# CLEAN TECHNOLOGIES AND MORE

There are a number of emission control strategies available to reduce diesel emissions. In this section, we provide more information on the types of emission control technologies, clean and alternative fuels, idle reduction technologies, hybrid/electric technologies and efficiency strategies.

## Emission Control Technologies

### Diesel Oxidation Catalysts (DOCs)

**ECT Background**

Diesel oxidation catalysts (DOCs) were one of the first retrofit emission reduction technologies to have widespread use. Similar to the size and shape of the conventional muffler, a DOC is essentially a direct replacement with the muffler. There are no requirements to modify or adjust engine controls. Generally, DOCs are a little heavier than a conventional muffler and may require more robust mounting brackets. A DOC's performance is further enhanced with the use of ultra low sulfur diesel fuel (ULSD) with a sulfur content of < 30 ppm.

DOCs generally exhibit PM reduction efficiencies of 20 percent, which is modest compared to other, more advanced technologies. However the ease of installation, minimal modification to the vehicle structure or operational parameters (such as engine recalibration or low-sulfur fuel substitution), coupled with their low-cost, makes them an ideal PM retrofit technology when used in large-scale applications.

As the name suggests, the oxidation catalyst "oxidizes", or "adds oxygen" to hydrocarbons in the exhaust, to form carbon dioxide ($CO_2$) and water. Oxygen is present in diesel exhaust in large quantities, so oxidation occurs naturally; a DOC speeds up the reaction rate. The soluble organic fraction (SOF) is the hydrocarbon derivative organic carbon (so called "wet" carbon) portion of PM; DOCs oxidize the SOF fraction of PM and this reaction results in PM reductions.

**"At A Glance"**
**Diesel Oxidation Catalyst**

| Benefits | Drawbacks |
|---|---|
| **1. Moderate emission reductions in PM (20 – 30%), HC (50 – 90%) and CO (70 – 90%).**<br>**2. Comparatively a low cost.**<br>**3. Direct muffler replacement making it an easy installation.**<br>**4. More tolerant of higher sulfured fuels <500 ppm.** | **1. Low PM reduction and no NOx reduction.**<br>**2. Ineffective in reducing elemental carbon or soot.**<br>**3. May require more robust mounting brackets.**<br>**4. Potential for sulfate make.** |

**Technical Considerations**

**"Sulfate Make"**
A potential concern with DOCs is their ability to create "sulfate make." Under certain operational conditions along with the type of fuel use, DOCs can generate unwanted sulfate. This can outweigh any benefit in total PM reduction. Sulfate make is dependent primarily upon sulfur content in the diesel fuel, the operating conditions of the vehicle (and hence the resultant catalyst temperature) and the formulation of the metal on the catalyst itself.

The best defense against sulfate make is to use low-sulfur fuels. DOCs are attractive for retrofits since they are not poisoned by the use of higher sulfur fuels (300 ppm and above) the way many DPFs are. However, higher sulfur content can contribute to sulfate make, and their use with lower sulfur content fuel will ensure minimal sulfate production. Additionally, DOCs are becoming more sophisticated and coating formulations are selectively minimizing sulfate make. Finally, sulfur formation tends to decrease with increasing temperatures above a certain threshold point; there is a design trend for modern diesel, engines toward higher engine and exhaust temperatures.

**Field Experience**
DOCs have widespread use in on-highway applications; become more prevalent for nonroad construction, cargo handling equipment and marine applications.

**ECT Cost**

<u>On-Road</u>
Trucks= $1,000 to $2,000

<u>Non-Road</u>
CHE (>750 hp= $1,000 to $2,000
Marine and CHE (<750 hp) = $3,000 to $4,000
Locomotives= Cost may vary (Currently in demonstration.)

**Closed Crankcase Ventilation (CCV)**

**ECT Background**

Closed crankcase ventilation (CCV) systems prevent "blow by" gases from entering the atmosphere. Crankcase emissions result from a diesel combustion process in the engine. There are a certain percentage of engine exhaust gases that pass by the piston rings and valve seals and essentially make their way into the crankcase of the engine. Eventually, these "blow by" gases make it into the atmosphere. The gases contain harmful pollutants such as PM, NOx, HC and CO.

To effectively and safely perform this "recirculation" operation requires a vapor separator, filtering and re-circulating device, generically known as *closed crankcase ventilation* or *CCV*.

**"At A Glance"**
**Closed Crankcase Ventilation (CCV) Systems**

| Benefits | Drawbacks |
| --- | --- |
| 1. PM reduction of 15 – 20%. Added emissions benefit when combined with a DOC.<br>2. Low cost.<br>3. Minimal maintenance – filter replacement. | 1. Negligible NOx, HC and CO reduction. Difficult to test.<br>2. Challenging installation on the first few retrofits. Becomes easier with installation experience. |

**ECT Cost**

On-Road
Truck= $700 for typical "on-highway" derivative engine.

Non-Road
CHE= $700 (engines >750hp)
Marine and Locomotives= NA

Cost for filter replacement=$48 to $50.

**Diesel Particulate Filters (DPFs)**

**ECT Background**

Diesel particulate filters (DPFs) are one of the most effective emission control technologies to reduce particulate matter (PM). When use in conjunction with a catalyst, DPFs are capable of reducing up to 90 percent of PM. This makes them a very attractive retrofit option. DPFs have been very successful across on-highway heavy duty diesel vehicles. More and more, demonstration projects are testing the feasibility of DPFs on non-road applications such as marine, locomotives and CHE.

DPFs remove PM through a two-stage process. First, the DPF physically entraps the elemental carbon portion of PM. Then, through elevated exhaust temperatures, the DPF oxidizes particulates to form gaseous products, primarily $CO_2$. This process is termed “regeneration.”

Passive DPFs vs. Active DPFs

*Passive DPFs* do not use an external source of heat to promote regeneration. Exhaust temperatures are elevated by the increased backpressure in the exhaust as the DPF fills with PM. As the PM level increases, the exhaust backpressure and hence the exhaust temperature increase to specific threshold values. When this threshold exhaust backpressure and temperature is reached, the PM is oxidized and removed, and the exhaust temperature subsequently reduces. The DPF starts to trap more PM and the process is repeated.

*Active DPFs* employ the same principal, but heat is added by one of a number of external means to promote regeneration – electric heating, injection of diesel fuel into the exhaust, or engine calibration to temporarily raise the exhaust temperature. Active DPFs are used when the engine exhaust temperatures are too low for the use of passive DPFs.

By combining a DPF with an oxidation catalyst (DOC), the SOF portion can also be removed, enhancing PM reduction up to 90 percent. Most DPF manufacturers have commercialized these dual-based systems into one container or “can”, using a DPF in addition with a DOC or applying a catalytic coating to the DPF substrate itself, to facilitate retrofit installation.

**“At A Glance”**
**Diesel Particulate Filters (DPFs)**

| Benefits | Drawbacks |
|---|---|
| 1. Excellent PM reductions up to 90%. HC and CO reductions from 60 to 90%.<br>2. Comparatively easy installation – not as straightforward as the DOC, but replaces the muffler. | 1. High cost.<br>2. Requires the use of ULSD.<br>3. Requires threshold exhaust temperatures to ensure regeneration.<br>4. Requires annual soot/ash removal. |

**Technical Considerations**

**Installation**
Similar to the installation of DOCs, DPFs are generally designed as a direct replacement for the original muffler. However, DPFs tend to be larger and heavier than DOCs and require some engineering to fit properly. Special adaptations such as mounting brackets must be designed to sustain the increased weight and larger size of the DPF.

**Exhaust Temperatures**
The requirements of certain threshold exhaust temperatures to promote regeneration can complicate the use of DPFs for some applications. To determine whether a specific application has the exhaust temperatures necessary for regeneration, it is important to conduct a thorough temperature analysis. This can be done by conducting exhaust temperature data logging. Data logging instruments are installed to record the vehicle's exhaust temperature "history" prior to DPF retrofit installation. This approach ensures that the exhaust temperature, on average, is sufficiently high to promote timely and consistent regeneration of the DPF. Once a DPF is installed, an exhaust backpressure sensor and dashboard-mounted indicator light is installed to ensure consistent regeneration in-use. Monitoring exhaust gas backpressure (EGBP) ensures that the DPF in not becoming plugged with soot due to insufficient regeneration. An increase in EGBP can result in an engine failure.

**Field Experience**
DPFs have proven successful with on-highway heavy duty diesel vehicles. There are numerous demonstration projects testing the viability of DPFs on non-road applications.

**ECT Cost**

<u>On-Road</u>
Trucks= $6 to $10K, depending upon engine displacement, for passive systems; active systems range up to $18K. Installation cost run around $4K. Annual cleaning can cost up to $500 per DPF.

<u>Non-Road</u>
CHE (>750 hp)= similar cost to an on-road application.
Marine and Locomotives= prices range and can go up to $40K. Currently under demonstration.

**Selective Catalytic Reduction (SCR)**

**ECT Descriptive Narrative**

SCR is one of three commercially available technologies that are proven to show significant reduction in NOx from diesel engines (emulsified diesel fuel and lean NOx catalysts are the others). SCR systems have a history of being used in stationary applications, such as diesel engines that power generator sets, compressors and pumps. They have also been successfully used in large powerplant and other industrial applications. Due to the more prevalent use of SCRs on stationary sources, there is a lack of mobility experience for on-highway and non-road applications. Some of the challenges include transporting the requisite supply of ammonia, and ensuring that the engine operates within a rather narrow exhaust temperature band to ensure proper SCR operation. Nevertheless, SCRs have been more widely used on-highway. In addition, with the less transient duty-cycle of many marine applications, as well as central-fuelling of vessels, typical of the ferry industry, makes SCR an attractive NOx-reduction option.

SCR systems are inherently more complex than other NOx-reduction strategies, or than typical PM-reducing retrofit options such as DPFs and DOCS, in that they require an elaborate injection or "dosing" mechanism to provide the correct measure of ammonia into the exhaust stream to reduce engine-out NOx. As a result, the initial unit cost is higher, as are the installation costs. Furthermore, a constant ammonia/urea supply is needed, and care must be taken to ensure operators maintain ammonia/urea in the SCR fill tank.

SCR uses an outside agent, ammonia, to convert NOx to harmless nitrogen ($N_2$) and water. Because ammonia is quite toxic and corrosive in its pure form, a non-toxic substitute, urea, is used. The urea essentially "locks in" ammonia in a non-toxic, easy to handle and commercially available solution. When the injection or "dosing" unit releases the urea into the exhaust, the heat from the exhaust (minimum temperature of 160 °C) releases the ammonia component of the urea stimulating the chemical reaction that converts NOx into $N_2$ and $H_2O$.

**"At A Glance"**
**Selective Catalytic Reduction (SCR)**

| Benefits | Drawbacks |
|---|---|
| 1. Excellent NOx reduction from 70 to 95%.<br>2. Does not require low sulfur diesel fuels.<br>3. No additional maintenance. | 1. High cost.<br>2. Requires infrastructure for urea additive.<br>3. Requires on-board dosing unit.<br>4. Requires careful urea injection strategy to avoid "ammonia slip."<br>5. Requires strict monitoring of exhaust temperatures to avoid excessive NOx formation. |

**Technical Considerations**

**SCR - A Complex System**
SCR units are large, heavy, complex and bulky systems. The system includes a catalyst (which is typically installed in series with the engine's muffler), a urea holding tank, and a dosing injection unit. The dosing unit includes an injector and attendant electronic controls, and usually requires compressed air to aerate the injected urea. Compressed air is used for this purpose, either from on-board systems or as a stand alone device consisting of the air compressor, accumulator, associated piping and pressure regulator. Due to the heavy weight of the SCR, extra brackets may be required as well as careful attention to weight influence on the vessel's maximum load rating.

**Dosing with Urea**
SCR systems must maintain a careful balance of proper urea dosing. Not using the appropriate amount of urea results in poor (sometimes zero) NOx reduction. Additionally, excessive amounts of urea result in a phenomena known as "ammonia slip", where pure ammonia – a toxic substance – discharges from the exhaust.

**Exhaust Temperatures**
Similarly, vessel operation and resultant exhaust temperatures that are too low (generally less than 200 °C) can cause "secondary reactions" that can increase NOx formation. SCR, if improperly engineered, will contribute to NOx formation, rather than reducing it. These lower temperatures are often characteristic of light-load vessel duty cycles.

**Field Experience**
SCRs have been widely used on on-highway heavy duty diesel vehicles. There has been reasonably extensive use of SCRs on marine applications. Of all potential NOx-reduction strategies, SCR has become the most attractive.

**ECT Costs**

<u>On-Road</u>
Trucks= $30K for on-highway derivative engines. Installation cost is around $6K. There is also the additional fuel cost of urea.

<u>Non-Road</u>
CHE (>750hp)= Similar cost to on-highway trucks.
Marine= Cost range from $60K to $120K.
Locomotives= currently under demonstration.

**Lean NOx Catalyst (LNC)**

**ECT Background**

Similar to an SCR, a lean NOx catalyst (LNC) selectively reduces NOx through the introduction of an enabling "outside agent." Instead of using urea as the fuel additive, a LNC injects a "shot of hydrocarbons" into the exhaust. This can be done in two ways, either through direct injection of fuel into the exhaust stream or through late injection of fuel, via the fuel injection equipment system, directly into the cylinder of the engine.

**Oxides of Nitrogen + hydrocarbons (typically diesel fuel sprayed into the exhaust stream) = atmospheric nitrogen + carbon dioxide + water**

$$\{HC\} + NOx = N_2 + CO_2 + H_20$$

While there are challenges to using a LNC, the capability of the technology to employ an activation mechanism already on board the vehicle, diesel fuel – makes it far more attractive than the urea-infrastructure-intensive SCR system.

**"At A Glance"**
**Lean NOx Catalyst (LNC)**

| Benefits | Drawbacks |
|---|---|
| 1. Moderate NOx reductions.<br>2. Diesel fuel is used as the enabling fuel additive that is already on board the vehicle; diesel fuel infrastructure already in place.<br>3. Emission control technology combinations available to reduce PM – such as LNC in combination with a DPF. | 1. High cost.<br>2. Lower NOx reduction that SCR. No reduction in PM, CO and HC.<br>3. Specific exhaust temperature required.<br>4. Must use ULSD.<br>5. Can create nitrous oxide, a greenhouse gas.<br>6. Fuel penalty 6 to 9%. |

**Technical Considerations**

**Size**
LNC units are typically designed and constructed in conjunction with some form of PM reduction device, usually a DOC or DPF. Size and weight become factors to consider when fitting the ECT in certain applications such as harbor craft.

**Fuel Penalty**
Both diesel/HC injection strategies (in-cylinder injection or direct injection into the exhaust) enable the lean NOx catalyst to convert NOx to harmless nitrogen, carbon dioxide and water. However, both strategies bring about penalties in fuel economy.

**Field Experience**
Pilot programs in the on-highway sector are becoming more prevalent: a number of programs are underway in California using Carl Moyer Program funds. There is, at present, little marine activity, in large part because the cost, complexity and comparatively smaller NOx reductions from LNCs, which make SCR more attractive.

**ECT Cost**

On-Road
Truck= $14,000 for on-highway derivative engines. Installation costs are similar to SCR around $6K.

Non-Road
Marine= Cost could cost up to $40,000.

**ON-ENGINE MODIFICATIONS**
**Exhaust Gas Recirculation (EGR)**

**ECT Background**

Exhaust gas recirculation systems (EGRs) reduce NOx by re-circulating a portion of the engine exhaust gases back into the engine. These essentially non-reactive exhaust gases reduce combustion temperatures and pressure in the engine, lowering NOx. There are two processes at work to reduce NOx.

1. *Dilution of the intake air* with non-reactive exhaust gases decreases oxygen content in the combustion process, reducing combustion temperatures and pressures.
2. *Heat absorption* by the EGR stream through the heat absorbing capacity of $CO_2$ (thermal effect) and dissociation of $CO_2$ (chemical effect) also leads to a reduction of engine combustion temperatures and pressures.

EGR systems work very well with DPFs. DPFs not only function to reduce PM but are very important to the functionality and effectiveness of an EGR system. Since EGR systems require a clean exhaust supply before the exhaust gases are directed back to the engine, the use of a DPF fulfills this process while reducing PM at the same time.

**"At A Glance"**
**Exhaust Gas Recirculation**

| Benefits | Drawbacks |
|---|---|
| 1. Moderate NOx reduction 40 to 50%.<br>2. Packaged with a DPF reducing PM up to 70%. CO and HC are also reduced with DPF combination.<br>3. Widespread use in field. | 1. Requires careful installation.<br>2. Slightly reduces engine power.<br>3. Exhaust cooling is required and may result in engine wear due to excess water vapor.<br>4. Requires ULSD.<br>5. Requires electronic control strategy to ensure operation. |

**Technical Considerations**

**Field Experience**
EGR is already in widespread use as an OEM strategy for heavy-duty diesel engines. EGR use on marine and locomotives are under demonstration.

**ECT Cost**

<u>On-Road</u>
Trucks= $12K including DPF, for on-highway derivative engines, more for larger engines. Installation cost around $6K.

## Clean and Alternative Fuels

### ULTRA LOW SULFUR DIESEL (ULSD)

### Fuel Background

Ultra low sulfur diesel fuel (ULSD) is a petroleum distillate product that undergoes hydro-desulfurization at the refining level to eliminate more than 99% sulfur content. Sulfur, a component of all petroleum based feedstocks and grades, serves the primary role of engine lubricant, though undesirably so because it creates corrosive combustion by products, releases sulfur oxides into the environment, and increases deposits on fuel injectors and combustion components[2].

October 2006 marked the widespread availability of ULSD in the United States. The movement was supported federally by an EPA final rulemaking that mandated that the fuel arrived at the retail and wholesale level for all on-highway applications. Sulfur levels in ULSD are set at 15 ppm allowing the facilitation of emission control technologies that require a lower sulfur fuel. This enables diesel engine manufacturers to meet more stringent diesel engine standards of 2007 which require a dramatic reduction in engine-outpollutants from heavy duty diesel vehicles. By contrast, some nonroad fuel grades contain sulfur in fuel levels of up to 3000 ppm. Even higher levels can be found in industrial boiler and marine applications. Future nonroad regulations will bring down sulfur in fuel standards to 2006 on-highway levels by 2014.

ULSD is an 'enabling technology' which allows the application of aggressive emission control technologies. Even without the use of ECTs, ULSD is used as a stand alone technology primarily for minimal PM reduction and secondary emissions of sulfate particles ($SO_4$).

**"At A Glance"**
**Ultra Low Sulfur Diesel (ULSD)**

| Benefits | Drawbacks |
|---|---|
| 1. PM reduction 5 to 15% as a stand alone technology.<br>2. Enables use of aggressive PM and NOx emission control technologies.<br>3. On road availability widespread in US.<br>4. Proven effective in maritime activities. | 1. No impact on other criteria pollutants (HC, CO, etc.).<br>2. Reduced lubricity.<br>3. May have availability issues internationally in some geographic locations. |

### Technical Considerations

**Field Experience**
ULSD has had widespread use for both onroad and nonroad applications on the West Coast, US and Canada.

[2] http://www.techtransfer.anl.gov/techtour/desulfur.html.

**Fuel Cost**
Cost surcharge of 5.0 to 15.0 cents per gallon.

**BIODIESEL FUEL (BXX)**

**Fuel Background**
Biodiesel fuel (BXX) operates as a cleaner burning fuel and a fuel additive, if mixed in concentration with petroleum diesel that is biologically derived from domestic, renewable sources such as fats and vegetable oils[3]. Biodiesel refers to the pure fuel ("neat") before blending with diesel fuel. Blends are denoted as "BXX", with "XX" representing the percentage of biodiesel contained in the blend; B20 is 20% biodiesel, 80% petroleum diesel. Pure biodiesel (B100) is biodegradable, non-toxic, and virtually free of sulfur and aromatics.

Biodiesel fuels are produced from different types of feedstocks that include soybeans, rapeseeds, canola oil, grease, tallow and lard. Most biodiesel production in the US is soybean-based due to the abundant supply of this feedstock in the heartland states.

Used as an alternative to conventional diesel fuel, biodiesel achieves emission reductions of PM, CO, HC and poly-aromatic hydrocarbons (PAH). The emission reductions vary with BXX%, where the lowest figure applying to B20 and the highest to B100. Generally, there is a modest, application specific NOx penalty of between 2 and 10 percent associated with the use of biodiesel. Increasing the level of biodiesel in the fuel blend increases NOx with a proportionally greater reduction in PM. Reduction in CO and HC improves linearly with the addition of biodiesel, according to the literature. This is indicative of more complete combustion, thought to be promoted by the increased presence of oxygen in the fuel.

From an air quality and emissions control technology perspective, fueling with biodiesel will reduce the solid or carbonaceous fraction of the PM which cannot be removed by an oxidation catalyst. Thus from a PM standpoint, the use of biodiesel in combination with a CCRT-SCR system (catalyzed, continuously regenerating trap and selective catalytic reduction) would serve to further remove the solid PM component from the exhaust, providing an opportunity to oxidize the soluble fraction stemming from engine lubricant and address NOx reductions[4].

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[3] http://www.biodiesel.org/resources/biodiesel_basics/.

[4] Schumacher, L.G. et al (1995). 6V-92TA Detroit Diesel Corporation Engine Emissions Test Using Soybean Oil/Diesel Fuel Blends - B10, B20, B30, B40.

**"At A Glance"**
**Biodiesel (BXX)**

| Benefits | Drawbacks |
|---|---|
| 1. PM, HC and CO emission reductions depending on the BXX ratio. (PM 15 to 70%, HC 10 to 40%, and CO 10 to 50%).<br>2. CO2 lifecycle emissions reductions potential of 70%.<br>3. Lower sulfur content.<br>4. Renewable fuel.<br>5. Biodegradable.<br>6. Better lubricity. | 1. Potential increase in NOx.<br>2. More corrosive.<br>3. Higher freezing temperature. Cold weather can cause operational issues.<br>4. Potential loss in engine power – about 2%.<br>5. Reduced fuel economy. |

**Biodiesel Schematic**

**Table 1: Biodiesel production process.**

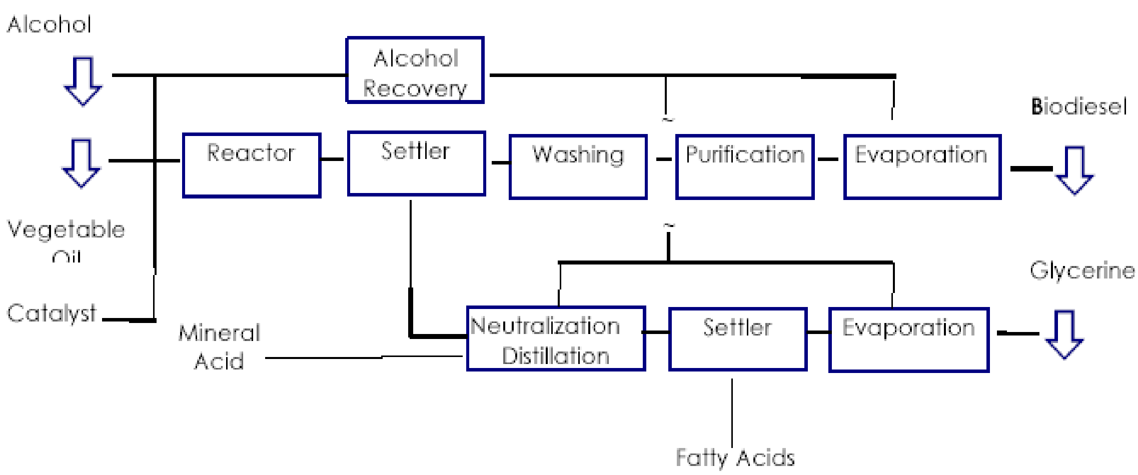


**Table 2: Biodiesel Emissions Reduction Potential (EPA Verified), National Biodiesel Board.**

| AVERAGE BIODIESEL EMISSIONS COMPARED TO CONVENTIONAL DIESEL, ACCORDING TO EPA | | |
|---|---|---|
| Emission Type | B100 | B20 |
| Regulated | | |
| Total Unburned Hydrocarbons | -67% | -20% |
| Carbon Monoxide | -48% | -12% |
| Particulate Matter | -47% | -12% |
| Nox | +10% | +2% |
| Non-Regulated | | |
| Sulfates | -100% | -20%* |
| PAH (Polycyclic Aromatic Hydrocarbons)** | -80% | -13% |
| nPAH (nitrated PAH's)** | -90% | -50%*** |
| Ozone potential of speciated HC | -50% | -10% |

* Estimated from B100 result
** Average reduction across all compounds measured
*** 2-nitroflourine results were within test method variability

**Technical Considerations**

**Field Experience**
Extensive onroad and offroad experience.

**Fuel Cost**
Projected cost surcharge of 25.0 to 40.0 cents per gallon.

**EMULSIFIED DIESEL FUEL (EDF)**

**Fuel Background**

Emulsified diesel fuel (EDF) is a petroleum distillate based fuel that undergoes emulsification, a process whereby one liquid is suspended within another, with a proprietary chemical additive agent to suspend water micro-droplets in the fuel, typically at the following ratio: 77% diesel, 20% water, and 3% emulsifying agent. Water content can range from 5 to 40%, depending on the production specification and end user application.

The practice of emulsifying fluids in diesel is not new, however the science of using additive chemistry and blending techniques to specifically address the air quality characteristics of diesel exhaust emissions is new and evolving, with a number of US based and international companies taking a lead role in its advancement. Key to this practice is the suspension of sub-micron sized water droplets in the fuel, a process accomplished by using additives that encapsulate and suspend the droplets during the blending process, thereby creating a secure, stabilized product ready for delivery, storage and combustion.

The principle effect of water in fuel is to lower the combustion temperature, i.e. reduce the peak flame temperature within the combustion chamber to modify the combustion process itself and mitigate the formation of NOx emissions. NOx formation in the diesel combustion engine is influenced by $N_2$, $O_2$, the temperature of combustion ($T_{combust}$), and the residency time ($t_{res}$). Water emulsions work by lowering the overall $T_{combust}$ to rate limit NOx formation and lower downstream engine out NOx emissions. Water also serves to alter fuel flow properties and injection characteristics, thus resulting in a PM (particulate matter) benefit. This benefit is realized due to:

1. Increased liquid column penetration during pre-mixed combustion, resulting in more entrainment and less PM formation; and
2. Larger flame light off length, resulting in a less rich combustion process and lower PM (especially at higher loads).

Actual emission reductions achievable using EDF are highly variable, depend on the engine, test cycle, emulsification process, water content, baseline diesel fuel properties, and peak torque vs. torque loss comparison (less work per composite duty cycle). There is conflicting data in the literature concerning PM mitigation/production; CO, HC, and toxic air contaminants have propensity to increase w/emulsion, some by factor of 2 or more though not in quantities above regulatory standards, due to inherently low emissions output.

From an operational perspective, significant losses in fuel economy have been experienced with EDF, on the order of 10-30%. This is due to the water in fuel %, on-road vs. off-road engine application, and age of the engine (mechanically vs. electronically controlled). In some engines, longer flame length may lead to excess PM due to EDF "splashing" on the combustion bowl during incomplete combustion. Higher PM is then expelled during the exhaust stroke.

The market for EDF in the United States is supported by counties in non-attainment that have an immediate need for an alternative to diesel that addresses both NOx and PM reductions simultaneously, by demonstration projects in those areas and others throughout the country, and by the EPA ETV program, which verified and approved EDF for use in diesel engines.

**"At A Glance"**
**Emulsified Diesel Fuel (EDF)**

| Benefits | Drawbacks |
|---|---|
| 1. Emission reduction benefits of both NOx and PM (NOx 10 to 20% and PM 15 to 60%).<br>2. No major engine modifications required.<br>3. No new fuel infrastructure needed.<br>4. No increase in other pollutants. | 1. Incremental cost differential.<br>2. Potential engine durability issues with older pre-1994 engines (corrosion).<br>3. Fuel stability – balanced mixture.<br>4. Reduction in engine power – potential 5 to 10 %.<br>5. Reduced fuel economy. |

**Technical Considerations**

**Fuel Penalty**
Emulsified diesel fuel may have a fuel penalty of 10 to 30% and peak torque loss of 6 to 7% peak torque loss. The engine will do less work per unit fuel consumption vs. No. 2 diesel over comparable duty cycle.

**Field Experience**
On-road and off-road application experience; Port of Houston, TX, Big Dig Project, Boston, MA; Texas Fuels Project – TX DOT, Houston and Dallas, TX; Marine application experience; MV Golden Gate, WTA (Water Transit Authority) San Francisco, CA.

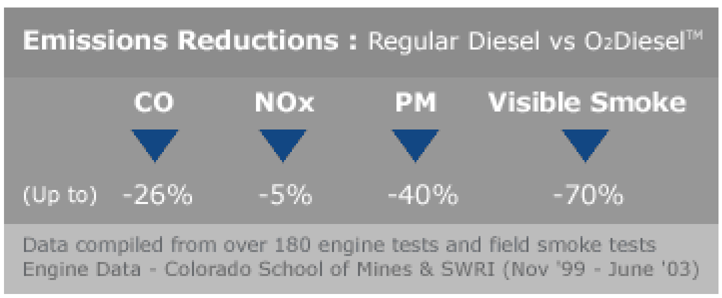
**Fuel Cost**
Projected cost surcharge of 25.0 to 40.0 cents per gallon

## OXYGENATED DIESEL FUEL (02D)

### Fuel Background

Oxygenated diesel fuel is a diesel fuel blend using the oxygenate ethanol and a stabilizing proprietary additive technology. Manufacturers of oxygenated diesel fuels claim a significant reduction in PM and visible smoke along with some NOx and CO reductions. The product can be used with all diesel fuels and can be blended effectively with any base diesel fuel. One manufacturer, O2Diesel Inc., provides a drop-in replacement fuel for "typical" No. 1 or 2 diesels, ULSD, etc. O2Diesel claims their oxygenated diesel results in cleaner combustion, decreased engine corrosion, reduced cylinder wear and extended life of the engine lubricant. O2Diesel's product has ARB (but not EPA) verification.

### Summary of Emission Reduction Performance (O2 Diesel Literature)




**"At A Glance"**
**Oxygenated Diesel Fuel (O2D)**

| Benefits | Drawbacks |
|---|---|
| 1. NOx reduction up to 6%. PM reduction potential of 46% when combined with a DOC. CO reduction of 25%.<br>2. Visible smoke reduction up to 70%.<br>3. Reduction of GHGs.<br>4. Provide cleaner combustion with decreased engine corrosion.<br>5. Improves overall performance.<br>6. Mixes with any type of diesel fuel. | 1. Low NOx reductions. |

**Technical Considerations**

**Field Experience**
O2 Diesel has completed the first testing of the oxygenated diesel fuel in a new Navistar DT -466 engine coupled with a DOC, and achieved nearly 50% PM reductions (Environment Canada). Department of Defense (DOD) is evaluating O2Diesel™ as a fuel for non-tactical military vehicles and other diesel powered equipment such as electric generators.

**Fuel Cost**
Price can range from zero net incremental cost, to 10 – 15 cents above "rack" No. 2 diesel fuel prices.