_2O over a flow-through catalyst. The introduction of nitrogen containing compounds, such as ammonia or urea, into the exhaust stream is required to promote chemical reduction. Urea, which will be discussed in greater detail later, is the primary reductant used in mobile SCR applications, due to the handling and toxicity concerns of ammonia (Majewski and Khair 2006).

The conversion of NO_X takes place through several reaction pathways, the three most important of which are listed below, according to reaction rate:

$$2NH_3 + NO + NO_2 = 2N_2 + 3\mathrm{H_2O} \quad (1)$$
$$4NH_3 + 4NO + O_2 = 4N_2 + 6H_2O \quad (2)$$
$$8\,NH_3 + 6NO_2 = 7N_2 + 12H_2O \quad (3)$$

The fastest reaction (1) occurs for equimolar concentrations of NO and NO_2, whereas the slowest (3) takes place when there is excess NO_2 (Johnson 2004). The second pathway is usually the most dominant of the three reactions (Cho 1994, 39-45; Majewski 2005). This is due to the fact that diesel NO_X emissions contain much more NO (85-95 percent by volume) than NO_2 (5-10 percent by volume) (Majewski and Khair 2006).

Mobile urea-SCR systems are made of base metal catalysts, such as vanadia or zeolite. Both catalyst types are differentiated in several respects. Their primary distinguishing feature is the temperature window over which they can effectively promote NO_X conversion. Vanadia catalysts are most effective over a range of approximately 260°C to 450°C, experiencing a plateau of maximum efficiency between 300°C and 400°C. The conversion of NO_X starts to decline above approximately 425°C, as nonselective reactions with oxygen begin to dominate, such as the oxidation of ammonia (NH_3) to NO. If even higher temperatures are exceeded, the performance of vanadia-based catalysts can become permanently damaged. At approximately 500-550°C, vanadium trioxide's (V_2O_5) co-catalyst, titanium oxide (TiO_2), irreversibly converts from a high surface area structure (anatose) to one with a much lower surface area (rutile). Stabilizers have been developed which help maintain thermal stability up to 700°C (Gieshoff et al. 2000; Majewski and Khair 2006).

In contrast to vanadia, zeolite-based catalysts generally exhibit better low temperature performance, while offering similar if not better levels of high temperature performance (Johnson 2004; Lambert 2005; Walker 2005). Although vanadia-based catalysts begin to show signs of aging at 600°C, similar levels of aging are not seen in zeolites until 650°C or even 700°C. Zeolites have an additional high temperature advantage in that they do not oxidize ammonia to NO. Therefore, the NO_X efficiency of zeolites continues to increase with temperature, as opposed to tailing off in the case of vanadia-based catalysts. In addition to more favorable performance characteristics, zeolite catalysts are also preferred because of health concerns with vanadia-based catalysts. Beginning with a 2004 Japan Automobile Research Institute report, concerns have been raised over the potential for vanadia-based urea-SCR catalysts to produce vanadium emissions. A particular variety of vanadium emissions (i.e. vanadium pentoxide) was recently added to Proposition 65, the state of California's database of carcinogens. As a result, it appears that the US and Japan will focus on developing zeolite-based catalysts, whereas the EU will continue researching the vanadia-based variety (California Office of Environmental Health Hazard Assessment 2006; Japan Automobile Research Institute 2004; Majewski and Khair 2006).

3.1.2 Catalyst Configurations

A urea-SCR catalyst can be incorporated into the exhaust stream through a variety of configurations. Depending upon whether an engine is equipped with a particulate aftertreatment device, urea-SCR catalysts in heavy-duty engines are typically positioned downstream of either a diesel oxidation catalyst (DOC) or catalyzed diesel particulate filter (DPF). The advantage of this arrangement is that the upstream oxidation catalyst converts NO to NO_2, which helps facilitate the equimolar reaction pathway, the fastest of the three (Johnson 2004; Majewski and Khair 2006; Walker 2003).[10] An additional oxidation catalyst is usually positioned downstream from the urea-SCR unit for the purpose of decomposing the excess ammonia that results from imperfect dosing control or catalyst failure. The cost of these catalysts is usually significantly lower than the cost of a primary DOC, since they require a lower concentration of precious metals (e.g. 10 g/ft^3 Pt compared to 90 g/ft^3 Pt) (Gieshoff et al. 2000; Majewski and Khair 2006). While ammonia emissions were not previously regulated under heavy-duty vehicle emission regulations, they are covered by many countries' ambient air quality standards, such as the US Clean Air Act. Accordingly, when the European Commission issued guidelines surrounding the use of urea-SCR they included a 25 ppm cap for ammonia emissions (European Commission 2006). The disadvantage of incorporating a so-called ammonia slip catalyst is the potential for its use to increase the concentration of nitrous oxide (N_2O) and NO emissions (Gieshoff et al. 2000; Majewski and Khair 2006). While the former is a known and potent greenhouse gas, production of the latter gas reduces the effective NO_X conversation efficiency of urea-SCR systems, which has important negative feedback implications on one's urea dosing control strategy.[11]

In addition to the various catalysts involved, urea-SCR systems also require urea storage, dispensing and control equipment. Aqueous urea solution, containing roughly 1/3 urea ($(NH_2)_2CO$) and 2/3 water, is stored onboard the vehicle in either a steel or high density polyethylene storage container that is equipped with temperature and level sensors. Heavy heavy-duty vehicle urea tanks can range in size from 90-145 l. in the EU to a projected 20 gal (75 l.) in the US (Bunting 2005; Schubert, Pont, and Jackson 2006). Urea flows from the storage tank through a delivery module before entering a dosing module. Inside the dosing module, urea is combined with compressed air to produce an atomized mist, which gets injected into the exhaust slightly upstream of the urea-SCR catalyst. Hot exhaust gases cause the urea to react with water in the urea solution via a

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[10] The configuration is usually reversed in a light-duty diesel vehicle, with the SCR catalyst positioned as close as possible to the exhaust manifold. This arrangement subjects the SCR to the highest possible temperatures and thereby, optimizes cold start NO_X conversion, which is a particularly challenging aspect of most light-duty test cycles (Lambert 2006).

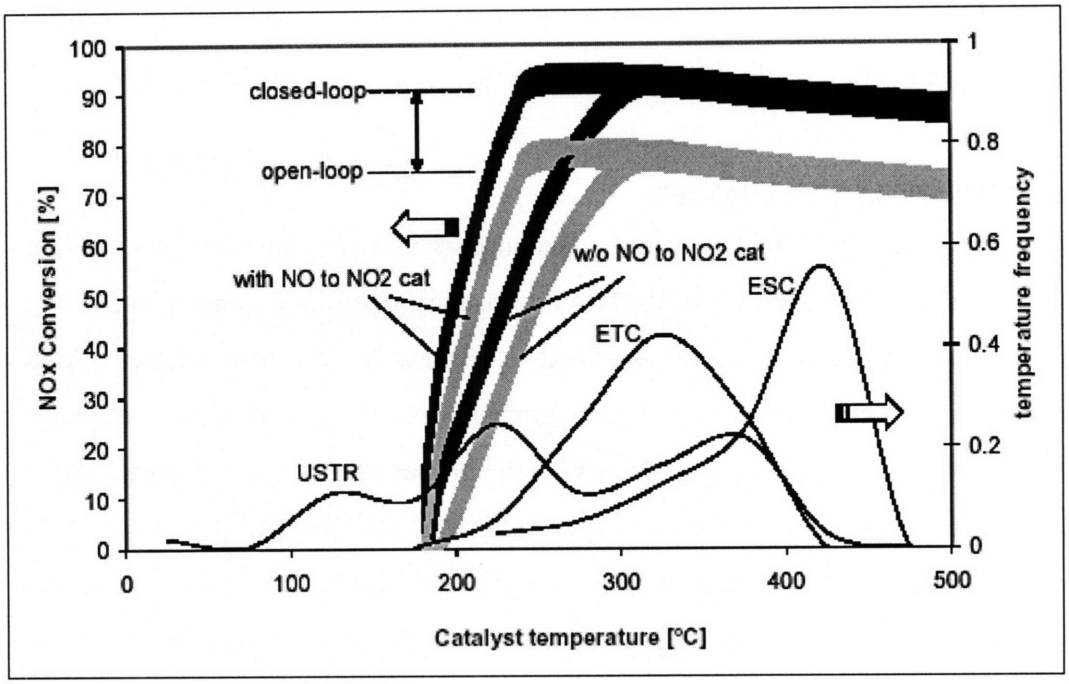
[11] Nitrous oxide has a global warming potential that is 296 times higher than the global warming potential of carbon dioxide (US DOE 2002).

hydrolysis reaction to form ammonia. If the exhaust gas temperature is below 200-250°C (e.g. during cold start), incomplete hydrolysis can produce ammonium nitrate and other species, which have the potential to foul the catalyst (Majewski and Khair 2006).

3.1.3 Urea Dosing and Control Strategies

Urea dosing in urea-SCR catalysts can be accomplished using one of two control strategies. The more straightforward of the two approaches, open-loop control, uses NO_X look-up tables that are based on speed and load to accurately dose urea upstream of a urea-SCR catalyst. Alternatively, closed-loop control uses NO_X and NH_3 sensors to measure the actual level of emissions to determine the proper rate of urea injection. These two strategies are differentiated by their NO_X conversion efficiency and their ability to minimize NH_3 emissions. Maximum NO_X conversion efficiencies for open and closed-loop control strategies are generally agreed to be 80 and 95 percent, respectively (Van Helden, Verbeek, and Willems 2004). Figure 6 illustrates this difference in NO_X conversion efficiency (Van Helden, Verbeek, and Willems 2004). It also shows how the test cycle and its associated temperature profile influence the decision of whether or not to incorporate an upstream DOC. For the reasons discussed above, open-loop control is the favored strategy for the EU, where Euro IV regulations only require a 30 percent reduction from Euro III levels (Schar, Onder, and Geering 2003; Van Helden, Verbeek, and Willems 2004). Open-loop control is also expected to be used to meet Euro V requirements beginning in 2008, when NO_X standards will be reduced 60 percent below Euro III levels. In the US, it is widely believed that a closed-loop strategy will be necessary to achieve the 85 to 90 percent NO_X reduction required for 2010. The interplay between emission regulations and control strategy have interesting repercussions on the viability of urea-SCR deployment and on the burden that compliance places on engine manufacturers and operators. For example, regardless of the technical feasibility of using open-loop control to meet US 2010 standards, EPA could institute on-board diagnostic (OBD) requirements that effectively mandate the use of a closed-loop system.

Figure 6: Open vs. Closed-Loop Urea-SCR Reduction Efficiency



Source: (Van Helden, Verbeek, and Willems 2004).

The open-loop, look-up table approach to urea control relies on multi-dimensional engine maps to anticipate the desired quantity of urea under a variety of situations. For example, Van Helden et al. (2002) used a Bosch control system that contained 12 three-dimensional maps. One map had the nominal exhaust gas temperature for different speed and load conditions. Another contained the required urea dosing level under steady state conditions. The remaining ten maps were used to determine an appropriate urea dosing level for prescribed speed and load conditions when the actual catalyst temperature did not match the theoretical temperature. The biggest difficulty with open-loop systems has been finding a cost-effective way to monitor the ratio of air and urea that get injected into the exhaust. One solution has been to compare the quantity of urea injected with the change in the tank volume (Nebergall 2005).

Since open-loop control systems do not directly monitor the level of NO_X emissions, they cannot accurately adjust to changing system performance, like catalyst aging and urea dosage variability (Van Helden, Verbeek, and Willems 2004). For instance, urea-SCR catalysts have been shown to lose up to 20 percent of their NO_X conversion efficiency over their lifetime as a result of poisoning from phosphorous and other lubricant-derived metals (Amon and Keefe 2001; Silver, Alletag, and Stefanick 2005b). While time controlled adjustment might be able to accommodate changes due to aging it may not reliably account for urea dosing variability, which could exhibit more erratic behavior. Due to their limited sensitivity, open-loop control systems therefore require some level of safety in NO_X conversion, which could in turn make it difficult to meet stringent NH_3 standards (Van Helden, Verbeek, and Willems 2004). The use of a DOC downstream of the urea-SCR catalyst has been proposed as a solution to ammonia slip. As already mentioned, there is some concern that this clean-up DOC could catalyze the formation of NO and N_2O (Majewski and Khair 2006).

Unlike open-loop control, closed-loop control will likely be required to achieve significant and continuous NO_X conversion over a catalyst's lifetime. In addition to NO_X and NH_3 sensors, closed-loop control modules often use catalyst inlet and outlet temperatures, as well as urea-SCR kinetic models to monitor urea dosing (Chi and DaCosta 2005; Johnson 2004; Schar, Onder, and Geering 2003).

The biggest challenge of closed-loop control lies in the accuracy and response time of NO_X and NH_3 sensors (Majewski and Khair 2006; Nebergall 2005; Schar, Onder, and Geering 2003). For example, the response time of current NO_X sensors is limited to approximately 0.75 seconds, which is slower than ideal (Majewski and Khair 2006). Also, zirconium oxide (ZrO_2) NO_X sensors have been shown to convert as much as 65 percent of the NH_3 they come in contact with to NO_X, thereby distorting the measured bulk exhaust NO_X concentration (Schar, Onder, and Geering 2003). Until a more discerning NO_X sensor is developed, one promising solution, called feed-forward process control, is to introduce a NO_X sensor upstream of the urea injection point (Majewski and Khair 2006; Schar, Onder, and Geering 2003). This upstream sensor, in coordination with a urea-SCR kinetic model and catalyst temperature measurements, is used to approximate the required urea injection. Researchers at Cummins have used this approach to achieve an 84 percent NO_X reduction over the challenging transient FTP US heavy-duty test cycle.

Simultaneously, they were able to maintain peak NH_3 emissions below 55 ppm and maintain an average value of 7 ppm (Chi and DaCosta 2005).

As an alternative to NO_X sensors, NH_3 sensors also have the potential to facilitate close-loop control. Although there has been comparatively less emphasis placed on NH_3 sensor development, a recent Delphi press release detailing their NH_3 sensor product plans is an encouraging sign that this technology could be ready in time for MY 2010 heavy-duty vehicles. According to Ivan Samalot, Delphi's chief engineer for exhaust sensors, their sensor is currently able to detect ammonia within a range of zero to 100 ppm (Market Wire 2007).

3.1.4 Urea Consumption and Potential Fuel Economy Benefits

The amount of urea that is consumed by a urea-SCR catalyst depends upon the required NO_X emissions reduction, which itself constantly changes with time depending upon conditions like speed, load, intake temperature and humidity. Normally, NO_X emission reductions are discussed in terms of averages. For example, an engine whose average "engine-out" (i.e. upstream of any catalyst) NO_X emissions are 2.7 g/kWh will consume more urea to achieve the US 2010 standard of 0.27 g/kWh than an engine whose engine-out emissions are 2.0 g/kWh. The amount of urea that gets consumed to achieve a specific NO_X reduction level is generally expressed as a percentage of the fuel consumption. This percentage can be calculated empirically or through the use of chemical kinetic models.

Based on a review of empirical data, the engineering consulting firm Tiax has proposed the following rule of thumb: 0.9 percent urea relative to diesel fuel will be consumed for every 1.34 g/kWh of NO_X reduced over the US transient FTP driving cycle (Tiax 2003). Tiax used this approximation to develop the following simple model for determining a vehicle's urea consumption, presented as a fraction of the diesel fuel consumption rate:

$$\textit{Urea Consumption \%} = 0.9\% * (\textit{Engine out} - \textit{urea-SCR out})$$

The model depends solely on the desired NO_X reduction (i.e. Engine-out minus urea-SCR-out) and holds only for situations when that reduction falls within or below the conversion efficiency range for urea-SCR catalysts, which is generally agreed to be 80 to 95 percent. Table 2 uses this model to present urea consumption estimates and urea refueling interval repercussions for different potential US 2010 engine-out emission scenarios. The best-case engine-out emission scenario is based on the fact that the US heavy-duty industry has come to a consensus that engines will probably be able to achieve a minimum engine-out NO_X level of 1.3 g/kWh (Johnson 2006).

Table 2. Urea Consumption and Refueling Estimates

Engine Out Scenario†	SCR Out‡	NO_X Reduction	Percentage	Ratio	Refueling Interval¥
(g/kWh)	(g/kWh)	(%)	(% urea / diesel)	(diesel : urea)	(miles)
2.7	0.20	93%	1.7%	60:1	7,650
2.0	0.20	90%	1.2%	82:1	10,850
1.3	0.20	85%	0.8%	131:1	16,250

† Engine-out NO_X emission estimates come from Tiax LLC (2003).
‡ This SCR-out estimate is intended to reflect the assumption that companies will choose a conservative engineering target below the 2010 NO_X target of 0.27 g/kWh.
¥ The refueling interval was calculated by assuming that the fuel economy of the average HHDD vehicle is 6.5 mi/gal and that an average urea tank will be 20 gal in the US (Schubert et al. 2006).

Sources: (Schubert, Pont, and Jackson 2006; Tiax 2003)

Given the fact that US 2007 engines are meeting the 1.3 g/kWh limit without any NO_X aftertreatment and Table 2 demonstrates that urea-SCR catalysts can accommodate as high as a 2.7 g/kWh engine-out NO_X level, this implies a potential for engine manufacturers to re-advance their fuel injection timing to gain a fuel economy benefit. Figure 7 presents an estimated brake specific fuel consumption versus NO_X emissions trade-off curve for a modern diesel engine with cooled EGR (Wall 1997).[12] Using the slope from Figure 7, it was determined that recalibrating engine-out NO_X emissions from

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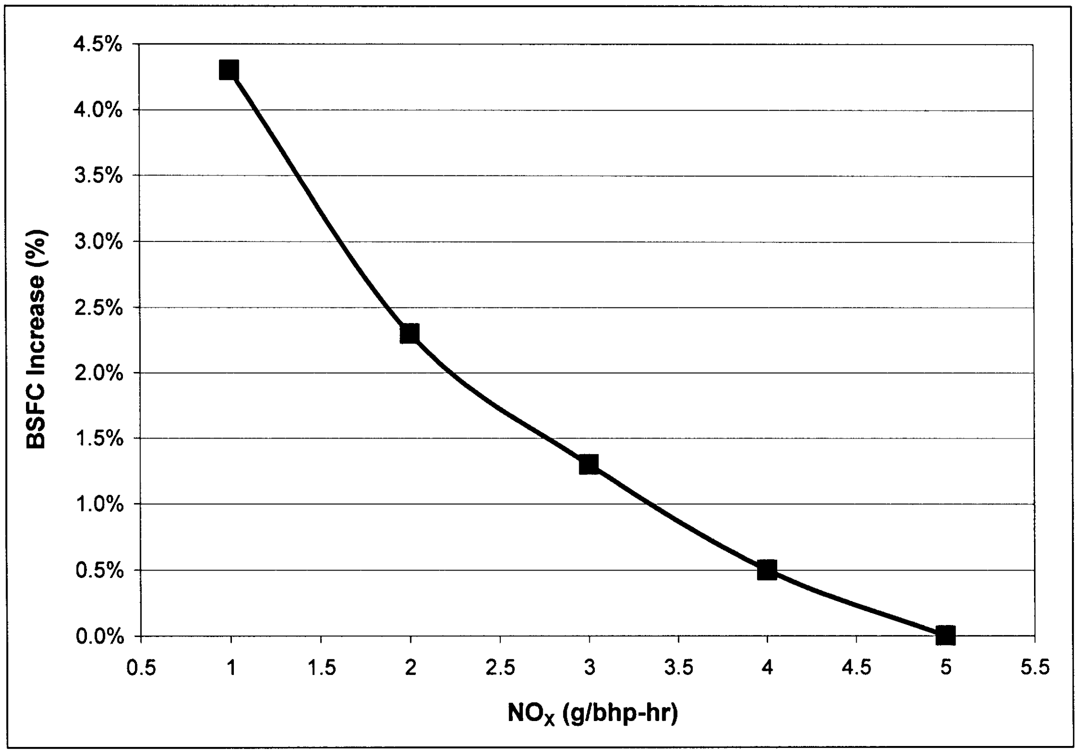
[12] Brake specific fuel consumption is a measure of the amount of fuel consumed per unit output of energy from an engine.

1.74 g/kWh to 2.0 or 2.7 g/kWh would result in a 0.4 or 1.2 percent fuel economy improvement, respectively, over US 2007 fuel economy levels. This improvement has the potential to partially or fully offset the extra cost of urea, depending upon the extent of recalibration and the relative cost of diesel fuel and urea. This topic will be discussed in further detail at the end of this chapter when the lifetime costs of urea-SCR systems are compared to LNT catalysts.

Figure 7: A Brake Specific Fuel Consumption vs. NO_X Emissions Trade-off

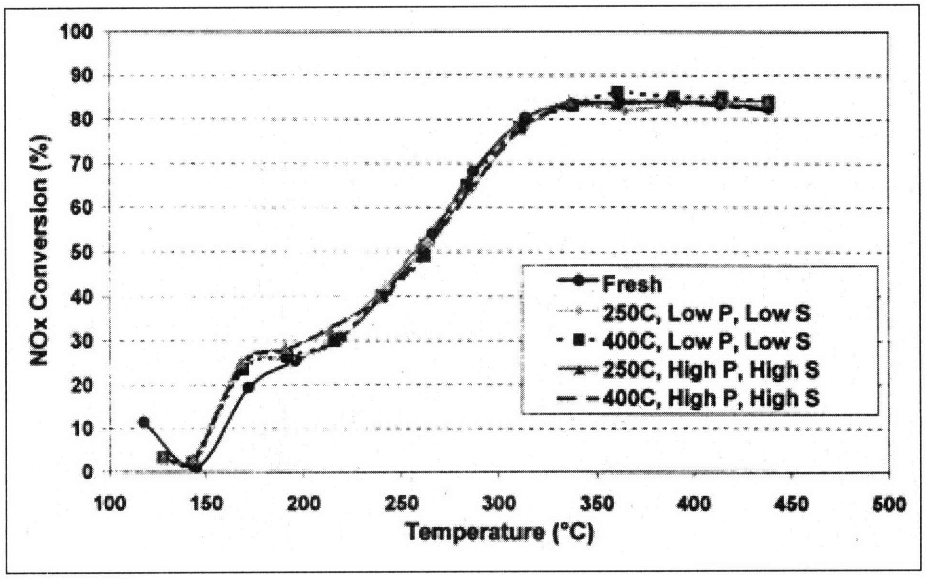


Source: (Wall 1997).

3.1.5 Susceptibility to Fuel and Lubricant-derived Poisons

The literature on the effects of fuel and lubricant-derived poisons, such as sulfur and phosphorous, generally support the conclusion that urea-SCR catalysts experience a mild poisoning effect (~10-20 percent loss in NO_X reduction efficiency) only after extended periods of aging.[13] For example, during a relatively short engine dynamometer study, equivalent to operating at 100 km/h over a distance of 40,000 km, no measurable loss of NO_X conversion efficiency was observed (Bardasz et al. 2006). This result is depicted by the catalyst light-off curve shown in Figure 8. The only on-road durability study of a urea-SCR system revealed that catalyst poisoning requires several hundred thousand kilometers to manifest and that the loss of NO_X reduction efficiency appears to tail off asymptotically with time. Specifically, Figure 9 shows that after 531,000 km the normalized NO_X conversion of a vanadia-based urea-SCR catalyst reached a nearly steady-state 90 percent efficiency (Amon and Keefe 2001).

Figure 8: NO_X Light-off Performance of Fresh and Aged Urea-SCR Catalysts



Source: (Bardasz et al. 2006).

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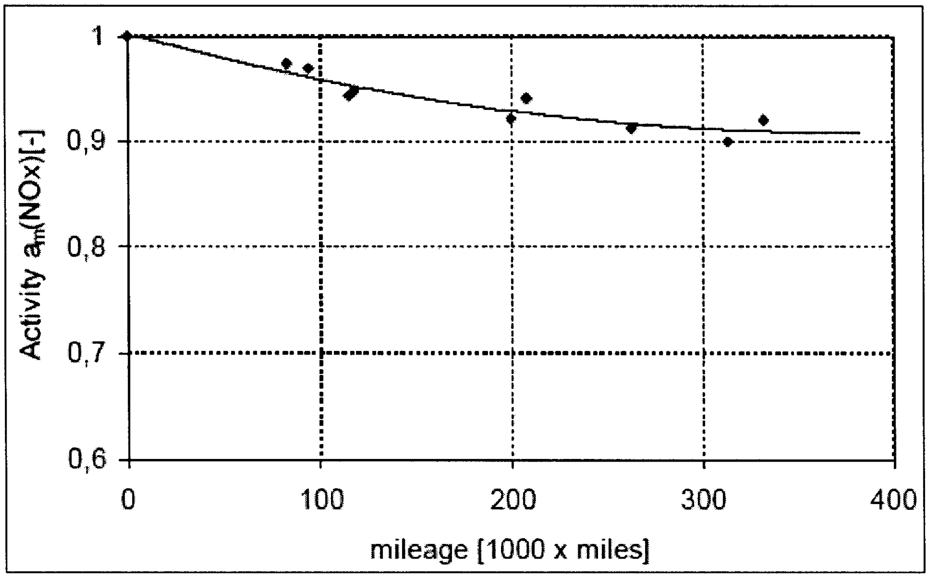
[13] Sulfur and phosphorus, as well as other elements inside lubricating oils, can make their way to the exhaust through a number of pathways. The dominant pathway is by escaping past the top piston ring and being consumed in the combustion chamber.

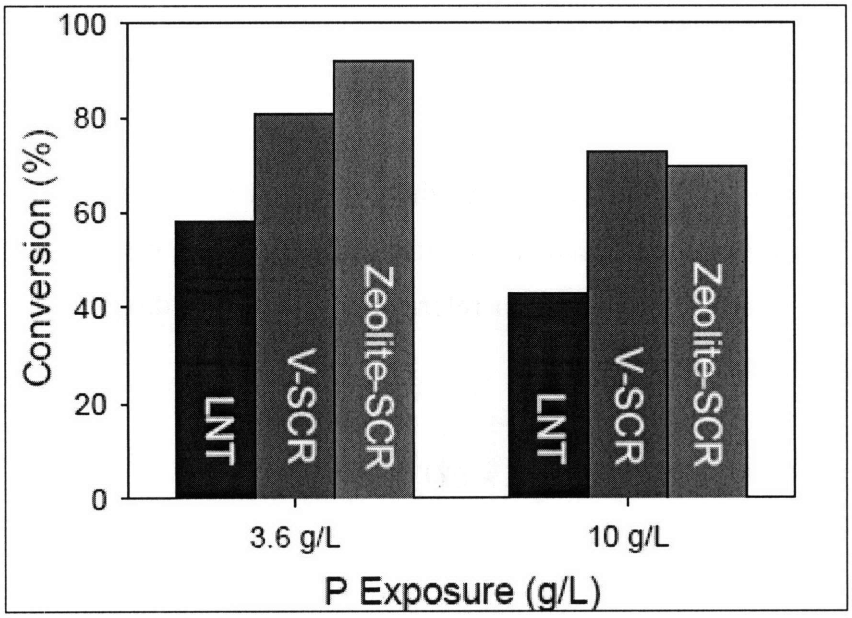
Figure 9: Urea-SCR NO$_X$ Reduction Efficiency during an On-road Durability Test



Source: (Amon and Keefe 2001).

Due to the fact that sulfur has previously been found not to react strongly with either zeolite or vanadia-based urea-SCR substrates (Sutton et al. 2004), some studies have chosen to focus exclusively on the impact of lubricant-derived phosphorus, which is known to accumulate preferentially on the inlet-face of urea-SCR catalysts (Amon and Keefe 2001; Bardasz et al. 2006). For instance, a recent bench test study used Tricresyl Phosphate gas to simulate urea-SCR catalyst exposure to lubricant phosphorus deriving from the common anti-wear additive, zinc dialkyl dithio phosphate or ZDDP (Silver, Alletag, and Stefanick 2005a). Two phosphorus exposure levels were used. On a per liter of urea-SCR catalyst basis, 3.6 g/L and 10 g/L were chosen to simulate 4,000 h and 10,000 h, respectively, of exposure to lubricants containing low concentrations of phosphorus (i.e. 800 ppm). These exposure intervals were approximately equivalent to long-haul distances of 400,000 km and one million km, respectively. As depicted by Figure 10, the equivalent of 400,000 km of exposure to low phosphorus lubricant resulted in an approximately 10 percent and 20 percent loss of NO$_X$ conversion efficiency for zeolite and vanadium-based urea-SCR catalysts, respectively. The 1 million km simulation showed greater loss of NO$_X$ conversion efficiency for both urea-SCR catalyst types. LNT catalysts, which were also tested, showed a considerable degree of poisoning. LNT catalyst fouling will be discussed in detail during a subsequent section of this chapter. In closing, it should be mentioned that although urea-SCR catalysts do not appear to suffer dramatically from exposure to fuel and lubricant-derived elements, the limited amount of literature on this topic implies that the potential for catalysts to become poisoned should not be ruled out.

Figure 10: **NO_X Conversion of Urea-SCR Catalysts Exposed to Phosphorus**



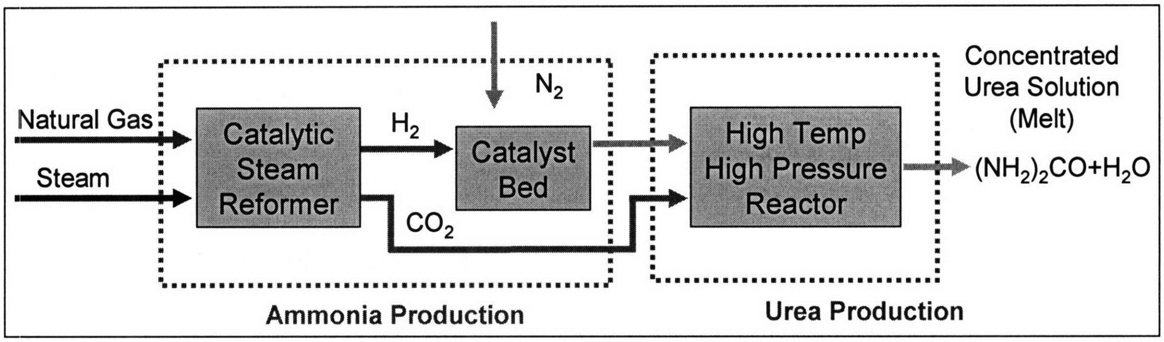
Source: (Silver, Alletag, and Stefanick 2005a).

3.2 Urea

3.2.1 Production

Urea is a colorless, crystalline and soluble organic compound whose chemical formula is $(NH_2)_2CO$. It occurs naturally in some molds and fungi and is also a byproduct of mammalian protein metabolism. For instance, the average human expels approximately 20-35 g of pure urea on a daily basis in their urine (Coffey Geosciences 2004; DGMK 2003). Synthetic urea is manufactured commercially, using two production processes, each comprising several chemical steps, as illustrated in Figure 11.

Figure 11: Ammonia and Urea Production Schematic



Source: (Fable, Kamakate, and Venkatesh 2002).

The two leftmost grey rectangles in Figure 11 describe the production of ammonia and the last rectangle details the conversion of ammonia into urea. In the first step, natural gas and water vapor are reacted over a catalytic steam reformer to produce hydrogen and carbon dioxide, according to the following reaction:

$$CH_4 + 2H_2O \Leftrightarrow 4H_2 + CO_2$$

Then, hydrogen is combined with atmospheric nitrogen to form ammonia:

$$4H_2 + N_2 \Leftrightarrow 2NH_3$$

In the third step, the ammonia is recombined at high pressure and temperature with the carbon dioxide that was produced during the first step to yield ammonium carbamate:

$$2NH_3 + CO_2 \Leftrightarrow NH_2COONH_4$$

During the last step, ammonium carbamate is dehydrated into urea and water:

$$NH_2COONH_4 \Leftrightarrow CO(NH_2)_2 + H_2O$$

After separating out any residual ammonium carbamate, the urea mixture is sent through evaporators to remove most of the water. The remaining highly concentrated liquid (e.g. 95-99.7 percent urea) is termed "urea melt" for its tendency to crystallize or "salt out" at temperatures below 100°C (DGMK 2003). Urea melt is then processed into one of the following three products (Fable, Kamakate, and Venkatesh 2002):

1. Urea Liquor – 10 to 50 percent liquid urea by weight with de-ionized water constituting the remaining volume.
2. Urea Prills – drops of liquid urea that have dried into spheres.
3. Urea Granules – drops of liquid urea that agglomerate as they dry.

3.2.2 Current Uses and World Demand

Three major commercial grades of urea are produced throughout the world: agricultural, industrial and high purity urea. Agricultural grade urea is either sold in prill or granular form. It is produced by introducing conditioners, which improve urea's handling and end-use properties (Fable, Kamakate, and Venkatesh 2002). Industrial and high-purity reagent grades of urea are sold in either solid or liquid form and, in contrast to agricultural grade urea, contain far fewer additives.

In 2005, slightly over 5.8 million short tons of urea were produced in the US, an amount which has declined on average 5 percent annually since 1998 (US Census Bureau 2006). As depicted in Figure 12, US domestic production capacity is primarily located in the Southeastern states, with some production in Iowa, Ohio and Alaska (Fable, Kamakate, and Venkatesh 2002).[14] Domestic demand is affected primarily by agricultural demand, which is primarily dependent on the seasons and the types of crops that are planted. Table 3 shows the fact that US urea production accounts for approximately 60 to 65 percent of total rated urea manufacturing capacity. It also illustrates the significant amount of excess production capacity that exists both in the US (approximately 40 percent) and the global market (approximately 25 percent). Nearly one-third of US demand for urea is met through imports from the Arab Gulf States, the states of the Former Soviet Union, and

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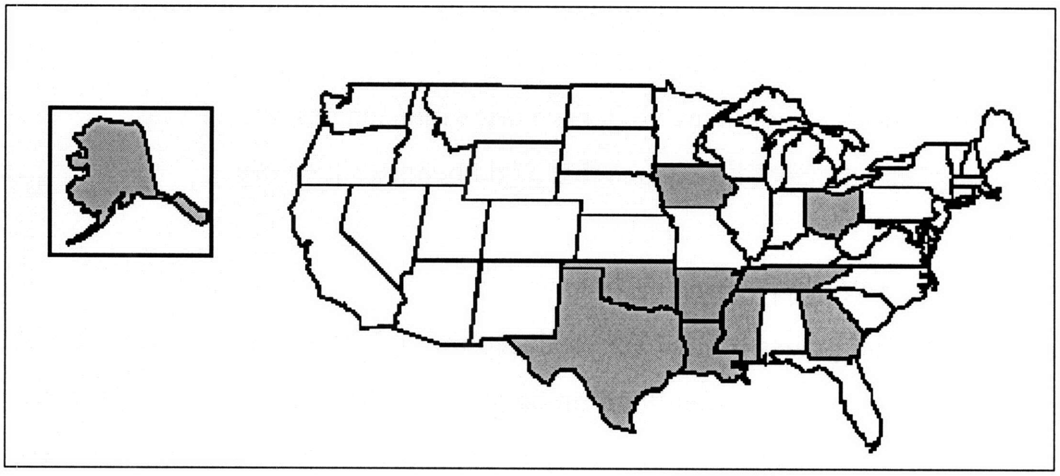
[14] Urea production is one of several ways in which stranded natural gas supplies are put to productive use in Alaska. Other common uses include ammonia production, LNG production, electric power generation and residential and commercial heating and cooking (Bailey 2006).

Venezuela (Fable, Kamakate, and Venkatesh 2002). The decision to import from foreign urea suppliers instead of utilizing excess domestic production capacity is largely based on the differential price of natural gas in domestic versus foreign markets.

Figure 12: US States with Major Urea Production Facilities



Source: (Fable, Kamakate, and Venkatesh 2002).

Table 3: Urea Manufacturing Capacity, Production and Demand

	Domestic	World
	(10^6 Short Tons/Year)	(10^6 Short Tons/Year)
Capacity	10	133
Production	6	110
Demand	9-10	100
Excess Capacity	4	23

Source: (Fable, Kamakate, and Venkatesh 2002).

Urea, which contains 47 percent nitrogen by weight, is the most widespread nitrogen-containing fertilizer in use (Coffey Geosciences 2004). In the US, approximately 80 to 85 percent of all domestically produced urea is used either directly as fertilizer (e.g. granular urea) or to produce other nitrogen-containing fertilizers (e.g. ammonium nitrate) (Fable, Kamakate, and Venkatesh 2002; US Census Bureau 2006). The remaining 15 to 20 percent of US urea production gets consumed in industrial processes, such as the manufacture of polymers. A small fraction of total US production is consumed by other uses, including as a reductant for small, stationary urea-SCR systems and as a feed supplement for ruminants, like cattle and sheep, to help them make better use of low protein roughage (Coffey Geosciences 2004).

3.2.3 Handling and Urea Quality Requirements

Urea that is intended for use as a reductant in on-road diesel engine urea-SCR catalysts has unique handling and quality requirements. First, it must be easy to dispense into the exhaust stream. Despite some effort to develop delivery systems that use solid urea, almost all existing configurations use liquid urea. Due to the tendency for concentrated urea solutions to crystallize at ambient temperatures, the most feasible means of dispensing urea involves blending it with water. It has been determined that a urea and water mixture's eutectic temperature of -11°C (14°F) can be achieved using a mixture ratio of 32.5 percent urea to 67.5 percent water by weight. This mixture ratio has therefore become the worldwide standard for on-road urea (Fable, Kamakate, and Venkatesh 2002).

There are many regions of the world, particularly North America and northern Europe, where temperatures can fall substantially below -11°C during the winter months. It is expected that vehicles will either come equipped with heating and insulation for their urea tank and dosing lines or they will use a reductant that has a lower freezing point. One commercially available alternative is ammonium formate ($HCOO \bullet NH_4$). Kemira, a European supplier and producer of fertilizers and industrial chemicals, has developed a product line called Denoxium™, which is a mixture of ammonium formate, urea and water (Chemical Engineering Progress 2005; Clancy 2005). Denoxium comes in -20°C (-4°F) and -30°C (-22°F) varieties. Denoxium -30°C contains approximately 26 percent ammonium formate, 20 percent urea, and 54 percent water by weight (Majewski and Khair 2006). Both varieties produce similar amounts of ammonia inside the exhaust stream as would be produced from using an equivalent volume of 32.5 percent urea solution. Thus, ammonium format is consumed at the same rate as urea and is not expected to require any deviation in reductant refueling.

Other than freezing concerns, urea must also meet stringent quality standards. Standards are needed to ensure the following:

1. Urea that is dispensed into the exhaust stream contains a consistent concentration of nitrogen and hydrogen (i.e. for ammonia production).
2. Urea-SCR catalysts or other exhaust components do not become poisoned or plugged by impurities.
3. Unwanted air pollutant emissions are not produced.

Initially, there was some concern that even reagent grade urea would not be pure enough for use in mobile urea-SCR catalysts, implying that additional contaminant control measures would need to be installed on existing manufacturing facilities (Fable, Kamakate, and Venkatesh 2002). The repercussion was that the viability of urea-SCR catalysts would be compromised by both the increased cost associated with producing contaminant-free urea and by corresponding infrastructure delays.

Impurities can enter at all stages of the urea manufacturing process. Natural gas, ammonia, and carbon dioxide are often present in small amounts in the original feedstock. Some impurities can also be created during the production process. For instance, ammonia and biuret can form during the evaporation process at temperatures above 50°C to 60°C. Contaminants can also derive from the dilution water. Finally, contact with piping and other transfer and transport equipment can introduce metals, such as iron and copper, as well as phosphorus from phosphorus-containing cleaning agents (DGMK 2003; Fable, Kamakate, and Venkatesh 2002). Of these various contaminants, the two biggest concerns have always been phosphates and metals. Phosphates are undesirable because they can poison urea-SCR systems. Likewise, metals are undesirable because they have the potential to lead to DPF plugging (Fable, Kamakate, and Venkatesh 2002).

In Germany, where the first urea standards were developed, engine and urea manufacturers collaborated on developing a mutually acceptable standard. Their goal was to develop a measure of quality that would meet the three requirements listed earlier, while still allowing urea to be produced in an economically reasonable manner (Strutz 2003). The resulting German Institute of Standardization (DIN) standard, named DIN 70070, is detailed in

Table 4. This standard has already been adopted by the EU and has helped form the basis for the corresponding ISO standard, ISO 22241-1:2006, which has already received the support of US emission control equipment manufacturers (Kubsh 2006). There is general agreement that meeting DIN 70070 standards does not require significant modifications to the traditional reagent-grade urea production process. It will, however, require using de-ionized dilution water and containers, piping and fittings made of corrosion-free materials like austenitic steel, aluminum and various plastics (DGMK 2003).

Table 4: Urea Quality Standards for On-Road Urea-SCR Catalysts

Standard	Units	Min.	Max.
Urea content	% by weight	31.8	33.2
Density at 20°C	g/cm^3	1.087	1.093
Refracting index at 20°C		1.3814	1.3843
Alkalinity as NH_3	%		0.2
Biuret	%		0.3
Aldehyde	mg/kg		5
Insolubles	mg/kg		20
Phosphate (PO_4)	mg/kg		0.5
Calcium	mg/kg		0.5
Iron	mg/kg		0.5
Copper	mg/kg		0.2
Zinc	mg/kg		0.2
Chromium	mg/kg		0.2
Nickel	mg/kg		0.2
Aluminum	mg/kg		0.5
Magnesium	mg/kg		0.5
Sodium	mg/kg		0.5
Potassium	mg/kg		0.5

Source: (Yara 2005).

3.2.4 Human Health and Environmental Effects

The use of urea as a reductant in mobile urea-SCR exhaust catalysts is not expected to pose a significant threat to humans or the environment. This is based largely on the fact that urea is currently used by the agricultural sector in great quantities and has exhibited minimal adverse effects. According to a 2002 survey of material safety data sheets (MSDS) by the consulting firm Arthur D. Little (ADL), most US federal agencies do not consider urea to be hazardous and none consider it carcinogenic (Fable, Kamakate, and Venkatesh 2002). Urea, however, may lead to acute irritation of the eyes and skin. For example, storing solid urea in confined spaces can cause ammonia and cyanuric acid vapors to accumulate (Coffey Geosciences 2004).

Urea has the potential to enter the environment through a variety of pathways, depending upon the nature of the spill. The biggest potential spill would be from a cargo vessel carrying solid urea. The largest of these ships have a maximum capacity of 40,000 metric tons. Next would be solid urea transported by rail. If an entire freight train transporting urea in all 90 of its cars were to derail, as much as 8,600 metric tons could be spilled, assuming a per car capacity of 96 metric tons. Liquid urea solutions, which introduce pathways that are unique to an on-road urea-SCR infrastructure, have the potential to be spilled from 50,000 gal below-ground storage tanks and 7,800 gal tanker trucks on down to vehicle-sized urea tanks (e.g. 20 gal). According to the MSDS sheets that the ADL survey reviewed, spills smaller than 55 gal do not require any special cleanup procedures (Fable, Kamakate, and Venkatesh 2002).

When urea comes in contact with soil it starts degrading immediately. Moisture and small amounts of the enzyme urease hydrolyze urea into ammonia and carbon dioxide. Initially, the high ammonia concentration and correspondingly high pH of the soil is toxic for plants. In the matter of a few days, however, microbes convert the ammonia to ammonium and nitrate, which the plants can effectively use (Fable, Kamakate, and Venkatesh 2002). When urea is released directly into a water body, it produces nitrate as a result of bacterially-mediated oxidation, which increases biological oxygen demand. Similarly, nitrate can also enter ground and surface waters through runoff (Coffey

Geosciences 2004; Fable, Kamakate, and Venkatesh 2002). Elevated nitrate concentrations are a potential concern because they have been linked to a blood disorder in infants, called methemoglobinemia. When urea is released into the air it reacts with photochemical hydroxyl radicals to rapidly form ammonia and carbon dioxide. The ammonia that gets produced can impact local air quality by forming secondary particulate matter (Fable, Kamakate, and Venkatesh 2002).

3.3. Lean NO_X Traps

Lean NO_X Traps (LNT), also commonly referred to as NO_X adsorber catalysts (NAC), function very differently than urea-SCR catalysts. Rather than using a nitrogen-containing compound to continually reduce NO_X emissions, LNTs capture NO_X emissions during lean operation and convert them periodically during rich conditions. They should also not be confused with Lean NO_X Catalysts (LNC), which use hydrocarbons to continuously and selectively reduce NO_X emissions.

3.3.1 Catalytic Reactions and Catalysts

Three types of catalysts are used inside LNTs: an oxidation catalyst, an adsorbent catalyst, and a reduction catalyst. Both the oxidation and the adsorbent catalysts operate during lean operation, while the reduction catalyst only functions during rich exhaust gas conditions. In the first step of LNT NO_X reduction, the oxidation catalyst converts NO to NO_2, as described by the following equation (Majewski and Khair 2006):

$$NO + \frac{1}{2}O_2 = NO_2$$

This oxidation reaction is necessary because the adsorbent catalyst requires NO_2, yet the majority of NO_X in engine-out diesel exhaust (90-95 percent) consists of NO. Platinum is the metal that is most often used as an oxidation catalyst in LNTs. Platinum is preferred because it is more active at oxidizing NO than other metals. While the oxidation reaction is taking place, the adsorbent catalyst stores the NO_2 that is created as an organic nitrate on the catalyst surface. This reaction is depicted below for barium oxide, the most common adsorbent:

$$BaO + NO_2 + \tfrac{1}{2}O_2 = Ba(NO_3)_2$$

Once a large number of barium oxide sites become saturated with NO_2, the engine control unit initiates mixture enrichment of the exhaust gas.[15] Mixture enrichment can either be accomplished by injecting hydrocarbons into the exhaust upstream of the LNT catalyst or via post-injection by altering the fuel injection timing and rate, or through the use of exhaust gas recirculation. Under these conditions, the nitrate species become thermodynamically unstable and desorb from the adsorption catalyst, producing NO and NO_2, as described by the following reactions:

$$Ba(NO_3)_2 = BaO + 2NO + 1\tfrac{1}{2}O_2$$
$$Ba(NO_3)_2 = BaO + 2NO_2 + \tfrac{1}{2}O_2$$

Similar to a traditional gasoline three-way catalyst, the resulting NO_X emissions react with the carbon monoxide, hydrogen and hydrocarbons in the rich exhaust over the reduction catalyst to form N_2 and CO_2. One potential reaction pathway is depicted below. Rubidium (Rh) is the metal that is most frequently used in this reaction to facilitate reduction (Majewski and Khair 2006):

$$NO + CO = \tfrac{1}{2}N_2 + CO_2$$

Exhaust gases are typically made rich to initiate regenerations every 30 to 120 seconds. Because catalysts are regenerated fairly frequently, each regeneration only lasts an average of a few seconds. Regeneration cycles require closed-loop control systems that monitor NO_X concentration and temperature, among other parameters, to maintain high NO_X conversion efficiencies over the lifetime of a catalyst (Majewski and Khair 2006).

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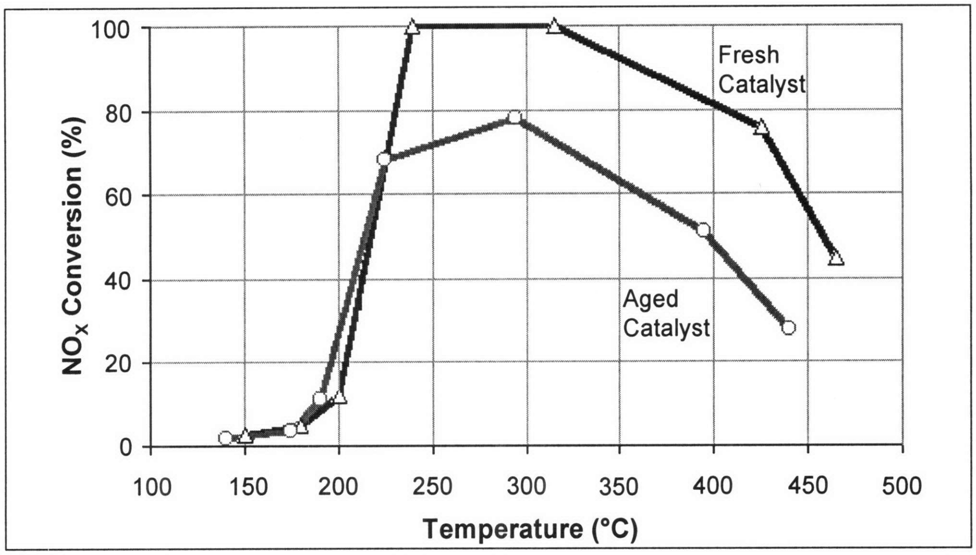
[15] The typical capacity of a barium oxide adsorber catalyst is approximately 2 grams of NO_2 per liter of catalyst volume (Majewski and Khair 2006).

3.3.2 Conversion Efficiency

As Figure 13 illustrates, LNTs offer high conversion efficiencies, often in excess of 90 percent. These levels can be achieved over a relatively wide temperature window, ranging approximately 200°C to 450-500°C (Brogan, Clark, and Brisley 1998; Johnson 2006; Majewski and Khair 2006; Roth 2005). High conversion efficiency at low temperatures (e.g. less than 200°C) is constrained by the ability to catalyze NO to NO_2. At high temperatures the conversion efficiency of LNT catalysts is limited by the fact that stored nitrates become thermodynamically unstable and spontaneously decompose under lean conditions. Good low temperature performance is the major hurdle for light-duty vehicles. For heavy-duty vehicles, the problem is reversed (Majewski and Khair 2006).

Figure 13: LNT Conversion Efficiency of Fresh and Aged Catalysts

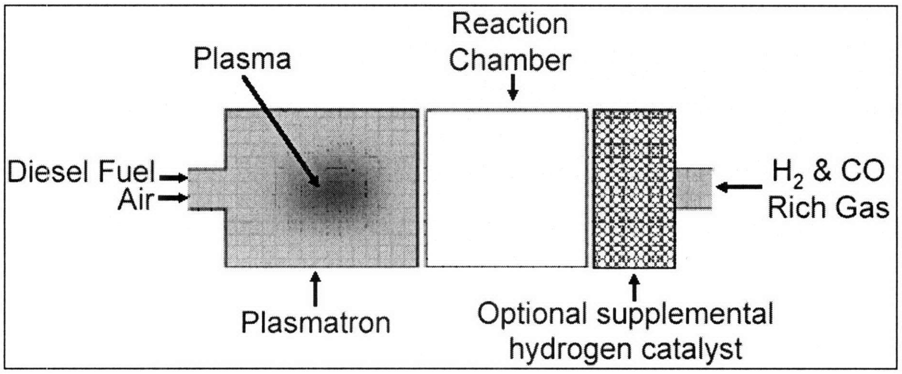


Source: (Brogan, Clark, and Brisley 1998; Majewski and Khair 2006).

Aside from making continual advances in catalyst formulation, several other methods have been devised to improve both the temperature range and NO_X conversion efficiency of LNT catalysts. One popular technique is optimizing the configuration of catalysts in the diesel exhaust stream. For example, it has been determined that low temperature performance can be improved by introducing a DOC upstream of the LNT catalyst (Dou 2002; Majewski and Khair 2006). As discussed earlier, DOCs offer a benefit in that, besides catalyzing hydrocarbons and carbon monoxide to harmless species, they also convert NO to NO_2. A second method, which is particularly attractive for light-duty applications, is the integration of an LNT catalyst with a DPF. This is achieved by applying the LNT trimetal washcoat formulation directly to the surface of a wall-flow filter. One of the advantages of this setup is that the NO_2, which is produced prior to LNT NO_X adsorption, enhances DPF regeneration. Additionally, Toyota has determined that the active oxygen species, which are formed during adsorption and LNT regeneration, are very effective at oxidizing soot (Koichiro et al. 2002; Majewski and Khair 2006).

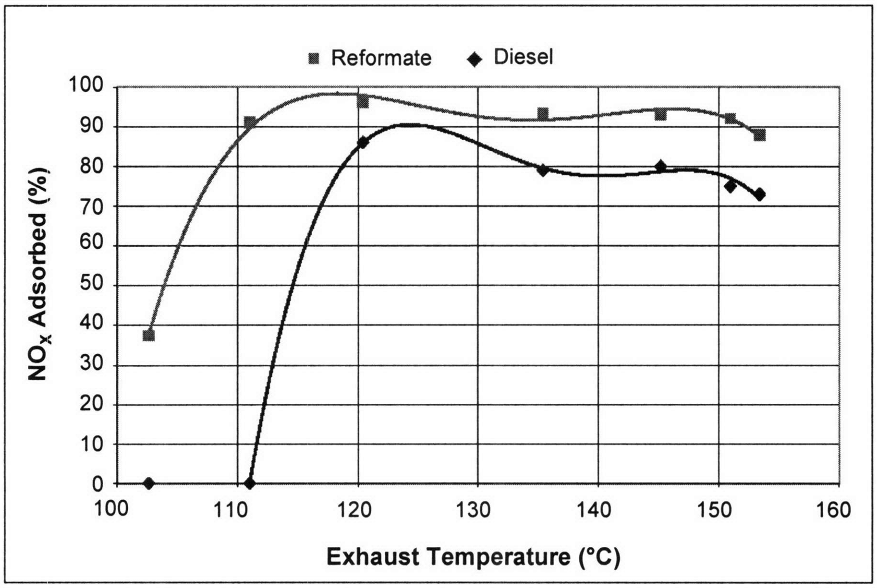
A second optimization technique uses a diesel fuel reformer to partially oxidize diesel fuel to produce H_2 and CO-rich gas, both of which are more effective at regenerating LNT catalysts than diesel fuel alone. ArvinMeritor, in collaboration with the Massachusetts Institute of Technology, developed one particularly promising version of the fuel reformer, called a plasma fuel reformer. Depicted in Figure 14, the plasma fuel reformer uses a plasma to initiate a partial oxidation reaction, as opposed to an electrode, which is the more common and less efficient method employed in most fuel reformers. After the fuel air mixture passes through the plasma it enters a reaction chamber where the oxidation to H_2 and CO takes place. It leaves as a mixture of hydrocarbons, containing approximately 8 percent H_2 and 14 percent CO. An optional additional oxidation catalyst can be incorporated to increase the yield of H_2 and CO. As shown in Figure 15, the use of hydrogen-rich reformate improves both the conversion efficiency and operating temperature range of a standard LNT catalyst. As will be discussed later, the use of a fuel reformer also lowers the overall fuel penalty associated with using an LNT catalyst.

Figure 14: Schematic Diagram of a Plasma Fuel Reformer



Source: (Cohn 2006).

Figure 15: LNT Conversion Efficiency Using Reformate (H_2 and CO Rich Gas)



Source: (Koichiro et al. 2002).

3.3.3 Susceptibility to Fuel and Lubricant-derived Poisons

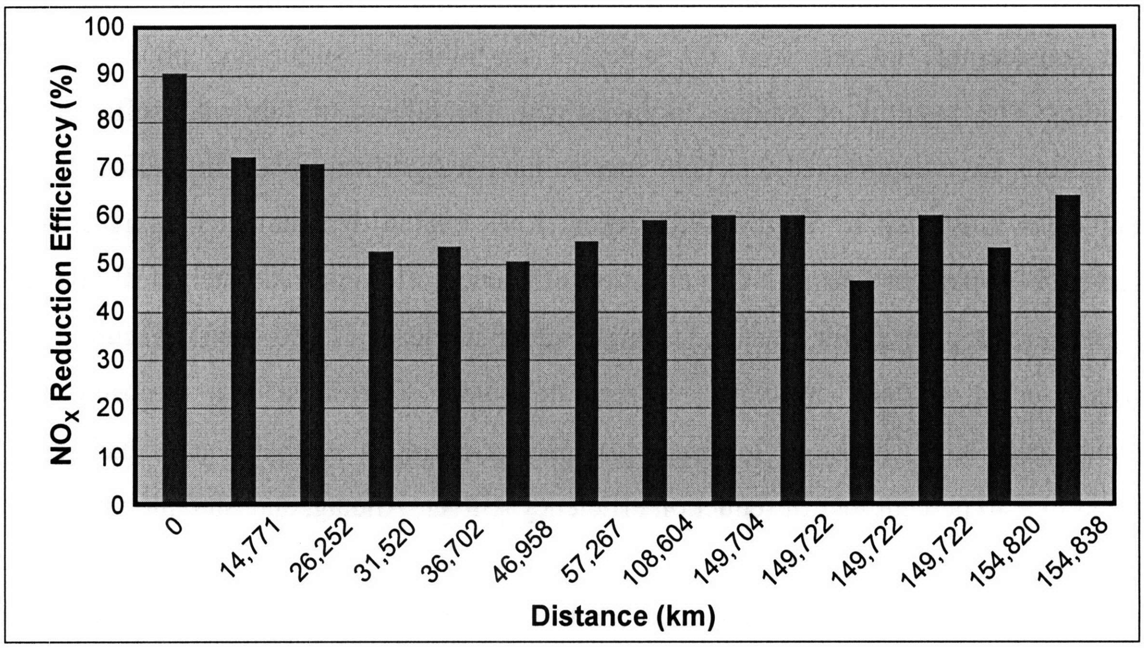
The largest challenge to LNT adoption is sulfur poisoning. Poisoning is especially an issue for HHDD vehicles, whose aftertreatment durability requirements are significantly more stringent (i.e. 435,000 mi) than medium or light-duty vehicle standards. Sulfur in the exhaust stream originates primarily from fuel sulfur. Up until October 2007, the sulfur concentration in diesel fuel was capped at 500 ppm and averaged approximately 350 ppm. Beginning in October 2006, a new EPA regulation came into effect that required all diesel fuel to be sold with less than 15 ppm sulfur. Some exhaust sulfur also derives from the small amount of engine oil that is consumed during normal operation. Engine oil, which gets consumed at approximately 1/1,000 the rate of diesel fuel, has a maximum sulfur concentration of 4,000 ppm. When fuel and lubricant sulfur are combusted inside the combustion chamber they primarily form sulfur dioxide (SO_2), which behaves in a similar manner to NO_2, as shown below (Majewski and Khair 2006).

$$SO_2 + \tfrac{1}{2} O_2 = SO_3$$
$$BaO + SO_3 = BaSO_4$$

Accordingly, SO_2 saturates the barium oxide sites inside LNT catalysts, causing a loss of activity towards the adsorption of NO_2. Since the resulting sulfates of barium are more stable than barium nitrate. The sulfates, however, require much higher temperatures to regenerate or "desulfate". This leads to a gradual loss of LNT activity towards the adsorption of NO_2, which translates into lower NO_X conversion efficiencies (Majewski and Khair 2006).

In order to desulfate LNT catalysts, temperatures of approximately 500 to 700°C, as well as mixture enrichment, are required. Although desulfations should theoretically be able to fully restore an LNT catalyst back to its original adsorption capacity. In reality, some permanent and irreversible poisoning always occurs. The extent of LNT capacity loss has been declining over time with improvements in catalyst formulation and desulfation strategy. Early durability tests consistently showed upwards of a 50 percent loss in LNT NO_X conversion efficiency, whereas more recent studies are only exhibiting a 10 to 20 percent loss. Most of the loss in conversion efficiency has been found to occur during approximately the first twenty desulfations, which would be equivalent to the first 100,000 km in a typical heavy-duty vehicle's useful life (Johnson 2004). Limited data exists on the extent to which the reduction efficiency of heavy-duty catalysts can be restored after experiencing sulfur poisoning in the field. Light-duty vehicle studies indicate, however, as depicted in Figure 16, that the NO_X reduction efficiency drops to an approximately steady-state level of 60 percent after extended aging, even despite regular desulfations (Dorenkamp 2006; Godwin 2006; Schindler 2006).

Figure 16: LNT Conversion Efficiency of a Volkswagen Touran



Source: (Dorenkamp 2006).

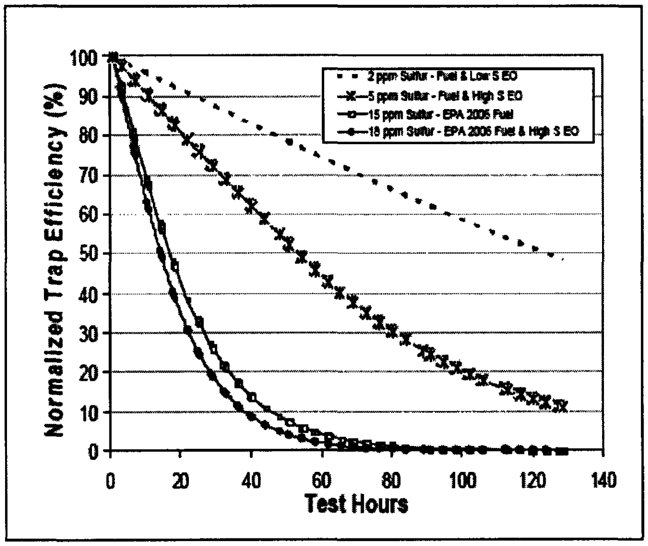
Besides a loss of LNT NO_X conversion efficiency, sulfur poisoning also results in two indirect effects, thermal degradation of the catalyst substrate and washcoat, as well as an additional fuel consumption penalty. Therefore, the key challenge faced by aftertreatment suppliers is to develop a desulfation interval that is not so long that it compromises the NO_X conversion efficiency nor too frequent that it causes accelerated thermal deterioration and a significant fuel economy penalty (Majewski and Khair 2006). As such, desulfation intervals typically range between a few hundred to several thousand kilometers (Johnson 2004).

Like NO_X regeneration, desulfations are also more effective and can be achieved at lower temperatures using H_2 and CO rich gas. The only downside of this approach is that it can lead to the production of unwanted secondary emissions, like H_2S (Johnson 2005;

Takahashi et al. 2004). It has been determined, however, that pulsed desulfations minimize H_2S emissions, while also mitigating thermal deterioration (Johnson 2006).

The majority of poisoning studies have historically focused solely on the effects of fuel sulfur. Although the recent introduction of so-called "ultra low sulfur diesel" fuel has raised considerable interest over the potential for lubricant sulfur and phosphorous poisoning. The handful of studies to investigate the effects of lubricant sulfur and phosphorous have determined that both species have a significant poisoning effect. For example, as illustrated by Figure 17, a recent LNT engine dynamometer aging study observed a 90 percent loss in NO_X reduction efficiency after approximately 130 hours, using only a 2 ppm sulfur fuel and a high sulfur lubricant (7,000 ppm) (Figure 17) (Bardasz et al. 2004a). Similarly, a separate study determined that exposure to approximately 4,000 hours of lubricant phosphorus during a synthetic gas bench test resulted in a 40 percent loss of reduction efficiency (Silver, Alletag, and Stefanick 2005a). Despite a clear poisoning effect, at least two authors have noted that the net impact from lubricant sulfur and phosphorus on catalyst performance will most likely be overshadowed by the impact of fuel sulfur, even at ultra low sulfur diesel fuel concentrations of 15 ppm (Bardasz et al. 2004a; US DOE 2006). This phenomenon is depicted in Figure 17, where the fuel sulfur level dominates any lubricant-derived poisoning effect. Put differently, using a high sulfur lubricant (7,000 ppm) is equivalent to increasing the sulfur concentration of the diesel fuel by a mere 2-3 ppm.

Figure 17: Fuel and Lubricant-derived Sulfur Effects on LNT Catalysts



Source: (Bardasz et al. 2004a).

3.3.4 Fuel Penalty

Diesel fuel penalty is another factor that will dictate the viability of LNT catalysts, especially for heavy-duty applications where fuel costs represent a considerable fraction of total operating costs. Diesel fuel is primarily used during NO_X regeneration but some fuel is also used on a less frequent basis for desulfations. The majority of the fuel that is introduced into the exhaust stream during LNT regeneration is not directly used to reduce NO_X emissions. Instead, approximately 2/3 of it reacts with excess oxygen to produce the rich environment that is required for the reducing catalyst to function properly (Tsumagari et al. 2006).[16] For this reason, almost all of the LNT systems that are currently being developed incorporate techniques to reduce the concentration of oxygen during LNT regeneration.

The most prevalent oxygen-reducing design is the dual-leg configuration shown in Figure 18 The concept involves regenerating one leg of the system while diverting the exhaust gas flow through the other leg. Usually, the volume of one of the catalysts is much larger than the other catalyst. The smaller of the two is just large enough to

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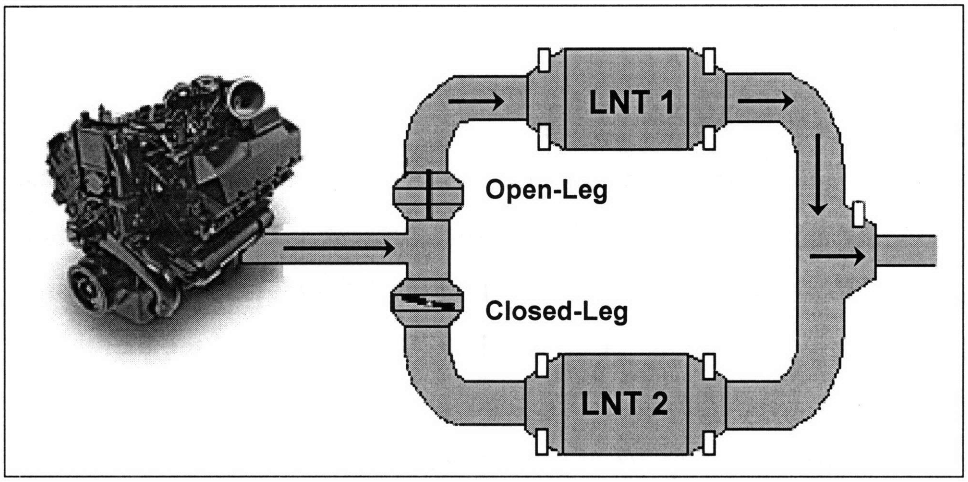
[16] The concentration of oxygen in the exhaust stream has to be limited to less than approximately 4 percent by weight for reduction to take place (Tsumagari et al. 2006).

accommodate the NO_X that accumulates while the other catalyst is being regenerated. This helps lower the total initial cost of the system by reducing the amount of precious metals that are required. A recent study even demonstrated the potential to achieve high NO_X reduction efficiency using an LNT system with an exhaust by-pass valve instead of a second-leg (Hinz et al. 2005). Other more preliminary concepts, such as transmural catalysis and selective regeneration, also appear to be promising. Transmural catalysis involves injecting the reductant directly at the catalyst surface, within the exhaust flow boundary layer (Atkinson and Clark 2006). Selective regeneration continually regenerates an LNT catalyst by blocking the exhaust flow to certain catalyst channels while they are being regenerated (Bodek 2006).

Figure 18: Dual-leg LNT Configuration



Source: (Motorcraft 2006).

Table 5 presents a review of NO_X reduction and fuel penalty data from several recent studies of US 2010 concept aftertreatment systems. The majority of these studies exposed a medium heavy-duty (MHDD) diesel engine (i.e. a 6-8 liter engine) plus aftertreatment system to both the US SET and FTP heavy-duty engine dynamometer test cycles. Except for one study (SAE 2004-01-1940), all of the rest either used a dual-leg or by-pass configuration. Additionally, all but two studies incorporated an upstream DOC to help facilitate the conversion of NO to NO_2. The results show that on the SET test cycle, an average reduction efficiency of 89 percent could be achieved at an average fuel penalty of approximately 3 percent. On the FTP test cycle, an average reduction efficiency of 84 percent was achieved at an average fuel penalty of approximately 5 percent. The difference in NO_X reduction efficiency and fuel penalty between the two cycles is believed to result from the fact that engines run on the SET test cycle maintain a higher average load and therefore, higher exhaust temperature than engines run on the FTP cycle. A higher exhaust temperature implies that the LNT catalyst is operated closer to its optimum NO_X reduction efficiency and that less fuel is required to maintain the catalyst above the 200°C cutoff temperature. Finally, limited data suggests that the use of a fuel reformer can lower the fuel penalty of NO_X and SO_X regeneration by approximately 25 to 50 percent (Crane 2003; Crane et al. 2005).

Table 5: US 2010 Heavy-Duty LNT Fuel Penalty Results

Source	Configuration	Test Cycle	NOX Reduction	Fuel Penalty
Tsumagari et al. SAE 2006-01-0211 (2006)	duel-leg, no DOC	100% speed & load	78.0%	1.4%
Hinz et al. SAE 2005-01-1084 (2005)	single-leg, DOC	SET	79.0%	2.8%
Hinz et al. SAE 2005-01-1084 (2005)	single-leg, DOC	FTP	66.6%	5.4%
Cizeron et al. SAE 2004-01-1940 (2005)	single-leg, no DOC	50% load	87.0%	3.8%
Whitacre et al. SAE 2004-01-0587 (2004)	dual-leg, DOC	SET	94.5%	4.5%
Whitacre et al. SAE 2004-01-0587 (2004)	dual-leg, DOC	FTP	92.0%	8.2%
Schenk et al. SAE 2001-01-1351 (2001)	dual-leg, DOC	SET	93.50%	2.40%
Schenk et al. SAE 2001-01-1351 (2001)	dual-leg, DOC	FTP	93%	2.30%

Sources: (Cizeron et al. 2004; Crane et al. 2005; Hinz et al. 2005; Schenk, McDonald, and Olson 2001; Tsumagari et al. 2006).

3.4 Lifetime Cost Comparison of Urea-SCR versus LNT

In the event that the LNT sulfur poisoning issue can be resolved, it is instructive to perform a lifetime cost comparison between LNT and urea-SCR catalysts to determine which technology would be preferred for use with heavy-duty engines. Lifetime cost can be broken down into the categories of initial and operating costs. Initial costs for both systems include the cost of the catalyst, as well as the cost of the reductant dosing system. Operating costs consist solely of the cost of the reductant. Since both systems share many similar characteristics, such as a flow-through substrate and OBD requirements, this comparison will focus exclusively on the differential cost between LNT and urea-SCR catalysts.

3.4.1 Initial Costs

The largest difference between urea-SCR and LNT systems is the cost of the catalyst metals. As discussed earlier, urea-SCR systems use a base metal catalyst and LNT systems use precious metals or so-called "platinum group" metals (PGM). The cost ratio between base metals and PGMs is approximately 2,000:1. Given the fact that urea-SCR and LNT catalysts are similar in size and use comparable metal loading levels, this implies that the cost of urea-SCR base metals is negligible (Lambert et al. 2004). The total cost associated with precious metals for LNT catalysts depends upon the cost of the metals and in what quantity they are used. Table 6 details the 2006 average daily price per gram for platinum, rhodium, and palladium, which are the three PGM metals that are most often used in LNT catalyst formulations. It should be noted that the price of each of these metals has historically exhibited significant volatility, sometimes doubling in price within only a one to two year time span. Therefore, it is highly uncertain what the price of these metals will be starting in 2009/2010 or whenever LNT sulfur poisoning gets resolved.

Table 6: 2006 Average Daily PGM Prices

Metal	Cost
	($/g)
Platinum (Pt)	36.84
Rhodium (Rh)	146.51
Paladium (Pd)	10.37

Source: (Johnson Matthey 2007).

The amount of PGM metals that are used in an LNT catalyst is usually expressed as the PGM density multiplied by the size of the catalyst. A literature review of typical PGM density levels are presented in Table 7. It shows that the majority of catalysts either only contain platinum or that they contain a combination of platinum, palladium, and rhodium in approximately the following proportions 9Pt:3Pd:1Rh. Given the reciprocal nature of the price ratio between rhodium and palladium (Table 6), it is reasonable to make the simplifying assumption that the average cost of PGM metals in LNT catalysts is equal to the price of platinum, which in late 2006 was approximately $37/g. A review of Table 7 and estimates of LNT catalyst loading levels by the diesel aftertreatment experts Tim Johnson (2.82 g/L)) and John Hoard (1.77 g/L) indicates that 2.65 +/-0.88 g/L is a conservative PGM loading assumption for optimized catalysts (Hoard et al. 2004; Johnson 2006).

Table 7: Literature Review of LNT PGM Loading Levels

Source	**Pt**	**Rh**	**Pd**	**Total**
	(g/L)	(g/L)	(g/L)	(g/L)
Bonadies et al. 2006 DOE DEER Conference.	2.65			2.65
Disselkamp et al. DOE 2005 FY Progress Report.	2.44	0.28	0.81	3.53
Fridell and Skoglundh. SAE 2004-01-0080 (2004)	3.53	1.76		5.29
Amberntsson et al. *Appl Catal B* (2003) 429-439	1.76			1.76
Amberntsson et al. *Appl Catal B* (2003) 429-439	7.06	2.65		9.71
Daw et al. *Int J Chem React Eng.* 1(2003) 1-11	1.76			1.76
Daw et al. *Int J Chem React Eng.* 1(2003) 1-11	3.53			3.53
Daw et al. *Int J Chem React Eng.* 1(2003) 1-11	7.06			7.06
Nakatsuji et al. 2003-01-1158 (2003)	3.53			3.53
Dou and Ballard. SAE 2002-01-0734 (2002)	2.12	0.18	0.53	2.82
Dou and Ballard. SAE 2002-01-0734 (2002)	2.47	0.35	0.71	3.53
Geckler et al. SAE 2001-01-0510 (2001)	5.79			5.79
Engstrom et al. *Appl Catal B* (1999) L241-L248	2.19	1.06		3.25
Average	*3.60*	*1.05*	*0.68*	*4.30*
Min	*1.76*	*0.18*	*0.53*	*1.76*
Max	*7.06*	*2.65*	*0.81*	*9.71*

Sources: (Amberntsson, Fridell, and Skoglundh 2003; Bonadies et al. 2006; Daw et al. 2003; Disselkamp et al. 2006; Engstrom et al. 1999; Fridell and Skoglundh 2004; Geckler et al. 2001; Hoard et al. 2004; Nakatsuji et al. 2003).

Table 8 presents a literature review of the volume of LNT catalysts used in experimental studies, as well as the ratio of their volume to the total swept volume of the engine's they were installed on. Consistent with Johnson and Hoard's estimates, Table 8 suggests that 1.6 is a reasonable ratio to use for this calculation. In order to tease out the relative advantages of urea-SCR and LNT systems, this cost comparison will treat two different engine sizes, MHDD and HHDD. The California Air Resources Board (CARB) categorizes MHDDs as ranging between 4.25L and 8.9L in displacement and HHDDs as ranging between 8.8L and 15L (California Air Resources Board 2005b). For the purposes of this comparison, 6.5L and 12L will be used to represent the displacement of MHDD and HHDD engines, respectively.

Table 8: Literature Review of LNT Volume and Engine Swept Volume Ratio

Source	Engine Swept Vol.	LNT Vol.	Ratio
	(L)	(L)	(#)
Tsumagari et al. SAE 2006-01-0211 (2006).	7.685	20.8	2.7
DOE. APBF-DEC Phase 2 Report (2006).	5.9	7	1.2
Hinz et al. SAE 2005-01-1084 (2005).	12	20.8	1.7
Bardasz et al. SAE 2004-01-3011 (2004).	5.9	5	0.8
Whitacre at el. SAE 2004-01-0587 (2004).	15	22.2	1.5
		Average	*1.6*
		Max	*2.7*
		Min	*0.8*

Sources: (Bardasz et al. 2004b; Hinz et al. 2005; Tsumagari et al. 2006; US DOE 2006; Whitacre et al. 2004).

In addition to the catalyst, the other relevant component of the initial cost is the reductant dosing system and associated OBD equipment. A urea-SCR system requires a urea storage tank, refill system, a pump/metering system, heaters to prevent freezing, sensors, and controls (Hoard et al. 2004). An LNT system, on the other hand, only requires a pump/metering system, sensors and controls. The cost of the shared components is estimated to be equivalent for these two systems, assuming closed-loop control is required and that therefore, urea-SCR systems are forced to use a NO_X sensor instead of a NH_3 sensor, which is expected to be significantly less expensive (Hoard et al. 2004). Currently, the only public estimates of the additional cost for a urea dosing system have been for light-duty vehicle systems. Johnson and Hoard, respectively, estimate that these components will add an additional \$180 and \$250, respectively (Hoard et al. 2004; Johnson 2006). Since heavy-duty vehicles have much more stringent durability requirements, this cost comparison will assume that the extra cost for urea dosing equipment is \$500. An additional potential LNT component that has not been mentioned is the cost of a diesel fuel reformer to generate H_2 and CO-rich reformate. This analysis will assume that the added cost of the reformer would be approximately offset by the savings from needing less precious metals (Hoard et al. 2004).

3.4.2 Operating Costs

The operating costs of urea-SCR and LNT systems depend on the rate of reductant consumption, the number of vehicle miles traveled, and the price of the reductant. The rate of urea consumption by urea-SCR catalysts and the rate of diesel consumption by LNT catalysts were both discussed earlier in this chapter and will be considered to be 2 percent and 4 percent, respectively, plus or minus 1 percent. An LNT diesel consumption rate of 2 percent plus or minus 1 percent will also be considered for the case in which a diesel fuel reformer is used. Since both consumption rates are expressed as a percentage of the fuel economy, it is necessary to know an average fuel economy for MHDD and HHDD vehicles. According to the most recent US Census Bureau Vehicle Inventory and Use Survey, the average fuel economy of vehicles equipped with MHDD (Classes 3-6) and HHDD (Classes 7 and 8) engines is 8 mi/gal and 5.8 mi/gal, respectively (Davis and Diegel 2006). This comparison will treat the number of vehicle miles traveled as equal to the aftertreatment durability standard, which is 185,000 mi for MHDD vehicles and 435,000 miles for HHDD engines (Majewski and Khair 2006).

The cost of diesel fuel in 2010 or whenever the sulfur poisoning issue is resolved is difficult to predict. Therefore, this analysis will simply use the US national weekly average retail diesel fuel price in 2006, which was \$2.71/gal (US DOE 2007). The cost of urea-SCR grade urea is even more difficult to predict due to the fact that there is currently no US market for this substance. The consulting firm Tiax has performed a series of comprehensive analyses to estimate the potential price of urea to end-use customers. While their results will be discussed at greater detail in the following chapter, Tiax determined that the price would range between \$2/gal and \$7/gal (Schubert, Pont, and Jackson 2006).[17] In the EU, where heavy-duty urea-SCR equipped vehicles have already been introduced, the price of urea is approximately one half the price of diesel fuel (Mailard 2005). Given that this analysis focuses on the heavy-duty sector and that the

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[17] The \$2 per gallon figure is based on a high throughput truck stop that uses large, above or below-ground storage containers, whereas the \$7 per gallon figure is intended to represent the price of urea that would be sold in small, gallon-sized containers at fueling stations or retail outlets, like Wal-Mart (Schubert, Pont, and Jackson 2006).

price of diesel fuel is significantly lower in the US, we will assume a cost for urea of \$3/gal, plus or minus \$1.50/gal.

A final component of the operating cost is the potential for a fuel economy benefit to accrue from the fact that having a catalyst enables the engine to operate at a higher level of engine-out NO_X emissions than was possible in 2007. Recall that this is the case because in 2007 every US engine manufacturer opted to meet the new regulation of 1.74 g/kWh NO_X solely through in-cylinder control measures. A shift to higher engine-out NO_X emissions could be accomplished by re-advancing the fuel injection timing, which would result in a fuel economy benefit. While both urea-SCR and LNT configurations could conceivably capitalize on this opportunity, it is believed that only engines that are equipped with urea-SCR catalysts will choose to deploy this strategy. This is due to two factors. First, urea costs are expected to be less than LNT diesel reductant costs because of the per gallon price and reductant consumption rate differential. Secondly, this strategy would require a larger catalyst, which is disproportionately more costly for LNT systems due to its PGM content. As discussed earlier in this chapter, it is likely that the engine manufacturers who choose urea-SCR catalysts will decide to re-advance their fuel injection timing from 1.74 g/kWh to either 2.0 g/kWh or 2.7 g/kWh. This would correspond to a fuel economy benefit of between 0.4 and 1.2 percent. For the purposes of this analysis, an average fuel economy benefit of 0.8 percent plus or minus 0.4 percent was assumed.

3.4.3 Results and Sensitivity Analysis

Table 9 presents the calculations and results of the differential cost comparison for MHDD and HHDD vehicles. It shows that for both categories of vehicles, an LNT will cost more than a urea-SCR system. LNTs will cost approximately \$2,000 more for MHDD vehicles and approximately \$6,500 more for HHDD vehicles. The cost of operation accounts for the majority of the price differential, representing approximately 75 to 80 percent of the additional cost. Irrespective of its accuracy, this comparison reveals the important fact that the larger the vehicle, the more favorable urea-SCR aftertreatment systems become. This is primarily due to the following three factors, the importance of whose effects scale with engine size: (1), the relative proportion of the total initial costs attributable to PGM metals; (2), lower fuel economies and therefore higher reductant consumption levels; and (3), longer durability requirements. As for the breakeven point between these two technologies, Johnson estimates that the LNT will only become cost competitive for light-duty vehicles whose engine displacements are 2L or less (Johnson 2006). The above cost model reaches a similar result when the following light-duty vehicle assumptions are used: urea-SCR differential dosing equipment costs fall to $250; vehicle fuel economy increases to 25 mpg; the price of urea increases to $7 (i.e. the upper bound of Tiax's estimate); and vehicle miles traveled drops to 120,000 mi (i.e. the Tier 2 light-duty minimum durability standard for aftertreatment systems).

Table 10 presents a sensitivity analysis, showing the impact that each of several key variables has on the differential cost between urea-SCR and LNT systems. It demonstrates that there is no single variable that, when modulated across its uncertainty range, would have the effect of bringing the LNT into price parity with urea-SCR. It does, however, help highlight those variables that have the largest potential to influence the price differential, including the "effective" fuel economy benefit from using a fuel reformer for LNT regeneration and changes in the relative price of urea and diesel fuel. In fact, if you assume that the use of a fuel reformer reduces the LNT fuel penalty by 50 percent, that the price of urea is $4.5/gal instead of $3/gal, and you disregard any fuel economy benefit from re-advanced fuel injection timing, the LNT becomes the preferred aftertreatment system for MHDD, as well as HHDD vehicles.

Table 9: Differential Lifetime Cost Comparison Between Urea-SCR and LNT

COST CATEGORIES	**SCR**		**LNT**	
	MHDD	**HHDD**	**MHDD**	**HHDD**
INITIAL COSTS				
Precious Metals				
Loading Density (g/L):			2.65	2.65
Catalyst/Engine Volume:			1.60	1.60
Engine Displacement (L):			6.50	12.00
Average Weighted PGM Price ($/g):			$ 37	$ 37
Subtotal =			***$ 1,020***	***$ 1,883***
Hardware				
Urea Dosing Equipment ($):	$ 500	$ 500		
Subtotal =	***$ 500***	***$ 500***		
Total =	***$ 500***	***$ 500***	***$ 1,020***	***$ 1,883***
OPERATING COSTS				
Reductant				
Consumption Rate (% of diesel fuel consumption):	2%	2%	4%	4%
Fuel Economy (mi/gal):	8	5.8	8	5.8
Price of Reductant ($/gal):	$ 3	$ 3	$ 2.70	$ 2.70
Vehicle Miles Traveled (mi):	185,000	435,000	185,000	435,000
Subtotal =	***$ 1,388***	***$ 4,500***	***$ 2,498***	***$ 8,100***
Fuel Economy Improvement				
Change in BSFC due to injection advancement	-0.8%	-0.8%		
Subtotal =	***-$500***	***-$1,620***		
Total =	***$ 888***	***$ 2,880***	***$ 2,498***	***$ 8,100***
GRAND TOTAL =	***$ 1,388***	***$ 3,380***	***$ 3,517***	***$ 9,983***
	MHDD		**HHDD**	
APPROX. LNT ADDITIONAL COST =	**$2,000**		**$6,500**	

Table 10: Differential Lifetime Cost Comparison Sensitivity Analysis

Variable	Range	ADDITIONAL COST OF LNT	
		MHDD	HHDD
Base Case	*NA*	*$2,100*	*$6,600*
PGM Price	($37/g +/- $5/g)	$2,000-$2,300	$6,350-$6,900
PGM Loading	(2.65g/L +/- 0.88 g/L)	$1,800-$2,500	$6,000-$7,300
Catalyst/Engine Volume	(1.6 +/- 0.5)	$1,800-$2,500	$6,000-$7,200
Urea Consumption Rate	(2% +/- 1%)	$1,450-$2,800	$4,400-$8,900
LNT Diesel Consumption Rate	(4% +/- 1%)	$1,500-$2,800	$4,600-$8,700
Fuel Reformer Fuel Economy Improvement	(25%-50%)	$900-$1,500	$2,600-$4,600
Urea Price	($3/ga; +/- $1.5/gal)	$1,500-$2,800	$4,400-8,900
Diesel Price	($2.70/gal +/- $0.70/gal)	$1,400-$2,900	$4,100-$9100
Fuel Economy Benefit from Re-advanced Injection Timing	(0.8% +/- 0.4%)	$1,900-$2,400	$5,800-$7,400

CHAPTER 4: INTRODUCING UREA-SCR IN THE US

The previous chapter demonstrated that urea-SCR aftertreatment offers a superior approach to meeting EPA's 2010 NO_X emission regulations. Not only is it favored from a cost perspective, but urea-SCR is also the only technology that is capable of providing high emission reduction efficiency over a heavy-duty vehicle's warranted lifetime. The question is, given the variety of issues that are associated with the use of urea, what needs to happen over the next three years to make urea-SCR a viable aftertreatment strategy in 2010? It appears that two things must occur. One, all of the conceivable stakeholders must collectively support urea-SCR and they must commit to working with one another to implement this technology. Secondly, the stakeholders must agree on how to resolve several critical issues, from mundane ones, like developing a urea quality standard, to more controversial questions, like how to guarantee emission compliance and how best to introduce a urea-refueling infrastructure. Reaching a consensus, let alone getting all of the stakeholders onboard in the first place, will be especially difficult in light of the limited time window, number of players involved, and context of their often adversarial, historical relationships.

4.1 Stakeholder Analysis

Despite its cost and durability advantages, it is unclear whether the majority of potential stakeholders will choose to support urea-SCR. Many of these groups, comprising regulatory, demand, and supply-side interests have significant concerns with urea-SCR. Also, each of these groups, as listed in Table 11, have different abilities to impact the ultimate outcome of urea-SCR.

Table 11. Urea-SCR Stakeholder Categories and Example Members

STAKEHOLDERS	TYPICAL MEMBERS
Regulatory	
Government	EPA
Demand-Side	
Engine Manufacturers	Caterpillar, Cummins, DetroitDiesel, Hino, Isuzu, International, and Mack/Volvo
Truck Manufacturers	International, PeterBilt, Freightliner, Isuzu, Ford, etc.
Catalyst & Urea Dosing Equipment Manufacturers	Argillon, ArvinMeritor, BASF, Delphi, Johnson Matthey, Robert Bosch
Truck Operators	Private Fleets: UPS, FedEx, Waste Management, etc. For Hire Fleets: Ryder, J.B. Hunt, Schneider, single-owners, etc.
Supply-Side	
Urea Manufacturers	Agrium, Terra Industries, Mississippi Chemicals, etc.
Potential SCR Urea Distributors	Existing petroleum marketers, agricultural & stationary power generation urea distributors, and other independent entrants such as Cummins Filtration
Potential Urea Retailers	Bulk: truck stops, card locks and central fleet fueling facilities Containers: Walmart, Target, Autozone, PepBoys, etc.

Source: (Tiax 2003).

4.1.1 Government

EPA is the stakeholder who has been the most vocal about their concerns with urea-SCR. They are also the group with the largest ability to influence the success or failure of urea-SCR. As the author of the 2007 Diesel Rule, EPA is legally bound to ensure that the regulations they promulgate are met. As such, EPA has two major concerns with urea-SCR, compliance and availability (Charmley 2005). Compliance is an issue because vehicle owners and operators do not benefit from refueling their urea tanks. Instead, they incur the cost of having to purchase urea. They are also inconvenienced by the need to monitor, refuel and potentially locate a source of urea. If a urea-SCR vehicle is operated without urea the emission reduction efficiency of the catalyst drops to zero. Emissions of NO_X could increase over tenfold from the 2010 regulatory limit (0.27 g/kWh) to 2007 (1.74 g/kWh) or 2004 (3.35 g/kWh) levels (Charmley 2005).

Another angle of the compliance issue is the potential for vehicle owners, operators and even manufacturers to elude or game the vehicle systems, such as OBD equipment, that are designed to guarantee compliance. For example, one major concern is that vehicle operators will be able to avoid using urea by refueling their tanks with water or a highly diluted mixture of urea. EPA is especially sensitive to these types of issues, given the embarrassment they experienced when they discovered that 95 percent of all heavy-duty diesel engines had been sold with emission control defeat devices for ten year period (General Accounting Office 2004).

EPA's second concern is the broad-based availability of urea. Beginning when urea-SCR was first discussed in earlier 2001 as part of the 2007 Diesel Rule, they have been very explicit about the need for a sufficient infrastructure to be in place by the time the first urea-SCR vehicles are introduced (Charmley 2005). Aside from being a clear prerequisite for compliance, EPA is motivated to avoid a situation where engine and vehicle manufacturers could argue "after-the-fact" that they met their end of the bargain and that they cannot be held responsible for the infrastructure not being available.

A third and less pressing EPA concern is the avoidance of unwanted secondary emissions. As discussed earlier, an inaccurate urea-dosing control strategy can lead to ammonia slip. Aside from its acute respiratory toxicity, EPA regulates ammonia because it is a precursor and promoter of fine particulate, one of six so-called criteria pollutants (US EPA 2006a). The introduction of a DOC downstream of the urea-SCR catalyst has been proposed as a solution to excess ammonia emissions. This clean-up DOC, however, could catalyze the formation of NO and N_2O, a form of NO_X and a global warming gas, respectively. In the former case, this would have the effect of increasing the effective NO_X emissions of the vehicle. In the latter case, it would increase the effective emission of global warming gases. Although there is no record of EPA raising concerns over secondary NO and N_2O emissions, there is evidence of similar state-level precedent. In late 2006, the California Air Resources Board (CARB) introduced legislation that regulates the proportion of NO to NO_2, in addition to total NO_X emissions, from diesel retrofits (DieselNet 2006a).

More than any other stakeholder, EPA has a unique ability to determine the fate of urea-SCR because it is responsible for implementing the US government's highway vehicle emission regulation program. Entitled "Control of Emissions from New and In-Use Highway Vehicles and Engines", this program is detailed in Title 40, Part 86 of the US Code of Federal Regulations (US Government Printing Office 2007). In addition to demonstrating compliance with the emission levels that were discussed in Chapter 2, heavy-duty engines (including their aftertreatment systems) must meet a variety of other requirements to achieve EPA certification. According to EPA, there are two requirements in the code that apply to urea-SCR and that therefore, afford EPA the authority to dictate the conditions under which engines that rely on urea-SCR aftertreatment will be granted certification (US EPA 2006b).

The first requirement is the "Allowable Maintenance" provision, discussed in 40 CFR §86.004-25. This provision prescribes the minimum allowable mileage interval before scheduled maintenance can be performed on emission-related components. According to paragraph (b)(4), emission-related maintenance on heavy-duty engines at shorter intervals than 150,000 miles will not be accepted as "technologically necessary." Citing the fact that SCR catalysts do not function without reducing agent, EPA has argued that SCR, including the replenishment of the reducing agent tank, is subject to these requirements (US EPA 2006b). Since urea refilling intervals are estimated to occur every 8,000 – 17,000 miles (Table 2), urea-SCR clearly falls short of the required minimum interval. EPA, however, has stated that paragraph (b)(7) authorizes the agency to consider changes to the scheduled maintenance interval, including a shorter interval. Such a change must be requested by the manufacturer and accompanied by supporting data that substantiates the suggested interval.

The second requirement is the "Adjustable Parameter" provision, discussed in 40 CFR §86.094-22 and §86.1833-01. This provision gives EPA the authority to test a vehicle for emissions over the full range of an adjustable parameter. An adjustable parameter is defined as the following:

> ...any parameter on any vehicle (Otto-cycle or diesel) which is physically capable of being adjusted, may significantly affect emissions, and was not present on the manufacturer's vehicles (or engines) in the previous model year in the same form and function. §86.094-22(e)(1) and §86.1833-01(a)(1)

The concern with adjustable parameters is that vehicles could be operated at a different setting than what the manufacturer recommends, possibly resulting in emission levels above the regulated limit. If a parameter can be shown to be adequately inaccessible, however, EPA will only test it at the setting the parameter was adjusted to during production. §86.094-22(e)(2) and §86.1833-01(a)(2). Adequate inaccessibility is defined as "a physical limit, stop, seal, or other means used to inhibit adjustment of a parameter..." which should be considered in light of the "...likelihood that it will be circumvented, removed, or exceeded on in-use vehicles." §86.094-22(e)(2)(iv) and §86.1833-01(a)(2)(iv).

Given the above definitions, EPA considers an SCR system requiring a reducing agent that must be replenished to be an adjustable parameter that is not adequately inaccessible (US EPA 2006b). This is due to the fact that without a driver warning and an available source of reductant, there is a high likelihood that the adjustable parameter will be circumvented and that emissions will increase. As a result, EPA believes it has the authority to test a urea-SCR equipped vehicle that contains varying levels of urea, including none at all. If the vehicle is capable of meeting the NO_X standard without urea then it would not be in violation of the regulation. But EPA expects to deny engine certification if the emissions standard is exceeded (US EPA 2006b). Therefore, if a manufacturer can prove that its SCR system will not run out of reducing agent, EPA has said it may determine that the design is acceptable and certify the engine/vehicle.

4.1.2 Engine Manufacturers

The other critical stakeholder in the urea-SCR debate are the manufacturers of heavy-duty on-highway diesel engines. They both determine the emission control strategy that will be used and are responsible for satisfying EPA's engine certification requirements. In the US, this group is represented by the Engine Manufacturers Association (EMA). There is a general consensus within the EMA that urea-SCR is the only viable technology for obtaining the 2010 NO_X emission threshold and that even if LNT were robust enough to withstand the heavy-duty durability standards, urea-SCR would still be preferred. Although the industry is quite supportive of urea-SCR, it is nonetheless apprehensive about certain issues.

The single largest concern that engine manufacturer's have is that they will be held liable for guaranteeing the accessibility and availability of a reducing agent, like urea, at dealerships, truck stops, filling stations and other locations for the life of an engine. Their concern stems from EPA comments stating that urea-SCR-equipped engines will not be certified unless an adequate urea infrastructure is in place and that engine manufacturers are the ones who are responsible for ensuring urea availability (Oge 2006; Peckham 2003b). This prospect has the potential of being prohibitively costly, not to mention practically impossible due to conditions outside the control of engine manufacturers.

According to one engine manufacturer, making them solely responsible for an adequate urea infrastructure puts them "in the position of subsidizing third-parties to guarantee access to a product that the third-parties may have no interest in supplying (Charbonneau 2006)." The potential costs could become particularly onerous if urea-SCR is only used for a couple of years because a better technology comes along that does not require a reducing agent other than diesel fuel. Specifically, engine manufacturers could be held responsible for ensuring urea availability for a small population of vehicles for their entire lifetime.

Some engine manufacturers are more vulnerable to these costs than others. For instance, an engine manufacturer like International stands to lose for two reasons. First, its network of independent dealers is considerably smaller than many of its larger competitors. Secondly, International's engines are primarily used on pickups and delivery vehicles, which rely mostly on urban and suburban filling stations as opposed to large, high throughput interstate truck stops. Given the fact that there are over 30,000 diesel stations that individually supply less than 200,000 gal/mo of diesel fuel and that there are only slightly greater than 2,000 stations that supply more than that much per month, guaranteeing urea availability at urban and suburban stations would surely be significantly more challenging than assuring it at highway truck stops (Tiax 2003).

Cost implications aside, engine manufacturers are concerned about being held accountable for actors who are outside of their control, such as truck stops and retail stores (e.g. Wal-Mart, AutoZone, etc.). Even the idea that integrated truck and engine manufacturers have control over dealerships is a misconception. Most dealerships are not owned or controlled by manufacturers. Furthermore, state franchise laws dictate what manufacturers can require of their dealerships. Some states even have additional laws that serve to further enhance a dealer's autonomy (Dillon 2006).

Some engine manufacturers also argue that this infrastructure guarantee, if enforced, would be inconsistent with the precedent set by existing EPA policy. For example, when the 2007 Diesel Rule was published it stipulated that the fuels industry was responsible for assuring access to ultra low sulfur diesel fuel, which was deemed necessary for emission control. In the present case, however, truck stops, filling stations and other players in the urea distribution supply chain would be free of any legal obligation to assure an adequate supply of urea (Charbonneau 2006).

4.1.3 Diesel Fuel Retailers and Potential Urea Distributors

The third category of absolutely critical stakeholders in this debate are the foreseeable downstream players in the urea supply chain, including travel plazas, truck stops, petroleum marketers, distributors of agricultural urea, and other independent distributors. All of these groups stand to play some role in the inventory, distribution and retail of urea. This constituency is represented by a number of trade associations, including, most notably, the National Association of Truck Stop Operators (NATSO) and the Petroleum Marketers Association of America (PMAA). NATSO represents over 900 travel plazas and truck stops that are responsible for selling approximately 75 to 80 percent of all on-road diesel fuel in the US (Dodge 2006). PMAA is an alliance of 45 state and regional trade associations representing 8,000 independent petroleum marketers. The marketers they represent operate in both a wholesale and retail capacity. As such, several of their members also own truck stops (Stewart 2006).

Diesel fuel retailers and existing members of the petroleum distribution supply chain are extremely concerned that if urea-SCR is introduced, they will be forced to shoulder a disproportionate fraction of the total infrastructure costs. Although EPA has made it clear that it will not require the fuel industry to supply urea, the fear is that it will become a de-facto industry mandate. Without an alternative approach for meeting emission regulations, NATSO and PMAA members could be forced to supply urea, regardless of the repercussions to their bottom-line (Dodge 2006). If the total cost of supplying urea exceeds the price at which urea could reasonably be sold then retailers would either be forced to sell urea at a loss or not sell urea and lose the potential business.

There are two major cost categories of concern, storage and delivery. It is widely agreed that urea storage can occur in underground or below ground storage tanks (UST or AST), as well as in plastic containers that are either shelved or warehoused until the point of sale. The capital cost alone of an UST is estimated to be approximately $60,000 for a 5,500 gal tank. Similarly, an AST is expected to cost approximately $10,000 for a 1,200 gal stillage (Schubert, Pont, and Jackson 2006).[18] Neither of these estimates include the cost to ensure against freezing, which is unknown but assumed to be high. Nor do they account for the corrosive nature of urea and the potential risk it imposes on fuel retailers' properties (Dodge 2006). Although the sale of plastic containers only requires minor, if any, capital investment, it would involve moving or even discontinuing other products, which may be more profitable than the urea containers that they are replaced by. Urea is expected to have an approximately one year shelf life. If it is heated or exposed to the

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[18] The term stillage is synonymous with above-ground storage tank.

elements, however, its shelf life can shorten dramatically. Therefore, uncertainty over the shelf-life of urea is expected to make stakeholders hesitant about installing infrastructures that could later be deemed unnecessary (Dodge 2006).

Delivery is the other cost category that petroleum marketers are particularly concerned about and it is making them very hesitant to use their tanker trucks for transport. The delivery of urea would either require the use of separate, dedicated tanker trucks or it would introduce the need to sufficiently flush existing trucks to avoid product co-mingling. In either case, petroleum marketers would be further burdened by the cost and inconvenience of product integrity testing (Dodge 2006).

In addition to cost concerns, there are also other issues that give diesel fuel retailers and potential urea distributors trepidation. As the first line of contact with the customer, they are worried about putting their employees in a potentially volatile situation if urea is either not available, it freezes on-board the vehicle, or it is available at the fuel station but not accessible because it is frozen. An additional and probably more manageable concern is that they receive formal notification from engine manufacturers that they will need to supply urea, as well as a sufficient window of time within which to do so (Dodge 2006). Finally, the recent inclusion of urea into the Department of Homeland Security's (DHS) "Chemical Facility Anti-Terrorism Standards" regulation has raised some concerns over whether large travel plazas would be required to file Security Vulnerability Assessments with DHS if they exceeded the Screening Threshold Quantity of 2,000 lbs. (Department of Homeland Security 2007). While it is anticipated that aqueous liquid urea solution will be exempt from this requirement, facilities could still be required to register with DHS (dieselscr.org 2007).

4.1.4 Other Important Players

Besides EPA, engine manufacturers and diesel fuel retailers & potential urea distributors, there are other important players, including vehicle owners & operators, catalyst & urea dosing equipment manufacturers, truck manufacturers, and urea producers. These actors, however, will not be discussed at great depth because either their influence is less significant or because their issues with urea-SCR, if they have any at all, do not threaten its viability.

The most conspicuous of these less prominent stakeholders are vehicle owners and operators. In the US, this constituency is represented by the American Trucking Associations, a federation of motor carriers, state trucking associations, and national trucking conferences whose membership comprises over 2,500 trucking companies and industry suppliers. Their major concerns are the availability of urea in the field, the sufficiency of vehicle operator training, and the types of driver warnings and inducements that will be employed to ensure compliance. With respect to the last point, this group is particularly apprehensive of a driver inducement strategy that would involve the complete shut down of an engine if the vehicle runs out of urea. This could present serious safety concerns, especially if the vehicle was located in a remote area or one that was prone to dangerous weather (Routhier 2006).

A second notable constituency is the manufacturers of MHDD and HHDD vehicles, who are represented in the US by the Truck Manufacturers Association. As the primary customer of engine manufacturers, this group has a strong influence over vehicle aftertreatment decisions, which impact their competitive positioning (e.g. fuel economy effects, maintenance requirements, etc). Since urea-SCR currently presents the only viable strategy for meeting the 2010 NO_X standard, truck manufacturers have had few concerns to voice. Their only interest is in verifying that, consistent with previous regulations, engine manufacturers rather then truck manufacturers would be responsible for meeting the conditions for urea-SCR engine certification, such as the assurance of an adequate urea supply (Clarke 2006).

Catalyst and urea dosing equipment manufacturers are another relevant group of stakeholders. They are represented worldwide by the Manufacturers of Emission Control Association (MECA). While MECA stands behind urea-SCR as a proven NO_X control technology, they are concerned that compromises to urea quality and supply chain integrity could impact the durability of these catalysts. Defective catalysts have implications on aftertreatment system warrantees, as well as on the public perception of urea-SCR systems. To protect the durability of these catalysts, MECA has made two proposals. To determine an appropriate urea quality standard. The second is to establish safeguards against cross-contamination. This is especially critical while the urea distribution system transitions from a largely agricultural-based supply chain to one that must handle different grades of urea with a variety of purity requirements (Kubsh 2006).

A final important stakeholder are manufacturers of urea, who are represented in the US by the Agricultural Retailers Association (ARA). Given the potential to further develop their non-agricultural market, it is believed that this constituency is generally very supportive of urea-SCR. For instance, during a recent investor relations presentation by Terra Industries, a representative of the company expressed optimism over the potential increased demand for liquid urea in North America if the US adopts a urea-SCR aftertreatment strategy (Bennett 2006). This group's only conceivable, yet unconfirmed concern is that they invest in the additional equipment (if at all necessary) to produce catalyst-grade urea and yet the market never materializes.[19]

4.2 Developments to Date

The following section describes important milestones in the evolution of urea-SCR in the US. These developments are presented in timeline form in Figure 12 and discussed in detail below.

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[19] Whether or not the production of catalyst-grade urea involves the purchase and use of additional equipment by urea manufacturers will depend on whether they or the urea distributors are responsible for blending urea melt with de-ionized water to produce the final 32.5 percent concentrated product. This will be discussed at greater detail later in this chapter.

Table 12: Timeline of Urea-SCR Activity to Date

Year	Milestone
1999	May - EPA issues notice of proposed rule-making.
	Nov. - Publication of West Coast SINOx demonstration results.
2000	Dec. - EPA issues Regulatory Impact Analysis.
2001	Jan. - EPA publishes emission regulation, entitled "2007 Highway Rule".
2002	Jul. - 1st Tiax urea infrastructure report published.
2003	Early - Informal stakeholder conversations initiated regarding '07.
	Mar. - Publication of East Coast SINOx demonstration results.
	Jul. - 2nd Tiax urea infrastructure report published.
	Sept. - 1st formal "Urea Distribution Stakeholder Group" meeting.
2004	Early - Discussions with EPA suspended after '07 product plans announced.
2005	Nov. - Detroit Diesel & Freightliner announce intent to use urea-SCR for '10.
2006	Jun. - 3rd Tiax urea infrastructure report published.
	Jun. - 1st "Urea Infrastructure Multi-Stakeholders Group" meeting.
	Jul. - Mack/Volvo announces its intent to use urea-SCR for '10.
	Nov. - EPA issues "Draft Guidance Document" for engines using SCR.
	Dec. - "Draft Guidance Document" comment period ends.
2007	Mar. - EPA issues revised "Guidance Document".
	Jul. - Public comment period opened.

Sources: (Brodrick et al. 1999; Charmley 2003; Charmley 2005; EMA 2006; Fable, Kamakate, and Venkatesh 2002; Mack Truck 2003; Overdrive 2005, 10-66; Scarnegie et al. 2003; Schubert, Pont, and Jackson 2006; Tiax 2003; US EPA 1999; US EPA 2000; US EPA 2001a; US EPA 2006b; US EPA 2006b; Volvo Trucks 2006).

The origin of US interest in urea-SCR NO_X aftertreatment can be traced to May, 1999 when the US EPA first issued advance notice of proposed rule-making for heavy-duty engine emission regulations (US EPA 1999). Before this point, emission regulations had been met solely through in-cylinder techniques and it was anticipated that subsequent emission reductions would require some form of PM and NO_X aftertreatment.

Simultaneously, enthusiasm for urea-SCR was growing in the EU. The heavy-duty industry began viewing it as preferable for meeting upcoming Euro IV and Euro V emission regulations. Buoyed by their European prospects, DaimlerChrysler, along with a consortium of other companies, initiated US vehicle fleet testing of urea-SCR in California in an attempt to win over a previously apathetic US audience. Mack/Volvo, another European engine manufacturer, also headed up a similar vehicle demonstration program on the East Coast a few years later (Ng 2006).

In December 2000, soon after publishing its proposed emission requirements, EPA issued a follow-up Regulatory Impact Analysis. The RIA included a cost-benefit analysis, as well as a discussion of the technical feasibility and likely approaches for complying with the proposed regulation. In their Regulatory Impact Analysis, EPA opted to base their NO_X emission compliance cost assessment on LNT rather than urea-SCR aftertreatment. The following excerpt explains their reasoning:

> While other technologies exist that have the potential to provide significant emission reductions, such as selective catalytic reduction systems for NO_X control, we believe that the NO_X adsorber will likely be the only broadly applicable technology choice by the makers of engines and vehicles for the national fleet in the 2007-2010 time frame (US EPA 2000).

During the public comment period that followed, engine manufacturers expressed concern over the state of development of LNT systems and proposed a more gradual phase-in of EPA regulations (Ng 2006).

On January 18, 2001 EPA published the final version of the proposed regulation, which they abbreviated as the 2007 Highway Rule. With the regulation, EPA for the first time outlined the additional engine certification requirements that they would place on urea-SCR, stating:

> The infrastructure for delivering urea at the diesel fuel pump would need to be in place...In addition to this, there would need to be adequate safeguards in place to ensure the urea is used throughout the life of the vehicle...(US EPA 2001a)

At approximately the same time, the US DOE commissioned the consulting firm ADL to perform a urea infrastructure study (Fable, Kamakate, and Venkatesh 2002). Under the assumption that urea-SCR would be introduced in model year 2007 (MY2007), ADL was charged with assessing the potential on-road demand for urea, the cost of the associated production and distribution infrastructure, and the potential environmental impacts. Their most significant finding was that the price of urea (excluding fuel station markup) was expected to range from $0.70/gal to as high as $35/gal. The span in price was attributed to two factors. First, was the fact that the cost to store and dispense urea at the retail station represented a large fraction of the total cost. Secondly, this cost component was highly dependent upon station throughput. In other words, the owner of a small station would have to charge a higher price to recover his infrastructure investment within three years than someone who owned a larger station with higher throughput. Other results, as well as findings from subsequent urea infrastructure studies will be discussed in more depth later in this section.

The release of ADL's 2002 urea infrastructure report garnered significant interest among industry, helping to prompt the first informal stakeholder conversations and an EMA-sponsored follow-up report (Mack Truck 2003; Tiax 2003). The new study was performed by Tiax (formerly ADL), who was asked to build upon the previous study and determine whether a viable business case existed for developing a urea infrastructure. They were also asked to examine the case in which urea-SCR was not introduced until MY2010. The Tiax report's key findings were that $0.81/gal to $4.20/gal was a more accurate estimate for the price of urea and that annual on-road urea demand would be significantly lower if urea-SCR was not implemented until MY2010.

Like the earlier ADL report, the 2003 Tiax study had a strong effect on the industry. It helped lead the Alliance of Automobile Manufacturers (AAM), the major trade association of car and light truck manufacturers, to commission Tiax to examine the urea infrastructure for light-duty vehicles (Schubert, Pont, and Jackson 2006). Also, two months later Detroit Diesel Corporation and Volvo Powertrain hosted the first meeting of the Urea Distribution Stakeholder Group on September 10th (Mack Truck 2003). The gathering included 25 individuals representing all segments of the potential urea supply chain, from fleet operators and truck manufacturers to urea producers and truck stop operators. The purpose of the meeting was to discuss potential infrastructure scenarios and to gain a better understanding of the various components within the urea supply chain.

The meeting also served to advance discussions around developing a urea-SCR compliance and infrastructure proposal to submit to EPA.

During early 2004, US engine manufacturers announced their intention to use EGR instead of urea-SCR to meet the 2007 NO_X standard. As a result, the pace of stakeholder discussions slowed and all conversations regarding urea-SCR between industry and EPA were suspended (Charmley 2005). The next major development did not take place until November of the following year when the truck manufacturer Freightliner, a subsidiary of DaimlerChrysler, announced its intention to use urea-SCR to meet the 2010 standard.

Six months later in June of 2006, Tiax released a second EMA-commissioned urea infrastructure study (Schubert, Pont, and Jackson 2006). The goal of the report was to integrate the previous heavy and light-duty vehicle studies into one report and to make certain key revisions to account for the following factors: a) MY2007 implementation was no longer a possibility; b) light-duty vehicles were being projected to adopt urea-SCR to meet US EPA Tier 2 Bin 5 regulations starting in MY2008; and c) the potential for interaction between the light and heavy-duty urea markets. The study's main conclusion was that it would be possible to introduce a full-scale urea infrastructure from USTs to bottles in time to meet both light and heavy-duty emission regulations but that a clear signal from vehicle manufacturers would be needed by early 2007 for the urea supply chain to meet construction and manufacturing lead times.

Also in June 2006, the Urea Infrastructure Multi-Stakeholders Group was formed (EMA 2006). The creation of a new group with a modified title was presumably intended to rejuvenate interest around the topic and reflect the fact that the composition of the stakeholders had become more diverse (i.e. light-duty vehicle players became involved). The group's objectives were threefold. One, facilitate the exchange of information between the US government and other urea stakeholders. Two, develop effective methods for educating vehicle owners and operators and retail outlets about urea, its use and availability. Three, work with the potential members of the urea supply chain to determine the requisite conditions for economic viability.

A month later, Volvo and Mack Trucks followed Freightliner's lead by announcing their intention to use urea-SCR on their MY2010 trucks (Volvo Trucks 2006). Shortly thereafter on November 8th, EPA issued a draft guidance document, outlining proposed urea-SCR light-duty vehicle and heavy-duty engine certification requirements (US EPA 2006b). Public comments on the draft were accepted through December 15th, 2006. On March 27, 2007 EPA issued a revised, although not final, guidance document based on the responses that they received. According to Allen Schaefer, Director of the Diesel Technology Forum, a diesel engine advocacy group, the changes EPA made since the draft version of the Guidance Document signal their willingness to compromise and that they are warming up to the idea of urea-SCR aftertreatment (Nguyen 2007). It is not surprising that the revised document gained support from Mack/Volvo and DaimlerChrysler, both of whom have already committed to using urea-SCR . DaimlerChrysler was quoted as saying that it "welcomes and supports" EPA's newest guidance document (Fleet Owner 2007; Peckham 2007d).

Finally, on July 23, 2007 EPA designated their revised Guidance Document, according to Office of Management and Budget bulletin requirements, a "Significant Guidance Document" and opened it up to one final round of public comment. The public comment period will extend until July 23 2009 (Simon 2007).

4.3 Obstacles to Overcome

There are currently two issues that will need to be addressed for urea-SCR to be introduced in time to meet upcoming 2010 heavy-duty NO_X regulations. First, EPA and heavy-duty engine manufacturers must agree on the exact criteria for guaranteeing vehicle compliance and infrastructure availability. Second, an infrastructure for supplying urea to these vehicles will need to be built by urea supply chain stakeholders. The following section explores both of these challenges in greater depth, as well as their degree of interaction. It begins with a discussion of EPA's Draft Guidance Document, the comments that were submitted by industry, and the revisions EPA subsequently made in March 2007. It then concludes by reviewing the business case for introducing a urea infrastructure, as investigated by Tiax in their most recent 2006 report.

4.3.1 Reaching Agreement on Engine Certification Criteria

EPA's Draft Guidance Document

The Draft Guidance Document that EPA initially released in November 2006 served two functions (US EPA 2006b). It both clarified their interpretation of the regulatory requirements that impact the certification of urea-SCR equipped engines (i.e. Allowable Maintenance and Adjustable Parameters) and it proposed criteria for fulfilling those requirements. While EPA had previously communicated its general interpretation of the regulatory requirements, it had not discussed the specific "Adjustable Parameter" acceptance criteria it would require and therefore, their publication was met with much anticipation.

EPA's adjustable parameter acceptance criteria were grouped into three categories: vehicle compliance; reducing agent availability and accessibility; and education and outreach for potential owners and the service industry. The vehicle compliance category was further sub-divided into five topics.

Driver Warning System was the first topic. It stipulated that vehicles have a unique visual alarm to indicate to the driver when the level of reducing agent in the vehicle's tank is low. Therefore, the light would need to be different from the "check engine" or "service engine soon" light. The warning system, which would preferably include an audible component, is required to escalate in intensity as the supply of reducing agent is depleted. EPA's Draft Guidance Document also suggested that the vehicle would most likely require an additional light or audible alarm to indicate when the reducing agent tank is empty. For heavy-duty vehicles, EPA wrote that activation of the initial warning light should be timed so that, at a minimum, the vehicle operator has the opportunity at two diesel refuelings to refill their reducing agent tank.

The second vehicle compliance category was *Driver Inducement*. The purpose of the driver inducement measure, according to EPA, is to persuade users to replenish their reducing agent supply before their tank becomes empty. EPA is not interested in prescribing a specific driver inducement design. The only requirements written in the Draft were that the driver inducement mechanism be robust and onerous enough to act as a strong noncompliance deterrent, while not posing undue safety concerns. The following is a list of hypothetical designs that EPA said they thought could satisfy their objectives:

- <u>No-Engine Restart After Restart Countdown</u> – once the reducing range reaches a minimum mileage or level (e.g. the range of one tank of fuel), the vehicle is only able to restart a limited number of times before it is not allowed to restart at all.
- <u>No-Start After Refueling</u> – once the reducing range reaches a minimum mileage or level, the vehicle is not allowed to start after it has been refueled with diesel fuel.
- <u>Fuel-Lockout</u> – once the reducing range reaches a minimum mileage or level, a fuel filler lockout mechanism disallows the user from refilling their tank.

Although it was not mentioned in the same context as the other examples, EPA commented that employing a method that degrades engine performance might also be acceptable. They wrote that the difficulty with this approach is determining an acceptable level of torque-limiting.[20] EPA alluded to de-rating techniques that also enabled emission compliance as being particularly appealing (e.g. greatly retarded injection timing).

Identification of Incorrect Reducing Agent was the third vehicle compliance category described by EPA. This category stemmed from their concern that a urea-SCR system could be operated with an incorrect reducing agent, such as water or highly diluted reducing agent. They suggested that NO_X sensors or urea sensors could be used to detect when this occurs. They did not, however, explain how the use of NO_X sensors would make it possible to determine whether incorrect reducing agent was the root cause of a failure as opposed to some other problem, such as a faulty injector. EPA explained that

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[20] A torque limiting device caps the power that an engine is allowed to produce to some fraction of the maximum power that it is capable of producing.

the response to incorrect reducing agent should be similar to when a vehicle runs low on reducing agent (i.e. warning, followed by driver inducement).

The fourth vehicle compliance category was *Tamper Resistant Design*. EPA is concerned about tampering with the visible and audible warning system, driver inducement mechanism, and reducing agent dosing system. For example, they wrote that the fuel door in a vehicle that employs a "fuel-lockout" strategy should not be capable of being pried open. Similarly, the electrical connection should not be capable of being disconnected from a urea doser.

Durable Design was the fifth and final vehicle compliance requirement. Similar to other aftertreatment technologies (e.g. DOCs and DPFs), EPA indicated that engine manufacturers would have to demonstrate that their urea-SCR systems, including catalyst, dosing system, reducing agent storage tank, and lines and hoses be durable up to 110,000 mi, 185,000 mi, and 435,000 mi for light, medium, and heavy heavy-duty vehicles, respectively. Due to the complexity and newness of urea-SCR systems, EPA said they expected needing to perform full-vehicle emissions compliance testing as opposed to relying on the existing dynamometer-based method.

In addition to vehicle compliance criteria, the other major requirement EPA's Draft Guidance Document stipulated was that reducing agent be available and accessible. The purpose of these requirements is to ensure that reducing agent will be readily available to consumers by the time the first 2010-compliant vehicles are introduced. EPA defined sufficient availability as requiring "widespread distribution…at locations that are easy to find…during the vehicle operator's normal course of business or operation." They expected that this could be accomplished through a variety of reducing agent availability schemes (i.e. availability outside of the original equipment manufacturer network is required).

In order to achieve certification, EPA also wrote that engine manufacturers would be responsible for presenting them with a plan for guaranteeing reducing agent availability and accessibility. The plan must include, at a minimum, procedures for supplying urea to dealerships and public truck stops, as well as other common refueling locations (e.g. cardlocks and fleet refueling facilities). Engine manufacturers would also be required to provide an emergency backup plan. EPA stated that consumers should be able to call a toll-free telephone number if they needed but could not obtain reducing agent. The backup plan should deliver it to them quickly, perhaps overnight, and it could not be priced higher than the cost of reducing agent sold at a dealership. In addition, manufacturers would need to show that it will be possible to obtain reducing agent from other commercial outlets, such as public fueling stations, branded oil change facilities, repair and service facilities, and retail outlets (e.g. NAPA, Pep Boys, and even Wal-Mart).[21]

The third and final adjustable parameter acceptance criterion was education and outreach. According to EPA's Draft, manufacturers would need to educate any groups or individuals involved in the purchase, sale, and service of urea-SCR equipped vehicles, as well as those involved with the sale of reducing agent. This would include vehicle owners, dealership staff, aftermarket service facilities, fueling station staff, retail staff, etc. EPA indicated that information would need to be provided on a variety of questions, including the following: "How do urea-SCR systems work and why is it important to replenish the reducing agent tank?" and "What are the consequences of not refilling one's tank?" Information could be provided to the public through a number of medium, from owner and service manuals to company websites and messages written on reducing agent tank doors.

Aside from compliance and infrastructure-related certification criteria, EPA also stipulated additional requirements related to reducing agent quality, protection from freezing, and refilling interval. Engine manufacturers would need to establish a quality standard and specifications. EPA wrote that deducing agents that met these criterion must be easy for consumers to identify, regardless of their brand name. EPA suggested having

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[21] This appeared to apply primarily to light-duty vehicles, approximately 50 percent of whose users perform their own oil changes, which is when light-duty urea tank refilling is expected to occur.

a similar symbol to the American Petroleum Institute's "starburst", which is used to distinguish approved motor oils.

According to EPA, manufacturers will either need to find ways to prevent freezing, for example through the use of heated lines and a heated tank, or they will need to use a reducing agent that does not freeze at low temperatures. If the former approach is taken, reducing agent that becomes frozen due to extensive exposure should be able to be thawed relatively quickly. EPA suggested a potential interval of less than 20 minutes.

EPA was less prescriptive when discussing an appropriate reducing agent refill interval. Other than referring to the allowable maintenance requirements of provision §86.094-25(b)(7), their only recommendation was that manufacturers adopt the longest interval possible. As discussed earlier, provision §86.094-25(b)(7) states that manufacturers must submit a request, including a demonstration of need, for approval to the EPA Administrator for "new scheduled maintenance." Upon granting their approval, the Administrator would be charged with establishing a technologically necessary maintenance interval.

Points of Industry Contention

A total of 20 comments were submitted in response to EPA's Draft Guidance document. As expected, most of the statements originated from diesel engine and vehicle manufacturers either directly or through their respective US and international trade associations. With the exception of the sections on "Education & Outreach" and "Urea Quality Specification", every other topic provoked considerable response.

The first issue that was brought into contention was whether, as claimed by EPA, the "Allowable Maintenance" and "Adjustable Parameter" provisions of the statute gave EPA the authority to impose certification measures on vehicles and engines equipped with urea-SCR systems. While they did not dispute EPA's authority to impose these measures, the EMA and Detroit Diesel contended that the source of their authority derived instead from a different paragraph in the "Allowable Maintenance" provision than the one cited by EPA and that the "Adjustable Parameter" provision did not apply at all.

Specifically, Detroit Diesel and EMA disagreed with EPA's argument that the existing 150,000 mile minimum maintenance interval cited in paragraphs §86.004-25(b)(3) and (4) apply to SCR systems (Duerr 2006; EMA 2006). They instead argued, citing paragraph §86.004-25(b)(2), that since "The Administrator has determined that emission-related maintenance at shorter intervals…is not technologically necessary to ensure in-use compliance," then clearly the Administrator never intended section (b)(4)(iii)(F) ("catalytic converter") to apply to urea-SCR systems or reducing agent refill intervals. Their claim was that, had the Administrator conducted a reasoned technical assessment of the maintenance requirements, they would have discovered that a shorter interval would be unavoidable. Detroit Diesel and EMA proposed rather that paragraph §86.004-25(b)(7), which pertains to "new scheduled maintenance", is the appropriate authority for establishing urea-SCR system maintenance requirements.

As for the appropriateness of the "Adjustable Parameter" provision, EMA and Detroit Diesel argued that the level of fill of the urea-SCR reducing agent reservoir should not be considered an adjustable parameter. They cited the fact that the emissions from urea-SCR systems are not effected until the reducing agent tank becomes completely empty. They also reasoned that provisions §86.094-22 and §86.183301 were probably only intended to apply to physical engine adjustments, since they primarily referenced parameters like idle fuel-air mixture adjustments on carbureted engines, bimetal springs, and threaded adjustments. §86.094-22(e)(2).

As might have been expected, International had the strongest objections of any engine manufacturer to EPA's statutory authority. In fact, they called for formal EPA rulemaking on urea-SCR, stating "as a legal and practical matter, the draft guidance is an amendment to the [2010] NO_X standards and could be adopted only through rulemaking" (Charbonneau 2006; Peckham 2007c). According to Jack Peckham of Diesel Fuel News, if rulemaking were to be carried out, it could have the effect of delaying the full implementation of the 2007 Diesel rule by 2 years, until 2012., statements like these could potentially be seen as "prelude to a lawsuit" (Peckham 2007c).

The exact interpretation of EPA's statutory basis for the proposed certification measures are not expected to change the types of criteria that will be applied to urea-SCR systems. It is, however, expected to impact the relative bargaining power of EPA and engine manufacturers. Over the last several years, EPA has threatened that, because urea-SCR systems do not meet the current minimum maintenance interval, EPA has the authority to deny certification if their compliance and infrastructure requirements are not satisfied. If the industry's interpretation of EPA's authority turns out to be correct, EPA's grounds for denying engine certification will become much less concrete.

The majority of industry comments focused on the specific details of EPA's proposed certification criteria. Beginning with vehicle compliance, the need and effectiveness of a two-light warning system was heavily contested (Dillon 2006; EMA 2006; Routhier 2006; Schaefer 2006). Several groups cited the fact that a single light could be used to differentiate between a low versus empty tank (e.g. flashing versus solid).

In terms of driver inducement, there were relatively few comments. The ATA was the only group to argue that driver inducement should not be initiated until after a vehicle runs out of reducing agent (Routhier 2006). There was, however, strong consensus that emergency vehicles (e.g. fire trucks and ambulances) should be exempt from this requirement (Dillon 2006; EMA 2006; Schaefer 2006). Aside from their important role in public safety, they were identified as being less susceptible to non-compliance because they are usually professionally maintained.

A common theme emerged from the comments on tamper resistance and the need to identify the use of incorrect reducing agent. Industry expressed the view that, so long as emissions sensing OBD equipment was tamper-resistant, other safeguards should not be necessary (EMA 2006). They also referred to the immaturity of fluid quality-sensing technology and the potential for false failures to actually encourage tampering. The state of California via CARB has also weighed in, commenting that engine restart should be conditional on OBD functionality and rationality checks (Nguyen 2006). Their comments are relevant because there is a strong desire among light-duty diesel vehicle manufacturers for EPA and CARB to harmonize their requirements of urea-SCR systems.[22]

As far as durable design, heavy-duty engine manufacturers were very much against EPA's suggestion of performing full-vehicle emissions testing (EMA 2006). Cummins, for example, cited how the shear number of vehicle configurations and applications could make it extremely difficult to identify a representative vehicle for each engine family (Wagner 2006).

EPA's criteria for urea availability and accessibility also prompted numerous comments. In general, manufacturers expressed their reluctance at being responsible for guaranteeing an adequate urea infrastructure by requesting that EPA tone down their language (e.g. "'guarantees' to 'best efforts'") (Charbonneau 2006; Dillon 2006; EMA 2006).

Perhaps the Draft Guidance Document proposal that drew the widest criticism was the emergency backup plan concept, especially the overnight delivery at no extra cost requirement. The general sentiment was that such a plan would provide a disincentive to drivers to obtain their reducing agent from truck stops and other locations. DaimlerChrysler asked EPA to include an exception stating that manufacturers would no longer be responsible to maintain a backup plan as a condition of certification, once the urea infrastructure became widespread (Dillon 2006).

While not included among the list of proposed criteria, additional certification issues like thaw time and reducing agent refill interval, garnered quite a number of comments. EPA's suggestion that the minimum thaw time be less than 20 minutes was met by concern from industry that extremely cold temperatures might make it impossible to meet EPA's target (Dillon 2006; EMA 2006; Schaefer 2006).

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[22] Note, CARB has yet to discuss their certification criteria for urea-SCR systems.

Heavy-duty engine and truck manufacturers also expressed unease over tying the reducing agent refill interval to a "minimum mileage interval" (EMA 2006). The consistent point of view was that the number of conceivable variations in vehicle application, duty cycle, and packaging constraints were too large to implement that type of blanket requirement in the heavy-duty sector. According to the EMA, manufacturers would, at a minimum, size their reducing agent tank such that it will last one fuel tank range, plus a modest margin.

EPA's Revised Guidance Document

EPA's March 2007 Revised Guidance Document contained several important changes. The most significant modification was the substitution of the words "best efforts" for the term "guarantee" within the section pertaining to engine manufacturer's responsibilities to ensure the accessibility and availability of urea. This new language had been preferred by engine manufacturers, who expressed their concern during the comment period about the legal ramifications of "guarantee". The second concession EPA made was removing the requirement that so-called "backup urea" be provided at a price no higher than the cost of obtaining it from a dealership or diesel fueling station. Additionally, EPA purged any language suggesting that urea-SCR equipped heavy-duty engines would be subjected to full vehicle testing, due to the number of components in such systems. They wrote, instead, that deterioration factors would be established at certification for the various urea-SCR components. Finally, EPA also eliminated their proposal that urea thaw times be limited to 20 minutes or less.

EPA's decision to scale back their original Guidance Document requirements was probably motivated by two factors. One, EPA realized that by including too many additional requirements, they risked exceeding a threshold beyond which formal rulemaking would be required. Formal rulemaking is associated with the danger that not only would full implementation of the NO_X standard be delayed two years but it could potentially be compromised altogether. A second driver was the recognition that EPA was in danger of having another defeat device debacle on their hands. Unlike light-duty vehicle manufacturers, heavy-duty engine manufacturers could afford to play chicken with the regulation if EPA was not willing to concede to some of their exceptions. By conceding, EPA has largely shielded themselves from future criticisms that urea-SCR certification criteria are too stringent. At the same, their actions did not significantly compromise the integrity of the standard, which is protected by the driver inducement requirements. That is, EPA recognizes that, if engine manufacturers want to sell urea-SCR equipped engines, they will have to ensure that their customers can easily access urea.

4.3.2 The Business Case and Feasibility of a Urea Infrastructure in the US

Of the issues that need to be resolved, introducing a urea infrastructure is clearly the most difficult. What makes it challenging is that the infrastructure will need to be rolled out ahead of demand. For potential downstream urea supply chain stakeholders to decide to construct the infrastructure they must be convinced that demand will materialize and that selling urea will be profitable.

Demand is primarily dependent upon the strategies of US engine manufacturers, which as discussed earlier, is currently unclear. In particular, Caterpillar and Cummins have yet to publicly disclose their 2010 NO_X aftertreatment strategies. Given that, collectively, Caterpillar and Cummins account for nearly 50 percent of MHDD and HHDD engine sales, their decisions are crucial indicators of the future demand for on-road urea (Ward's Reports 2005b).

Profitability will depend primarily on whether the cost of urea processing, transportation, storage and dispensing equipment is justified given projected demand levels. Infrastructure cost studies have been the subject of a series of recent Tiax reports and they will be the focus of the remainder of this chapter. However, before turning to that discussion, it is important to recognize that profitability, from the standpoint of someone like a fuel station owner, also depends on how the costs are divided among the various stakeholders. If the supply of urea by fueling stations becomes a de-facto industry mandate than it is highly likely that they will be the ones forced to shoulder most of the financial burden. While it may seem reasonable to assume that they could simply pass on these costs to the customer, they would nonetheless be left in a risky situation, especially if they were unable to recover their investment. The compromises made by EPA in their revised Guidance Document probably did little to assuage these fears. In fact, the revisions most likely exacerbated the concerns of potential urea retailers because they limited the responsibility of engine manufacturers and made it less clear as to who would bear ultimate accountability for ensuring the availability of urea.

Urea Demand

To evaluate the potential profitability of introducing a urea infrastructure, each of the previous studies began by calculating the projected demand for urea. This was accomplished for each class of diesel vehicle by multiplying the product of the following four numbers:

1. The annual vehicle miles traveled (VMT).
2. Vehicle fuel consumption (g/mi).
3. The estimated urea consumption as a percentage of the fuel consumption (i.e. 1-2 percent).
4. The sales volume forecasts.

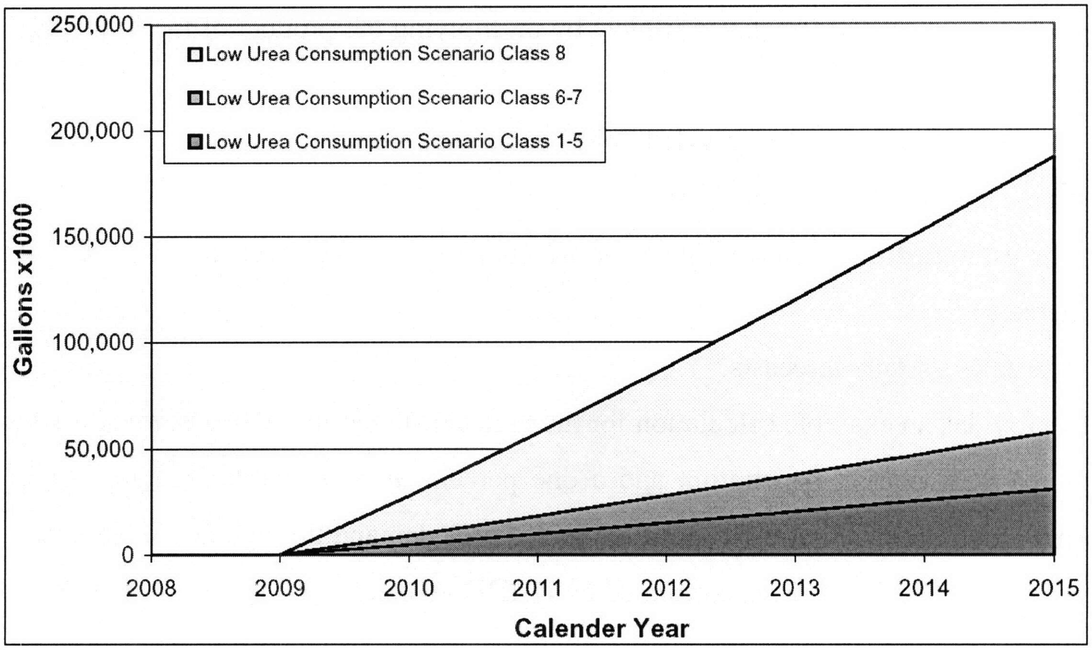
Table 13 provides an example calculation for the urea consumed in 2010, assuming a 100 percent urea-SCR market penetration and a one percent urea consumption rate. Using these same assumptions, Figure 19 shows projected urea demand through 2015. Note that by 2015, 70 percent of the urea is consumed by HHDD vehicles.

Table 13: Example Urea Demand Calculation for MY2010[23]

	Light-Duty	**Light & Medium Heavy-Duty**	**Heavy Heavy-Duty**
Class:	1-5	6&7	8
GVW (lbs.):	6,001 - 19,500	19,501 - 33,000	> 33,001
Annual VMT:	11,020	13,150	41,500
Fuel Economy (mpg):	14	8	7
Gallons of Urea/Truck	*8*	*17*	*64*
# of Vehicles:	600,000	280,000	295,000
Gallons of Urea/Class	*9,270,892*	*4,651,927*	*18,805,684*
		Total Gallons of Urea =	*32,728,502*

Source: (Schubert, Pont, and Jackson 2006).

Figure 19: Projected Urea Demand for 2010-2015[24]



Source: (Schubert, Pont, and Jackson 2006).

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[23] This calculation assumes 100 percent urea-SCR market penetration and a 1 percent urea consumption rate.

[24] This figure assumes a 100 percent urea-SCR market penetration, a 1 percent urea consumption rate and a 3.7 percent annual diesel truck population growth rate.

Vehicle and Fuel Station Segmentation

Next, the most appropriate urea distribution mode and infrastructure pathway for different fuel station sizes was investigated by examining fuel station profiles, heavy-duty vehicle fueling habits, and fuel station diesel throughout ranges. As shown in Table 14, over half of the on-road diesel fuel that is consumed in the US is sold by public truck stops. Table 14 also portrays the fueling habits of “For Hire” and “Private” trucks, which currently split the commercial market on a revenue basis. With average distances of 375 mi to 425 mi, For Hire trucks do most of their refueling at public truck stops. Private fleets, however, do most of their refueling at company-owned fueling stations, since their average distances are considerably shorter at 50 mi to 100 mi.

Table 14: Fuel Station Profile and Truck Fueling Habits

	Public truck Stops	Single Contract Cardlocks	Central Fueling Stations
Station Profile			
# of locations:	5,000	2,500	25,000
% of diesel consumption:	54%	4%	16%
Average Fuel Throughput (gal/mo):	200,000	80,000	25,000
Fueling Habits:			
For Hire:	62%	2%	35%
Private:	23%	6%	66%

Source: (Schubert, Pont, and Jackson 2006).

Table 15 aggregates all of the public truck stops, cardlocks, and central fueling stations in the US and separates them according to existing diesel and projected urea throughput in 2010 and 2015. It shows that a large majority of the urea that is purchased will be sold by a relatively small number (i.e. approx. 1,500) of very large fueling stations (i.e. XXL and XL), which are primarily public truck stops. It also shows that nearly 75 percent of all of the fueling stations (i.e. XS) in the US will sell less than 50 gal of urea per month for the first five years that the infrastructure is in place. These stations consist primarily of central fueling stations.

Table 15: Projected Urea Throughput Ranges by Station Size

Heavy-Duty Station Size Designation	Monthly Diesel Throughput		Number of Stations	Monthly Urea Throughput (gal./station)			
				2010		2015	
	High	Low		High	Low	High	Low
XXL	2,000,000	1,300,000	310	2,114	1,057	14,427	7,213
XL	1,300,000	1,000,000	1,128	1,473	737	10,055	5,028
L	1,000,000	300,000	515	833	416	5,683	2,842
ML	300,000	200,000	262	320	160	2,186	1,093
M	200,000	140,000	2,436	218	109	1,486	743
MS	140,000	80,000	1,115	141	70	962	481
S	80,000	10,000	2,491	58	29	393	197
XS	10,000	100	24,251	6	3	44	22

Source: (Schubert, Pont, and Jackson 2006).

Several conclusions can be drawn from the results in Table 14 and Table 15. First, because of the large span in projected urea throughput, it would be wise to distribute urea via more than one mode and pathway. Second, major For Hire truck operators should be enlisted to help compel the early introduction of the urea infrastructure at the very largest public truck stops. Their leverage derives from the fact that they do the majority of their refueling at public truck stops, as well as from their superior ability to self-organize when compared to the large number of smaller private fleets.

Pricing Various Distribution Modes and Pathways

Given the anticipated range in fuel station urea demand, distribution via more than one pathway and mode would appear to present the most economical means of supplying urea to the on-road market. Like other end uses, it is probable that each on-road urea pathway would originate from a central distribution facility (CDF).[25] Conceivable pathways and modes of distributing 32.5 percent urea solution include the following, which are also depicted in Figure 20:

1a. Urea trucked in tanker loads to retail stations that are equipped with above and below ground storage containers (Station Sales: >2,500 gal/mo).

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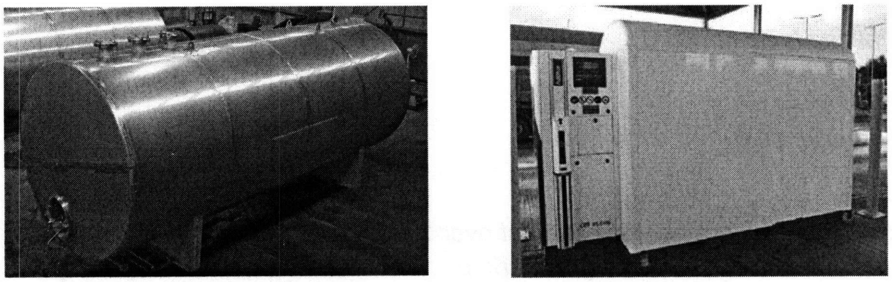
[25] While on-site blending at large truck stops is a potential option, it has been ruled out due to EPA tampering concerns and a lack of interest by retailers in performing this task.

1b. Urea trucked in tanker loads to retail stations for dispensing in medium-sized, above-ground dispensing systems called stillages, whose storage capacity is 5,500 gal or less (Station Sales: 500-7,500 gal/mo).

2a. Urea packaged and shipped to retailers in 55-280 gal totes/barrels (Station Sales: <1,000 gal/mo).

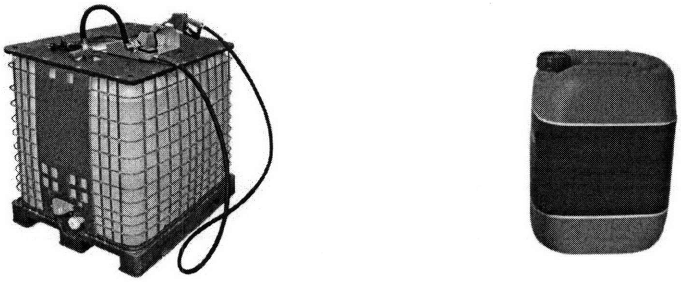
2b. Urea packaged and shipped to retailers in 1-5 gal bottles (Station Sales: <500 gal/mo).

Figure 20: Potential Urea Storage and Dispensing Modes



<u>Pathway 1a</u> – Above and Belowground Storage Containers

<u>Pathway 1b</u> – Aboveground Storage Containers



<u>Pathway 2a</u> – Totes

<u>Pathway 2b</u> – Bottles

Sources: (Aski Australia 2006; Univar 2005b; Yara 2006)

The equivalent per gallon retail price of urea for each of these pathways depends upon several costs, including the following categories: production; transportation from the producer to the CDF; processing at the CDF; transportation from the CDF to the retailer; and storage and dispensing at the retail station. Table 16 provides an example calculation for the final retail cost of distributing urea through pathway 1a at a fueling station with a monthly urea throughput of 10,000 gal/mo. It shows that the price of urea is expected to range between $1.24/gal and $1.44/gal and that retailer costs represent the largest individual component. The reason retail storage and dispensing costs are significant is because the installation of a 5,500 gal underground storage container comes with a $60,000 capital cost and a $3,000 operating cost. While stillages generally come in much smaller volumes (~1,300 gal), their capital and operating costs are $10,000 and $1,700, respectively.

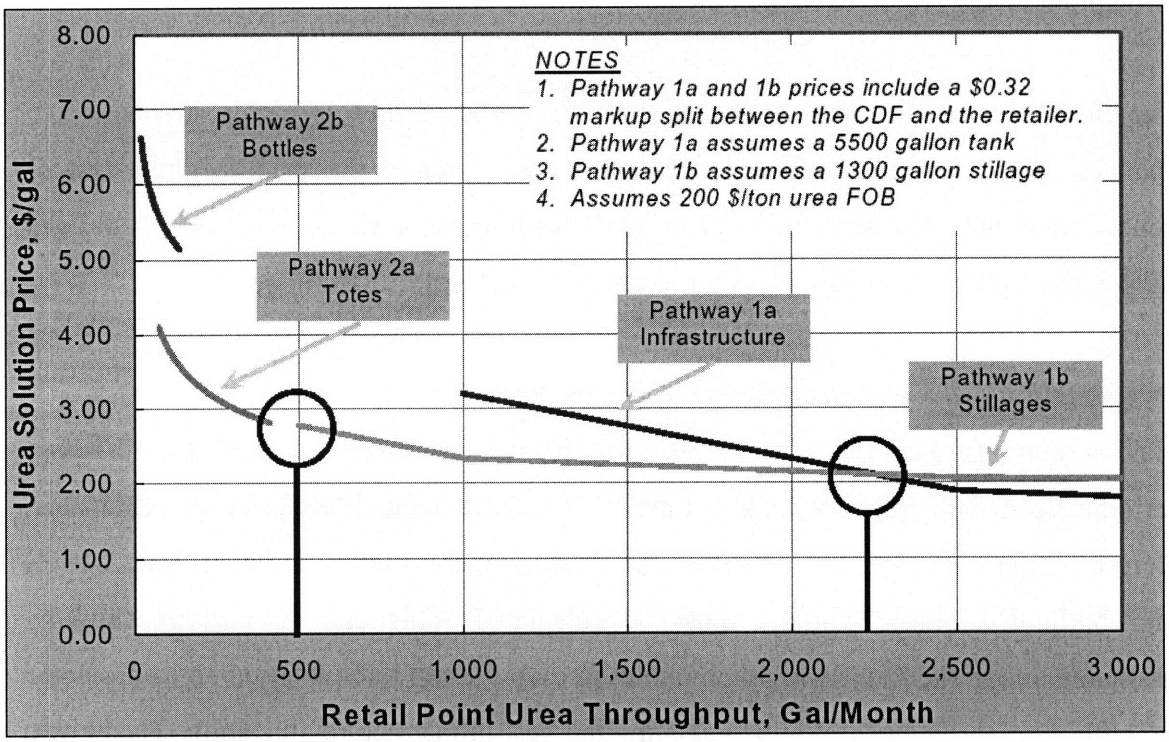
Table 16: Example Cost Calculation for Pathway 1a

Cost Category	Price ($/gal.)
Urea Production:	0.24
$200/ton when natural gas is $6/MMBTU	
Transportation to the CDF:	0.12
800 miles from plant to CDF (75% rail, 25% truck)	
Processing at the CDF:	0.22 - 0.37
$470k capital cost, $16k operating cost, 12% interest over 2.5 yrs, 2 million gal./yr throughput, and $0.09-$0.24/gal. markup	
Transport to Retail:	0.13
350 miles from CDF to retailer, $3.33/mile for a full 5,200 gal. load	
Retail Station Storage & Dispensing:	0.53 - 0.58
5,500 gal. capacity, $60k capital cost, $3k operating cost, 12% interest over 3 yrs, 10,000 gal/month throughput, and $0.07-$0.12/gal.markup	
Total =	**1.24 - 1.44**

Source: (Schubert, Pont, and Jackson 2006)

Similar calculations to the one described in Table 16 were performed by Tiax for each of the four pathways to develop a continuous, throughput-dependent urea cost model. Shown graphically in Figure 21, this model highlights both the anticipated price range for urea ($2-$7/gal) and the break-points where the different distribution pathways overlap in price. For example, the cost to dispense urea via a 280 gal tote and a 1,300 gal stillage is equivalent for stations whose urea throughput is approximately 500 gal/mo. The stillage becomes more cost-effective for higher throughputs, whereas the tote is more economical for lower throughputs.

Figure 21: Urea Cost Model Results



Source: (Schubert, Pont, and Jackson 2006).

Tiax's sensitivity analysis of their cost model revealed three key findings. One, the retail cost of urea is expected to be highly dependent on station throughput, which has a significant influence on the cost of retail storage and dispensing. Since a condition of the model is that the retail storage and dispensing infrastructure are paid off within three years, this cost can account for a significant fraction of the total cost of urea for stations with low throughputs. For instance, at a 1,000 gal/mo station, retailer costs account for 2/3 ($2) of the total cost. On the other hand, retailer costs contribute only 1/8 ($0.1) of the total cost at a station with a 20,000 gal/mo urea throughput.

A second important finding was that the cost of transportation from the CDF to the retailer can make up a large percentage of the total cost if the storage capacity at the station is less than a truckload (i.e. <5,500 gal). At a 2,500 gal/mo throughput urea station that uses a 1,300 gal stillage, for example, the cost of delivery ($1.00/gal) accounts for 60 percent of the total point of sale urea price. It was also determined that installing capacities greater than a full tanker load were not justified for the range of urea throughput levels projected in their study.

The final relevant discovery was that the retail price of urea is highly insensitive to changes in the cost to produce concentrated urea. Even if the manufactured cost of concentrated urea climbs from $150 to $250 per ton (i.e. a $5-12/MMBTU natural gas range), the final retail price will only increase by $0.15/gal.[26]

Assigning Pathways and Distribution Modes to Diesel Fueling Stations

Having demonstrated the business case, it is now necessary to determine whether introducing a urea infrastructure in time for the 2010 regulations is at all achievable. Before this can be assessed, however, the total number of tanks, stillages, totes/barrels and bottle-distributing stations must be calculated. This can be accomplished by assigning one of the four distribution modes to each fueling station, based on its projected monthly urea throughput. While evaluating the best infrastructure allocation, Tiax's own analysis was guided by one important criterion. The final allocation should ensure that enough time exists for each station to pay off the capital it owes, before a growth in urea demand forces that station to upgrade its storage and dispensing equipment to a larger capacity.

The findings from Tiax's 2006 report are summarized in Table 17. It shows that approximately 2,000 tanks, 2,700 stillages, 3,600 totes/barrels, and 6,000 bottle-distributing fuel stations would be required in 2010.[27] Similarly, Figure 22 shows the number of additional tanks and stillages that would be required during each subsequent year. It demonstrates that the infrastructure that is required for 2010 would be able to accommodate most of the increase in urea demand that is projected to occur during the first five years after implementation.

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[26] This example is for a 5,000 gal/mo throughput station that has a 5,500 gal underground storage tank.

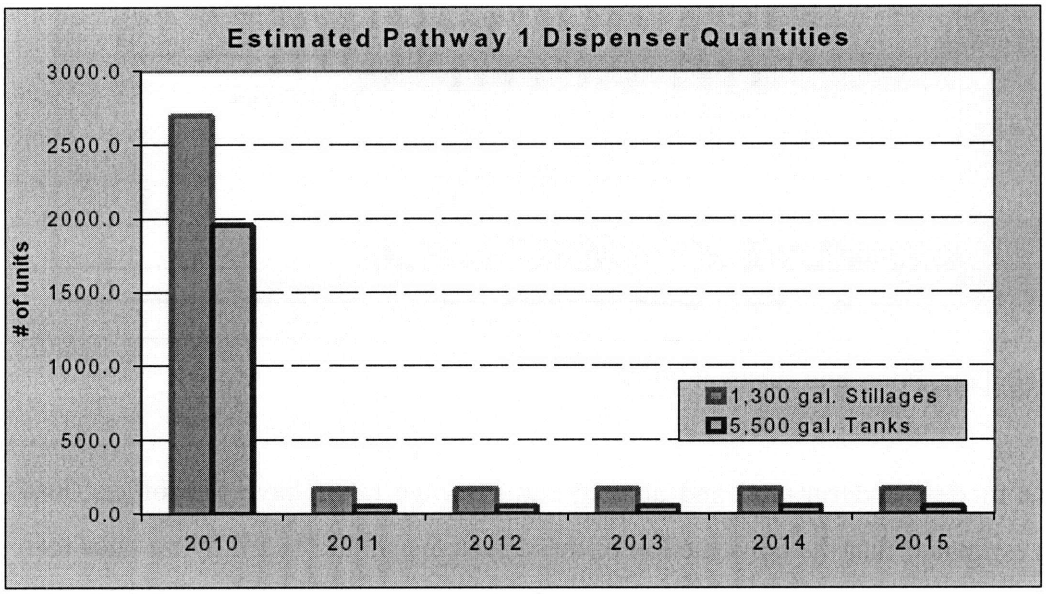
[27] Despite the fact that there are over 24,000 XS-sized fueling stations, the distribution of bottles at only 6,000 stations is expected to be sufficient, since 6,000 stations provides coverage within 20 mi to over 80 percent of the US population. The total number of one gallon bottles that are needed in 2010 was estimated by Tiax to range between 2.5 and 7.5 million, the large majority of which are designated for the light-duty market. Light-duty urea demand will be discussed in more detail during Chapter 6.

Table 17: Fueling Station Distribution Assignments[28]

Heavy-Duty Station Size Designation	# of Stations	Urea Throughput (gal/month)	% of Urea Sales	2010			
				Tanks	Stillages	Barrels / Totes	Bottles
XXL	310	5,000 - 2,500	17%	310			
XL	1,128	2,500 - 1,000	44%	1,128			
L	515	1,000 - 500	11%	515			
ML	262	500 - 250	2%		262		
M	2,436	250 - 100	14%		2,436		
MS	1,115	250 - 100	4%			1,115	
S	2,491	<100	4%			2,491	
XS†	24,251	<100	4%				6,000
			Totals =	*1,953*	*2,698*	*3,606*	*6,000*

Source: (Schubert, Pont, and Jackson 2006).
† See footnote number 27.

Figure 22: Urea Infrastructure Buildup during the First Five Years



Source: (Schubert, Pont, and Jackson 2006).

Critical Path Analysis

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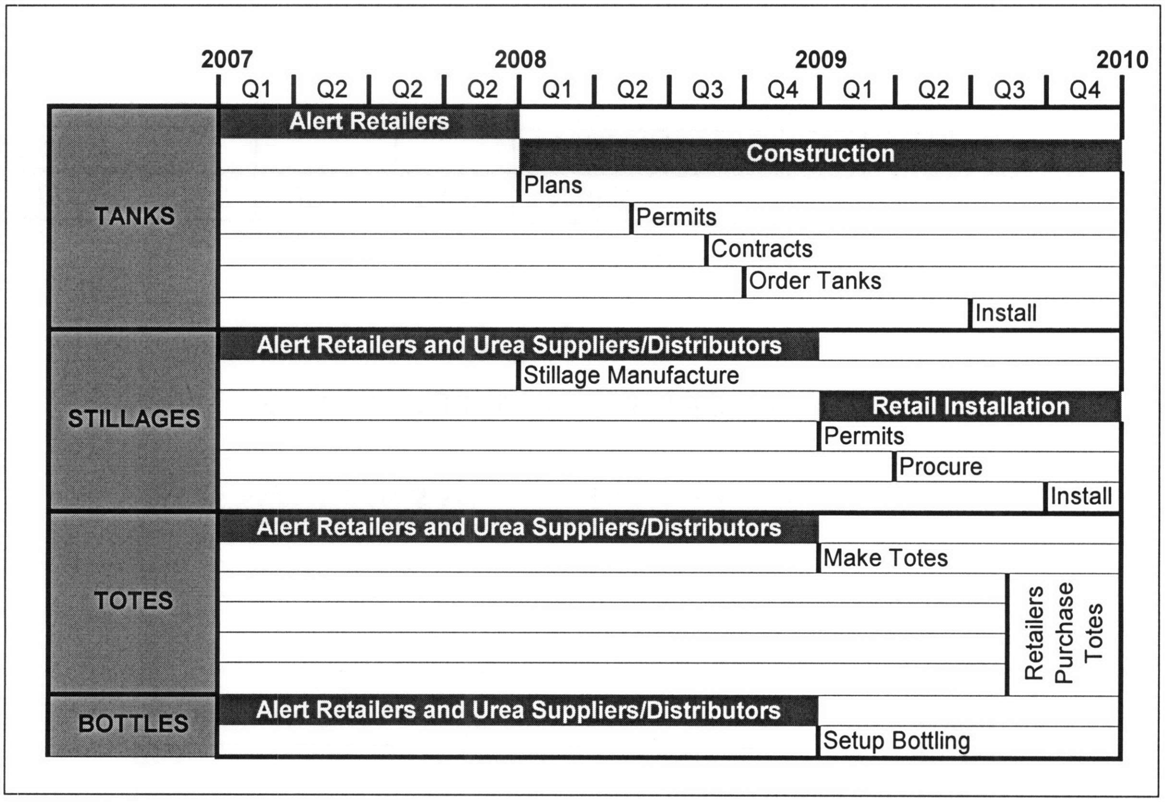
[28] This analysis assumed the following: 5,500 gal UST, 1,300 gal stillage, 264 gal tote, and 55 gal barrel.

Having computed the total number of units for each storage and dispensing technology, Tiax went on to determine the feasibility of producing, constructing and installing all of the necessary infrastructure components before the 2010 deadline. The timeline for each distribution mode is depicted in Table 18 and described in greater detail below.

Table 18: Urea Infrastructure Implementation Timeline



Source: (Schubert, Pont, and Jackson 2006).

Of the four modes, underground and aboveground storage tanks have the longest lead time. Tiax estimated that the construction of these systems should begin by no later than January of 2008 to account for the 2 years required to plan, permit, contract, order, and install each storage tank. Construction is expected to be completed by local fuel station contractors, who are experienced in this level of work.

Stillages are the distribution mode with the next longest lead time. Once they are manufactured, stillages are anticipated to require approximately one year to site and install. Since stillages are less common than storage tanks, they will initially require nearly two years to design and fabricate. It is likely that US, as well as EU vendors will design and build stillages. For example, there are three stillage vendors that currently source to the EU market, including GreenChem, Dureal, and Univar.

Totes, barrels and bottles do not have nearly the same lead time issues. For these distribution modes the only potential concern is manufacturing capacity. Tiax has reported that adequate capacity to manufacture the requisite number of totes, barrels and bottles currently exists. In fact, Cummins Filtration (StableGuard™) and Terra Industries both currently provide 32.5 percent urea solution in totes and barrels for stationary urea-SCR applications, such as backup diesel generators at hospitals. It is also likely that the same European manufacturers mentioned above will compete to supply totes to the US market through their corresponding US affiliates. Given their expertise in providing DIN 70070 compliant totes and barrels, Tiax expects that companies like Cummins Filtration and Terra Industries will also begin to provide bottled urea.

CHAPTER 5: LESSONS LEARNED FROM THE EU

The previous chapter discussed the compliance and infrastructure challenges associated with introducing urea-SCR, as well as what will need to take place to meet the 2010 implementation deadline. This chapter examines the circumstances surrounding the recent and successful introduction of urea-SCR aftertreatment systems in the EU heavy-duty vehicle market. The goal of this analysis is to uncover the policies and market factors that played a role in the EU's success and to determine how readily those lessons could be applied here in the US.

5.1 Policies

5.1.1 Industry

Beginning in 2001, the EU heavy-duty vehicle industry began pursuing policies that would lay the foundation for urea-SCR's successful introduction (VDA 2002). The first of these policies was the almost unanimous decision by the EU's engine and vehicle manufacturers to use urea-SCR to meet Euro IV emission regulations. Implemented in October 2005 for new type approvals and October 2006 for all type approvals, the Euro IV standard has a NO_X emission limit of 3.5 g/kWh (Majewski and Khair 2006).[29] Although significantly more stringent than the earlier Euro III standard (7 g/kWh), this new limit was capable of being met using in-cylinder emission control techniques.[30] The

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[29] A "type approval" is a term for the status that products are granted in the EU after they demonstrate that they can meet a standard set of technical and safety criteria. In this context, "new type approvals" refers to entirely new engine designs that are entering the market for the very first time. Likewise, "all type approvals" refers to both new and previously introduced engine designs. Thus, new engine designs were required to meet Euro IV in October of 2005, whereas, existing engine designs did not have to meet Euro IV until October of 2006.

[30] This assessment is based on the fact that US manufacturers were able to meet the 2004 US standard of 3.35 g/kWh using in-cylinder emission control, namely cooled exhaust gas recirculation and retarded injection timing. Recalling that the 2004 standard was implemented two years ahead of time, as part of the defeat device decree's "pull ahead" requirements, it is clear that engines capable of meeting the Euro IV

EU trucking industry's desire to have a single emission control strategy that could be used to comply with both Euro IV and V regulations, however, prompted them to adopt urea-SCR earlier than technologically necessary. Their goal was to avoid having to switch strategies during the short three year window between Euro IV and Euro V, the latter of which is to be implemented in October 2008 (Bunting 2005).

This decision had important implications on the demand for urea in the EU. As Table 19 shows, when compared to predicted urea consumption rates for US 2010 vehicles, Euro IV and Euro V vehicles are expected to consume between 2 and 5 times more urea per unit volume of diesel fuel consumed. The difference in the rate of urea consumption results from US engine manufacturers opting to achieve most of their emission reductions through in-cylinder control measures, whereas EU manufacturers have decided to rely more heavily on urea-SCR.

Table 19: Urea Consumption for US 2010, Euro IV and Euro V HHDD Vehicles

Regulation	Engine Out Scenario†	SCR-Out‡	NO_X Reduction	Percentage	Ratio	Refueling Interval¥
	(g/kWh)	(g/kWh)	(%)	(% urea / diesel)	(diesel : urea)	(miles)
US 2010	2.7	0.20	93%	1.7%	60:1	7,650
	2.0	0.20	90%	1.2%	82:1	10,850
	1.3	0.20	85%	0.8%	131:1	16,250
Euro IV (2005)	10.0	3.5	65%	4.4%	23:1	3,450
	8.0	3.5	56%	3.0%	33:1	5,000
Euro V (2008)	10.0	2.0	80%	5.4%	19:1	2,850
	8.0	2.0	75%	4.0%	25:1	3,800

† Engine-out NOX emission estimates for US 2010 and Euro IV/V come from Tiax LLC (2003) and Van Helden et al. (2004), respectively.

‡ This SCR-out estimate is intended to reflect the assumption that companies will choose a conservative engineering target below the 2010 NOX target of 0.27 g/kWh.

¥ The refueling interval was calculated by assuming that the fuel economy of the average HHDD vehicle is 6.5 mi/gal (Schubert et al. 2006) and that an average urea tank will be 20 gal in the US (Schubert et al. 2006) and 90 l in Europe (Dixon 2004 and Bunting 2005).

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limit of 3.5 g/kWh were under development during the time when Europe's manufacturer's decided to use urea-SCR to meet the Euro IV standard.

The implication is that, on a fleet basis, the demand for urea in the EU should be significantly larger than it will be in the US. Greater levels of urea consumption have two consequences. The first is that, regardless of who pays for capital equipment like fueling station storage and dispensing systems, that party should be able to recover their initial investment more quickly than if the demand for urea was lower. Also, high demand levels make it possible to sell urea for less at each stage along the supply chain, thanks to economy of scale benefits.

Currently, a liter of urea at an average EU retail establishment costs a little more than one half as much as a liter of diesel fuel. For example, in Germany urea sells for between 0.59 Euro/l and 0.69 Euro/l and diesel costs approximately 1.15 Euros/l. Integer Research, a UK-based consultancy with expertise in fertilizers and chemicals, estimates that prices in well established, high throughput markets could fall to as low as 0.4 to 0.5 Euro/liter (Mailard 2005). In the US, the best estimate for the price of urea at mid to high throughput stations is in the range of $2/gal to $4/gal (Schubert, Pont, and Jackson 2006). Given a diesel price of approximately $2.50/gal, urea sold in the US can be expected to cost as much or more than diesel fuel.

The second important industry policy was the clear and unified manner in which the EU's heavy-duty vehicle manufacturers announced their intent to use urea-SCR to the various urea supply chain stakeholders. The decision to use urea-SCR was first initiated in 2001 when the German Association of the Automotive Industry (VDA) was asked by the EU commercial vehicle manufacturing industry to establish an ad hoc working group to examine the feasibility of urea-SCR aftertreatment (VDA 2002). The group included engine and vehicle manufacturers, oil companies, aftertreatment system suppliers, manufacturers of urea products and refueling systems, and commercial vehicle operators (Barton and Lonsdale 2003; Peckham 2005). Given the EU-wide nature of the issue, the VDA invited the Association of European Automobile Manufacturers (ACEA) to become involved in the study as well. The working group explored many of the same issues that the Urea Infrastructure Multi-Stakeholder Group is currently investigating in the US, including appropriate urea standards, demand and cost projections, and OBD systems (DGMK 2003; VDA 2002).

After having studied the technology for approximately two years, ACEA issued a report to the AdBlue working group (formerly the ad hoc working group), entitled "Selective Catalytic Reduction: The most promising technology to comply with the imminent Euro IV and Euro V emission standards for HD engines" (ACEA 2003; Peckham 2003a). Prior to the announcement, it was decided that urea should be marketed using the name AdBlue, which had been previously developed by a consortium of urea manufacturers and oil companies (VDA 2002). At the heart of the report was a call by the heavy-duty vehicle manufacturing industry "seeking the co-operation of the industries active in the production and distribution of urea and of the oil companies to make [the EU urea infrastructure] a reality" (ACEA 2003).

5.1.2 Government

A combination of deliberate, as well as seemingly inadvertent government policies also had an important role in facilitating the introduction of urea-SCR. Two policies in particular promoted the early adoption of urea-SCR during the first few years before and after the Euro IV standard was implemented. The first of these was the European Commission's (EC) piecemeal approach towards regulating NO_X aftertreatment systems.

The Euro-IV and Euro-V emission threshold values were first introduced in 1999 as part of *EC Directive 1999/96/EC*. Perhaps anticipating the use of aftertreatment systems, the Directive included a requirement that emissions control systems be outfitted with OBD equipment and that they meet minimum durability standards. The Directive, however, did not address the test procedures or other requirements that would be necessary for demonstrating compliance with both criteria. One source has attributed this lack of detail to the fact that the European Commission was not expecting engine and vehicle manufacturers to use urea-SCR to meet the Euro-IV standard (Coffey Geosciences 2004). Detailed durability and OBD requirement specifics were only outlined in a subsequent regulation, entitled *European Parliament & Council Directive 2005/55/EC*. Among other requirements, this Directive stipulated that OBD systems signal the presence of a fault to the driver whenever emissions exceeded 7.0 g/kWh of NO_X, which is twice the Euro IV threshold. However, it was not until the promulgation of *Commission Directive 2005/78/EC* that the technical requirements for OBD systems and for demonstrating emissions durability were specified (Bowyer 2005). Included in this Directive (which was later amended by *Commission Directive 2006/51/EC*) were several new measures that focused specifically on NO_X control and consumable reagents (i.e. urea). From the perspective of urea-SCR stakeholders, the most significant aspect of *Commission Directive 2005/78/EC* was that engines that used NO_X aftertreatment systems needing an additional reagent were required to incorporate a torque limiting device, as well as a system for storing non-erasable fault codes (European Commission 2006).

A torque limiting device caps the power that an engine is allowed to produce to some fraction of the maximum power that it is capable of producing. Normally this is accomplished using the engine control unit. Torque limiting has the same objective as the strategies that were described under the *Driver Inducement* section in EPA's Guidance Document. Its goal is to persuade vehicle operators to replenish their reducing agent supply before the tank becomes empty and the urea-SCR catalyst is rendered useless. The EC's driver inducement criteria, however, are much more prescriptive and less flexible than the host of options that have been suggested by EPA. According to *Commission Directive 2005/78/EC*, torque limiting must take effect if a vehicle runs out of urea, its emission control monitoring system fails, or if either the NO_X levels in the exhaust exceed the OBD threshold limit of 7 g/kWh or if reagent dosing activity is interrupted.[31] Torque limiting is required to be activated within 50 hours of one of these events occurring, upon the first time the vehicle becomes stationary. If the vehicle does not accommodate standing passengers, its torque is to be limited to 60 percent of its engine's maximum power. If it does accommodate standing passengers, the maximum engine torque is limited to 75 percent (European Commission 2006).

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[31] Whether or not torque limiting is induced by NO_X levels exceeding the OBD threshold limit of 7 g/kWh or interrupted reagent dosing activity depends on whether the engine and vehicle manufacturer opted to employ an emissions or reagent-based OBD approach, respectively. An emissions-based control strategy involves monitoring the level of NO_X in the vehicle's tailpipe emissions. A reagent-based strategy determines compliance by monitoring reagent quality and consumption rate (European Commission 2006).

The purpose of requiring a vehicle to store a non-erasable fault code is so that it can be retrieved at a later date by the appropriate emission compliance authorities. It can also be used to detect the source of a malfunction when a vehicle is brought in to be repaired. Fault codes are required to be stored if either the emission standard's NO_X limit is exceeded by 1.5 g/kWh or if there is a deviation of more than 50 percent in the average rate of reagent consumption, monitored via tank level and reagent flow rate into the exhaust stream.[32] Fault codes must be stored for a minimum of 400 days or 9,600 hours of operation, whichever is longer(European Commission 2006).

In addition to torque limiting and fault code storage, urea-SCR systems are subject to a variety of additional requirements, many of which are similar to what EPA has said it will require of heavy-duty vehicles in the US. One additional requirement that is outlined in *Commission Directive 2005/78/EC*, which EPA has yet to discuss, is that tailpipe ammonia emissions shall not exceed a mean value of 25 ppm over the applicable test cycle.

Despite the EC's restrictive torque limiting, fault code storage and ammonia emissions requirements, the way in which these criteria were introduced actually appears to have had the effect of encouraging the early adoption of urea-SCR equipped vehicles in the EU. That is because these requirements did not go into effect until November 9, 2006 for new type approvals and October 10, 2007 for all heavy-duty vehicle registrations. Therefore, they lag the first-phase detection/warning OBD requirements by a year. This split-level directive offers EU engine and vehicle manufacturers a brief period during which to sell vehicles that do not store fault code data and whose performance will not be penalized by torque limiting because of non-compliance. Although vehicles would still be subjected to periodic highway inspections, the opportunity to skirt these other safeguards offers a strong early-purchase incentive to EU fleets. This possibility is especially concerning to Scania, who, along with MAN, is one of the EU engine and vehicle manufacturers that opted to go with exhaust gas recirculation instead of urea-SCR. They cite the fact that the

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[32] As alluded to in the previous footnote, how fault code storage is triggered depends on whether the engine & vehicle manufacturer opted to employ an emissions or reagent-based OBD strategy.

split-level directive offers urea-SCR vehicle operators a fuel economy benefit without the added cost of urea, not to mention the fact that the emissions from these vehicles would be on par with Euro-I vehicles (8 g/kWh NO_X), which were first introduced starting in 1992 (Motor Transport 2004).

Although the EC's split-level regulatory approach should be discouraging to members of the urea supply chain, it also provides an advantage in that, unlike EPA's infrastructure-related engine certification criteria, it does not stipulate that an adequate urea distribution infrastructure needs to be in place ahead of the Euro IV regulations. As will be discussed below, this is mostly due to the fact that EU fleets largely refuel at fleet fueling stations, as opposed to public truck stops or cardlocks.

A second and more deliberate government policy is the decision by several countries in the EU to offer financial incentives to vehicle operators who purchase Euro IV and Euro V compliant vehicles before their respective standards begin to be enforced. Currently, this strategy is employed by Germany, Austria, the Netherlands and Switzerland (Mailard 2005). For example, urea-SCR-equipped vehicles in the Netherlands receive a more favorable tax write-off rate than similar vehicles that are not pre-compliant (AutoTechnology 2004). By comparison, the US does not have any federal or state-level early adoption incentive programs directed towards consumers. Instead, the emphasis is placed on incentivizing producers through banking and trading programs.

The most influential country-level early adoption incentive policy has been Germany's reduced road toll program. Introduced in January 2005, MAUT is a government toll that applies to both loaded and empty vehicles weighing over 12 tons (equivalent to US Class 6-8 truck). Charges are based on the distance that is driven on the German Autobahn, number of axles and the emissions category of the vehicle. The average toll today is approximately 0.12 EUR/km (Road Traffic Technology 2006). Vehicle operators of pre-compliant Euro IV and Euro V vehicles have their road toll reduced by 0.01 EUR/km and 0.02 EUR/km, respectively. According to Dekra, a Stuttgart-based transportation consultancy, a 40 ton, Euro V advanced compliant truck traveling an average of 180,000 km/yr would need to be driven 80 percent of the time on German highways to recoup the extra cost of a Euro V vehicle within 2 years (Dralle 2005). Given Germany's geographic location and the number of producers and consumers within its borders, the economics are favorable for a significant number of EU vehicle operators. In fact, according to Daf Trucks, the European truck manufacturer, MAUT discounts are encouraging fleets to go straight to Euro V compliant vehicles, skipping Euro IV vehicles to guarantee concessions through 2009 (Bunting 2005).

Some stakeholders, however, have criticized the German incentive program, which is set to expire in January 2007 for Euro IV and January 2009 for Euro V. Daf Trucks has stated that the Euro IV incentives should have been introduced earlier and that there should have been a larger interval of time between when the incentive was first offered and when it expired. Daf highlighted the fact that many vehicle operators were unwilling to pay the extra cost of a Euro IV truck, knowing that the incentive would last at most two years (Bunting 2005).

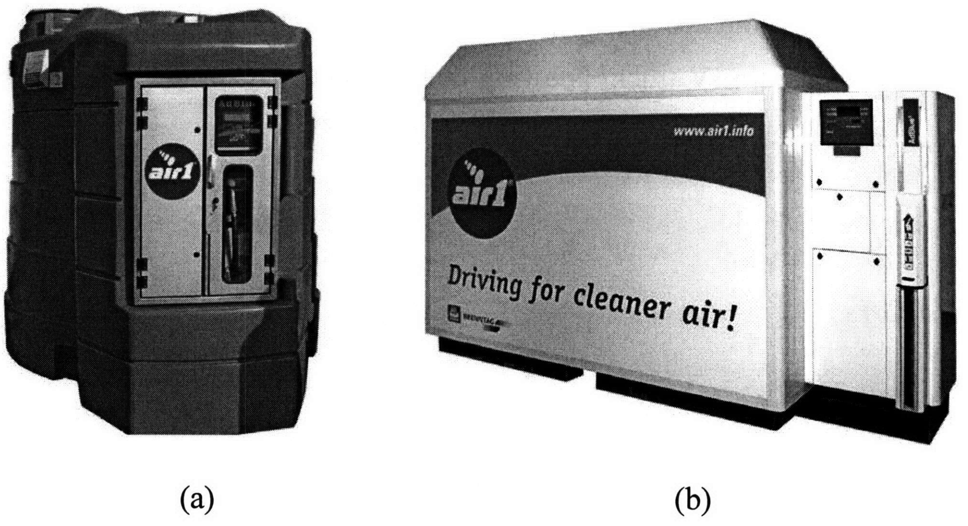
5.2 Market Factors

5.2.1 Structural Features

In addition to a generally more lax regulatory approach and the existence of consumer-oriented early compliance incentives, there are several structural features that appear to have played a role in the EU's successful introduction of urea-SCR equipped vehicles. The first of these features is that in most EU countries, commercial vehicle refueling is largely carried out at home fueling depots. For instance, approximately two-thirds of commercial refueling in Germany is done at fleet facilities (Mailard 2005). This, in combination with the absence of minimum infrastructure requirements, has made it possible to introduce the urea infrastructure in phases.

During the first phase, which is already well underway, most vehicles are being supplied from their home depots by 1,000 liter and larger above-ground storage units, such as the one pictured in Figure 23 (Bunting 2005; Clancy 2005; Commercial Motor 2004, 18; Industrial Environment 2004; Mailard 2005). Urea suppliers anticipate that 70 to 80 percent of vehicle operators will have their own supply and will buy small Jerry Cans for emergencies from retail filling stations. These small containers have proven to be an effective way to extend one's urea refilling interval by between 300 km (i.e. 5 liter can) and 1080 km (i.e. 18 liter can). For operators who have several depots, urea distribution equipment provider Dureal is recommending that they aggregate their urea-SCR-equipped vehicles at one or two large 10-15 truck depot to minimize on infrastructure costs (Clancy 2005).

Figure 23: Above-ground Fleet (a) and Public (b) Urea Filling Systems



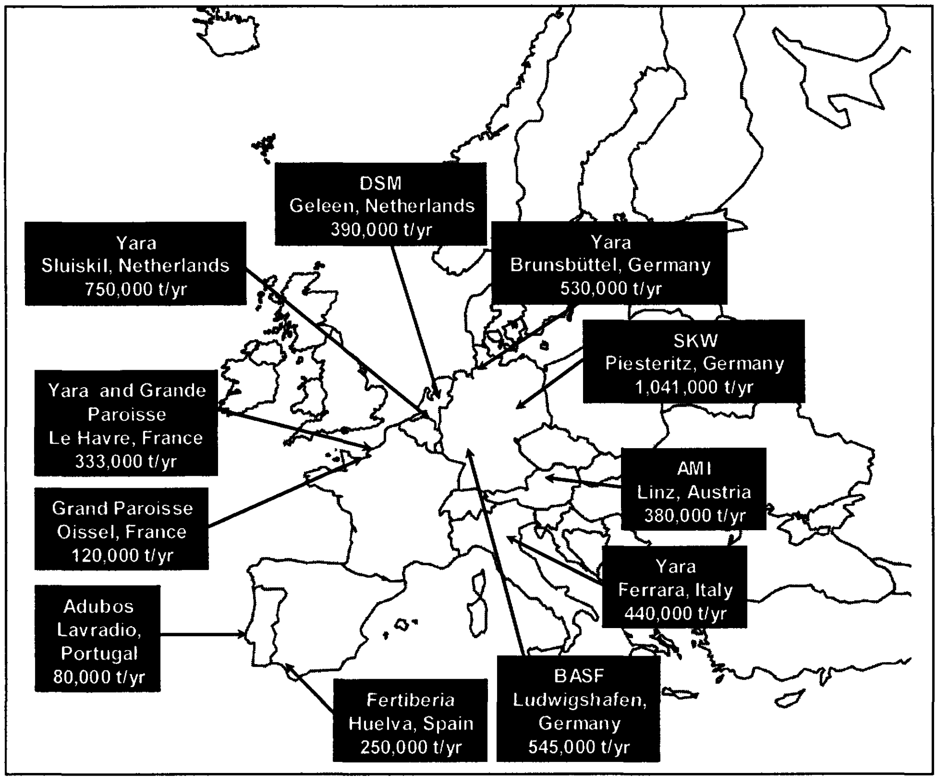
(a) (b)

Source: (Yara 2006).

In the second stage of infrastructure development, urea will be sold at public truck stops alongside to diesel fuel pumps. Urea will either be distributed to retail stations by the same large oil companies, such as OMV and Total, that currently provide diesel fuel or by separate chemical distribution companies. A third and more nascent stage will involve smaller stations supplying take-away cans to tradesmen, who may only have one or two medium-duty urea-SCR vehicles (Bunting 2005).

A second relevant structural feature in the EU is the fact that urea manufacturing facilities, as shown in Figure 24, are well distributed geographically compared to the US, where most facilities are located in the Southeastern States (Figure 12). The EU's urea manufacturers are therefore able to focus on regional markets. The benefit of this approach is that the significant logistic costs of transporting urea, owing primarily to its high water content, can be minimized (Mailard 2005).

Figure 24: EU Urea Production Facilities and Capacities as of 2004



Sources: (AutoTechnology 2004; Hayes 2005; Industrial Environment 2004; Integer Research 2004; Strutz 2003).

A final structural feature is that, unlike in the US, the EU heavy-duty engine and vehicle manufacturing markets are vertically integrated. Although it cannot be shown explicitly, it is reasonable to assume that having engines and vehicles produced by the same company both simplifies the urea-SCR stakeholder landscape and perhaps even eliminates some of the need to withhold one's strategy for the sake of maintaining competitive advantage. This would explain the ability of the industry to band together and jointly announce their support of urea-SCR.

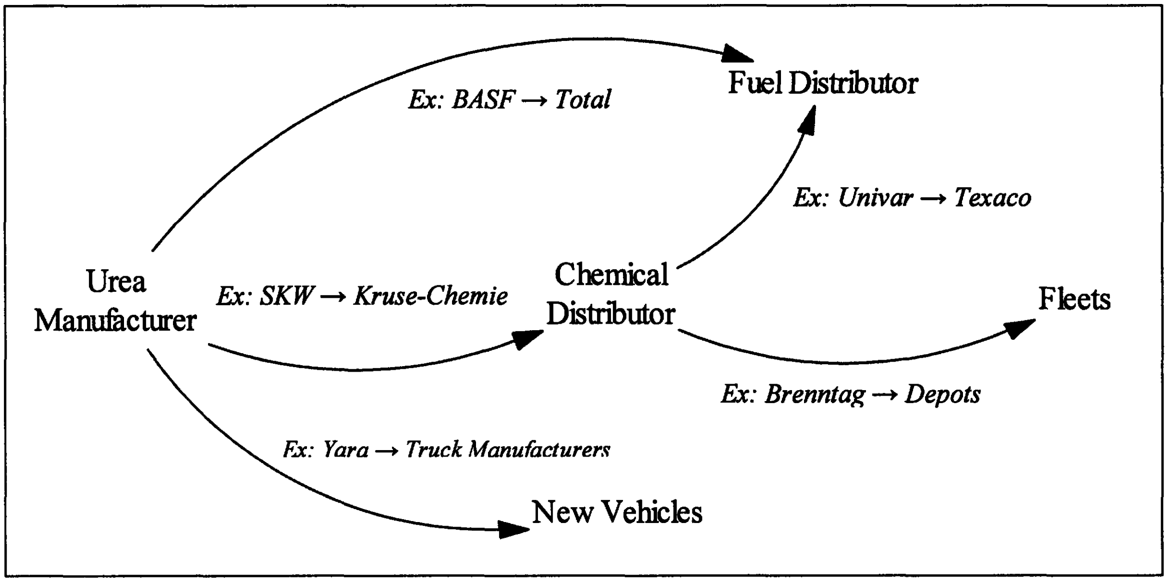
5.2.2 Market Proven Strategies

Despite a number of successful yet non-transferable EU strategies, there is at least one lesson that can be learned from the EU's real-world experience with urea-SCR and potentially applied in the US context. Having chemical distribution companies not only supply urea but also provide the necessary storage and dispensing equipment, via some form of leasing arrangement, is probably a more promising business model for growing a urea infrastructure during its initial stages than is expecting traditional public fueling stations to step up to the challenge.

In the EU, distribution to the customer is occurring through a variety of pathways, as illustrated in Figure 25. Due primarily to the initial reluctance of European oil companies, urea is mainly being distributed by traditional chemical distribution companies, including Brenntag, Kruse-Chemie, and Univar (Industrial Environment 2004; Process Worldwide 2005). Manufacturers are relying on distributors to ensure delivery within 48 hours across a network of approximately 200 distribution points, including both retail stations and fleet depots. In most cases, producers have decided to partner with only a few well-established distributors due to concerns over urea purity. For example, Yara, maker of Air1® branded urea, has an exclusive distribution contract with Brenntag. Likewise, SKW, maker of BlueSky® branded urea, distributes solely through Kruse-Chemie. Not withstanding these agreements, manufacturers have retained control over marketing and have dealt directly with large private accounts (Mailard 2005). For example, Yara will sell directly to the largest fleets, allowing Brenntag to supply smaller fleets and public stations (Clancy 2005).

Although urea producers will retain the marketing rights, chemical distributors will be responsible for obtaining contracts with branded and independent fuel distributors to supply urea solution, as well as to install dispensing and storage equipment. For instance, in 2005, Univar and Texaco Netherlands announced a joint venture, whereby Texaco would install Dureal™ storage units and dispensing equipment at their retail service stations (Univar 2005a).

Figure 25: Urea Distribution Pathways in the EU



Other distribution pathways include selling directly to fuel distributors and truck manufacturers. In Germany, BASF has entered into an exclusive urea supplier agreement with Total (Mailard 2005). Also, Yara has approached truck manufacturers about filling new vehicles before they leave the factory (Hayes 2005).

As far as traditional public fueling stations are concerned, only the three largest oil companies, OMV, Total and Shell have decided to begin selling urea at their filling stations. France's Total and Austria's OMV were the first to develop a strategy for serving commercial vehicle urea demand (AutoTechnology 2004). As early as 2003, Total began operating two pilot stations with urea in Germany. It is currently rolling out 12 more stations in Germany and has announced the opening of its first station near Lyon, France (Hayes 2005; Mailard 2005). Total has said that over the course of the next three years it intends to sell urea through a network of 400 service stations and truck stops (Hayes 2005). OMV is also an active player. In 2005 it announced that it plans to add urea dispensing units to 67 stations across 12 markets from southern Germany to the far reaches of Eastern Europe. Shell, who holds the largest diesel fuel market share in Europe, entered the urea market a few years after its European rivals, not disclosing its intentions until late 2005 (Mailard 2005). According to Helmut Grafe, Shell's global urea implementation project manager, Shell "can't afford not to offer urea at truck-stops and larger filling stations. Otherwise they would risk losing fuel business from operators going to one-stop shops that sold urea, as well as fuel (Bunting 2005).

Other more practical lessons include the following. Except for special cases, above-ground storage and dispensing systems should be designed such that their capacities can be expanded as the urea throughput of a fleet or public fueling station grows. GreenChem, for example, sells a 5,000 l above-ground storage container for public truck stops that can be expanded in units of 5,000 l up to a maximum of 15,000 l (GreenChem 2005). Secondly, while some large public fueling stations have opted to offer combined diesel/urea pumps that give a single receipt, there have been no reports of the use of co-fueling dispenser nozzles (AutoTechnology 2004). Lastly, it appears that it may be necessary for the large 15,000-20,000 l, industry-standard, liquid chemical bulk container trucks to always be sent out full and returned empty to avoid instability problems associated with partially-full containers (Process Worldwide 2005). This assessment is based on the policies of some chemical distributors, such as Brenntag. They offer their customers quality assurance by providing them with a tracking number that can be used to determine the batch that their shipment came from and how well that batch conformed to the EU-wide quality standard, DIN 70070 (Process Worldwide 2005).

CHAPTER 6: IMPACT OF NEW TECHNOLOGIES AND MARKETS

According to a recent study, entitled "The Future of Heavy-Duty Powertrains: 2007 to 2020", many of the exhaust aftertreatment technologies that are just now entering the market (e.g. DPF, urea-SCR, LNT) may become obsolete in the future if so-called "advanced combustion" developments continue to progress (Tiax and Global Insight 2005). Similarly, at recent technical conferences, such as DOE's 2005 DEER Conference, Ford, Honda and other light-duty diesel vehicle manufacturers have unveiled novel NO_X aftertreatment systems that incorporate both LNT and SCR catalyst functions. These systems have generated significant interest because they promise to eliminate the need to carry a separate, replenishable supply of area on-board one's vehicle (Lambert 2005). As these two examples illustrate, on a five to ten year time horizon, NO_X control technologies will likely be introduced that could replace urea-SCR and the need for a urea infrastructure. For other technologies this fact would not be hugely significant. For urea-SCR, however, it undermines the financial rationale of building an infrastructure for distributing urea. Without the promise of future demand, fueling stations may be hesitant to invest in the equipment to store and dispense urea, especially if there is a risk of not being able to pay-off their initial investment. Likewise, fleet owners might become wary that, even if the urea infrastructure was robust during the first few years, it could deteriorate over time, detracting from the resale value of urea-SCR equipped vehicles.

Greater diesel penetration within the light-duty fleet, however, could potentially have a countervailing influence. With most of the major light-duty diesel manufacturers committed to introducing urea-SCR equipped diesel vehicles for MY2009, including BMW, DaimlerChrysler, and Volkswagen (O'Dell 2006), the incentive to invest in developing some form of urea infrastructure is strong.

This chapter evaluates the potential impact that these new technologies and markets could have on the future viability of heavy-duty urea-SCR. It closes by discussing the implications that this has on the decision to both purchase urea-SCR vehicles and invest in their infrastructure.

6.1 Emerging Emission Control Technologies

6.1.1 Advanced Combustion

Advanced combustion, also known as low temperature combustion (LTC), is a term that is used to describe a class of combustion schemes that combine the high efficiency of compression-ignited engines and the low PM emissions of spark-ignited engines at considerably reduced NO_X levels. All advanced combustion techniques are guided by the principle of keeping the flame temperature and equivalence ratio of the fuel-air mixture inside the combustion chamber out of PM and NO_X formation regimes.[33] This concept is illustrated graphically in Figure 26 (Assanis 2006). Advanced combustion is accomplished by using exhaust gas recirculation, mixing, and fuel injection to precisely control the onset and characteristics of combustion (Johnson 2006).

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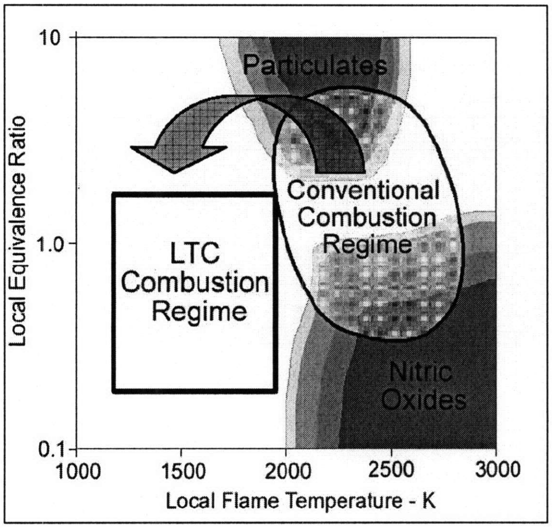
[33] The equivalence ratio is equal to the ratio of fuel and air inside the combustion chamber divided by the stoichiometric ratio of fuel and air for that particular fuel.

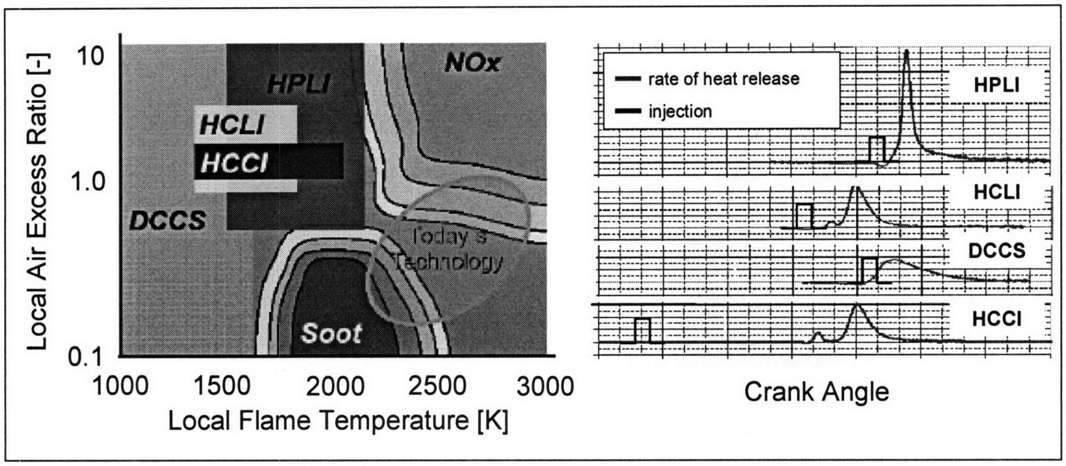
Figure 26: The Principles of Advanced Combustion



Source: (Assanis 2006).

Figure 27 depicts a few of the most popular advanced combustion schemes. The most common of these techniques is called homogeneous charge compression ignition (HCCI). In contrast to traditional diffusion flame diesel combustion, HCCI is characterized by the simultaneous combustion of a fully vaporized homogeneous distribution of fuel and air throughout the entire cylinder volume (Ryan 2006). The higher efficiency of HCCI derives from the fact that it is compression-ignited. Its minimal PM emissions and dramatically reduced NO_X emissions (e.g. 20 vs. 200 ppm) result from having a well-mixed charge and from considerably lower combustion temperatures, respectively (Epping et al. 2002).

Figure 27: Popular Advanced Combustion Strategies[34]



Source: (Johnson 2005).

Advanced combustion, however, suffers from three major drawbacks (Johnson 2006). Emissions of HC and CO can be significantly higher than from conventional diesel combustion. Advanced combustion is also commonly associated with a 3 percent, although sometimes lower, fuel penalty when compared to conventional diesel combustion. Third, HCCI and other advanced combustion strategies are difficult to control, especially at high loads. Although HC and CO emissions can be eliminated with an oxidation catalyst and fuel penalties of less than one percent have started being reported, controlling the combustion characteristics of advanced combustion schemes is proving to be much more difficult to resolve.

In the meantime, a concept called "mixed-mode" combustion is emerging. The concept is to run an engine in advanced combustion mode during low loads and convert to traditional diesel combustion for high load operating points (Johnson 2006). Currently, the only obstacle that is preventing the commercialization of mixed-mode combustion is the ability to switch between the two regimes, especially during transient operation. While mixed-mode combustion does not completely eliminate the need for heavy-duty aftertreatment, it does limit the need for low-temperature NO_X control and for low-load

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[34] The acronyms used in Figure 27 are: HPLI – highly premixed late injection, HCLI – homogeneous charge late injection, DCCS – dilution controlled combustion system, and HCCI - homogeneous charge compression ignition.

DPF regeneration. Tim Johnson of Corning (2006) estimates that when the first US heavy-duty mixed-mode engines are introduced commercially, they will require approximately 30-50 percent NO_X control at high load. According to International's Future Technology Director, Alan Karkkainen, such schemes will probably not be ready until 2012 to 2014 (Peckham 2007a).

Mixed-mode combustion is likely to have an even greater impact on US light-duty diesels, the market for which advanced combustion is primarily being developed.[35] This is due to the fact that US test cycles largely operate at relatively low load, making it possible to run in advanced combustion mode for the majority of the cycle. Accordingly, Tim Johnson (2006) estimates that the 50-state Tier 2 Bin 5 emission standard could potentially be achieved without the use of aftertreatment.

6.1.2 LNT/SCR

Another technology that has the potential to displace urea-SCR, perhaps over an even shorter time horizon, is LNT/SCR. Leveraging the fact that LNT catalysts generate ammonia when they are being regenerated, the LNT/SCR concept introduces a SCR catalyst to a conventional LNT catalyst system as a means of sharing the NO_X reduction burden. In most of the configurations that have been proposed, a fuel reformer is incorporated upstream of the catalyst, since it has been shown that the presence of hydrogen helps promote the generation of ammonia (Hu et al. 2006).

A schematic representation of an LNT/SCR concept using separate catalyst cans, including a depiction of the various chemical states, is shown in Figure 26. During lean operation, NO_X is stored by the LNT catalyst. Once the LNT catalyst becomes saturated, regeneration is initiated. The fuel reformer is used to generate CO and H_2, which both enhance LNT regeneration and improve the yield of NH_3. Hu et al. (2006) observed that over 50 percent of the NO_X that was stored by the LNT could be converted to NH_3. Inside the SCR catalyst, NO_X and NH_3 react to form N_2 and H_20. Depending upon the relative

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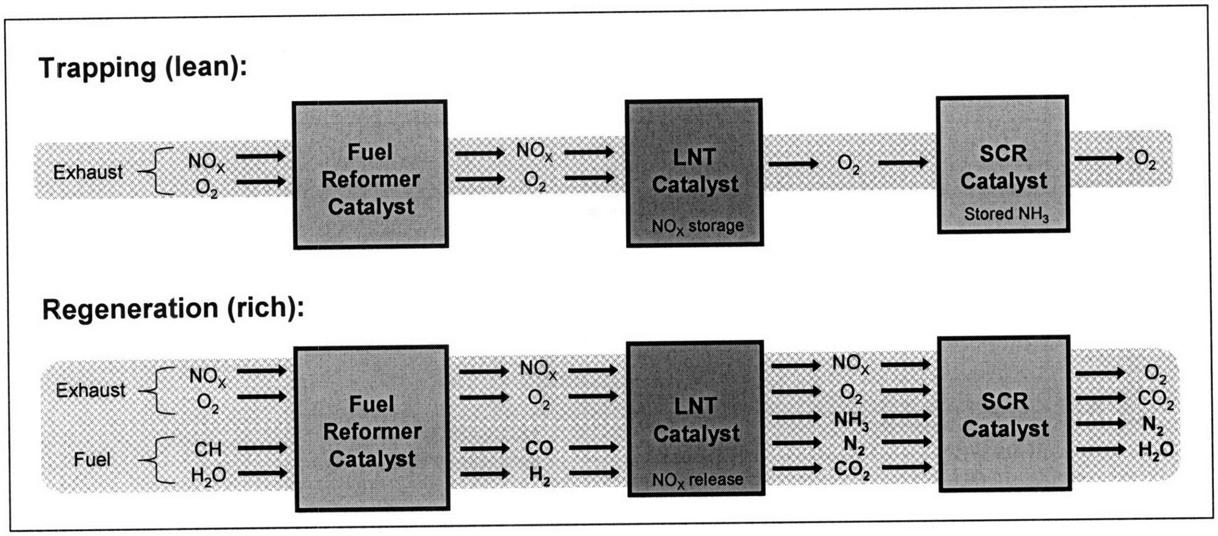
[35] Advanced combustion development is targeted at the US light-duty diesel market because its emission standards are significantly more stringent than regulations in the EU and Japan.

size of the LNT and SCR catalysts, some NH_3 will be stored in the SCR catalyst during LNT regeneration. Therefore, the SCR catalyst is then capable of providing further NO_X reduction after the transition to lean operation.

Recently, Honda appears to have improved upon the separate LNT/SCR catalyst can configuration (Johnson 2007; Morita et al. 2007; Peckham 2007b). They have devised a way of combining both catalysts into a single can, using a double layer. Not only is this a packaging innovation but the catalyst itself works in a fundamentally different way than previous LNT/SCR systems. The top layer is a platinum-containing cerium oxide material. Unlike traditional LNT catalysts, the ceria in their catalyst does not trap NO_X by forming nitrates, instead it relies on chemisorption. This gives it superior low temperature NO_X conversion efficiency, down to as low as 350°C. It also implies that desultations can be performed at much lower temperatures, perhaps as low as 500°C, since sulfates are more loosely bound than in standard LNT catalysts (Johnson 2007). During periodic rich operation, the desorbed NO_X reacts with hydrogen over the platinum to form ammonia, which gets stored by the bottom layer zeolite catalyst. The hydrogen derives from the exhaust and via a water-gas shift reaction that occurs on the top layer of the catalyst (Peckham 2007b). Once lean operation is restored, the ammonia on the zeolite catalyst releases and reacts with the NO_X in the exhaust to form molecular nitrogen.

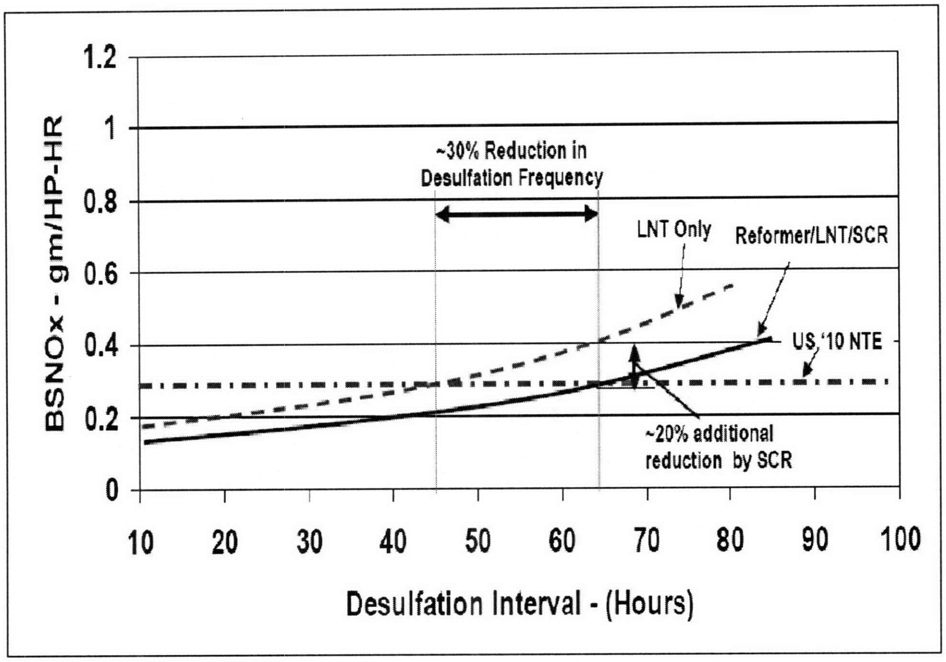
Figure 28: LNT/SCR Process Diagram



Source: (Hu 2006).

The limited number of studies to investigate this technology have reported achieving approximately 80 to 90 percent efficiency over the steady-state SET heavy-duty test cycle (Hemingway 2006; Hu et al. 2006; Lambert 2005). Hu et al. observed that the LNT segment of their two-can configuration reduced NO_X emissions by 74 percent. The SCR segment contributed an additional 44 percent reduction, leading to an 85 percent total reduction in NO_X emissions (i.e. an 11 percent overall reduction from the SCR catalyst alone). During a system durability test, Hu et al. determined that the SCR's cumulative NO_X reduction contribution could reach as high as 20 percent. Therefore, an LNT catalyst in this configuration would be allowed to deteriorate, as a result of sulfur poisoning, to a 65 percent NO_X reduction efficiency before needing to be desulfated. This is in contrast to a conventional LNT catalyst, which would require an almost constant 85 percent efficiency over its regulated lifetime. Hu et al. (2006) estimated, as shown in Figure 29, that the time between desulfations could be lengthened by up to 30 percent for an LNT/SCR system, when compared to a traditional LNT. As a result, the lifetime of LNT catalysts in this type of configuration is expected to be significantly longer. Since the Honda system reduces the temperature at which desulfations ordinarily take place by 200-250°C, it is anticipated to significantly extend the life of its LNT/SCR catalyst (Johnson 2007).

Figure 29: Improved Durability of a Two-Can LNT/SCR System



Source: (Hu et al. 2006).

Besides eliminating the need for urea, as well as offering durability advantages over conventional LNT systems, the various LNT/SCR configurations provide other benefits over standard LNT or urea-SCR aftertreatment systems. First, the use of an SCR catalyst makes it possible to reduce the size of the LNT catalyst, and thereby, eliminate the amount of precious metals that would otherwise be needed. For instance, using the heavy-duty catalyst volume (i.e. 20 liters) that was referenced in the urea-SCR versus LNT lifetime cost comparison (Table 9), it can be determined that a 20 percent LNT size reduction would result in an approximately $400 PGM savings. The other advantage that an LNT/SCR system has over a conventional urea-SCR system is reduced aftertreatment system volume. Hu et al. (2006) estimated that the aftertreatment volume could be reduced by 0.5-2.5 times the engine swept volume, not to mention the additional space savings from not needing an approximately 20 gal urea tank. The space savings from employing the Honda system is unknown but presumed to be even greater than that associated with more conventional LNT/SCR deployments.

An LNT/SCR configuration has some drawbacks. Like conventional LNT systems, it uses diesel fuel (or reformate made from diesel fuel) to regenerate and desulfate the LNT catalyst. As such, two-can systems have been reported as having an approximately 2 percent fuel penalty, which is roughly one half of the fuel penalty of a standard LNT catalyst and on par with an LNT catalyst that incorporates a fuel reformer (Hemingway 2006; Hu 2006). The single-can Honda system has a 4 percent fuel penalty compared to a similar Euro IV-compliant light-duty diesel (Peckham 2007b). Mack/Volvo North America's Vice President of Engineering, Tony Greszler, estimates that if urea costs reach $5 to $6/gal, than a two-can LNT/SCR catalyst using an upstream fuel reformer could begin to compete with a traditional urea-SCR system on an equivalent fuel penalty basis (Peckham 2007a). The other drawback continues to be the susceptibility of LNT catalysts to sulfur poisoning. At this stage, further studies are required to determine whether the Honda system or a two-can system that enables approximately 30 percent fewer desulfations translates into a catalyst that is durable enough to last 435,000 miles, the durability standard for HHDD engines.

6.1.3 Impact on Heavy-Duty Urea-SCR Viability

The potential for urea-SCR to be substituted by alternative NO_X emission control strategies has important implications on the decisions that today's stakeholders make and therefore, the viability of the urea-SCR approach as a whole. Large heavy-duty fueling stations are the group who should be most concerned about technologies like advanced combustion and LNT/SCR aftertreatment. At the moment, engine manufacturers are using the Tiax studies, as well as other information, to convince them to commit to installing urea storage and dispensing equipment. The prospect of competing technologies, however, only serves to heighten their existing concerns over whether the demand for urea will materialize.

Even if fueling stations are confident in short-term urea demand and their ability to pay off their capital investment, there is one other issue that might make them reconsider offering urea at their facilities; the prospect that EPA will require them to continue to supply urea into the future, despite inadequate demand. For instance, imagine a scenario in which urea-SCR equipped vehicles commanded 100 percent of the heavy-duty market from 2010 to 2015 but that advanced combustion begins to displace urea-SCR thereafter. That would create a "legacy fleet" of approximately a few million vehicles that would require urea refilling facilities for the remainder of their useful life, which is on average 15 to 20 years for heavy-duty trucks (California Air Resources Board 2005a). Given the fact that EPA currently places the infrastructure burden on engine manufacturers, this scenario is relatively unlikely. The situation could change, however, once the infrastructure is already in place.

Fleet owners are another constituency that should be concerned about the introduction of competing NO_X technologies. Heavy-duty vehicles are typically operated by their primary owners for 5 years before being sold to a secondary owner (Tiax 2003). The secondary owner usually sells that same vehicle again after approximately three years. Without an adequate urea infrastructure, owners of urea-SCR equipped vehicles would have trouble finding buyers in the secondary market. It is conceivable that even though urea-SCR is economically superior to LNT systems, fleet owners would prefer to purchase LNT equipped vehicles if they suspected that LNT equipped vehicles would have a higher resale value.

Engine manufacturers were also recently given a reason to worry about the long term viability of urea-SCR. EPA's December 2006 Guidance Document stipulates that engine manufacturers need to have an emergency "backup plan" for distributing urea. As it is currently worded, this plan does not include an expiration date. As such, it would appear to create a precedent for EPA to hold engine manufacturers accountable for ensuring the availability of urea as long as their engines were in operation.

6.2 Greater Light Duty Penetration

It is tempting to assume that the use of urea-SCR to promote greater diesel penetration within the US light-duty fleet will have a countervailing effect on the negative impact of competing NO_X emission control technologies. As the following discussion highlights, however, light-duty urea-SCR serves primarily to address the more immediate problems associated with introducing a urea infrastructure in the first place. This analysis shows that the introduction of urea-SCR into the light-duty market does little to reduce forward-looking concerns associated with a legacy fleet scenario and vehicle resale value.

6.2.1 US Light-Duty Emission Regulations

As of MY2007 for cars and starting in MY2009 for light trucks, EPA's Tier 2 emission standard will become fully implemented and all light-duty vehicles sold in the US will be held to a new minimum emission standard. Rather than being allowed to emit at so-called "Tier 2 Bin 10" levels, these vehicles will be required to achieve Bin 8, which is a Tier 2 certification level of considerably greater stringency. As shown in Figure 30, this shift from Bin 10 to Bin 8 will require a 75 and 65 percent reduction in PM and NO_X emissions, respectively. Assuming that improvements to in-cylinder emissions control can be used to obtain approximately 45 and 25 percent of the PM and NO_X reduction, respectively, aftertreatment systems will need to achieve a further 55 percent reduction in both PM and NO_X.[36]

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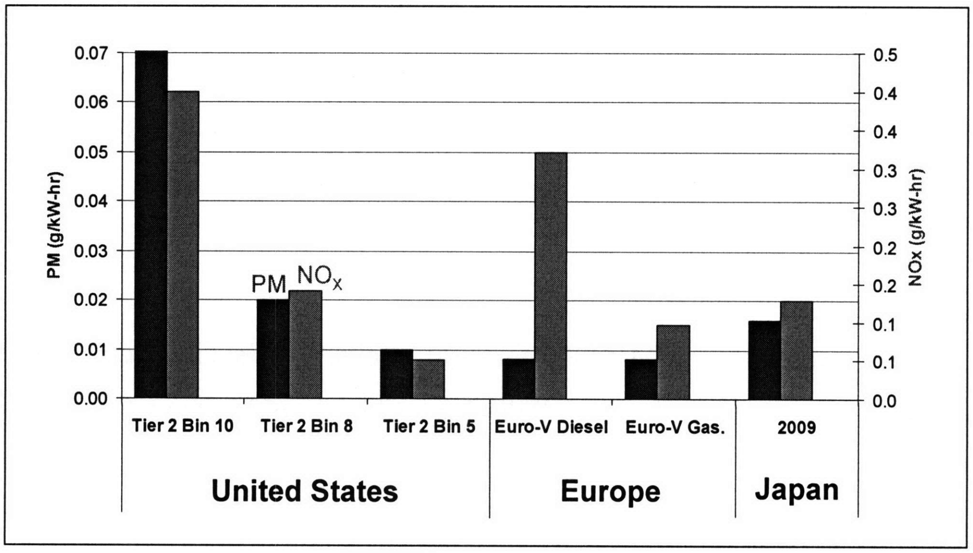
[36] This estimate assumes that light-duty vehicles will be able to achieve engine-out emission levels of 0.045 g/mi PM and 0.32 g/mi NO_X. The PM estimate comes from a presentation at the 2006 DOE DEER Conference in which Daimler Chrysler estimated the engine-out PM levels that they expected they could achieve (Godwin 2006). The NO_X estimate is simply the Euro V NO_X limit (0.2 g/km), shown in Figure 30, which was strategically determined to lie just above the limit of what can be achieved through in-cylinder control (i.e. no NO_X aftertreatment required).

Figure 30: Worldwide Light-Duty Vehicle PM and NO_X Emission Standards



Source: (Majewski and Khair 2006).

Although Tier 2 Bin 8 is the minimum emission standard nationally, California, as the only state allowed to establish a different standard, has chosen to adopt a more rigorous benchmark. Named LEV II, for low emission vehicles, the California standard is exactly harmonized with EPA's Tier 2 Bin 5, which is three certification bins more stringent than Bin 8. For comparison, the PM and NO_X limits for Tier 2 Bin 5 or LEV II are also shown in Figure 30. Compared to Tier 2 Bin 10, which is the level that US diesels are currently certified to, Tier 2 Bin 5 requires an approximately 88 percent reduction in emissions of both PM and NO_X. Therefore, accounting for in-cylinder improvements, Tier 2 Bin 5 would require approximately 78 and 84 percent efficient PM and NO_X aftertreatment systems, respectively.

Even though California is the only state that is legally authorized to develop its own standard, other states are allowed to adopt California's light-duty emission regulations. The other states that have chosen to follow California are Massachusetts, Maine, New York, and Vermont (Kavanagh 2006). This translates into a need for manufacturers to achieve Tier 2 Bin 8 to sell in 45 US states and Tier 2 Bin 5 to sell in all 50 states. Given that these five states account for approximately 20 percent of the light-duty market, manufacturers are understandably motivated to produce diesels that can be sold in all 50 states (Ward's Reports 2005a).

6.2.2 Urea-SCR and the 50-State Diesel

Four automobile manufacturers have announced their plans to introduce Tier 2 Bin 5 compliant diesels into the US market, including the following companies and their brands: BMW, DaimlerChrysler (Jeep and Mercedes Benz), Honda, and Volkswagen Group (Volkswagen and Audi). In each case, these companies' statements and actions annunciate the fact that their target is Bin 5 compliance and that it is not worth their effort to settle for being able to sell their vehicles in only 45 states.

The first announcement was issued by DaimlerChrysler in January, 2006 at the North American International Auto Show in Detroit (DieselNet 2006f). During the show, they unveiled a production-ready diesel version of the Mercedes-Benz E320, called the E320 Bluetec. They also introduced a full-size diesel SUV concept vehicle, called the Mercedes-Benz Vision GL 320 Bluetec, and an engineering concept, called the Bluetec Jeep Grand Cherokee. The Bluetec name derives from AdBlue, the EU trade name for urea. Rather than referring solely to urea-SCR, however, Bluetec is meant to be inclusive of more than one technology. The Mercedes-Benz E320 uses the LNT/SCR concept (DieselNet 2006f), while the Mercedes-Benz Vision GL 320 Bluetec and Bluetec Jeep Grand Cherokee both feature urea-SCR. DaimlerChrysler announced that the Mercedes-Benz E320, whose LNT-based NO_X aftertreatment system achieves up to 80 percent efficiency, would be launched in all 50 states beginning in the fall of 2006 (i.e. MY2007).

The next announcement was issued by BMW in May, 2006 at the annual Society of Automotive Engineers World Congress meeting in Detroit. BMW's director of diesel engine development claimed that urea-SCR was the "key" to Bin 5 certification and that offering diesels that comply with higher bins (e.g. Bin 8) was "not a solution" (Peckham 2006).

Volkswagen Group, who was the only manufacturer that sold light-duty diesel vehicles in the US between MY2000 and MY2006, announced their "50-State" plan three months later at DOE's annual DEER Conference (Dorenkamp 2006; Ward's Reports 2005a). Similar to DaimlerChrysler, Volkswagen Group disclosed a dual-technology approach. It will use urea-SCR on all of its larger vehicles, starting at the Passat (2.0 liter, 4-cylinder). Smaller vehicles will use some form of LNT-based system. This cutoff point is consistent with both Tim Johnson's prediction and the cost model in this study's prediction that LNT becomes cost-competitive with urea-SCR below two liters of engine displacement (Johnson 2006). At the recent 2007 North American International Auto Show, Volkswagen Group reported that their first Tier 2 Bin 5 compliant diesel vehicles would be the Volkswagen Jetta and Audi Q7 and that these models would be introduced in fall 2008 (DieselNet 2007b). One month after Volkswagen's announcement, Honda revealed their intent to introduce their first diesel vehicle into the US market by 2009, using their innovative single-can LNT/SCR system (DieselNet 2006d). The diesel vehicle that Honda introduces, probably an Accord, may also partially rely on advanced combustion strategies, like pre-mixed charge compression ignition (PCCI).

In October 2006 Mercedes-Benz introduced its first E320 Bluetec into the US market (DieselNet 2006e). Unlike originally planned, the E320 was only able to achieve Tier 2 Bin 8 certification during EPA emissions testing. Therefore, it is only capable of being sold in 45 out of 50 states. In light of this setback, Mercedes-Benz took the opportunity to announce that it would be introducing 320 Bluetec diesels in its M, R, and GL-Class models. They expressed their confidence that urea-SCR would enable these vehicles to achieve 50-state compliance, beginning in the fall of 2008.

Just prior to the Los Angeles Motor Show in November 2006, DaimlerChrysler, Audi and Volkswagen announced that they would jointly promote the use of the Bluetec name as the designation for Tier 2 Bin 5 compliant diesels (DieselNet 2006b). Although it had considered it, BMW opted not to join the Bluetec group, stating instead that they would launch a 50-state diesel BMW using a different brand for their emission control system.

6.2.3 A Driving Force in EPA-Industry Negotiations

When compared to their heavy-duty counterparts, light-duty manufacturers appear to be playing a more significant role in driving the negotiations with EPA over urea-SCR towards finality and consensus. Their heightened motivation can be attributed to two factors. First, the ability of light-duty manufacturers to sell diesels in all 50 states probably hinges on the acceptance of urea-SCR.[37] Although it appears that urea-SCR may also be the only viable strategy for meeting the 2010 regulations, heavy-duty engine manufacturers are not subject to the same pressures. The US economy can survive without the roughly 600,000 or so light-duty diesels that are expected to be sold in MY2009. The economy, however, cannot forego the nearly 600,000 heavy-duty trucks that are expected to be sold in 2010. The other driving factor is the timeframe for implementation. Light-duty manufacturers have targeted 2009 for the introduction of urea-SCR vehicles so as to coincide with the complete phase-in of EPA's Tier 2 standards. Heavy-duty manufacturers, on the other hand, effectively have an additional year to negotiate.

The desire among light-duty manufacturers to help resolve EPA's compliance and infrastructure concerns is evident by their interactions with the regulatory agency. For example, light-duty manufacturers are credited with proposing the "limited restart" scheme, which EPA has cited as a potential driver inducement strategy in their urea-SCR Guidance Document (Peckham 2006). This desire is also apparent when reading the comments that were submitted by light-duty manufacturers in response to EPA's Draft Guidance Document. For instance, when compared to the comments that were submitted by heavy-duty manufacturers, statements from light-duty manufacturers, like the following excerpt from the Alliance of Automobile Manufacturers came across as much more conciliatory (Alliance of Automobile Manufacturers 2006):

> The Alliance agrees with the relative importance and the need for certification guidance of the five categories EPA has outlined. The guidance provides sufficient direction and latitude to meet automaker needs, with a few exceptions.

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[37] This was illustrated by DaimlerChrysler's recent inability to achieve the Tier 2 Bin 5 NO_X limit using an LNT/SCR aftertreatment system.

6.2.4 A Separate but Complementary Infrastructure

The other favorable influence greater light-duty diesel penetration will have is that it will lead to the development of a significantly different, although complimentary urea infrastructure. The main reason light-duty vehicles require a different infrastructure is because they are expected to be able to operate for one or more oil change intervals before needing to have their urea tanks refilled. This difference is attributable to both the higher fuel economy of light duty vehicles and to the fact that the standard US light-duty oil change interval is considerably shorter than the interval for heavy-duty vehicles.[38] As determined by Tiax in their latest urea infrastructure study, Figure 31 depicts the number of additional gallons of urea needed between maintenance intervals versus the length of the maintenance interval for light, medium and heavy-duty vehicles with different size urea tanks. It shows that using a 4 gal urea tank in a car and a 9 gal urea tank in a light-truck would be more than sufficient to last not only one but probably two oil change intervals. This is consistent with a recent announcement from Volkswagen, who expects their urea tanks to go "two garage inspections" before needing refilling (Peckham 2007e).

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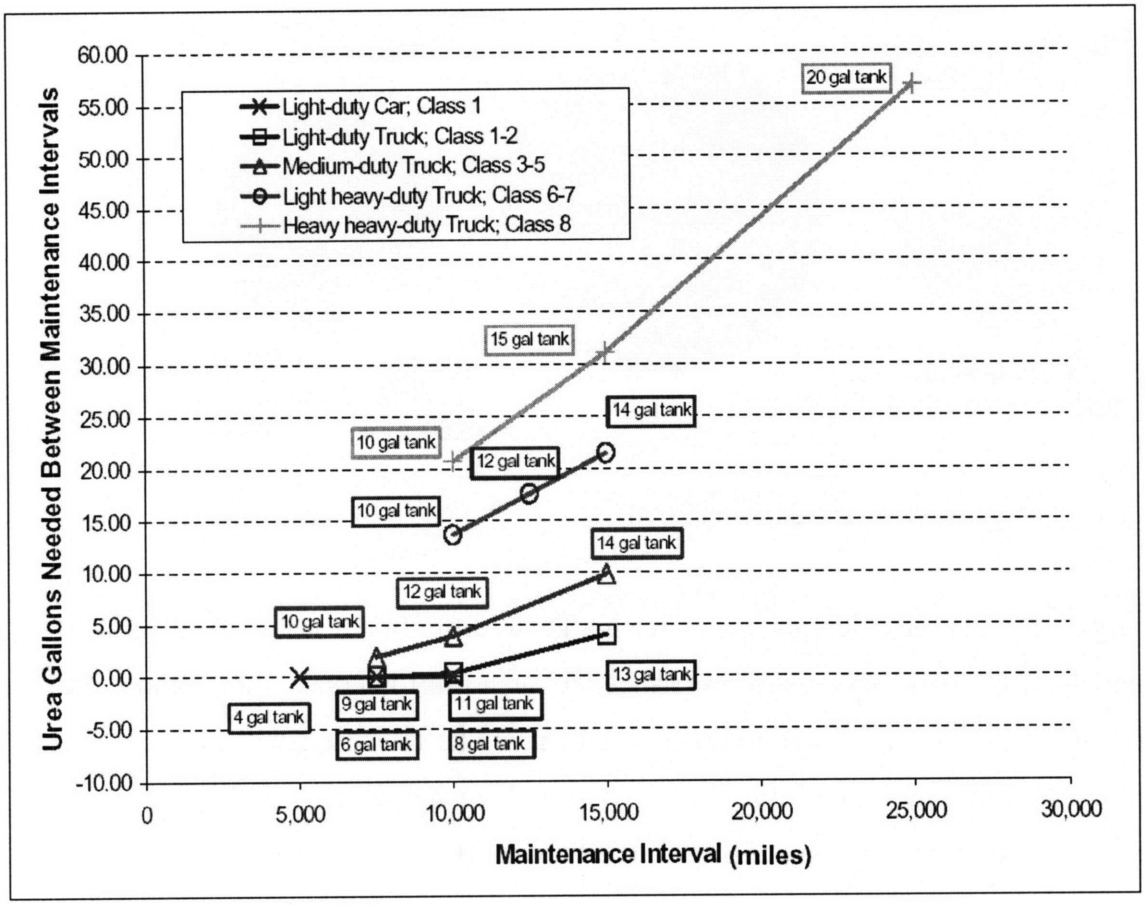
[38] The US Corporate Average Fuel Economy regulation dictates that light duty cars and trucks obtain 27.5 mpg and 23.5 mpg, respectively, whereas the HHDD vehicles achieve an average fuel economy of 5-6 mpg. The conventional US light-duty vehicle oil change interval is 3,000 miles, whereas heavy-duty vehicle intervals can range from as low as every 10,000 miles to greater than every 35,000 miles.

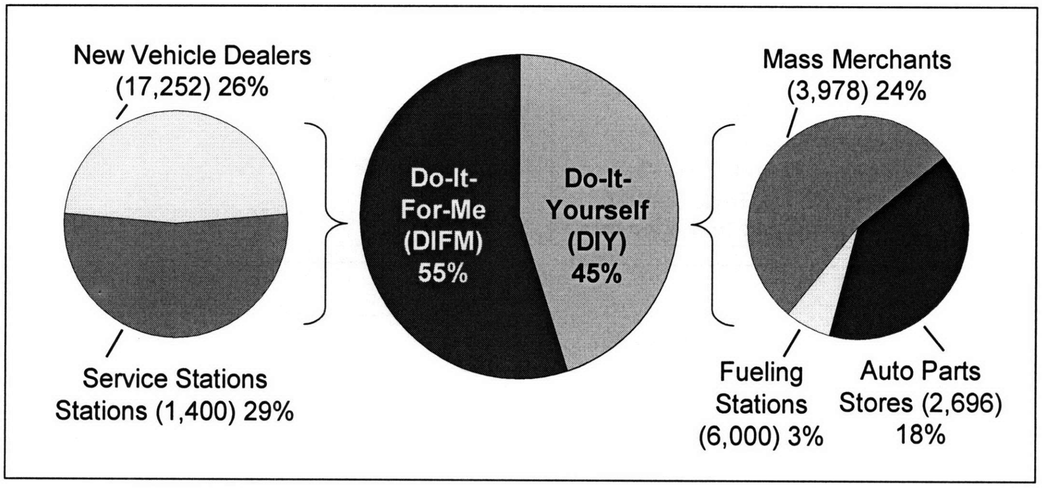
Figure 31: Urea Refilling Requirements Between Maintenance Intervals



Source: (Schubert, Pont, and Jackson 2006).

According to Tiax, due to the ability to refill one's urea at oil change intervals, a mature light-duty urea market is expected to resemble the automotive functional fluids maintenance market (e.g. motor oil, coolant and brake fluid) (Schubert, Pont, and Jackson 2006). As illustrated in Figure 32, the light-duty vehicle functional fluids maintenance market is split almost evenly between those customers who prefer to change their own oil (i.e. Do-It-Yourself or DIY) and those who would rather bring it in to either a dealer or service station chain (i.e. Do-It-For-Me or DIFM). Looking within each segment, mass merchants (e.g. Wal-Mart) are the largest distributor of automotive fluids to the DIY market and service station chains (e.g. JiffyLube) are the largest maintenance providers to the DIFM market.

Figure 32: Light-Duty Automotive Maintenance Market



Source: (Schubert, Pont, and Jackson 2006).

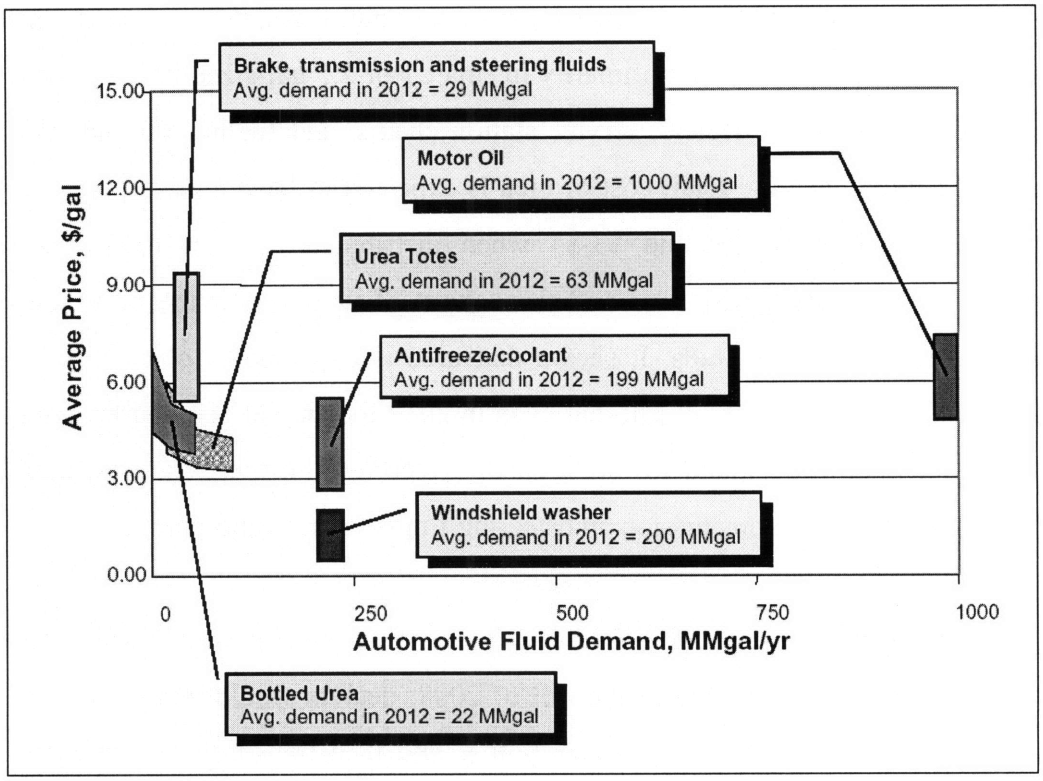
Tiax, however, expects the light-duty urea market to differ in a few important ways. Due to anticipated variations between oil change and urea refill intervals, they estimated that some of the customers who would normally behave like DIFM'ers will be occasionally required to refill their own urea tanks. This will lead fueling stations to capture a relatively larger fraction of the market, since they are the most convenient option among all the potential DIY retailers.

The distribution of urea at light-duty fueling stations would also benefit the heavy-duty sector. As discussed in Chapter 4, one impediment to introducing a heavy-duty urea infrastructure would be if EPA were to require urea to be sold at all heavy-duty diesel fueling stations, particularly the over 24,000 extra-small stations with very low anticipated urea throughput levels. A potential solution to this dilemma would be the ability for heavy-duty customers to obtain their urea from one of the 6,000 light-duty fueling stations. This alternative should be acceptable to EPA, given the fact that those 6,000 stations provide coverage within 20 miles to over 80 percent of the US population (Schubert, Pont, and Jackson 2006).

Light-duty urea demand, as detailed in Table 13, is expected to be approximately 9.25 million gallons in 2010. This assumes that approximately 4 percent of the light-duty vehicle market or 600,000 new passenger vehicles will be equipped with urea-SCR systems. Given this estimate and the anticipated distribution pathways, it is expected that most light-duty urea will be distributed primarily in small 1 or 2.5 gal-sized bottles, with some barrels and totes used by dealers, service station chains, and fueling stations. As calculated earlier (Figure 21), the retail cost of urea is expected to have a price range of \$5-\$7 when distributed in bottles and \$3-\$4 when distributed in totes or barrels. Figure 33 compares the anticipated price and throughput of urea versus the price and throughput of other automotive fluids. It shows that urea is expected to come in at a similar price point as most other fluids but that even in 2012 the annual demand for urea will be much lower than the demand for other fluids. According to these metrics, urea most closely resembles brake, transmission and steering fluids in price and volume.

Depending upon EPA requirements, the light-duty urea infrastructure would ideally be introduced in three phases. Beginning in the fall of 2008, dealers would be the first to carry urea. They are initially expected to carry bottles and then transition to barrels or totes as diesel vehicle sales grow. Shortly thereafter, service station chains will begin to stock barrels or totes to compete for the oil change services of light-duty diesel vehicles. Once urea demand is high enough to meet minimum inventory turnover requirements, auto parts stores and mass merchants will begin stocking bottles of urea. Tiax estimates this will take approximately two years for auto parts stores and three years for mass merchants (Schubert, Pont, and Jackson 2006).

Figure 33: Anticipated Price and Demand for Urea versus Other Automotive Fluids



Source: (Schubert, Pont, and Jackson 2006).

The big unknown is at which point urea will be sold at light-duty fueling stations. The foregoing analysis would suggest that it would be approximately around the same time that service stations begin stocking urea. If EPA makes it a prerequisite of emission certification, however, fueling stations would be required to sell urea earlier. Without a strong business case, Tiax believes the sale of urea at light-duty fueling stations could require subsidization. Given both light and heavy-duty interests in these stations, there is reason to believe that they may decide to collaborate in helping this segment of the infrastructure develop.

CHAPTER 7: CONCLUSION

7.1 Summary

Heavy-duty diesel vehicles currently make up less than 5 percent of the highway vehicle population, however, they account for over 50 percent of PM and NO_X emissions from on-road sources. Consistent with regulatory policies that were first introduced in 1988, EPA recently implemented a new regime of heavy-duty emission regulations, which are incorporated within the 2007 Highway Rule. This standard requires PM and NO_X emissions from heavy-duty vehicles to be reduced by 90 percent from 2004 levels within the 2007-2010 timeframe.

It is widely agreed that further improvements to the in-cylinder techniques that were used to meet previous rounds of emission regulations will no longer be sufficient to comply with the 2007 Highway Rule and that aftertreatment systems will now be required. While diesel particulate filters are the clear choice for handling PM emissions, the best approach to eliminating NO_X is less straightforward. Unlike gasoline engine exhaust, diesel exhaust contains significantly more oxygen on a volumetric basis. This fact poses a problem when trying to chemically reduce NO_X to N_2 using conventional catalytic converters.

The two most promising diesel NO_X aftertreatment technologies are urea-SCR and LNT catalysts. While each are capable of achieving the 85 percent NO_X reduction efficiency that is required to bring engine-out emission levels below the 2010 standard, both face important and, in some cases, limiting technical challenges that will need to be addressed before they can be commercialized.

LNT technology has the most difficult hurdles to overcome. The largest challenge will be to reduce their susceptibility to poisoning. Poisoning primarily results from the accumulation of fuel-derived sulfur, in the form of sulfates, on the active barium sites of the LNT catalyst substrate. This accumulation, as well as the thermal aging that results from the need to perform periodic "desulfations", significantly reduces the NO_X conversion efficiency of LNT catalysts over time. In fact, the loss of efficiency has been so severe that they have been unable to satisfy the US HHDD engine minimum aftertreatment durability requirement (i.e. 435,000 mi). A second challenge for LNT catalysts is cost reduction, particularly if they hope to compete with urea-SCR in the heavy-duty sector. The two most costly features of LNT catalysts are that they utilize precious metals, which are expensive, and they require consuming excess diesel fuel during regenerations and desulfations. Typical LNT precious metal loading levels and diesel fuel penalties are approximately 2.5 $g/L_{catalyst}$ and 4 percent, respectively. These costs can be expected to decrease over time as LNT aftertreatment systems become optimized.

Although most of this thesis is dedicated to urea-SCR's other challenges, there are also important technical issues that need to be resolved, none of which are as critical as those faced by LNT catalysts. One topic is the improvement of urea dosing and control strategies. It appears likely that closed-loop control will be required to achieve significant and continuous NO_X conversion, while also minimizing ammonia slip. The lack of an accurate and fast-response NO_X and/or NH_3 sensor, however, has limited the advancement of this approach. While workaround solutions and recent NH_3 sensor developments are encouraging, additional work is still needed. A second issue is a thorough understanding of the susceptibility of urea-SCR catalysts to poisoning. Of the limited number of studies to investigate fuel and lubricant-derived poisons, the results are encouraging in that only minimal catalyst deactivation (e.g. 10 to 20 percent) has been observed after extended periods of exposure (e.g. 400,000 km). More studies are probably needed, particularly ones that investigate the impact of urea decomposition products, which have been reported to accumulate on urea-SCR catalyst surfaces.

Despite LNT's durability concerns, the lifetime differential cost comparison that was performed in Chapter 3 demonstrated that urea-SCR catalysts are currently the more economic option for heavy-duty applications. It was determined that LNTs would cost approximately $2,000 more for MHDD vehicles and approximately $6,500 more for HHDD vehicles. The cost of operation was found to account for most of the price differential (i.e. 70 to 80 percent). A sensitivity analysis demonstrated that there is no single variable that, when modulated across its uncertainty range, would have the effect of bringing the LNT into price parity with urea-SCR. The variables with the largest potential influence were the size of the benefit associated with using a fuel reformer for LNT regeneration and changes in the relative price of urea and diesel fuel. For instance, if one were to assume that the use of a fuel reformer reduced the LNT fuel penalty by 50 percent, that the price of urea was $5/gal and that a fuel economy offset for urea-SCR equipped engines from re-advancing the fuel injection timing was not feasible, an LNT would come out as the preferred aftertreatment system for MHDD, as well as HHDD vehicles. The lifetime differential cost comparison exercise also highlighted that the attractiveness of urea-SCR scales with engine size. Consistent with earlier work, this model predicts that the breakeven engine displacement below which the LNT becomes more attractive is approximately 2 L (e.g. a Volkswagen Passat).

The need to carry urea on-board heavy-duty vehicles, however, introduces significant compliance and infrastructure challenges. These issues are especially concerning to two stakeholders, EPA and potential urea retailers. EPA is aware that the cost and inconvenience of replenishing an additional fluid creates a strong incentive for drivers not to refill their urea tank. They also worry whether a robust infrastructure for distributing urea will be in place in time for the 2010 regulations. Aside from being a prerequisite of compliance, EPA is particularly hesitant to put themselves in a position where engine manufacturers could argue after the fact that they had met their end of the bargain and that it was not their responsibility to ensure the availability of a urea infrastructure. EPA's sensitivity to these issues is heightened by their previous experience with emission control defeat devices. Not only were they ignorant to the industry's deliberate non-compliance with federal regulations but they also later introduced an emissions "pull ahead" policy that had the effect of rewarding the engine manufacturers who continued to sell non-compliant engines. As such, EPA has established a set of compliance and infrastructure criteria that they will require before certifying engines equipped with urea-SCR aftertreatment.

Potential urea retailers, such as truck stops, are also apprehensive. Their largest concern is that it will be uneconomical for them to store and dispense urea. Although EPA has placed most of the burden on engine manufacturers, potential urea retailers are afraid that selling urea could become a de-facto industry mandate if engine manufacturers unanimously adopt urea-SCR aftertreatment.

In order for urea-SCR to be viable in 2010, engine manufacturers have two key issues to resolve. The first obstacle is reaching agreement with EPA on the criteria that will be required for engine certification. Following the release of EPA's December 2006 Guidance Document, there was significant divergence between the industry and EPA on issues like warning systems, driver inducement strategies, and infrastructure requirements. While some of the industry's major points of contention were addressed in EPA's March 2007 revised Guidance Document, several significant issues and challenges still remain. One important obstacle is the development of manufacturer-specific or an industry-wide urea availability and accessibility plan. Although there do not appear to be any deal-breaking matters at stake, there is a concern that the time it will take to resolve these issues could be detrimental to the ability to implement the infrastructure before the 2010 deadline.

The second and perhaps more significant hurdle will be introducing a robust infrastructure for distributing urea in time to meet the 2010 deadline. This will require engine manufacturers to convince potential retailers that demand for urea will materialize and that investing in the necessary urea storage and dispensing equipment will be profitable.

Demonstrating sufficient demand will be more difficult than it sounds. Although urea-SCR is the clear industry favorite, there is a natural incentive for engine manufacturers to withhold their 2010 aftertreatment strategy for as long as possible. Part of their incentive stems from the fact that discussions are still underway between EPA and industry. Not revealing their preferred approach gives them more leverage to negotiate with EPA than, for example, if they had already publicly committed to using urea-SCR. Industry's tendency towards secrecy is also motivated by competitive strategy. Having learned the hard way following the defeat device consent decree (see Figure 4), many engine manufacturers are acutely aware of the impact that an emission control strategy can have on one's market share.

Validating the business case for urea distribution, assuming certain demand level assumptions, has proven to be more straight-forward. In fact, it has been the topic of several EMA-sponsored reports by the consulting firm Tiax. Their most recent analysis showed that, assuming 100 percent urea-SCR penetration, demand for urea is expected to start at approximately 33 million gallons in 2010 and grow to 190 million gallons by 2015. An examination of existing diesel throughput levels suggests that most of the urea that will be consumed on an annual basis (i.e. approximately 80 percent) will be sold primarily by a handful of very large highway truck stops (i.e. 2,000 of the nation's 32,500 diesel stations).

The wide range in diesel throughput across stations implies that urea should be distributed by a diversity of modes. Conceivable pathways include below and aboveground storage tanks (~5,500 gal), stillages (~1,300 gal), totes (~280 gal), barrels (55 gal), and bottles (1-5 gal). Allocating these pathways by projected urea throughput indicates that approximately 2,000 tanks, 2,400 stillages, 3,600 totes/barrels, and 6,000 bottle-distributing fueling stations would be needed by 2010. This level of infrastructure is projected to be sufficient to handle most of the increase in urea demand that is anticipated to occur through 2015.

Assuming a three year capital recovery period, Tiax developed a cost model that projected the price of urea would range between $2/gal and $7/gal. The $2/gal figure was for high throughput stations that had installed below or aboveground storage tanks. The $7/gal figure was for urea distributed in bottles at urban and suburban diesel stations.

Tiax's critical path analysis determined that a minimum two year lead time would be required to implement the entire infrastructure. Tanks are expected to take the longest to introduce, requiring nearly two years for construction. Once they are designed, stillages will need approximately one year for siting and installation. Discussions with manufacturers established that sufficient production capacity existed to produce the additional totes and bottles that would be required by 2010. Tiax's conclusion was that engine manufacturers would need to send a strong signal to down stream urea stakeholders during the first quarter of 2007 to leave enough lead time for the infrastructure to develop. Thus far, there has been no indications that this has occurred.

Although urea-SCR is the only viable heavy-duty aftertreatment strategy currently available, there are several reasons to believe that demand for urea could be significantly lower than Tiax projected. One reason is that alternative compliance strategies, such as emissions banking, trading and averaging, will make it possible for engine manufacturers to accumulate credits ahead of time that can then be applied towards the 2010 NO_X emissions threshold. Cummins' recent announcement, that they will certify their pre-compliant LNT-equipped Dodge Ram engines to the heavy-duty emission standard, illustrates that alternative compliance may become a popular approach for some engine manufacturers. A second reason is that cost, performance and infrastructure availability concerns will prompt many fleet owners to pre-buy MY2009 vehicles. A third reason to question urea demand is that, factoring in engine test cycle not-to-exceed limits (i.e. 1.5x the standard), the rate at which real vehicles will consume urea could be considerably lower than the rate that was used by Tiax in their projections.

An assessment of the EU urea-SCR experience to date uncovered the policies and market factors that contributed to the successful introduction of a urea infrastructure. Industry-led policies played a crucial role in laying the early groundwork. The first of these was the nearly unanimous decision by engine and truck manufacturers to use urea-SCR instead of exhaust gas recirculation to achieve the Euro IV and Euro V NO_X standards. Faced with a similar decision (i.e. the first phase of the 2007 Diesel Rule), US engine manufacturers opted instead for exhaust gas recirculation. When the urea infrastructure was first introduced in the EU, Euro IV compliant vehicles consumed urea at a rate of 4 to 5 percent the rate of diesel fuel consumption. In the US, the rate of urea consumption is anticipated to be closer to 1 to 2 percent when heavy-duty urea-SCR equipped vehicles are first introduced in 2010. On a per-vehicle basis, urea throughput levels will have been significantly higher when the infrastructure was first introduced in the EU than they are expected to be in the US. Higher throughput levels makes urea more attractive to producers and consumers. Producers make more profit and are able to pay off the initial capital investments more quickly. Consumers pay less for urea because producers are able to charge less due to higher volumes. Ironically, this policy was not at all motivated by urea infrastructure considerations. It was based on a desire to implement one aftertreatment technology that could be used to meet two consecutive emission regulations. The industry's second policy was more deliberate. Beginning in September 2001, the EU's engine and vehicle manufacturers publicly disclosed their intent to use urea-SCR. This allowed downstream urea stakeholders more than three years to prepare for the introduction of an infrastructure for distributing urea.

Government policies played an equal or even greater role. The first of these was the split-level regulatory regime that resulted from the fact that the European Commission did not anticipate that urea-SCR would be used to comply with the Euro IV standard. As a result, the European Commission was prohibited from issuing compliance and infrastructure-oriented engine certification criteria that could take effect any earlier than one year after the standard was introduced. This had two important repercussions. First, it enabled the infrastructure for distributing urea to be introduced in phases as opposed to prior to the introduction of urea-SCR equipped vehicles, allowing it to develop symbiotically in response to growing demand. The other benefit of a lax regulatory climate was that the urea-SCR vehicles that were sold during the first year of the new standard were not required to have systems for penalizing non-compliance. Driver inducement, in the form of torque limiting and the storage of non-erasable fault codes, did not become a requirement until 2006, one year after the Euro IV standard was implemented. This split-level approach made it possible for the drivers of these vehicles to operate them on an empty urea tank, thereby providing an indirect incentive to purchase urea-SCR vehicles during the first year they were available. Although the European Commission's policy probably caused NO_X emissions to increase, it ultimately helped stimulate urea-SCR vehicle adoption and infrastructure development.

A second government policy critical to the EU's success was the existence of country-level early adoption incentive programs. For example, the ability for pre-compliant vehicles to obtain discounts off of the German road toll MAUT was especially effective, given Germany's prominent economic and geographic position in Western Europe. In conjunction with a piecemeal regulatory approach, early adoption incentives provided a counterbalancing force against the natural tendency for fleets to pre-buy their vehicles during the year before the Euro IV regulation took effect. The combined influence of these two policies was especially crucial, given the potentially harmful result a pre-buy could have had on the motivation of retailers to invest in the infrastructure for storing and dispensing urea.

Chapter 5's analysis of the EU also revealed several structural features that most likely facilitated urea-SCR's introduction. For example, in many EU countries commercial vehicles largely refuel at fleet fueling stations. This helped make it possible to roll-out the infrastructure in phases, beginning with high-use company-owned fueling stations first. Secondly, the widespread distribution of urea manufacturing throughout the EU made it possible for each facility to focus on regional markets and thereby limit logistic costs. Given the concentration of urea manufacturing capacity in Southeastern States, the transport of urea in the US, is expected to be more expensive. A third factor is that, unlike in the US market, the EU heavy-duty industry is vertically integrated. Having engines and vehicles produced by the same company both simplifies the stakeholder landscape and eliminates some of the need to withhold one's strategy for the sake of competitive advantage.

There is at least one lesson to be learned from the EU's experience which could be applied in the US context. Having chemical distribution companies not only supply urea but also provide the necessary storage and dispensing equipment through some form of leasing arrangement is a promising business model for distributing urea. From a fueling station's perspective, the major advantage of this approach is that it removes most of the financial risk associated with selling urea. Rather than paying a high upfront capital cost, fueling stations would only need to commit to multiyear, annual or even semi-annual contracts. Other advantages of the chemical distribution model are that it is simple (e.g. no permitting, etc.) and that it eliminates the need to perform or procure maintenance. The question is whether US chemical distributors are interested in entering this market. Given the large number of multinational chemical distributors operating in the US, it seems likely that many of them will wish to capitalize on their experience distributing urea in the EU.

Finally, the last chapter of this thesis examined the effects that emerging technologies and new markets are likely to have on the future viability of urea-SCR. It showed that, individually or in combination, advanced combustion schemes and LNT/SCR aftertreatment could replace urea-SCR within the next five to ten years. This prospect should be highly discouraging to urea-SCR stakeholders. For urea retailers and engine manufacturers it implies that one of them could potentially be held responsible for subsidizing the supply of urea to a "legacy fleet" of vehicles for the duration of their useful life (i.e. approximately 2.5 million vehicles for 15-20 years). The potential for the urea infrastructure to deteriorate due to a lack of demand should also caution fleet owners from purchasing urea-SCR vehicles, whose resale value could become severely compromised.

The introduction of urea-SCR equipped light-duty diesel vehicles was investigated for its potential to have a countervailing effect. Urea-SCR adoption by the light-duty diesel vehicle fleet was determined to primarily help resolve the short term problems of reaching consensus with EPA on certification criteria and distributing urea at the lowest throughput diesel stations. It was not, however, expected to have an important effect on the more forward-looking challenges that are posed by emerging and alternative NO_X control strategies.

7.2 Expected Outcome

Between the end of 2007 and early 2008, it is expected that engine manufacturers will have secured urea distribution commitments from most of the 2,000 largest truck stops. However, rather than opting for invasive and capital intensive distribution modes, like above or belowground storage tanks, these stations will choose instead to use stillages, totes and barrels to store and dispense urea. A significantly smaller number of independent stations are anticipated to commit to selling urea. Some may decide to carry totes or barrels but most will only stock a limited supply of small bottles.

Shortly after agreements are reached with EPA, the remaining engine manufacturers who have yet to reveal their 2010 aftertreatment strategies (i.e. Caterpillar, International and Cummins) will separately announce their commitment to using urea-SCR on some of their engines, perhaps as few as 50 percent. Engine manufacturers will obtain compliance for their remaining engines by applying emissions credits that they achieved ahead of time through banking, trading and averaging. Similar to what occurred during previous rounds of emission regulations, fleet owners will again choose to pre-buy their vehicles. As a result, heavy-duty vehicle sales will be approximately 33 percent lower during the first quarter of 2010 than they would have been were there no regulation.

Vehicle purchases will rebound again during the fourth quarter of 2010. Urea-SCR will continue to be used as the dominant aftertreatment strategy in heavy-duty vehicles through 2015. At this point, the success of advanced combustion schemes and LNT/SCR in light-duty vehicles will prompt more manufacturers to start adopting these technologies in heavier and heavier vehicles. Durability issues related to sulfur poisoning will limit LNT/SCR from penetrating into vehicles with HHDD engines (i.e. Classes 6-8).

Once advanced combustion strategies and LNT/SCR begin to displace urea-SCR, the demand for urea will start to decline. The rate of decline will depend on two factors: the fuel economy benefit or disadvantage from moving to one of these alternative schemes, and the propensity of vehicle operators to discard their urea-SCR vehicles before their resale value becomes compromised.

7.3 Recommendations

1. Engine manufacturers need to engage urea supply chain stakeholders in discussions to a), demonstrate that developing an infrastructure for distributing urea to the US heavy-duty fleet will be profitable, and b), solicit their help in putting together a urea availability and accessibility plan for EPA.

The most open and unresolved question in the whole urea-SCR debate is whether and to what extent potential urea supply chain stakeholders, namely fueling stations, will choose to invest in developing a urea infrastructure. As demonstrated by NATSO and PMAA's responses to EPA's Draft Guidance Document, this group of constituents have expressed significant concern over the impact that supplying urea would have on their business. In fact, EPA's revised Guidance Document, which relaxed the infrastructure requirements placed on engine manufacturers (e.g. "best efforts" instead of "guarantee"), further exacerbates those concerns. Thus, it is crucial for engine manufacturers to demonstrate that supplying urea will be profitable. Additionally, now that a majority of engine manufacturer concerns were resolved with the release of EPA's revised document, their next obstacle is to develop an urea availability and accessibility plan, which EPA has said they would require before certifying engines that use urea-SCR aftertreatment. Although each engine manufacturer can choose to submit a separate plan, it would seem that developing a single industry-wide plan is the most practical approach. The challenge in both of these recommendations, however, is that they probably require engine manufacturers to divulge their 2010 product plans earlier they would normally choose to do so, which raises important competitive strategy considerations.

2. Urea-SCR stakeholders should strongly consider a urea infrastructure model in which chemical distributors are responsible for not only supplying urea but also providing and maintaining the necessary retail storage and dispensing equipment.

Ever since urea-SCR was first discussed as a potential 2007 Highway Rule compliance strategy, chemical distributors have been viewed as an integral stakeholder. All indications, however, show that very little consideration has been given to having them provide and maintain the actual storage and dispensing equipment. In fact, the EMA has commissioned Tiax to perform several studies to demonstrate the feasibility of introducing a urea infrastructure to fueling station owners and other downstream players. Yet, each study has been based on the assumption that fueling stations will be the party who are responsible for financing and installing the urea storage and dispensing equipment. The EU example shows that having chemical distributors provide a turnkey infrastructure solution could be a successful implementation model because, among other things, it shifts much of the financial risk away from fueling stations.

3. Heavy and light-duty vehicle stakeholders should work together to help ensure urea availability at fueling stations that cater to both of their customers but whose low anticipated throughput levels could make urea distribution uneconomical.

Of the 24,000 heavy-duty vehicle fueling stations with low projected urea throughput levels (i.e. less than 100 gal/mo), only 6,000 of them would be required to provide coverage within 20 mi to 80 percent of the population. Many of these stations also cater to the light-duty market, given their location within suburban and rural areas. By working together intelligently, heavy and light-duty vehicle stakeholders could reduce the financial burden placed on these low throughput stations.

4. EPA and Industry should collaborate to limit heavy-duty vehicle pre-buy and promote early compliance leading up to 2010.

If previous rounds of emission regulations are any estimate, fleet owners will deviate from their normal purchasing habits to buy MY2009 vehicles before the 2010 NO_X threshold becomes effective. Even though some projections expect that MY2010 urea-SCR vehicles could be fuel consumption neutral when compared to their MY2009 counterparts, higher initial costs will nonetheless motivate people to pre-buy vehicles. EPA and industry stakeholders should work together to find ways of mitigating this effect. Pre-buy not only delays the air quality benefit of more stringent emissions standards but it also compromises the financial basis for retailers to invest in the infrastructure for storing and dispensing urea.

5. As also concluded by Tiax, industry should recruit major for-hire trucking companies and branded truck stops to catalyze the development of the urea infrastructure.

For-hire trucking companies, like Ryder and J.B. Hunt, do 2/3 of their refueling at public truck stops. As major customers of the largest highway truck stop chains, for-hire trucking companies have enough leverage to convince their fueling partners that they should begin providing urea at their facilities. After all, it is in their best interest to do so. For-hire trucking companies could potentially suffer a financial loss if an inadequate urea infrastructure resulted in delayed or missed shipments. While installing or leasing urea storage and dispensing equipment could present a significant cost, it would also be a wise investment for branded truck stops to make. If urea is initially only available at the largest fueling stations, vehicle operators that might otherwise not refuel at a public truck stop may be forced to do so, adding to their business. Additionally, branded truck stops are better able to shoulder the upfront capital burden than an independent fuel station. Lastly, major for-hire trucking fleets and branded fueling stations have a superior ability to self-organize, when compared to smaller outfits.

6. Industry should enlist the involvement of private fleets to help grow urea demand.

The proliferation of urea refueling facilities at fleet-fueling stations will do little for the urea infrastructure as a whole. However, recruiting private fleets like UPS and Waste Management to purchase urea-SCR vehicles and install urea storage and dispensing equipment at their private fueling depots would bolster urea consumption, making the economics more favorable for urea producers and central distribution and blending facilities.

7. Lastly, EPA should augment the highway vehicle emission regulation's early compliance incentives to include demand-side measures.

EPA's current emission banking, trading and averaging early compliance incentives are focused solely on engine and vehicle producers. While these strategies are effective methods of pushing vehicles out into the marketplace, they do little to stimulate consumer demand for pre-compliant vehicles. US regulators should borrow from the EU example and offer a portfolio of demand-side measures, such as tax incentives and reduced road tolls.

A potential strategy for integrating several of these recommendations would be for EPA and industry to develop what might be termed *Urea Corridor Projects*. Involving for-hire trucking companies and branded fueling stations, the goal would be to develop large demonstration projects along several major US trucking routes. Once the 2007 Diesel Rule becomes fully implemented in 2010, these corridors could serve as a backbone for a fully functional urea infrastructure.

APPENDIX

Commonly Used Acronyms

AST – above ground storage tanks

BHP – brake horsepower

BSFC – brake specific fuel consumption

CARB – California Air Resources Board

CDF – central distribution facility

CO – carbon monoxide

DIFM – do-it-for-me

DIY – do-it-yourself

DOC – diesel oxidation catalyst

DPF – diesel particulate filter

EMA – Engine Manufacturers Association

EPA – Environmental Protection Agency

FTP – federal test procedure

HC - hydrocarbons

HHDD – heavy heavy-duty diesel

LTC – low temperature combustion

MHDD – medium heavy-duty diesel

NATSO - National Association of Truck Stop Operators

NO_X – nitrogen dioxide, collective for nitric oxide (NO) and nitrogen dioxide (NO_2)

NTE – not-to-exceed

OBD – on-board diagnostics

PM – particulate matter

PMAA – Petroleum Marketers Association of America

PGM – platinum group metals

SET – supplemental emissions test

Urea-SCR – urea selective catalytic reduction

UST – underground storage tanks.

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Acknowledgements

I would like to sincerely thank my thesis supervisor, Dr. Daniel Cohn. Not only did he make it possible for me to perform this work, by taking me on as a research assistant and personally funding my participation in the 2006 US DOE DEER Conference, but he also provided generous amounts of encouragement and advice, pertaining both to my thesis and my general professional development. I most certainly will remember our weekly research meetings that often concluded with an enjoyable discussion about bigger picture energy topics or one another's favorite hiking trails.

My thesis readers, Professor Ernest Moniz and Dr. Victor Wong, also deserve much gratitude. Professor Moniz, through his leadership of the Laboratory for Energy and Environment and the MIT Energy Initiative, secured the majority of my funding for this research. He also proffered insightful advice through his comments on my oral and written progress reports. I owe Dr. Wong a great deal of appreciation for taking me on when I first arrived at MIT and for captivating my interest in diesel technology. I am also thankful for his support while I transitioned from performing detailed technical research to broader systems-level studies.

I feel fortunate to have spent my time at MIT working in the Sloan Automotive Laboratory. My interaction with fellow lab mates, whose technical knowledge was much more expansive than my own, significantly deepened my understanding of automotive technology and policy issues. In particular, Simon Watson, Alex Sappok and Anup Bandivadekar deserve special thanks.

Lastly, I would like to thank my family for their encouragement in everything I do. It was especially appreciated during the difficult process of becoming a student again after having spent time in the working world. In particular, I would like to thank my fiancé Allyson for her unbounded love and support, especially on those beautiful weekends when I refused her invitations to leave the apartment, deciding instead to do work.