Measurement and Control of Accumulating Diesel Particulate Matter
The Causal Relationship Between Fuel Waste and DPM

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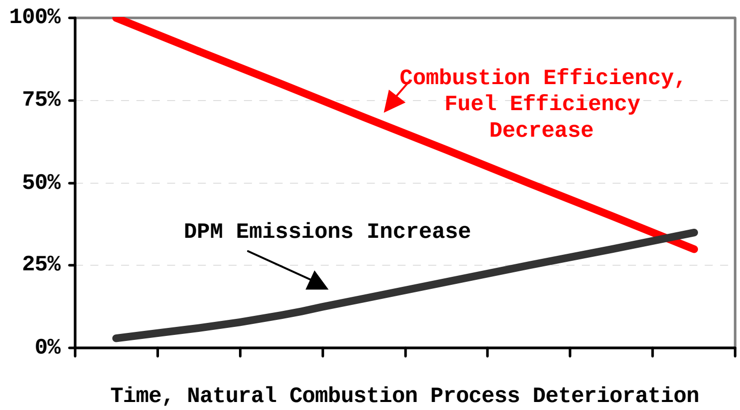
Executive Summary

As internal combustion engines age, the combustion process naturally deteriorates and degrades due to a variety of uncontrollable physical factors. With degradation comes a decrease in the engine's ability to efficiently convert 100% of the fuel it receives into energy.

Accompanying this natural phenomenon is increased Diesel Particulate Matter (DPM) and decreased fuel efficiency.



Unable to sense the level of combustion process degradation within the engine, operators regularly and unknowingly over-fuel the engine. Resulting in more DPM and lower fuel efficiency.

Considering the increasing regulations on DPM within mining operations, Mirenco designed a series of tests to demonstrate the accumulation of diesel emissions within an enclosed environment. The tests were structured to isolate the over-fueling variable by using technology designed to dramatically reduce engine over-fueling, asking the simple question, "Why not reduce/eliminate the excess fuel?" Consistently, Mirenco's technology demonstrated a 75% reduction in accumulation of particulate matter (both PM 10 and PM 2.5) within the enclosed environment.

Diesel Fuel & DPM Risks

According to the Charles River Associates' paper "Diesel Technology and the American Economy," diesel fuel powers 94% of all freight moving in trucks, trains, boats and barges; two-thirds of all farm machinery; more than 95% of all public transit buses; and all heavy construction machinery. Further, the annual gross output of the diesel industry manufacturing diesel equipment, fuel and related materials, exceeds $85 billion, greater than the combined gross value of all the computer hardware and office machines manufactured in America.

Diesel fuel is so prevalently used for a reason – efficiency. The report notes that while freight traffic increased 25% in the last decade, the cost of moving those goods declined 4% due to the progressive efficiency of diesel powered transportation. The report further purports replacing diesel with the "next best" fuel alternative would increase freight costs and lower economic growth and productivity, requiring 50% more trucks and at least another $35 billion annually in increased labor costs. Given the extensive use of diesel fuel in the mining industry, Mirenco believes the same economies would be applicable to equipment used there as well.

The economic and efficiency case for diesel is strong and well documented, however the health risks are also well-documented and far more publicized. The particulates in diesel emissions are very small, making them readily respirable. These particles contain hundreds of chemicals absorbed onto their surfaces, including many known or suspected mutagens and carcinogens.

Although diesel emissions have changed and improved dramatically over the last 30 years, the health hazard remains strong. Furthermore, depending on a number of factors including engine type, operating conditions, fuel blend, and lubricating oil, among others, the composition of diesel emissions varies considerably and changes over time. Even with the ongoing improvements in diesel fuel and engine technology, health risks resulting from diesel emissions will decrease very slowly given the prevalence of use and long life of heavy-duty diesel engines.

Diesel emissions can be measured in different ways, however measurement of Particulate Matter (PM) has remained a common, practical method throughout the rapid evolution of emissions monitoring and management. PM has been categorized and measured generally by particle diameter size, expressed in microns. General categorization includes PM 10, indicating all PM of diameter size 10 microns and smaller, and PM 2.5, a subset of PM 10, measuring PM 2.5 microns in diameter or smaller. PM 2.5 is considered more hazardous since the smaller size enables these particles to reach and imbed deep within the lungs and readily make way into the blood stream.

Economics of Diesel & DPM – A Critical Choice

The positive economics of diesel fuel are evident. Likewise, the negative health risks of DPM are evident. These two opposing dynamics present an economic issue facing the industry today. Which is more valuable – the economies we gain from diesel, or the health impact to human beings?

From a pragmatic perspective, we can assume that all of industry will not replace heavy-duty diesel vehicles overnight. Likewise, it is equally unlikely a cure-all magic pill will hit the market and eliminate the health risks. The situation leaves us with a choice of possible “solutions” which keep diesel fuel in use and minimize the health risks.

Regulatory Role – Measured Change Over Time

The governmental regulatory agencies in many, if not most countries, work towards this issue with two basic strategies. First, new engine emissions certification levels continue to grow in stringency. Second, existing ambient air quality and tailpipe emissions standards strengthen as well, thereby affecting in-service equipment and operators.

In the U.S., for example, the Mining Safety and Health Administration (MSHA) oversee, among other things, the air quality regulations for underground mining. Recognizing the health risks and economics associated with DPM, Alexis M. Herman, Secretary of Labor commented on the recent rules regarding DPM, "Underground mines are unique workplaces where workers may be exposed to high concentrations of diesel emissions.... These rules will not eliminate all of the health risks to miners working around diesel-powered equipment, but they will significantly reduce the level of risk."

Assortment of Solutions

In order to meet air quality regulations and provide increased health safety for workers, mining operations are presented with an assortment of solutions, including, among others, new vehicles, traps, filters, screens, scrubbers, and alternative fuels and fuel blends. However attractive any one particular solution may appear in regards to controlling DPM, mining operations must weigh the health benefits of the solution with the economics of implementation. Furthermore, each solution is accompanied by an onslaught of sales and marketing collateral purporting claims and promises, resulting in an uncomfortable decision-making environment for mining operations. Adding to the situation is the fact that mining operations are generally very mature, lower-margin, stable businesses typically unable to implement new technology on a whim. In short, their decisions need to be consistently effective and economically justifiable.

Roots of DPM – Insight Into An Answer

It has been said that in considering solutions to problems, fully understanding and articulating the problem is half of the solution. A simple articulation of the DPM issue might be: “The DPM air quality issue results from converting diesel fuel into energy.” On the surface, this articulation appears complete, however, on consideration of the following logic, it is not:

1. New and just-overhauled diesel vehicles are more fuel and emissions efficient than their older counterparts.

2. Therefore we recognize that, as engines age, the complex combustion process degrades, yielding lower fuel economy and higher emissions.

3. Simple deductive logic tells us that, as engines age, some portion of the fuel delivered to the engine is not converted into energy.

Simply derived from this chain of logic is a fact: "tailpipes don't lie." Not only are tailpipes the source of DPM, tailpipes reveal the level of combustion efficiency of the engine. As the combustion process deteriorates, the tailpipe provides insight toward an answer.

Combustion & The Driver

Although there appears to be little, if any, documented study on heavy-duty diesel vehicle drivers, anecdotal evidence supports the theory that they have at least one common operator technique – when they accelerate, they go to full, or near-full power very quickly. When this occurs, large plumes of smoke are often seen belching from the tailpipe – i.e., DPM. This phenomenon is readily visible wherever heavy-duty diesel vehicles operate.

Although readily visible, this phenomenon is not apparent on every heavy-duty diesel vehicle in use. Newer and recently overhauled vehicles are more efficient; therefore the majority of the fuel provided to the engine is effectively converted into energy. But not all vehicles are new, and as time progresses, the tailpipe tells their age.

Generally, vehicles producing visible smoke are simply unable to efficiently convert fuel into energy. The results are environmental and economic. An increasing amount of unburned or poorly burned fuel escapes from the tailpipe in the form of DPM, while this unburned/poorly burned fuel costs the same as the efficiently burned fuel.

The driver is the ultimate and final control point of the amount of fuel used by the vehicle. If the driver could sense the engine's level of combustion efficiency, then perhaps the driver could apply a more appropriate throttle position to optimize the fuel flow. If this were possible, the driver would then be obtaining the effective potential horsepower from the engine while optimizing fuel consumption and minimizing DPM emissions. Unfortunately, without the aid of technology, most drivers cannot perform this effectively or consistently.

Furthermore, degradation is a moving target. To challenge the driver even more, the perfect driver would be required to sense an ever decreasing combustion efficiency since continued operation results in an ever-decreasing combustion process efficiency level.

Preemptively Attacking the Problem

Assuming complete overhauls, rebuilds and new equipment purchases are generally cost-prohibitive to many operations, the majority of current solutions fall into two broad categories: fuel-modifiers and after treatments. Fuel modifiers include alternative fuels (e.g., bio-diesel) and various “atomizers” and “magnets,” many of which come with varying claims and questionable logic. After treatments include filters, screens, catalysts and scrubbers, most of which come with a relatively high cost per unit, fuel penalties, and an often un-quantified ongoing aftercare and maintenance program.

Mirenco’s patented solution, known as DriverMax®, is unique in its approach. Rather than working to change the combustion itself or clean up DPM after it has been produced, DriverMax® technology attacks the root of the DPM issue. By using advanced programmable computer technology to manage throttle position in real time, DriverMax® works in concert with the driver to deliver the right amount of fuel to the engine in consideration of the engine’s current state of combustion efficiency.

Mirenco’s approach eliminates the majority of DPM emissions by converting a driver’s “snap” accelerations into programmable “ramp” accelerations. With this approach, excess fuel is not delivered to the engine, and the mass of the DPM is simply not produced.

Developed in conjunction with the United States Department of Energy Kansas City Plant Operated By Honeywell (DOE), Mirenco’s technology carries the DOE seal and has received “Energy 100” honors from the DOE in recognition of being one of the top 100 technical innovations in which they have participated. As well, DriverMax® carries an exemption number from the California Air Resources Board.

How It Works

There are three basic steps in the implementation of Mirenco’s technology:

1. BASELINE: Read the tailpipe. Assess the level of emissions being produced, which yields a relative combustion efficiency of each vehicle.

2. INSTALL: Install and configure DriverMax® between the throttle control and the fuel delivery system. Re-read the tailpipe.

3. ADJUST: Continue to read the tailpipe, periodically adjusting and reprogramming DriverMax® to compensate for ongoing engine wear.

The initial baseline tailpipe testing employs emissions sampling equipment using SAE procedure J1667, quantifying the amount of DPM being produced by each vehicle and in aggregate. SAE J1667 is the “Snap Acceleration Smoke Test Procedure For Heavy-Duty Powered Vehicles,” issued in February 1996 by the Society of Automotive Engineers, employing an opacity measurement (as opposed to a method yielding a gravimetric quantification).

Installation on electronic engines can be performed by any competent diesel mechanic in about one-hour, and is about as complex as a CB radio installation. Mechanical engine installation is slightly more involved, employing a Mirenco-supplied robotic arm, effectively converting a mechanical engine into an electronic engine. Ongoing adjustment and reprogramming is accomplished using the SAE J1667 and Mirenco’s personal computer configuration software.

Tailpipe testing and reprogramming is recommended at least twice annually and requires less than five-minutes per vehicle.

Benefits & Application

The benefits of Mirenco's DriverMax® are straightforward:

1. Reduced DPM emissions.
2. Reduced fuel consumption.
3. Reduced maintenance.

The application of the technology is best-suited and most effective in environments employing heavy-duty diesel vehicles with a high frequency of start/stop acceleration patterns. Applicable industries include mining, transit authorities, waste hauling, school buses, etc.

Fuel savings are welcomed in all industries and with DriverMax® typically range from 3-10%, depending on the frequency of acceleration cycles and the general level of combustion deterioration with the vehicles.

Enclosed Environment Application

In recognition of the potential application of DriverMax® to the mining industry, Mirenco conducted an extensive series of tests designed to measure particulate matter (PM) accumulation within an enclosed environment.

A 1987 Caterpillar 988B Front End Loader (19,271 hours), currently operating in a production mine, was utilized for the test. Prior to testing, an SAE J1667 procedure was employed to provide a standard measure of the tailpipe opacity of the vehicle in both unmodified and DriverMax® installed conditions (www.sae.org/technicalcommittees/ j1667.htm).

For the accumulation testing, the vehicle's exhaust was pumped into a 380 cubic meter enclosed space where PM emissions monitoring equipment was placed to record the accumulation in micrograms per cubic meter. An MIE DR-2000 DataRam was utilized to measure and record the PM accumulation (both PM 10 and PM 2.5). Circulating fans were set up within the enclosed space so as to more evenly distribute the accumulating emissions.

Prior to conducting the tests, observations were made in a production mine to determine a typical acceleration frequency. Through observation and extrapolation it was determined that, on average, there were 960 acceleration cycles in an eight-hour shift per machine (approximately two per minute).

Forty-four acceleration/deceleration cycles over a ten-minute period were used for all tests. Acceleration/ deceleration was performed electronically to eliminate potential human error and inconsistent throttle management.

Enclosed Testing Results

Summary results from the testing are outlined below:

Test Description	Baseline Unmodified	With DriverMax®	Absolute Difference	Percentage Difference
Tailpipe SAE J1667 (1)	73.80%	18.50%	55.30	74.9%
PM 10 (2)	46,105.50	11,167.10	34,938.40	75.8%
PM 2.5 (2)	43,644.60	9,736.80	33,907.80	77.7%

NOTES:
(1) Presented in standard terms of percent opacity, ranging from 0-100%.
(2) Presented in micrograms per cubic meter.

Testing results yielded three notable points regarding:

1. The relationship between tailpipe opacity and accumulated PM.

2. The significant impact of DriverMax® in reducing overall PM accumulation.

3. The relative levels of PM 10 and PM 2.5 in diesel emissions.

Each of these findings is discussed below.

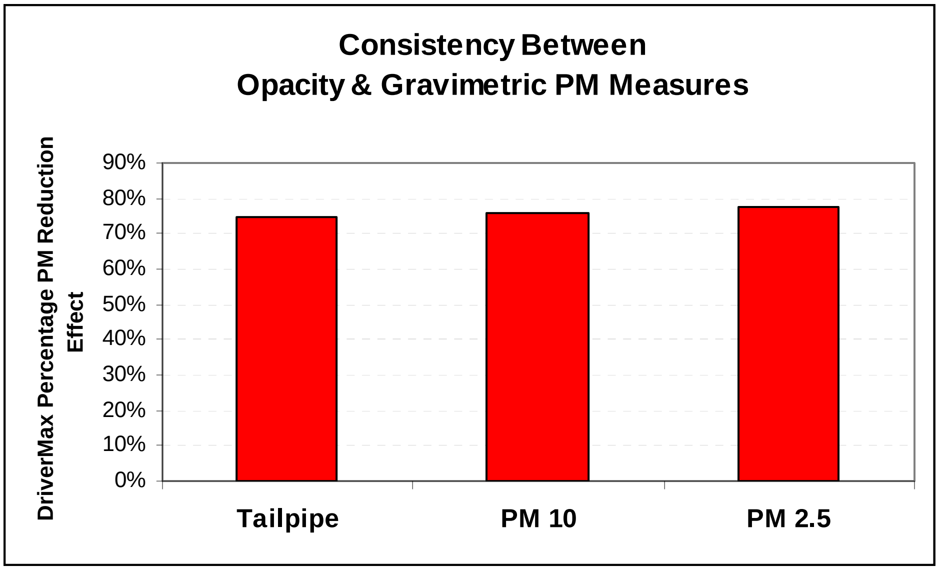
Tailpipe Opacity & Accumulated PM

Tailpipe opacity as measured via SAE J1667 was 73.8% in the unmodified baseline condition. Following installation and configuration of DriverMax®, tailpipe opacity measured 18.5%, barely visible to the human eye (tailpipe emissions become visible to the human eye at approximately a level of 15%). DriverMax® reduced the tailpipe emissions by 74.9%.

Accumulated PM in the unmodified baseline condition was 46,105.5 and 43,644.6 micrograms per cubic meter for PM 10 and PM 2.5, respectively. After DriverMax®, the accumulated PM was reduced to 11,167.1 and 9,736.8 micrograms per cubic meter for PM 10 and PM 2.5, respectively. In percentage terms, the reductions were 75.8% and 77.7% for PM 10 and PM 2.5, respectively.

The two metrics differ (opacity and a micrograms per cubic meter), but the results indicate a consistency in DriverMax®' effect (tailpipe reduction of 74.9%, and PM reductions of 75.8% and 77.7% for PM 10 and PM 2.5, respectively).

Based on these data and the intuitive nature of the emissions production and testing employed, the relationship between tailpipe opacity and accumulated PM measures is clear. Notwithstanding numerous variables with potential effect, SAE J1667 tailpipe opacity measurements provide an accurate relative measure of accumulated PM when employing technology to reduce PM.



Overall PM Accumulation

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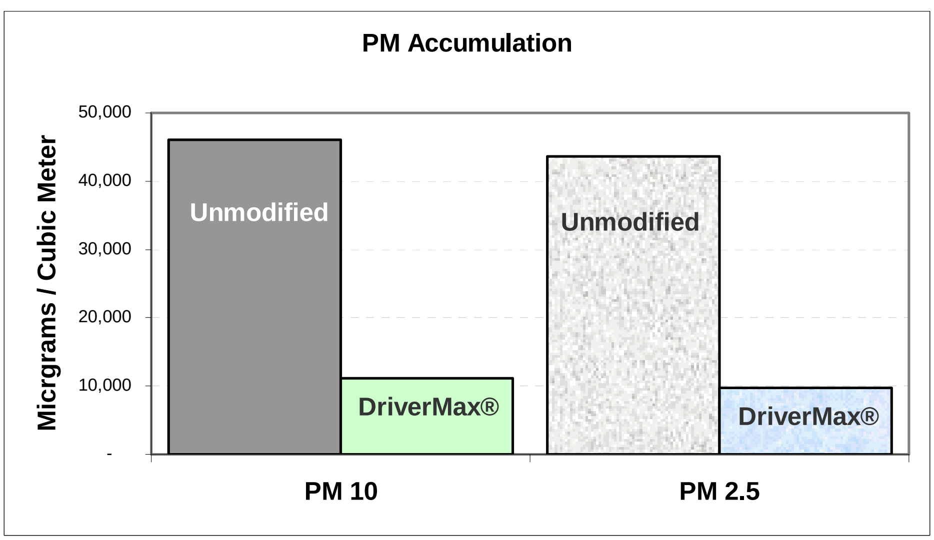
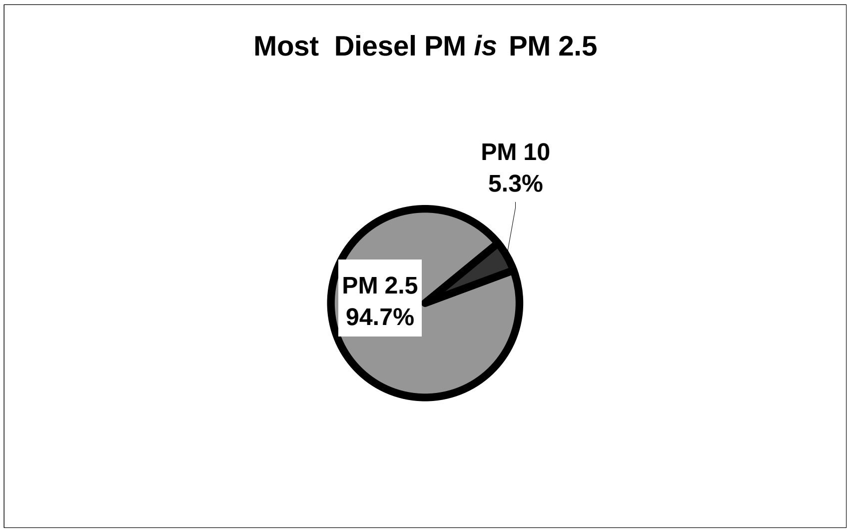


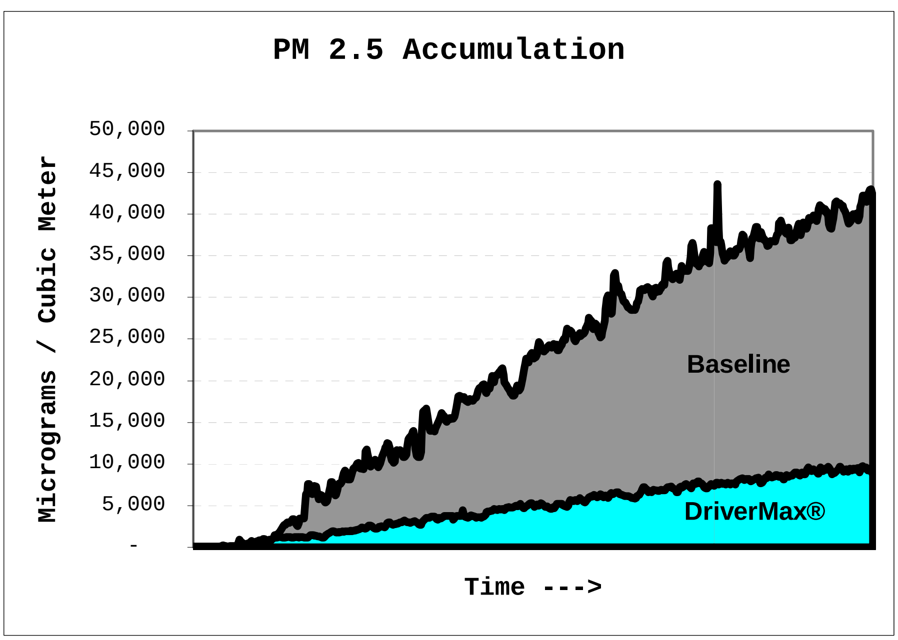
PM 2.5 and PM 10

The current understanding of PM health risks target PM 2.5 as a potentially far more hazardous element than its PM 10 counterpart. This understanding is based on the ability of a smaller sized particle to reach and imbed deep within the lungs and readily make way into the blood stream.

It is generally known the majority of diesel emissions are comprised of PM 2.5 or smaller. Testing indicated 94.7% of the PM was comprised of PM 2.5 or smaller.



The relative accumulation rates are more dramatically presented in graphical form as shown below.



Mining Equipment Sampling

Subsequent to the enclosed testing, Mirenco sampled a variety of different mines and pieces of equipment in order to obtain some representation of the combustion efficiency and emissions production now occurring in operating mines. The findings are outlined below:

					Baseline		With DriverMax®	
Make/ Model	**Year**	**Engine**	**Engine Size**	**Gallons/Year**	**Opacity**	**Pounds per Year**	**Opacity**	**Pounds Per Year**
Komatsu WA600	1999	Cum,425	19	30,000	55.9	1,993	15.88	566
Cat 769C	1987	Cat,450	19.5	18,600	55.1	1,250	30	681
Komatsu HO325	2000	Cum,375	19	18,600	56.6	1,251	20	442
Komatsu WA 600	2000	Cum,490	19	30,000	69.3	2,471	16.4	585
Cannon Face Drill	1998	Cat,190	7	10,000	19.6	86		
Cat 769D	1998	Cat,450	19.5	18,600	23.5	533		
Cat 769D	1998	Cat,450	19.5	18,600	35.3	801		
Cat 966C	1972	Cat,170	10.4	30,000	30.3	591		
Cat 988F	1997	Cat,375	19.5	30,000	28.8	1,054		
Cat 769D	2001	Cat,450	19.5	18,600	37.9	860		
Cat 988F	2001	Cat,430	19.5	30,000	31.4	1,149		
Komatsu N14	2000	Cum,335	14	30,000	32.9	864		
Komatsu WA500-1885C	1993	Cum,325	14	30,000	45.1	1,185		

Notes:

1. Only those vehicles with data under the "With DriverMax®" column had DriverMax® installed. All others were baseline readings taken on behalf of different mining operations.
2. Historical driving conditions vary and affect opacity readings taken at any given time.
3. "Pounds Per Year" provides the projected number of pounds of PM the vehicle will produce at its current pace and combustion efficiency level.
4. "Pounds Per Year" calculations are based on Mirenco's proprietary algorithms, derived to measure emissions and quantify emissions reductions progress over time. Required information includes opacity, fuel gallons consumed per year, and engine size in liters.

Causal Relationship & Solutions

There appears to be a strong causal relationship between combustion efficiency, acceleration and tailpipe DPM emissions. Decreasing the tailpipe emissions created during acceleration directly and ultimately leads to dramatically reduced levels of DPM within any environment, and in particular within enclosed environments.

Also noteworthy in regards to Mirenco's technology is the unique angle of attack to the DPM issue in contrast to that employed by various after treatments. PM is created by the engine's combustion process. DriverMax® eliminates the majority of the PM issue *before* it is created (i.e., *before* the combustion process has created DPM). After treatments work to clean up the DPM from the exhaust flow *after* it has been created.

It is also of value to note the applicability and complimentary nature of Mirenco's solution. Implementation of DriverMax® does not preclude the adoption of fuel modifying or after treatment solutions. Although no specific testing has been performed, it may be reasonably concluded that DriverMax® would significantly reduce the ongoing maintenance and service required with after treatment solutions (i.e., filter or trap replacement and/or recharging cycles would be logically extended with significantly less DPM emissions being generated and in turn handled by these type of devices). Furthermore, not only does DriverMax® not impose a fuel penalty like many after treatment alternatives, DriverMax® alone offers a fuel increase, and if used in conjunction with many after treatments, DriverMax® offers an offset to the fuel mileage penalty imposed by many of these solutions.

Summary

DPM represents a potential health risk issue for everyone who breathes. The risk is dramatically increased for those working in enclosed environments. DPM represents a hazardous byproduct of an otherwise very efficient and prevalent fuel source for our economy. Both of these facts will be within our economic choices for years to come given the prevalence of diesel equipment and its long-life cycle within numerous industries.

Until the ultimate environmentally friendly, horsepower effective, and economically justifiable solution becomes available, a variety of options are available to industry. Mirenco's technology operates on a simplistic and logical principal, lending itself to the complimentary realization of both environmental and economic objectives. Furthermore, in comparison to other solutions such as traps or filters, Mirenco's solution offers an assured method of dramatically reducing the more dangerous PM 2.5 emissions which may or may not be large enough to be effectively and consistently filtered or trapped.

Emissions reductions of 50-75% are typical with DriverMax®, with the welcomed byproduct of fuel savings, offering economic payback typically well within one year of operation. Average fuel savings are in the 5% range, depending on start/stop frequency, acceleration/deceleration cycles, engine age, operating conditions, etc.

Combustion process degradation and poor driver technique combine to effectively produce an increasing "fuel leak" with the hazardous by-product of emissions comprised mainly of PM 2.5. Until DriverMax® technology was produced and made affordable and readily available, there has been no practical and economic solution option to this "fuel leak."

In conclusion and as summary, DriverMax® testing has demonstrated that 50-75% of diesel emissions may be caused by only 5% of the fuel consumed by an engine. Eliminating (i.e., saving) this 5% wasted fuel can eliminate 50-75% of the emissions.

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