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TECHNICAL
REPORT

An Approach to Assessing the Technical Feasibility and Market Potential of a New Automotive Device

RAND Zero Emission Fuel Saver Study Team

Prepared for Save the World Air, Inc.

RAND
Environment, Energy, and Economic Development

A RAND INFRASTRUCTURE, SAFETY, AND ENVIRONMENT PROGRAM

The research described in this report was conducted under the auspices of the Environment, Energy, and Economic Development Program (EEED) within RAND Infrastructure, Safety, and Environment (ISE).

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Preface

This report details the research and assistance that the RAND Corporation provided between 2002 and 2006 to Save the World Air (STWA). STWA has several patented products designed to improve fuel economy and reduce emissions from internal combustion vehicle engines. STWA approached RAND to assist the company in developing a plan for assessing the technical basis for one of its products, known as the Zero Emission Fuel Saver (ZEFS™), and to assist the company in understanding how to evaluate potential market opportunities for the product. STWA sought RAND's assistance because of RAND's reputation for independence and objectivity, as well as its emphasis on empirical analysis. STWA also looked to RAND for advice on how the technology might be applied, assuming its technical viability.

RAND made recommendations to STWA on structuring laboratory assessments of its products, including independent testing and verification of the theoretical concepts and the protocols for such testing. RAND also assisted STWA in assessing national markets for devices intended to reduce emissions in the United States and around the world. This report may be of interest to individuals and organizations in the private and public sectors who seek an understanding of the challenges in bringing this kind of device to market.

The RAND Environment, Energy, and Economic Development Program

This research was conducted under the auspices of the Environment, Energy, and Economic Development Program (EEED) within RAND Infrastructure, Safety, and Environment (ISE). The mission of ISE is to improve the development, operation, use, and protection of society's essential physical assets and natural resources and to enhance the related social assets of safety and security of individuals in transit and in their workplaces and communities. The EEED research portfolio addresses environmental quality and regulation, energy resources and systems, water resources and systems, climate, natural hazards and disasters, and economic development—both domestically and internationally. EEED research is conducted for government, foundations, and the private sector.

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Summary

This report describes research and assistance that the RAND Corporation provided to Save the World Air (STWA), a Nevada company with headquarters in North Hollywood, California. STWA has developed a number of magnet-based devices, including its Zero Emission Fuel Saver (ZEFS™), that it claims can improve vehicle fuel economy and reduce emissions. These devices are designed to be fitted as original equipment onto internal combustion engines or to be retrofitted onto existing engines. STWA approached the RAND Corporation for assistance in developing a plan for assessing the technical basis required for successful commercialization of ZEFS. STWA also sought RAND's advice in examining potential market opportunities for ZEFS. This report summarizes RAND's analysis of these two issues.

Understanding the Scientific Basis of the Device

The ZEFS device contains permanent, rare-earth magnets that are known to produce strong magnetic fields. According to STWA, when gasoline or diesel fuel passes through such magnetic fields, both the fuel's viscosity and its surface tension are lowered. This reduction in viscosity and surface tension is thought to cause improved atomization, and, thereby, improved combustion.

RAND researchers conducted a review of the published literature to determine what credible experimental evidence may be available regarding a magnetically induced reduction in the viscosity of automotive fuels that will persist as the fuel undergoes atomization. (Viscosity is a property of a fluid and a measure of its resistance to flow.) RAND found that the existing peer-reviewed literature does not contain credible evidence that the application of magnetic fields to either gasoline or diesel fuel oil will reduce the viscosity of these automotive fuels.

In light of the absence of supporting evidence in the scientific literature, RAND suggested that STWA consider funding research directed at measuring the viscosity of gasoline and diesel fuel after exposure to a strong magnetic field. At STWA's request, RAND managed a competitive proposal process that resulted in a research grant from STWA to Professor Rongjia Tao of the department of physics at Temple University.

Recent experimental work published by Tao and Zu (2006) shows that a pulsed magnetic field can reduce the viscosity of some crude oils. Tao and Xu also examined the effect of pulsed magnetic fields on gasoline and diesel fuel. Tao has reported to RAND that he has detected a

small effect, but this work on automotive fuels has not been fully documented nor yet submitted to and published in a peer-reviewed technical journal.

Further research could strengthen the knowledge base regarding the relationship between magnetic field treatment of fuels and engine performance. First, the results of Tao's research on gasoline and diesel fuel need to be fully documented, peer-reviewed, and published. Second, research is needed on the impact of magnetic field treatment on the surface tension of fuels, since surface tension also plays an important role in atomization. Third, important insights may be obtained by measuring the effect of magnetic treatment on the liquid droplet distribution leaving fuel injectors and carburetors. To be useful, this research needs to examine fuel systems operating at temperatures and pressures characteristic of those in use in actual engines. Further work is also needed to establish and verify the theoretical basis, if any, underlying the effect of magnetic fields on fuel viscosity, surface tension, and atomization.

Approaches to Testing and Verification

RAND developed a test protocol to measure the ZEFS device's effect on tailpipe emissions and fuel economy. RAND also analyzed a series of tests conducted on automobiles and motorcycles. The protocol was intended to support preliminary engineering tests and product development, as opposed to certification tests. RAND oversaw testing of the device designed for automobiles at an independent lab in California. STWA provided RAND with results from test facilities in Hong Kong, Thailand, and China.

An independent laboratory in California tested two vehicles and fitted devices, all supplied by STWA. The vehicles tested included a 1971 Volkswagen Beetle (VW) and a 1984 Ford Mustang (Ford). Results showed no statistically significant effects of the device on most pollutant emissions or fuel economy for the VW tested at this lab. Results showed no statistically significant effect of the device on the ozone precursors total hydrocarbons (THCs) and nitrogen oxides (NO_X) or on fuel economy for the Ford tested at this lab. However, the lab found statistically significant effects on carbon monoxide (CO) and carbon dioxide (CO_2) emissions in the Ford tests, with CO decreasing and CO_2 increasing. These findings led STWA to reassess and redesign the device for automobile applications.

STWA has also developed a magnet-based device for motorcycle engines and arranged for laboratories in Hong Kong, Thailand, and China to test the device. To test motorcycles in the various Asian labs, RAND recommended that testing should follow at least the reduced set of requirements, as developed by RAND, for conducting "engineering tests," and that test procedures relevant to the countries in which the motorcycles were being tested also be applied.

STWA provided RAND with the results of tests conducted on motorcycles in laboratories in Hong Kong, Thailand, and China. Among all test results provided, one set of results from an independent laboratory in Thailand was clearly consistent with RAND's basic protocol for testing. Based on the information provided, RAND could not ascertain the extent to which the data from other labs were consistent with all the criteria in RAND's basic protocol.

The results from the Thai laboratory's testing of a single motorcycle show a statistically significant reduction in CO and CO_2 emissions and fuel consumption (FC) when the device was installed. However, this same conclusion does not hold for the ozone precursors NO_X and hydrocarbons (HCs). In particular, the analysis shows a statistically significant increase in NO_X emissions in these tests when the device was installed. After RAND completed its work on this project, STWA informed RAND of additional tests conducted in California and completed in February 2007 on two on-road and one off-road motorcycles. These additional results may shed further light on the device's performance potential.

Market Potential

Should further laboratory analysis and in-use testing provide clearer and more positive outcomes, the market potential for the device will depend significantly on the advances realized from other technologies and regulatory policies for emissions reductions and on the cost-effectiveness of the device relative to other approaches. Markets within the United States may be limited, except perhaps in areas with large emissions of criteria pollutants from old off-road sources.[1] Potential international applications may be larger given the baseline for engine performance and environmental standards in developing countries. Assuming statistically valid and positive test results of the device, a more in-depth assessment of the international prospects of the retrofit device would need to be done.

If STWA pursues development of a retrofit device based on the magnetic treatment of automotive fuels, it should give highest priority to obtaining statistically valid data on performance in actual vehicles.

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[1] EPA uses measures of six criteria pollutants to indicate air quality. Each criteria pollutant has an EPA-established maximum concentration, above which adverse effects on human health are more likely to occur (EPA, 2007).

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Abbreviations

BAR	Bureau of Automotive Repair
CARB	California Air Resources Board
CO	carbon monoxide
CO_2	carbon dioxide
cP	centipoise
EEED	Environment, Energy, and Economic Development Program
ER	electrorheological
FC	fuel consumption
FE	fuel efficiency
FTP	federal test procedure
g/km	grams per kilometer
g/mi	grams per mile
H_A	alternative hypothesis
HC	hydrocarbon
HFET	highway fuel economy test
HHD	heavy heavy-duty trucks, which weigh 33,001–60,000 lbs
H_O	null hypothesis
IEC	International Electrotechnical Commission
ISE	RAND Infrastructure, Safety, and Environment
ISO	International Organization for Standardization
L/100km	liters of fuel consumed per 100km traveled
LDA	light-duty automobile

mpg	miles per gallon
MSERC	mobile source emission reduction credit
MTBE	methyl tertiary butyl ether
NO_X	nitrogen oxide
O_3	ozone
PM	particulate matter
PMx	particulate matter of diameter less than x micrometers
SB	school bus
SCAB	South Coast Air Basin
SCAQMD	South Coast Air Quality Management District
SEM	scanning electronic microscopy
STWA	Save the World Air
T1	light-duty truck weighing less than 3,750 lbs
T2	light-duty truck weighing 3,751–5,750 lbs
T3	medium-duty truck weighing 5,751–8,500 lbs
T4	light heavy-duty truck weighing 8,501–10,000 lbs
T5	light heavy-duty truck weighing 10,001–14,000 lbs
T6	medium heavy-duty truck weighing 14,001–33,000 lbs
THC	total hydrocarbon
TIS	Thai Industrial Standard
UB	urban bus
VOC	volatile organic compound
WAT	wax appearance temperature
ZEFS™	Zero Emission Fuel Saver

CHAPTER ONE

Introduction

Background

This report describes research and assistance that the RAND Corporation provided to Save the World Air (STWA), a Nevada company with headquarters in North Hollywood, California. STWA describes itself as "focused on the design, development and commercialization of technologies targeted at reducing harmful emissions from internal combustion engines" (STWA, undated). Toward this end, STWA has developed a number of devices, including its Zero Emission Fuel Saver (ZEFS™). These devices contain permanent, rare-earth magnets that are known to produce strong magnetic fields. According to STWA, when gasoline or diesel fuel passes through such magnetic fields, both the fuel's viscosity and its surface tension are lowered. This reduction in viscosity and surface tension is thought to cause improved atomization and, thereby, improved combustion. STWA has been granted patents for ZEFS in more than 20 countries, with patents pending in 40 countries. STWA has designed these magnet-based devices to be fitted as original equipment onto internal combustion engines or to be retrofitted onto existing engines. STWA claims that these devices improve fuel economy and reduce pollution, including emissions of hydrocarbons (HCs), carbon monoxide (CO), and nitrogen oxides (NO_X) from internal combustion engines. ZEFS is covered in the United States by patent number 6901917.

STWA approached the RAND Corporation for assistance in two related but distinct areas. One involved support to STWA in developing a plan for assessing the technical basis required for successful commercialization of ZEFS. The other area in which STWA sought RAND's advice concerned the issues that STWA should address in investigating potential market opportunities for ZEFS.

Organization of This Report

Chapter Two reviews literature relevant to an assessment of the technical basis for the product concept to work. Chapter Three summarizes some information on protocols for conducting testing of the installed product and reports some initial testing results. Chapter Four highlights the information that needs to be used in evaluating the product's market potential, domestically and internationally. The final chapter presents some conclusions of the effort. Appendix A contains a more detailed listing of the literature review conducted as part of the assessment of the technical basis for the product. Appendix B contains more detailed information on the testing of the installed device.

CHAPTER TWO

Understanding the Scientific Basis of the ZEFS

In this chapter, we discuss the key technical claim underlying the ZEFS device: that exposure of gasoline or diesel fuel to a strong magnetic field will result in a decrease in viscosity that will persist as the fuel undergoes atomization. Viscosity is a property of a fluid and a measure of its resistance to flow. RAND researchers reviewed the published literature to determine what credible experimental evidence may be available regarding a magnetically induced reduction in the viscosity of automotive fuels. RAND also assisted STWA in its evaluation of the scientific basis for the device by selecting a university-based researcher who, using funding from STWA, conducted theoretical and experimental research directed at elucidating this issue.

Literature Review

The fact that magnetic fields can increase the viscosity of certain fluids is well established in the literature (Ginder, 1998). Commercial applications exist that are based on the large increase in viscosity that results when a magnetorheological fluid is exposed to a magnetic field. These applications include engine mounts, shock absorbers, seat dampers, and exercise equipment, among others.

There are also recent reports of magnetic fields causing viscosity changes in crude oil. Rocha et al. (2000) described experiments showing that magnetic fields appear to reduce the viscosity of crude oils and mixtures of long-chained paraffins. Chow et al. (2000) also reported decreases, as well as increases, in the viscosity of crude oil when exposed to magnetic fields.

In reviewing the published literature, the RAND research team did not find scientifically credible substantiation that exposure of automotive fuels, such as gasoline or diesel fuel, to magnetic fields would cause the viscosity or the surface tension of these fuels to decrease. The literature review did reveal that a number of firms have attempted to market magnet-based devices that they claimed would improve fuel economy or reduce emissions. RAND could not identify a single instance in which either theory or testing substantiated such claims. For example, unsubstantiated claims were the basis of a 2001 Federal Trade Commission consent order that ceased manufacture, distribution, and promotion of any fuel-line magnet or any purported fuel-saving or emission-reducing product for use in conjunction with a motor vehicle (FTC, 2001).

New Research

In light of the absence of supporting evidence in the scientific literature, RAND suggested that STWA consider funding research directed at measuring the viscosity of gasoline and diesel fuel after exposure to a strong magnetic field. At STWA's request, RAND managed a competitive proposal process that resulted in a research grant from STWA to Professor Rongjia Tao of the department of physics at Temple University.

Tao and his research collaborators at Temple University exposed gasoline, diesel fuel oil, and crude oil to pulsed magnetic fields and found that a pulsed magnetic field results in a reduction in the viscosity of the exposed fluids. They have also proposed a physical mechanism to explain this effect. Their work on crude oil was published in 2005 and 2006 (see Tao and Xu, 2005, 2006). The experimental results of their work on gasoline and diesel have been reported to RAND but have not yet been published.

Investigations of Crude Oil

This section presents a summary and discussion of Tao and Xu's published theoretical and experimental work. Further elaboration of their theoretical and experimental work can be found in Tao and Xu (2006).

The theoretical explanation that Tao put forward is based on the fact that gasoline, diesel fuel oil, and crude oil are mixtures of many different molecules and the assumption that the larger molecules in these mixtures may be viewed as particles. According to Tao, applying a magnetic field to these mixtures induces magnetic dipole moments in the large particles. For sufficiently high magnetic fields, the resulting attractive forces cause the large particles to aggregate so that the liquid mixture contains far fewer but much larger particles after being exposed to a magnetic field. Tao's theoretical approach also predicts that, once the magnetic field is turned off, the aggregates should remain together for several hours, under the assumption that separation is driven primarily by Brownian motion.[1]

If this aggregation occurs, it is likely to cause a reduction in the suspension's viscosity, as experiments have shown with suspensions of particles of various sizes in liquids in the absence of applied magnetic fields.

To test this theory, Tao applied a magnetic field to a dilute magnetorheological fluid consisting of iron nanoparticles of 35 to 40 nanometers in diameter dispersed in silicon oil and measured a viscosity decrease of 43 percent, from 880 centipoises (cP) to 496 cP, after exposing the liquid to a 0.15 Tesla magnetic field for five minutes. After an hour without any field applied, the viscosity had increased to about 650 cP and, after four hours, to about 780 cP. After 12 hours, the suspension's viscosity returned to its original value. Using the same fluid but with a lower fraction of iron nanoparticles, Tao also measured the average size of the aggregated clusters of iron particles. For example, after a 1-second pulse of a 0.38 Tesla magnetic field, the 30–40 nanometer particles aggregated into clusters with an average size of 9.9 micrometers, which is about a 300-fold increase in diameter.

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[1] Brownian motion is "a random movement of microscopic particles suspended in liquids or gases resulting from the impact of molecules of the surrounding medium" (Merriam-Webster, 2002).

Tao also subjected two samples of crude oil to magnetic fields and measured viscosity before and after exposure. One crude oil sample was a light crude oil with a high paraffin content. Viscosity measurements were conducted at 10 degrees centigrade, which is below the sample's wax appearing temperature (WAT), which was estimated to be 17 degrees centigrade. After subjecting the sample to a magnetic field of 1.33 Tesla for 50 seconds, the viscosity of this light crude oil sample decreased from 41 to 33 cP. Afterward, the viscosity slowly increased; within 20 minutes after exposure, the viscosity reached 35 cP and, within one hour, 36 cP. The sample returned to its original rheological state within eight hours.

The second crude oil sample was a heavy crude oil that Tao described as an "asphalt-base crude oil." For this heavy crude oil sample, Tao found that a magnetic field pulse reduced the apparent viscosity but that the effect was much weaker than for the high-paraffin–content crude oil. No measurement data were reported on the magnitude of the viscosity reduction when a magnetic field was applied to this second sample.

This research on crude oils is pioneering work, and as such, a number of important issues remain unresolved. In particular, the theoretical explanation is based on a semiempirical approach, as opposed to an approach based on first principles. That said, establishing a rigorous theoretical explanation may be impossible, since the focus of the investigation is crude oil, which is an extremely complex mixture consisting of thousands of different chemical constituents, including non-HC impurities. For crude oil, very large molecules, such as asphaltenes, are present. Moreover, many of these high-molecular-weight species are not soluble in light oils and are present in crude oil in the form of insoluble particulates. Consequently, one of Tao's key assumptions, namely that (at least some of) the large molecules in crude oil can be considered as suspended particles in a low-viscosity liquid, with the low-viscosity liquid consisting of molecules normally found in gasoline and diesel fuel oil, appears reasonable. Tao does not address the issue of why these large molecules might interact with a magnetic field in a different manner than do the smaller molecules. Tao assumes that the magnetic permeability[2] of the large molecules differs from that of the smaller molecules that make up the bulk of the fluid. HC molecules are neither polar nor ionic and do not contain free charges. Therefore, their interaction with a magnetic field is extremely weak. Since the magnetic permeability of any HC, be it a large or small molecule, is extremely small, the phenomenon that Tao observed experimentally may be due the presence of non-HC impurities that are common in crude oil.

Investigations of Gasoline and Diesel Fuel Oil

Tao and his research collaborators have also investigated the effects of a pulsed magnetic field on samples of gasoline and diesel fuel oil. This work was reported to RAND in March 2004 but has not yet been independently peer reviewed and published. Since the gasoline and diesel investigations have not yet been subjected to independent peer review, Tao's results summarized here should be considered tentative until they are published in a scientific journal with rigorous peer-review processes.

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[2] Magnetic permeability is a measure of the extent to which an applied magnetic field causes a substance to become magnetized. Substances that are easily magnetized, such as iron, are characterized by a high magnetic permeability.

A sample of pure gasoline and a sample of pure diesel were obtained from Sunoco's Philadelphia refinery in December 2003. By *pure*, we understand that the samples were obtained before the refinery blended in additives, such as oxygenates, antioxidants, detergents, and dyes. Testing of the effect of exposure to a magnetic field was conducted on a sample of the pure diesel fuel oil, a sample of the pure gasoline blended with 190-proof ethanol (20 percent by volume), and a sample of the pure gasoline blended with methyl tertiary butyl ether (MTBE) (10 percent by volume).

The viscosity of the gasoline-ethanol blend prior to exposure to a magnetic field was measured at 0.95 cP at 10 degrees centigrade. After exposure to a 1.3-Tesla magnetic field for five seconds, the viscosity dropped to 0.81 cP but, within a few minutes, climbed to about 0.87 cP. After three hours, the apparent viscosity remained at between 7 and 8 percent below its original value.

The viscosity of the gasoline-MTBE blend prior to exposure to a magnetic field was measured at 0.84 cP at 10 degrees centigrade. After exposure to a 1.3-Tesla magnetic field for one second, the viscosity dropped to 0.77 cP. Over more than two hours, the apparent viscosity remained at about 7 percent below its original value.

For the diesel fuel sample, the viscosity was measured at 5.8 cP at 10 degrees centigrade. After application of a magnetic field of 1.1 Tesla for eight seconds, the viscosity dropped to 5.64 cP but, within minutes, rose to about 5.71 cP. Over several hours, the apparent viscosity remained at about 2 percent below its original value.

In work performed since March 2004, testing has continued with different field strengths and pulse durations. This more recent work confirms reductions in the viscosity of the gasoline blends by up to 10 percent and reductions in the viscosity of the pure diesel fuel by up to 4 percent. With longer pulse durations, the effect can be seen with magnetic fields as low as 0.3 Tesla (Tao, 2007.)

The experimental work conducted at Temple University on gasoline and diesel fuel oil raises the possibility that a brief exposure to a high magnetic field may cause a decrease in the viscosity of automotive fuels. However, all of the experiments have been performed on a single sample of gasoline and a single sample of diesel. Additional samples need to be acquired and tested. Testing additional samples may also resolve issues regarding whether fuel aging is causing the formation of resins and waxes that may affect the viscosity measurements. In addition, the viscosities of gasoline and diesel fuel oil are very sensitive to temperature. Other factors may also cause systematic errors. Finally, there is as yet no confirmation of Tao's proposed underlying mechanism, namely that the magnetic field is causing the larger molecules in gasoline or diesel fuel oil to aggregate and, if so, the cause of that aggregation. As Tao (2007) suggested, if this aggregation is occurring, it should be measurable by a variety of experimental techniques, such as neutron scattering. The range of molecule sizes and species in either gasoline or diesel fuel oil is considerably narrower than in crude oil, and, as such, the difference in the magnetic permeability of the larger and smaller HCs in either of these motor fuels is even smaller. Therefore, it is not clear that the HCs in these automotive fuels are causing the reduction in viscosity reported by Tao.

Fuel Viscosity and Combustion in Theory

In general, when gasoline or diesel fuel oil enters the combustion zone, namely the cylinder, of an internal combustion engine, it enters as a mist consisting of fuel vapors and fine droplets. The ratio of vapors to liquid droplets and the size distribution of the droplets depend on the fuel's properties, including its distillation profile and viscosity, as well as the fuel system's properties, be it carburetion or fuel injection. Moreover, once the engine warms up, the fuel system can involve extensive preheating of the fuel before it enters the cylinder. Although the quantitative relationship between viscosity and the droplet size distribution depends very much on the fuel system design, it is reasonable to hypothesize that, all other factors being equal, a fuel with a lower viscosity can be expected to yield a droplet size distribution with fewer large droplets and more small droplets.

For carbureted, gasoline-powered engines, smaller droplets of gasoline have a higher probability of being fully evaporated by exposure to the temperatures of the engine manifold. For those droplets that do enter the engine, the smaller droplets will be more quickly combusted. This is because, for a given amount of fuel, smaller droplets present a much larger surface area at which evaporation and combustion can occur. Likewise, for fuel-injected engines, either gasoline or diesel powered, smaller droplets should undergo combustion more quickly and more completely.

To the extent that combustion completeness is limited by the longer burning time required by the larger droplets entering the fuel chamber, it is reasonable to hypothesize that, all other factors being equal, a fuel with a lower viscosity could result in fewer of these larger droplets and in more efficient fuel utilization, yielding improved fuel efficiency (i.e., increased mileage per gallon) and reduced emissions of the products of partial combustion, including CO, HCs, and soot particulates.[3]

It is not possible to predict a general trend for NO_X emissions as a result of reduced droplet sizes. In particular, the faster combustion associated with reduced droplet sizes could lead to higher-temperature combustion reactions in oxygen-rich zones of the combustion chamber, which can cause increased formation of NO_X. Whether NO_X emissions will increase or decrease will likely depend very much on the detailed design of the engine and associated fuel and air delivery system.

Fuel Viscosity and Combustion in Practice

Although the as-yet-unpublished work by Tao and his study team suggests that a magnetic field can alter motor fuel viscosity, the applicability of this magnetic treatment within an actual vehicle engine remains unclear. However, internal combustion engines are complicated devices, which vary considerably from model to model. Additionally, the science of multiphase

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[3] If the products of incomplete combustion per unit of fuel are reduced, then carbon dioxide (CO_2) per unit of fuel use would rise, other things being equal. However, other factors influence CO_2 emissions; for example, improved combustion timing would improve fuel utilization and reduce CO_2 emissions.

flow (e.g., suspensions in liquids, atomization, and three-phase flow during combustion) contains major knowledge gaps that continue to challenge the scientific community.

Even if a magnetic field could reduce a fuel's viscosity, predicting whether the magnitude of the viscosity reduction will result in a measurable impact on fuel efficiency or emissions may not be possible. For example, fluid viscosity changes with temperature, with colder fluids being generally more viscous. This is important when one considers fuel combustion within a vehicle. Temperature ranges widely throughout an engine, depending on the ambient temperature, operating conditions, and vehicle type. The effect of natural temperature variations encountered in practical applications could easily supersede small changes in viscosity from a magnetic field.

Further research should strengthen the knowledge base regarding the relationship between magnetic field treatment of fuels and engine performance. First, the results of Tao's research on gasoline and diesel fuel need to be fully documented, peer-reviewed, and published. Second, research is needed on magnetic field treatment's impact on the surface tension of fuels, since surface tension also plays an important role in atomization. Third, important insights may be obtained by measuring a magnetic treatment's effect on the liquid droplet distribution leaving fuel injectors and carburetors. To be useful, this research needs to examine fuel systems operating at temperatures and pressures characteristic of those in actual engines.

CHAPTER THREE

Results of Vehicle Tests

Overview

This chapter describes testing protocols that RAND developed to measure the ZEFS device's effect on tailpipe emissions and presents results of a series of tests conducted on automobiles and motorcycles. The test protocols that RAND designed were intended to support preliminary engineering tests, not certification tests. That is, the manner of testing and the results themselves are intended to guide further research and development efforts and additional approaches to further testing of the device. Results are not intended to be used by any government agency for the purpose of evaluating or otherwise assessing an emission control device.

Testing Protocols

Assessing the market potential for the device involves testing whether it actually works as measured by standards that approximate those that government authorities use in regulating automotive emissions and evaluating retrofit devices. Initially, RAND reviewed results from various tests that STWA conducted on several automobiles. RAND judged these initial results to be insufficiently reliable for informing further product development because they were not conducted according to procedures specified by the relevant authority. As a consequence, STWA conducted subsequent tests described in this section.

In the United States, EPA conducts a program to evaluate aftermarket retrofit devices that are intended to improve automobile fuel economy or reduce their air emissions (EPA, 2000a). Unless ordered by the U.S. Federal Trade Commission or the EPA administrator, participation in the program is voluntary. In general, EPA will provide technical assistance to applicants in designing a test program to be performed at an independent laboratory. Although there is flexibility in certain test protocols, EPA has established standards for test formats and minimum test requirements. California Air Resources Board (CARB) guidance is consistent with EPA guidance (CARB, 2000), although it should be noted that CARB's relevant criterion is that retrofit devices not make emissions worse than would otherwise be the case and therefore be eligible to receive an exemption from California's antitampering law (California Department of Motor Vehicles, 1994). Air quality regulations and authority to regulate engine emissions and to evaluate emission control devices in other countries vary.

To help STWA evaluate the device's performance, RAND developed a testing protocol that was intended to serve two purposes: (1) to provide useful data for informing further product development and (2) to be largely consistent with the type of testing required by EPA for regulatory approval should the device show promise for commercialization. Although the protocol follows some key specifications of EPA's Motor Vehicle Aftermarket Retrofit Device Evaluation Program, as described in the following paragraphs, the protocol also includes an expanded set of automotive tests intended to inform future research and development efforts.

As part of its Motor Vehicle Aftermarket Retrofit Device Evaluation Program (EPA, 2000a), EPA specifies that testing should occur at an independent laboratory that is competent to conduct such testing and that a minimum of two vehicles be tested. Emissions and fuel economy tests are to be conducted using the federal test procedure (FTP), and fuel economy is to be further evaluated using the highway fuel economy test (HFET).[1] In general, testing involves triplicate runs in baseline, device-installed, and repeat baseline configurations (U.S. Code of Federal Regulations, 40 CFR 610).

EPA's program guidelines also require that a standard set of measures be evaluated. This standard set of measures (and their corresponding units) includes

- carbon monoxide (CO, grams per mile [g/mi])
- total hydrocarbons (THCs, g/mi)
- nitrogen oxides (NO_X, g/mi)
- carbon dioxide (CO_2, g/mi)
- fuel efficiency (FE, miles per gallon [mpg])
- particulate matter (PM, g/mi) (diesel-powered engines only).[2]

Basic Protocol

Because of the considerable effort and expense involved in conducting these tests and because STWA's initial intent was to guide further research and development, not to pursue certification or government agency evaluation, RAND ultimately proposed a "basic protocol" that specified a reduced set of requirements for conducting reliable engineering tests. The intent of this protocol was to identify significant effects attributable only to the installed device and not to other factors that influence combustion. Key features of the basic protocol included testing at a laboratory capable of conducting tests under carefully controlled conditions and according to standard test procedures (such as FTP and HFET) in a manner that generates triplicate data sets for baseline and device configurations. These configurations are described as follows:

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[1] These protocols simulate city and highway "drive traces" that vary in acceleration, cruising, and deceleration (so-called *modes*) and cold-start, hot-transient, and hot-start engine conditions (so-called *phases*). These conditions are varied and repeated over several cycles of the complete drive trace, simulating an 11.1-mile trip for the FTP, which is generally immediately followed by a 10.2-mile trip for the HFET. For both of these tests, the vehicle is placed on a chassis dynamometer after strict preparations and preconditioning. Exhaust emissions are diluted and proportionally sampled into a series of bags, and samples are chemically analyzed for a standard set of pollutants.

[2] g/mi represents grams emitted per mile traveled (or travel mile simulated). mpg represents miles traveled (or travel mile simulated) per gallon of fuel consumed.

- *Baseline:* No device installed. Vehicle is adjusted to original manufacturer specifications.
- *Device:* Device installed. No other adjustments to vehicle or test equipment are made.

The set of measures specified in the basic protocol were as follows:

- carbon monoxide (CO, g/mi)
- total hydrocarbons (THCs, g/mi)
- nitrogen oxides (NO_X, g/mi)
- carbon dioxide (CO_2, g/mi)
- fuel efficiency (FE, mpg).

The RAND-designed basic protocol does not specify that particulates be measured, notwithstanding the serious health concerns about this regulated pollutant. Diesel fuel, which tends to generate much more PM per unit when burned than does gasoline, does not power engines for which the device is currently designed.

Expanded Protocol for Automobile Testing

During the initial stages of automobile testing, RAND expanded the basic protocol in an effort to inform further research and development. This expanded protocol included two additional test configurations, for which triplicate data sets were collected:

- *Null device:* A device similar to the active device is installed. The null device differs from the active device in that stainless steel plugs replace magnets. No other adjustments to vehicle or test equipment are made.
- *Repeat baseline:* Device removed. Vehicle is returned to original manufacturer specifications.

The null device tests were added to explore the possibility that device geometry, separate from or in combination with magnetism, might influence possible effects of the device. Such a device resembles a carburetor spacer or high-rise manifold, which some car enthusiasts think enhance engine performance. Note that the device increases the distance between the carburetor and the intake manifold, in both automobile and motorcycle applications. The repeat baseline tests were intended to detect possible changes in the vehicle or device over the course of testing or possible instrument drift of the test equipment. Note that, although device operation does not require any additional adjustment to the engine, its installation does require removal and replacement of various engine parts, and a complete series of tests spans at least several days.

During initial stages of testing and analysis, RAND also asked that lab technicians monitor the following measures and report any inconsistencies between test runs:

- engine temperature
- exhaust temperature
- engine vacuum pressure
- engine revolution rate (revolutions per minute, or RPM)

- air flow rate
- fuel flow rate.

RAND also specified that continuous data be collected for one of the vehicles tested. These data described emissions specifically associated with each phase and mode of engine operation over the various cycles of the FTP and HFET drive traces.

Analysis

With regard to evaluating a retrofit device that claims emission reductions or fuel economy savings, a number of important issues should be addressed. These include not only the magnitude of the exhaust reductions and fuel savings, but also the device's effect on the durability and drivability of the vehicles on which the device is installed (EPA, 2000a). This section addresses a more fundamental issue, namely whether there is, in fact, any statistically significant reduction in emissions or improvement in fuel savings, regardless of magnitude, associated with the device. Specifically, two-sample t-tests were conducted on the test results using the t-distribution at a 95-percent confidence level. Taking a conventional hypothesis-testing approach, the t-tests evaluated the following null and alternative hypotheses:

- H_0: There is no difference between the average emissions (or fuel consumption [FC]) before and after installing the device.
- H_A: There is a difference between the average emissions (or FC) before and after installing the device.

In each test, the average is that of the corresponding triplicate test runs (tests 1, 2, and 3), for different test configurations (baseline and device) and for each measure (CO, THC, NO_X, CO_2, and FE). The standardized test statistic *t* was compared to the appropriate p-value at the conventional significance level of 5 percent. Where $p < 0.05$, the null hypothesis was rejected and it was concluded that a statistically significant effect was found. Where $p > 0.05$, there was insufficient evidence to reject the null hypothesis and, therefore, it was concluded that there was no statistically significant effect.

Test Results

RAND oversaw testing of the device designed for automobiles at an independent lab in California. RAND was also provided results from test facilities in Hong Kong, Thailand, and China. Results of these various tests and statistical analysis of them are provided in the remainder of this chapter. Additional detail is provided in Appendix B.

Automobile Tests in California

An independent laboratory in California tested two vehicles and fitted devices, all supplied by STWA. CARB identified this lab as being able to conduct the required tests. The vehicles tested included a 1971 Volkswagen Beetle (VW) and a 1984 Ford Mustang (Ford). Results of the VW tests, following the basic protocol described previously, are presented in Table 3.1.

THC, NO_X, CO, and CO_2 emission results from the FTP only are reported here, according to EPA guidelines for confirmatory testing. For the same reason, fuel economy results from the HFET are reported. These results were analyzed statistically, according to the analysis procedure described earlier. Results for the VW tests are summarized in Table 3.2. In these and subsequent tables, we report both the direction of the effect and its significance. When the direction of effect is beneficial, we use the term *desirable*, while *undesirable* refers to a direction of higher emissions or reduced fuel economy.

As shown in Table 3.2, results showed no statistically significant effect of the device on pollutant emissions or fuel economy for the VW tested at this lab.

Table 3.3 presents results of the Ford tests following the basic protocol. These results were analyzed statistically according to the analysis procedure described previously and are summarized in Table 3.4.

As shown in Table 3.4, results showed no statistically significant effect of the device on ozone precursor measures THC and NO_X or fuel economy for the Ford tested at this lab. However, statistically significant effects on CO and CO_2 emissions were found, with CO being

Table 3.1
Results of the Volkswagen Tests Conducted in California

Vehicle	Test	Configuration	THC (g/mi)	NO_X (g/mi)	CO (g/mi)	CO_2 (g/mi)	FE (mpg)
VW	1	Baseline	2.80	2.41	27.41	322	35.22
VW	2	Device	2.66	2.39	28.46	316	36.22
VW	3	Baseline	2.44	2.40	24.41	315	35.71
VW	4	Device	2.95	2.28	28.02	322	35.97
VW	5	Baseline	2.79	2.33	27.50	313	36.08
VW	6	Device	2.86	2.47	29.85	322	36.43

Table 3.2
Results of the Statistical Analysis of the Volkswagen Tests

Analysis	THC (g/mi)	NO_X (g/mi)	CO (g/mi)	CO_2 (g/mi)	FE (mpg)
Direction of the effect	Undesirable	Neutral	Undesirable	Undesirable	Desirable
Mean (baseline) – mean (device installed)	–0.15	0	–2.34	–3.33	–0.54
Statistical significance of the effect	Not significant	Not significant	Not significant	Not significant	Not significant
p-value	0.37	1.00	0.11	0.38	0.13

Table 3.3
Results of the Ford Mustang Tests Conducted in California

Vehicle	Test	Configuration	THC (g/mi)	NO_X (g/mi)	CO (g/mi)	CO_2 (g/mi)	FE (mpg)
Ford	1	Baseline	5.77	0.10	81.50	624	21.94
Ford	2	Device	5.71	0.10	71.77	681	21.94
Ford	3	Baseline	6.60	0.13	91.73	622	21.59
Ford	4	Device	5.51	0.08	74.29	677	21.98
Ford	5	Baseline	6.38	0.08	88.77	604	22.53
Ford	6	Device	6.02	0.10	72.67	669	22.41
Ford	7	Baseline	6.01	0.14	80.84	607	22.63

Table 3.4
Results of the Statistical Analysis of the Ford Mustang Tests

Analysis	THC (g/mi)	NO_X (g/mi)	CO (g/mi)	CO_2 (g/mi)	FE (mpg)
Direction of the effect	Desirable	Desirable	Desirable	Undesirable	Undesirable
Mean (baseline) – mean (device installed)	0.44	0.02	12.8	–61.42	0.06
Statistical significance of the effect	Not significant	Not significant	Significant	Significant	Not significant
p-value	0.14	0.32	0.01	0.00	0.85

decreased and CO_2 being increased. The findings that there were no consistent statistically significant effects for the two vehicles considered as a group and no statistically significant effects on THC and NO_X emissions in either test vehicle led STWA to reassess and redesign the device for automobile applications.

Motorcycle Tests in Asia

Initial market research suggested potential for emission control devices for motorcycles in Asia. Therefore, STWA developed a device for motorcycle engines and sought independent laboratories in Hong Kong, Thailand, and China for testing the device. Note that the equipment for testing small engines and motorcycles differs somewhat from that required for testing automobiles, as do the test procedures. To test motorcycles in the various Asian labs, RAND recommended that testing should follow at least the reduced set of requirements for conducting engineering tests, described earlier in this chapter as the basic protocol and that test procedures relevant to the countries in which the motorcycles were being tested also be applied.

RAND reviewed the results of tests conducted on motorcycles in laboratories in Hong Kong, Thailand, and China. Among all test results provided to RAND, one set of results from an independent laboratory in Thailand was most clearly consistent with RAND's basic protocol for testing. Based on the information provided, RAND could not ascertain the extent to which the data from other labs were consistent with all the criteria in RAND's basic protocol.

Missing information included one or more of the following: evidence of the independence and capability of the test lab, the consistency of test configurations with device and baseline specifications, and triplicate data sets required for statistical analysis. (After RAND completed its work on this project, STWA informed RAND of additional tests conducted in California and completed in February 2007 of two on-road and one off-road motorcycles. These additional results may shed further light on the device's performance potential.)

The Thailand lab is accredited according to International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) standard 17025.[3] The tests conducted at this lab included three baseline runs and three test runs after installing the device. According to the report provided by this lab, tests were conducted on a Suzuki Best 125 motorcycle (Suzuki) operated on a chassis dynamometer specially fitted for motorcycle testing.

Exhaust emissions were measured according to Thai Industrial Standard (TIS) 2130-2545, which is equivalent to the European drive cycle 97/24/EC. Mass emissions were collected and analyzed for THC, CO, NO_X, and CO_2, measured in units of grams per kilometer (g/km). Data on FC (in liters of fuel consumed per 100km traveled, or L/100km) were provided instead of data on FE (mpg). These differences in units and measures do not compromise the ability to statistically compare results in baseline and device configurations for these lab results.

Table 3.5 presents results of the motorcycle tests conducted in the Thai lab, following the basic protocol. Table 3.6 summarizes results of the statistical analysis.

The analysis presented in Table 3.6 shows that there is a statistically significant reduction in CO and CO_2 emissions and FC when the device is installed on the motorcycle tested. However, this same conclusion does not hold for the ozone precursors NO_X and THC. In particular, the analysis shows that there was a statistically significant increase in NO_X emissions in these tests when the device was installed.

Table 3.5
Results of Suzuki Motorcycle Tests Conducted in Thailand

Vehicle	Test	Configuration	THC (g/km)	NO_X (g/km)	CO (g/km)	CO_2 (g/km)	FC (L/100km)
Suzuki	1	Baseline	0.73	0.42	1.60	40.6	1.96
Suzuki	1	Device	0.77	0.43	1.01	39.2	1.86
Suzuki	2	Baseline	0.73	0.42	1.69	40.4	1.95
Suzuki	2	Device	0.71	0.47	1.14	38.8	1.84
Suzuki	3	Baseline	0.73	0.42	1.59	40.1	1.93
Suzuki	3	Device	0.75	0.46	1.14	38.7	1.85

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[3] ISO and IEC are responsible for a worldwide standardization system. Accreditation with respect to ISO/IEC standard 17025 represents consistency with "general requirements for the competence of testing and calibration laboratories" (ISO, 2005).

Table 3.6
Results of Statistical Analysis of Suzuki Motorcycle Tests

Analysis	THC (g/km)	NO_x (g/km)	CO (g/km)	CO_2 (g/km)	FC (L/100km)
Direction of the effect	Undesirable	Undesirable	Desirable	Desirable	Desirable
Mean (baseline) – mean (device installed)	–0.01	–0.34	0.53	1.47	0.10
Statistical significance of the effect	Not significant	Significant	Significant	Significant	Significant
p-value	0.61	0.04	0.00	0.00	0.00

CHAPTER FOUR

Identifying Markets for the ZEFS Device

Overview

This chapter addresses the roles that environmental improvements and fuel economy savings could play in affecting the potential domestic and international markets for the ZEFS device. The potential in either market could reflect the possibility for using the device (once its performance is validated as offering significant reductions in exhaust emissions or fuel usage) as an alternative to other measures for emission reduction in on-road, off-road, and stationary engines, as well as the possibility for consumer fuel cost savings after installation.

The basic principles behind an evaluation of the device's market value are easy to illustrate, though we do not undertake an actual empirical assessment here, since the ZEFS device's performance remains unclear. Suppose an older automobile is driven 12,000 miles per year and averages 15 mpg; annual fuel consumption is 800 gallons. Each 1-percent improvement in fuel efficiency would save eight gallons. Assuming fuel costs of $2.50 per gallon, the annual fuel cost savings is $20. Assuming consumers require a three-year payback, market uptake would occur if the device costs less than $60 per percent improvement in fuel efficiency. For example, a device with an installed cost of $300 would need to offer a 5-percent reduction in annual gasoline consumption.

The same calculation can be applied to motorcycles, with a higher baseline efficiency. If, for example, baseline efficiency were 30 miles per gallon, then fuel and fuel cost savings per annum would be only four gallons and $10 under the assumption that the motorcycle is driven 12,000 miles per year. Again assuming three-year payback for market acceptance, the threshold for market penetration then would be $30 per percent efficiency improvement. This calculation can be applied at a governmental level as well, for example, to assess the value of fuel cost savings in a national program of energy efficiency for improved energy security. In this case, however, the relevant fuel price is the basic wholesale price net of any taxes. Finally, this reasoning can be applied to compare the cost of any pollution reduction with the device to other alternatives (which could include stationary or mobile sources).

In the following sections, we discuss how environmental concerns might open markets for STWA products under the assumption that such products can be successfully developed and shown to offer significant reductions in emissions of pollutants from internal combustion engines.

Potential Domestic Markets

The two criteria pollutants that appear to be most relevant to the ZEFS device are CO and ozone (O_3). CO is a byproduct of the combustion process and an asphyxiating poison in humans. O_3 is a harmful oxidant that is formed through complex reactions in the atmosphere involving NO_X and certain hydrocarbons called volatile organic compounds (VOCs). NO_X is a byproduct of combustion in air, and VOCs derive from evaporated or incompletely burned fuel, as exemplified by the emissions of HCs from automotive exhausts. PM is another criteria pollutant that has been the focus of extensive regulation, based on its significant adverse impacts on human health.

Substantial amounts of CO, NO_X, and VOCs are emitted by internal combustion engines, though VOCs come mostly from gasoline-powered engines. A significant portion of these pollutants comes from on-road mobile sources such as cars, trucks, and buses and from off-road mobile sources (such as farm and construction equipment, lawn and garden equipment, and off-road recreational vehicles), as well as stationary sources such as power plants. Significant progress has been made over the past few decades in reducing emissions from on-road sources. Off-road mobile source emissions began to be addressed only in the mid-1990s. EPA (2000a) has reported that nationally

- off-road diesel engines, including tractors, backhoes, bulldozers, forklifts, generators, and pumps, contribute about 20 percent of NO_X and 36 percent of PM10 (PM less than 10 micrometers in diameter) from all mobile sources
- small gasoline engines less than 25 horsepower, including brush cutters, chainsaws, edgers, lawn mowers, and leaf blowers, contribute about 20 percent of HC and 23 percent of CO from all mobile sources
- recreational off-road vehicles, including motorcycles, ATVs, and snowmobiles, contribute about 8 percent of HC and 5 percent of CO from all mobile sources
- gasoline-powered outboard watercraft contribute about 12 percent of HC and marine diesel engines contribute about 7 percent of NO_X and 6 percent of PM10 from all mobile sources.

This picture is changing with the onset of significant new regulations on emissions from off-road recreational vehicles and restrictions on the sulfur content of diesel fuel used in off-road land and marine vehicles, among other rules.[1] Under these tougher regulations, emissions of NO_X, VOCs, and CO from new off-road sources are all expected to decline significantly. However, the existing stock of motorbikes, off-road vehicles, and equipment currently in use is large and relatively durable (see Table 4.1). New engine and fuel regulations do not address this aging group, which becomes more polluting with time.

The data in Table 4.1 indicate that most on-road vehicle engines use fuel injection, a technology to which the ZEFS device does not apply. Anticipating continuing vehicle fleet

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[1] Examples include EPA's 2004 nonroad rule for diesel engines (EPA, 2004b) and the 2002 rule on nonroad recreational and other engines (EPA, 2002).

Table 4.1
Estimated Stock of Selected Mobile Sources (millions)

	Reported			Estimated		
	California		United States	California		United States
Source	**1997**	**2000**	**1994**	**1996**	**2003**	**2003**
On-road						
Light-duty vehicles		19.30			22.00	163.00
Carbureted vehicles			76.00		1.00	7.50
Fuel-injected vehicles			78.00		21.00	156.00
Medium-duty vehicles		1.50			1.60	12.90
Heavy-duty vehicles		0.73			0.76	6.20
Motorcycles		0.40			0.40	3.30
Buses		0.05			0.05	0.43
Motor homes		0.01			0.01	0.09
Off-road						
Aircraft				0.02	0.02	0.02
Commercial boats and ships				NA		
Recreational boats				0.01	1.60	13.30
Recreational vehicles	0.40			0.09	1.30	10.40
Equipment				124.00	16.40	135.00
Farm equipment				4.70	0.62	5.10

SOURCES: EPA (1991, 2004a); Dolce (1998); EIA (2002); Davis, Truett, and Hu (1999); Dixon and Garber (2001); CARB (2004); Transportation Air Quality Center (1998); U.S. Census Bureau (2007).

NOTE: Current estimates for California based on national data consider proportionality of population in 2001 (California/United States = 35M/285M). 2003 estimates based on previous year's data consider average annual population growth (1.3 percent per year). Estimates of carbureted vehicles in 2003 consider proportion of pre-1985 in-use fleet, declining 5.3 percent per year since 1985.

turnover, the category of carbureted on-road vehicles will likely continue to get even smaller over time. The stock of off-road engines, especially for utility equipment, is comparable in size to on-road vehicles. These engines are typically carbureted rather than fuel-injected and thus could be an application for the device.

Potential Market for the Device Within the Southern California Air Basin

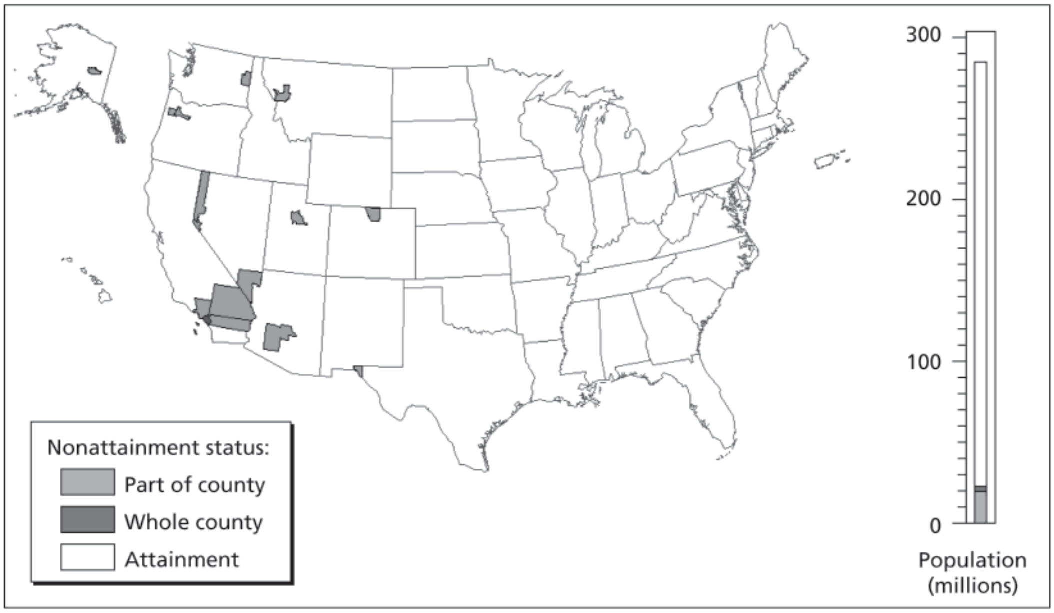
At the time of our analysis, the EPA reported that 18 counties in the United States did not achieve the federal standard for CO and that 251 counties did not achieve the federal O_3 standard. Figures 4.1 and 4.2 show the nonattainment areas for CO and O_3 across the United States at the time.[2]

Los Angeles County has the largest population of any nonattainment county. It is also one of the fastest-growing nonattainment counties. In terms of severity, the Southern California air basin exceeds the current federal standard for O_3 more frequently than any other location in the United States and is designated as an extreme nonattainment area for this pollutant.

California's South Coast Air Quality Management District (SCAQMD) has compiled estimates of recent and future emissions, as well as emission targets considered necessary to reach attainment. Table 4.2 shows these estimates by major source category in the SCAQMD. These are modeled estimates that illustrate general trends and breakdowns of VOC, NO_X, and CO emissions, their sources, and target reductions with respect to federal standards and planned attainment dates.

Large gaps remain between 2010 baseline and 2010 targets for VOCs from all sources, suggesting that additional control measures will be required to reduce VOC emissions overall by half. In particular, targets call for a 63-percent reduction from on-road mobile VOC sources

Figure 4.1
Nonattainment Areas for CO in the United States



SOURCE: EPA (2003).

RAND *TR313-4.1*

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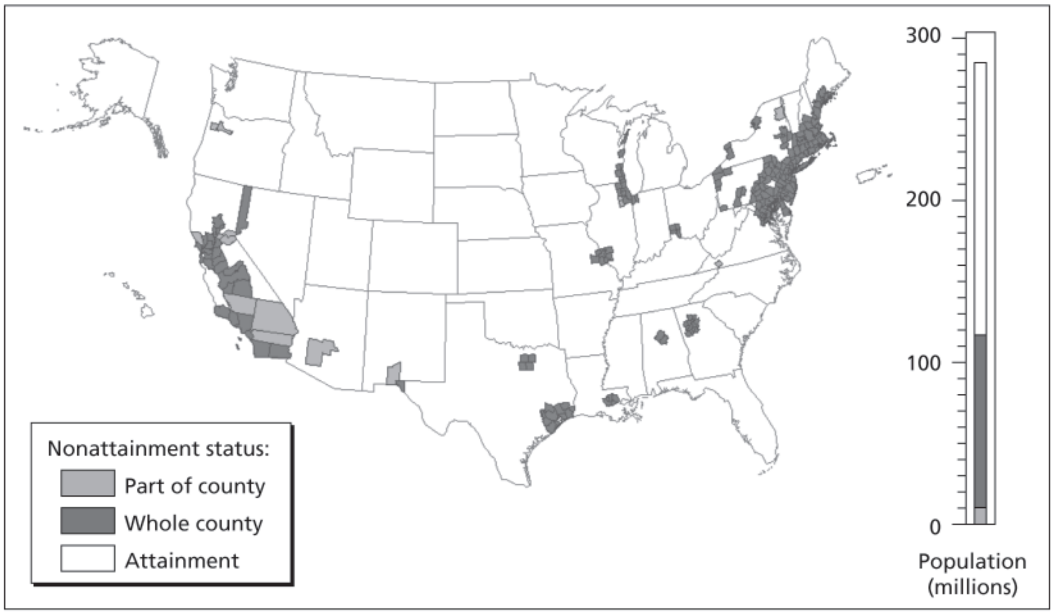
[2] Four of the CO nonattainment counties shown are in southern California. California has recently achieved the federal CO standard, but EPA review is still pending. Also, a stricter federal O_3 standard has been approved but has not yet been implemented. The effect of this new standard may be to increase the number of O_3 nonattainment areas in the United States.

Figure 4.2
Nonattainment Areas for O_3 in the United States



SOURCE: EPA (2003).
RAND *TR313-4.2*

and a 48-percent reduction from off-road mobile VOC sources in the South Coast Air Basin (SCAB).

Table 4.3 shows trends in relative contribution of various sources to the baseline average annual emission inventory by major source category. It shows comparisons between baseline inventories for 1997 and the planned attainment year—2003 for CO, 2006 for PM10, and 2010 for VOCs and NO_X.

Stationary sources in 2010 are contributing the most VOCs—more than half of total VOC emissions. On-road sources, particularly light-duty vehicles, also contribute a large portion of VOCs, despite substantial reductions between 1997 and 2010 baseline estimates. There is a consistent downward trend for on-road mobile sources for all pollutants, though they remain the largest expected source of NO_X in 2010, contributing more than half of total NO_X emissions. The downward trend in on-road mobile source emissions is generally countered by growth in stationary source emissions and mobile off-road sources. Mobile off-road VOC grows slightly, while mobile off-road NO_X and CO grow more substantially. The largest emerging categories for off-road engines in the SCAB include recreational boats and off-road equipment for VOC, NO_X, and CO, and aircraft, commercial boats, and ships, specifically, for NO_X. However, the 2010 figures in the 2003 SCAQMD plan would need to be adjusted for further improvements in emission reductions as a result of the various recent EPA regulatory actions noted previously.

Table 4.2
Emissions and Targets by Source in SCAB (annual average, tons per day)

	VOC			NO_x			CO			PM10		
	Baseline		Target	Baseline		Target	Baseline		Target	Baseline		Target
Source	**1997**	**2010**	**2010**	**1997**	**2010**	**2010**	**1997**	**2003**	**2003**	**1997**	**2006**	**2006**
Stationary	418	300	190	135	91	85–87	158	210	373	244	256	254
Fuel combustion	11	12		43	27		42	42		8	8	
Waste disposal	6	6		1	2		1	1		0	0	
Cleaning and surface coatings	122	64		0	0		0	0		0	0	
Petroleum production and marketing	63	35		0	0		5	5		1	1	
Industrial processes	23	23		0	0		4	5		6	7	
Solvent evaporation												
Consumer products	118	108		0	0		0	0		0	0	
Architectural coatings	51	24		0	0		0	0		0	0	
Others	3	3		0	0		0	0		0	0	
Miscellaneous processes	21	25		29	27		106	156		229	239	
RECLAIM sources[a]	0	0		62	34		0	0		0	0	
Mobile	703	290	120	1,145	665	445–521	6,416	4,093	3,531	37	37	37
On-road mobile sources	533	199	73	841	419	276–291	5,492	3,241	2,843	18	18	18
Light-duty vehicles	441	152		405	139		4,528	2,654		10	11	
Medium-duty vehicles	35	17		48	22		416	250		1	1	
Heavy-duty vehicles	42	21		356	231		375	194		7	0	
Motorcycles	9	5		1	1		50	52		0	6	
Buses	4	3		24	22		43	31		0	0	

Table 4.2—Continued

	VOC			NO$_x$			CO			PM10		
	Baseline		Target	Baseline		Target	Baseline		Target	Baseline		Target
Source	1997	2010	2010	1997	2010	2010	1997	2003	2003	1997	2006	2006
Motor homes	3	1		6	4		81	60		0	0	
Off-road mobile sources	170	91	47	304	246	169–230	924	852	688	19	19	19
Aircraft	8	5		16	31		56	50		1	1	
Trains	2	1		35	12		5	5		1	1	
Commercial boats and ships	3	4		43	58		5	6		3	4	
Recreational boats	42	23		6	10		192	186		2	3	
Off-road RVs	10	5		0	0		62	55		0	0	
Off-road equipment	68	41		193	126		594	541		12	10	
Farm equipment	1	1		11	6		9	8		1	1	
Other off-road mobile sources	37	10		1	2		0	1		0	0	
Total (stationary and mobile)	1,122	590	310	1,281	756	530–608	6,574	4,303	3,904	281	293	291
Total reductions (%)												
1997: attainment year		47.4			40.9			34.6			–4.2	
Attainment-year baseline target			47.4			19.6–29.9			9.3			0.7

SOURCE: SCAQMD (2003).

NOTE: Light-duty vehicles are passenger cars (light-duty automobiles, or LDAs) and light-duty trucks weighing less than 5,750 lbs (light-duty trucks weighing less than 3,750 lbs, or T1s, and light-duty trucks weighing 3,751–5,750 lbs, or T2s). Medium-duty vehicles are medium-duty trucks weighing between 5,751 and 8,500 lbs (T3). Heavy-duty vehicles are light-, medium-, and heavy-duty trucks weighing more than 8,501 lbs running on gas and diesel (T4s are light heavy-duty trucks weighing 8,501–10,000 lbs, T5s are light heavy-duty trucks weighing 10,001–14,000 lbs, T6s are medium heavy-duty trucks weighing 14,001–33,000 lbs, and heavy heavy-duty [HHD] trucks weigh 33,001–60,000 lbs). Buses are gas and diesel urban buses (UBs) and school buses (SBs). Off-road recreational vehicles include ATVs and snowmobiles. Off-road equipment includes lawn and garden equipment and portable generators. Farm equipment includes tractors. Other off-road mobile sources are fuel storage and handling and truck stops. Figures shown aggregate over gasoline and diesel engines, thus not showing environmental differences between them.

[a] RECLAIM = Regional Clean Air Incentives Market.

Table 4.3
Relative Contribution to Total Annual Average Baseline Emissions, by Source in the SCAB (%)

	VOC		NO_x		CO		PM10	
Source	**1997**	**2010**	**1997**	**2010**	**1997**	**2003**	**1997**	**2006**
Stationary	37.3	50.8	10.5	12.0	2.4	4.9	86.7	87.2
Mobile	62.8	49.2	89.5	88.0	97.6	95.1	13.3	12.9
On-road mobile sources	47.6	33.7	65.7	55.4	83.5	75.3	6.5	6.3
Light-duty vehicles	39.4	25.7	31.6	18.4	68.9	61.7	3.4	3.8
Medium-duty vehicles	3.1	2.8	3.8	2.9	6.3	5.8	0.3	0.4
Heavy-duty vehicles	3.7	3.6	27.8	30.6	5.7	4.5	2.6	0.1
Motorcycles	0.8	0.9	0.1	0.2	0.8	1.2	0.0	1.9
Buses	0.3	0.5	1.9	2.9	0.7	0.7	0.2	0.2
Motorhomes	0.3	0.2	0.5	0.5	1.2	1.4	0.0	0.0
Off-road mobile sources	15.2	15.5	23.8	32.5	14.1	19.8	6.8	6.6
Aircraft	0.7	0.8	1.3	4.1	0.8	1.2	0.3	0.2
Trains	0.1	0.2	2.7	1.6	0.1	0.1	0.3	0.2
Commercial boats and ships	0.3	0.7	3.3	7.6	0.1	0.1	1.1	1.2
Recreational boats	3.7	3.9	0.5	1.3	2.9	4.3	0.7	1.1
Off-road RVs	0.9	0.8	0.0	0.1	0.9	1.3	0.0	0.0
Off-road equipment	6.1	7.0	15.0	16.7	9.0	12.6	4.1	3.5
Farm equipment	0.1	0.2	0.8	0.9	0.1	0.2	0.2	0.2
Other off-road mobile sources	3.3	1.8	0.1	0.2	0.0	0.0	0.0	0.0

SOURCE: SCAQMD (2003).

Historically, emission reductions from on-road vehicles have been attributed largely to improved vehicle technologies, although reformulated fuel and other programs have also contributed. Catalytic converters and fuel injection systems historically have been the biggest heroes in the war on transportation air pollution in the United States. In Los Angeles, O_3 levels were cut by approximately half between 1970 and 1990 despite a 60-percent increase in vehicle miles traveled during that time. Driven by increasingly strict emission standards, several new-car technologies can be anticipated in the next several years, including stagedcombustion engines, pollutant-trapping exhaust systems, and gasoline-electric hybrid vehicles. Fleet turnover and incorporation of these technologies is anticipated to further reduce the emissions from the on-road vehicle fleet by 2010.

However, because an older vehicle can emit more pollution than a comparable style of newer vehicle can, incentive programs to accelerate turnover have been implemented. In some cases, between $500 and $1,000 is generally offered to owners of older vehicles or those that have failed emissions tests to remove these vehicles from the on-road fleet. In California, the Bureau of Automotive Repair (BAR) ran one such program, but that program was canceled in 2002. If an aftermarket emission-reduction retrofit device could reduce emissions at a cost per unit of emissions reduced that is significantly less than the payments to induce faster vehicle turnover, such a device could become another component in programs to cut emissions from older on-road vehicles. The same would apply in comparing the cost and effectiveness of such a device to the cost that California paid for assistance to lower-income consumers for repairs needed to pass inspection (up to $500 per vehicle from the BAR at the time of this writing).

Although newer off-road engines will also incorporate improved emission controls and utilize cleaner fuels, a substantial stock of these engines is already in use with poorer environmental performance. Should further laboratory analysis and in-use testing provide more positive outcomes, use of a ZEFS-type device as a retrofit for these engines could also be explored as an alternative to other control options.

Finally, emission-offset programs may provide opportunities to generate emission-reduction credits from existing sources based on retrofits. SCAQMD runs a mobile source offset program that manages a market for mobile source emission reduction credits (MSERCs). MSERCs, once approved, can be traded or sold on the open market and used to offset emissions from stationary sources or as part of employee commute programs. As above, should further development work and in-use testing provide more positive outcomes, the device might be applied to various on- and off-road sources to generate MSERCs with market value.

Assessing the Potential International Market

Although on-road sources are a shrinking emission category within the United States (as shown earlier), on-road sources are a growing category of emissions in many developing countries. Moreover, vehicles in these countries are often older and do not use the same modern technologies as developed countries do to increase fuel efficiency or control emissions. In particular, the proportion of the fleet that has carbureted engines is much larger.

Along with the growing concern for reducing emissions in the developing world is a significant interest in increasing fuel efficiency where gasoline prices are high, populations are relatively poor, and vehicles are older and less efficient. Older vehicles can find their way into urban transit services (especially intra- and intercity taxi services). Because service costs and profitability are tied to fuel cost, increased fuel efficiency may be attractive, for example, to owners of taxi services.

The potential can be illustrated by briefly examining the situation in Mexico and Asia. Mexico's large, aging fleet and high public awareness of air pollution create a market ripe for introduction of emission-control technologies and, thus, a potential marketing opportunity for an aftermarket retrofit device that offers significant emission reductions and fuel savings. Asia is home to most of the world's very large cities and many of the world's most severe air-quality problems. Indonesia, Malaysia, and the Philippines, in particular, have large fleets of highly polluting carbureted two-stroke motorcycles (McDonald et al., 2005) that may represent an important market for retrofit devices, if effectiveness is demonstrated with the mixed fuels commonly encountered in two-stroke vehicle engines.

Two common themes influence the potential market for a retrofit device internationally. One is the degree of *effective* environmental control, including enforcement of policies and norms. If these are either weak or weakly enforced, incentives for use of the device will be greatly diminished. The other concerns the device's cost in developing countries and the options for its financing. Although the cost of the installed device may ultimately be relatively modest by the standards of developed countries, it could be expensive relative to the much more limited household incomes of the developing world.

CHAPTER FIVE

Findings and Conclusions

The RAND analysis of the magnetic treatment of fuels for the purpose of reducing automotive emissions and improving fuel economy supports the following findings and conclusions:

- The existing technical literature does not contain credible reports that the application of magnetic fields to either gasoline or diesel fuel oil will reduce the viscosities of these automotive fuels. Recent experimental work published by Tao and Xu (2006) shows that a pulsed magnetic field can reduce the viscosity of crude oil. Tao and his collaborators have extended this experimental work to examine the effect of pulsed magnetic fields on gasoline and diesel fuel. Pending peer review and publication of this newer work, it is premature to conclude that application of magnetic fields has been shown to lower the viscosity of automotive fuels. Even if this effect is subsequently established, several other factors must be addressed to establish that the application of magnetic fields can reduce emissions and improve economy.
- Establishing a theoretical basis (if any) underlying the effect of magnetic fields on fuel viscosity, surface tension, and atomization might provide useful information, in addition to empirical testing, for the development and evaluation of magnetic field-based fuel treatment devices. However, we cannot predict a priori how productive further research to establish the device's underlying theoretical basis might prove to be.
- So far, the test results for use of the device are, at best, mixed. Focusing on tests of motorcycles after STWA redesigned the device, the test results indicate a statistically significant and desirable impact of the device on CO emissions and fuel economy relative to operations without the device. Other tests indicate a change in the direction toward worsening fuel economy or emissions. Moreover, there is no theoretical basis for predicting that the direction of impact on NO_X emissions will fall due to the aftermarket application of magnetic fuel treatment. The motorcycle tests, in fact, showed a statistically significant increase in those emissions. (After RAND completed its work on this project, STWA informed RAND of additional tests conducted in California and completed in February 2007 on two on-road and one off-road motorcycles. These additional results may shed further light on the device's performance potential.)
- Should further laboratory analysis and in-use testing provide clearer and more positive outcomes, the market potential for the device will depend significantly on the advances realized from other technologies and regulatory policies and on its cost-effectiveness rela-

tive to other outcomes. Markets within the United States may be limited, except perhaps in areas with large emissions of criteria pollutants from old off-road mobile sources. Potential international applications may be larger, given the baseline for engine performance and environmental standards in developing countries. Assuming statistically valid and positive test results, a more in-depth assessment of the international prospects of the retrofit device would need to be done.

- If STWA pursues development of a retrofit device based on the magnetic treatment of automotive fuels, it should give highest priority to obtaining statistically valid data on performance in actual vehicles.

APPENDIX A

Selected Publications Relating to Magnetic Treatment of Fuel

Trade Journals, Technical Reports, and Conference Papers

Arthur, Charles, "Warren Spring Denies Car Magnet Claims," ***New Scientist*****, Vol. 138, No. 1873, May 15, 1993, p. 19.**

According to this article, the UK government's Warren Spring Laboratory was forced to issue a rebuttal of its own work after the company that commissioned a confidential report quoted selectively from its conclusion. The company, Technical Development (UK), asked the laboratory to test a magnetic device that straps around the fuel intake to the carburetor. Technical Development claimed that it increased power and fuel efficiency 9 and 7 percent, respectively, with carbon deposits and vehicle emissions falling between 10 and 24 percent. The laboratory issued a detailed rebuttal, asserting that the test conditions did not warrant such claims.

Brodkey, Robert S., K. Park, S. Weng, A. Ouibrahim, and S. F. Lin, "Kinetic-Elastic Approach for Time-Dependent Rheological Data on Slurry Fuels and Polymers," Ohio State University Research Foundation, January 1984, pp. 1–212.

The abstract reads as follows:

> At the Ohio State University, we have been developing our kinetic interpretation of non-Newtonian fluid behavior under support from the Aero Propulsion Laboratory with materials of interest to the Air Force. Specifically, we have considered slurry fuel systems and a reference, high-viscosity lubricant (5P4E). In addition, we continued to obtain data on a polymeric system previously studied by us so as to ascertain the adequacy of our measurements and of our theory.

Golovitchev, Valeri, "Modeling of Spray Formation, Ignition and Combustion," lecture on combustion modeling, Lund, Sweden, December 9, 1999.

This presentation overviews major combustion models, including atomization and breakup submodels. In particular, it demonstrates the relationship between droplet size, breakup rate, surface tension, and viscosity in some current combustion models.

Gordienko, V. A., A. S. Kovalev, and L. M. Makal'sky, "Catalysts in Your Car: Auto-Wave Self-Reproduction of Organic Substances and Some Aspects of Ecology of a Car," conference paper, Moscow State University, 1998. In Russian.

This paper discusses the principle at work with regard to the proposed magnetic treatment. It claims that magnetic fields create conditions under which molecules in the fuel self-organize in a form with more free radicals. There are several forms of molecules in the fuel. The authors claim that, once the process of self-organization of molecules in this form starts, it takes little energy (a small magnetic field) to support the process for a long time.

Huang, Jie, Boyd F. Edwards, and Donald D. Gray, "Thermoconvective Instability of Paramagnetic Fluids in a Uniform Magnetic Field," *The Physics of Fluids*, Vol. 9, No. 6, June 1997, pp. 1,819–1,825.

———, **"Magnetic Control of Convection in Nonconducting Paramagnetic Fluids," *Physical Review: E, Statistical Physics, Plasmas, Fluids, and Related Interdisciplinary Topics*, Vol. 57, No. 1, January 1998a, pp. R29–R31.**

———, **"Thermoconvective Instability of Paramagnetic Fluids in a Nonuniform Magnetic Field," *Physical Review: E, Statistical Physics, Plasmas, Fluids, and Related Interdisciplinary Topics*, Vol. 57, No. 5, May 1998b, pp. 5,564–5,571.**

Nayyar, N., "Combustion Efficiency with Magnetism," *Metallurgia*, Vol. 65, No. 7, July 1998, pp. 233–234.

The journal appears to be a trade journal that does not require a peer-review process for its articles. The author is an energy efficiency consultant with Powersure Solutions in Windsor, UK. Quoting from the article, "Absolute combustion efficiency (no particulate and zero flue emissions) would remain ideal for the combustion control technologist to continue striving for; but in the practical world, as succinctly put by Dr. I. Brown, 'all combustion control must be to some extent a trade-off between combustion efficiency and the control of emissions. . . .'" (p. 233).

Powell, Mike R., "Magnetic Water and Fuel Treatment: Myth, Magic, or Mainstream Science?" *The Skeptical Inquirer*, Vol. 22, No. 1, January–February 1998, pp. 27–32.

The abstract reads as follows:

> Magnetic treatment has been claimed to soften water and improve combustibility of fuels. A literature review reveals that these claims are not well supported by data. Magnets are not just for refrigerators any more. In fact, according to some magnet vendors, magnets can be used to improve blood circulation, cure and prevent diseases, increase automobile mileage, improve plant growth, soften water, prevent tooth decay, and even increase the strength of concrete. Some of these claims are backed by experimental evidence. Many are not. This article focuses specifically on the claimed benefits of magnetically treated fuel and water.

Rocha, Nelson, Gaspar Gonzalez, Luiz Carlos do C. Marques, and Delmo Santiago Vaitsman, "A Preliminary Study on the Magnetic Treatment of Fluids," ***Petroleum Science and Technology*****, Vol. 18, No. 1, 2000, pp. 33–50.**

This study by industry engineers and scientists presented at an industry conference study reports that magnetic fields appear to reduce the viscosity of fluids. The abstract reads as follows:

> Although the influence of magnetic fields on paraffin deposition is still dimly understood, magnetic devices have been exploited by the petroleum industry to mitigate this problem. In this study, a series of experiments were carried out using a lab-scale magnetic conditioner and two kinds of samples: paraffin mixture and crude oil. The investigated parameters were: exposition time, temperature, magnetic field intensity, paraffin type and content in the fluid and the reversibility of the observed alterations. The results indicate that magnetic fields, up to 1 Tesla applied at a temperature close to the Wax Appearance Temperature (WAT), reduce the apparent viscosity of the samples. This effect has been ascribed to changes in the paraffin crystal morphology promoted by the magnetic field. Scanning Electronic Microscopy (SEM) was fundamental to confirm this hypothesis.

The article deals with the magnetic conditioning of crude oil and mixtures of long-chain paraffins, rather than refined fuels. The theoretical explanations depend specifically on the magnetic effect on paraffin crystal morphology near the WAT, at which paraffins begin to nucleate and form waxes.[1] Since the samples had long-chain paraffins in the C16–C38 range, their WATs were necessarily at a very high temperature (~20–35C). This is much higher than gasoline (smaller chain, C5–C12). However, diesel (C10–C19) is known to exhibit cloudy behavior in winter conditions, since it can get near its WAT, but refineries typically blend additives to deal with this in winter. Although refined fuels have a lot of paraffins, they are lower molecular weight paraffins and therefore have much lower cloud points, which would not be encountered in typical vehicle operating conditions.

Tao, Rongjia, "Electro-Rheology Fluids and Liquid Fuel Flow," Southern Illinois University at Carbondale Department of Physics, ***Annual Performance Report*****, July 1, 1991–June 30, 1992a.**

The abstract reads as follows:

> Goals of this research are to understand and clarify the physical mechanism underlying the electrorheological (ER) response of fluids and establish a theory for the phenomenon; to study the structure of ER fluids and their properties, to investigate the change of viscosity of ER fluids with an applied electric field; to apply the ER phenomenon to liquid fuel flows, to control their viscosity and hence their velocity; to examine the necessary theoretical and technique problems associated to the design of a new class of liquid fuel control devices which are based on the ER phenomenon.

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[1] The term *WAT* is synonymous with *cloud point*. *Pour point* is another term that is used; it is the point at which the waxy crystals actually solidify and the substance loses its fluid qualities, usually 10–15 degrees centigrade below cloud point.

Tao, Rongjia, and X. Xu, "Viscosity Reduction in Liquid Suspensions by Electric or Magnetic Fields," ***International Journal of Modern Physics*****, Vol. 19, Nos. 7–9, April 10, 2005, pp. 1,283–1,289.**

See Chapter Two for description of work.

———, **"Reducing the Viscosity of Crude Oil by Pulsed Electric or Magnetic Field,"** ***Energy and Fuels*****, Vol. 20, No. 5, September 2006, pp. 2,046–2,051.**

See Chapter Two for description of work.

Tretyakov, I. G., M. A. Rybak, and E. Yu Stepanenko, "Method of Monitoring the Effectiveness of Magnetic Treatment for Liquid Hydrocarbons," ***Soviet Surface Engineering and Applied Electrochemistry*****, Vol. 6, 1985, pp. 80–83.**

This article provides evidence that magnetic treatment affects the dielectric properties of fuels and also the resistance of the fluids. The quality of this journal is not clear. The abstract reads as follows:

> The quality of the magnetic treatment of liquid hydrocarbons is determined from the maximum change in the tangent of the dielectric losses angle and the minimum electrical resistance level in the temperature range 293–573 degrees Kelvin. This article discusses one method of evaluating the magnetic treatment of aviation fuels and oils with a view to enhancing their performance. It is based on measuring the electrophysical characteristics of the products as a function of temperature.

Wakayama, Nobuko I., "Magnetic Buoyancy Force Acting on Bubbles in Nonconducting and Diamagnetic Fluids Under Microgravity," ***Journal of Applied Physics*****, Vol. 81, No. 7, April 1997, pp. 2,980–2,984.**

Zhakin, A. I., "The Surface Tension of Solutions and Suspensions as a Function of the Magnetic- and Electric-Field Strengths," ***Magnitnaya Gidrodinamika*** **(in English,** ***Magnetohydrodynamics*****), Vol. 25, No. 3, 1989, pp. 75–80 (in English, pp. 342–347).**

Surface tension γ as a function of magnetic-field strength H may significantly affect surface processes (for example, the stability of drops and of a jet of magnetic fluid). Regarding the effect of the electric field E on γ , this phenomenon is familiar to us as the electrocapillary effect. In each of these cases, the precise theories are far from fully refined in light of the mathematical difficulties encountered in finding two-particle distribution functions for the impurity component. For this reason, the value of γ in the solutions is determined under certain assumptions, i.e., by means of phenomenological methods.

Environmental Protection Agency Reports

Barth, Edward Anthony, *EPA Evaluation of the POLARION-X Device Under Section 511 of the Motor Vehicle Information and Cost Savings Act*, Washington, D.C.: GPO, EPA-AA-TEB-511-82-9, August 1982a.

The abstract reads as follows:

> This document announces the conclusions of the EPA evaluation of the POLARION-X device under the provisions of Section 511 of the Motor Vehicle Information and Cost Savings Act. The evaluation of the POLARION-X device was conducted upon receiving an application from the marketer of the device. The POLARION-X is installed in the fuel line between the pump and the carburetor. It incorporates two permanent magnets that subject the fuel to the magnetic field. This device is claimed to reduce emissions, to improve fuel economy and performance, to provide more complete combustion, to eliminate engine carbon buildup and dieseling, and to reduce the octane requirements of the engine.

EPA fully considered all of the information that the applicant submitted. The overall conclusion was that there was no reason to expect that the POLARION-X would improve either the emissions or fuel economy of a typical motor vehicle in proper operating conditions.

Barth, Edward Anthony, *EPA Evaluation of the Petromizer Device Under Section 511 of the Motor Vehicle Information and Cost Savings Act*, Ann Arbor, Mich.: Test and Evaluation Branch, Emission Control Technology Division, Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, EPA-AA-TEB-511-83-2, December 1982b.

The abstract reads as follows:

> This document announces the conclusions of the EPA evaluation of the PETRO-MIZER device under the provisions of Section 511 of the Motor Vehicle Information and Cost Savings Act. The evaluation of the "PETRO-MIZER" device was conducted upon receiving an application for evaluation by the marketer. The "PETRO-MIZER" consists of a tube made from non-magnetic material through which the fuel to be treated flows. Permanent bar magnets are mounted against the tube and sealed in place with resin. A metal casing acts as the outer shell of the device. The "PETRO-MIZER" is a device that, when used in a fuel line leading to the engine of an automobile or truck, results in improved fuel efficiency and reduction in the amounts of polluting emissions. EPA fully considered all of the information submitted by the applicant. The evaluation of the "PETRO-MIZER" device was based on that information and EPA's engineering judgment and the results of EPA's experience with similar devices. The information supplied by the applicant was insufficient to adequately substantiate either the emissions or fuel economy benefits claimed for the device. We have concluded there is not technical basis to justify an EPA confirmatory test program on the device or to expect that the device would improve either emissions or fuel economy.

Shelton, John C., *EPA Evaluation of the Wickliff Polarizer Device Under Section 511 of the Motor Vehicle Information and Cost Savings Act*, Washington, D.C.: U.S. Environmental Protection Agency, EPA-AA-TEB-511-81-17, June 1981.

This document announces the conclusions of the EPA evaluation of the Wickliff Polarizer device under provisions of Section 511 of the Motor Vehicle Information and Cost Savings Act.

U.S. Environmental Protection Agency, *EPA Motor Vehicle Aftermarket Retrofit Device Evaluation Program*, Ann Arbor, Mich.: U.S. Environmental Protection Agency, Office of Mobile Sources, EPA/420/B-00/003, May 2000a.

EPA conducts a program to evaluate aftermarket retrofit devices that are intended to improve automobile fuel economy or reduce their air emissions. This report is designed to help investors applying for an EPA evaluation of their product.

———, ***Program Update: Reducing Air Pollution from Nonroad Engines*, Washington, D.C.: U.S. Environmental Protection Agency, EPA420-F-00-048, November 2000b.**

———, **"Gas Saving and Emission Reduction Devices Evaluation," *Cars and Light Trucks*, Web page, last updated December 18, 2006.**

This page contains downloadable test reports for specific products that EPA tested under the Aftermarket Retrofit Device Evaluation Program, also know as the "511 Program." EPA evaluates aftermarket retrofit devices, which are claimed to improve fuel economy or reduce exhaust emissions. The program's purpose is to generate, analyze, and disseminate technical data; EPA does not approve or certify retrofit devices.

Product Literature and Web Site Information

AZ Industries Incorporated, "History of Polarion-X," 1981a.
———, **"Principle of Polarion-X," 1981b.**

The product literature reads as follows:

> POLARION-X is a new product based on strong magnetic fields affecting liquids passing over a magnet surface. This causes gasoline to burn cleaner and more completely. The magnetic energy increases the combustion ratio to get more mileage from the tank of gasoline. Japanese scientists working with magnets discovered electromagnetic forces could be used in fuel lines to increase combustion and cause a greater vaporization of hydrocarbon fuels and water. This report also contains testing results of the product POLARION-X Fuel Saver Device from Transportation Testing Incorporated of Texas.

ECOFLOW, Ltd.

This company makes the same claims cited in the article by Powell. There were several related articles in trade journals, a report by a UK government lab, and hints that other labs (including the Florida Department of Highway Safety and Motor Vehicles) also tested the equipment. There is no credible data given to support claims or the scientific basis for the equipment. The best evidence given is the government report. However, the government lab contested the results itself. The office in Florida that the company listed could not verify that the tests had occurred.

Fitch Fuel Catalyst, "The Fitch® Fuel Catalyst," homepage, undated(a).
This Web page provides fuel and emission test results and summary information regarding the Fitch fuel catalyst.

———, **"The Fitch® Fuel Catalyst: About Our Company," Web page, undated(b).**
This Web page provides a detailed product description.

Shelley, Tom, "Magnetised Fuel Feeds Engine Efficiency," ***Eureka*****, Vol. 17, No. 1, January 1997, pp. 27–30.**
The article reports on a controversial magnetic field development that has the potential to reduce fuel bills dramatically.

TornadoFuelSaver, homepage, undated.
This Web site contains information regarding the TornadoFuelSaver.

APPENDIX B

Results of Two-Sample t-Tests on Data from California and Thailand Testing Laboratories

This appendix presents the results of statistical tests (two-sample t-tests) conducted on the test results provided to RAND by STWA from independent testing laboratories in California and Thailand. These labs tested emissions (TCH, NO_X, CO, and CO_2) along with FE or FC for vehicles in baseline and device configurations, according to the basic protocol described in the body of this report. The vehicles tested in California included a 1971 VW Beetle (VW) and a 1984 Ford Mustang (Ford). The vehicle tested in Thailand was a Suzuki Best 125cc motorcycle (Suzuki).

VW Tests

Test results for the Volkswagen are presented in the different panels of Table B.1.

We ran several t-tests to define whether there is a statistically significant decrease or increase in emissions and efficiency measures between the two test configurations for the VW. The results are provided in the panels of Table B.2. Note that, in these tables, *group 1* refers to the baseline test configuration and *group 2* refers to the device installed test configuration.

Table B.1a
Test Results for Volkswagen

Mark	Run	Configuration	THC (g/mi)	NO_x (g/mi)	CO (g/mi)	CO_2 (g/mi)	FE (mpg)
VW	1	Baseline	2.80	2.41	27.41	322	35.22
VW	2	Device	2.66	2.39	28.46	316	36.22
VW	3	Baseline	2.44	2.40	24.41	315	35.71
VW	4	Device	2.95	2.28	28.02	322	35.97
VW	5	Baseline	2.79	2.33	27.50	313	36.08
VW	6	Device	2.86	2.47	29.85	322	36.43

Table B.1b
Summary of Test Results for Baseline Test Configuration

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
THC	3	2.68	0.21	2.44	2.80
NO_X	3	2.38	0.04	2.33	2.41
CO	3	26.44	1.76	24.41	27.50
CO_2	3	317	5	313	322
FE	3	35.67	0.43	35.22	36.08

Table B.1c
Summary of Test Results for Device Installed Test Configuration

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
THC	3	2.82	0.15	2.66	2.95
NO_X	3	2.38	0.10	2.28	2.47
CO	3	28.78	0.96	28.02	29.85
CO_2	3	320	3	316	322
FE	3	36.21	0.23	35.97	36.43

The results of the t-test on NO_X (Table B.2a) show that, on average, the mean of NO_X emissions of the device installed test configuration is the same as that of the baseline configuration. As apparent from Table B.2, the p-value is very large. Therefore, we can conclude that, at the conventional significance level of 0.05, there is no significant difference between the NO_X emissions under these two test configurations.

The results of the t-test on THC (Table B.2b) show that the estimated mean of THC emission for the device installed configuration is 0.15 g/mi larger than that of the baseline configuration. However, since the p-value (0.37) is larger than 0.05, at the conventional significance level of 0.05, there is no significant difference between the THC emissions under these two test configurations.

The results of the t-test on CO (Table B.2c) show that the estimated mean of CO emission under the device installed configuration is 2.34 g/mi larger than that of the baseline configuration. Also, the p-value (0.11) is larger than 0.05. Therefore, we conclude that, at the conventional significance level of 0.05, there is no significant difference between the CO emissions under these two test configurations.

The results of the t-test on CO_2 (Table B.2d) show that the estimated mean of CO_2 emission under the device installed configuration is –3 g/mi larger than that of the baseline configuration. Also, the p-value (0.38) is larger than 0.05. Therefore, we conclude that, at the conventional significance level of 0.05, there is no significant difference between the CO_2 emissions under these two test configurations.

Table B.2a
t-Test on NO_x: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	3	2.38	0.03	0.04	2.27	2.49
2	3	2.38	0.06	0.10	2.14	2.62
Combined	6	2.38	0.03	0.07	2.37	2.45
Difference		0	0.06		–0.17	0.17

NOTE: diff = mean(1) – mean(2). t = 0.00. H_O: diff = 0. Degrees of freedom = 4.
(H_A): diff < 0 H_A: diff ≠ 0 H_A: diff > 0
Pr(T < t) = 0.50 Pr(|T| > |t|) = 1.00 Pr(T > t) = 0.50

Table B.2b
t-Test on THC: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	3	2.68	0.12	0.21	2.17	3.19
2	3	2.82	0.09	0.15	2.45	3.19
Combined	6	2.75	0.07	0.18	2.56	2.94
Difference		–0.15	0.15		–0.55	0.26

NOTE: diff = mean(1) – mean(2). t = –1.0036. H_O: diff = 0. Degrees of freedom = 4.
H_A: diff < 0 H_A: diff ≠ 0 H_A: diff > 0
Pr(T < t) = 0.19 Pr(|T| > |t|) = 0.37 Pr(T > t) = 0.81

Table B.2c
t-Test on CO: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	3	26.44	1.02	1.76	22.07	30.81
2	3	28.78	0.55	0.96	26.40	31.15
Combined	6	27.61	0.73	1.80	25.72	29.50
Difference		–2.34	1.16		–5.54	0.87

NOTE: diff = mean(1) – mean(2). t = –2.02. H_O: diff = 0. Degrees of freedom = 4.
H_A: diff < 0 H_A: diff ≠ 0 H_A: diff > 0
Pr(T < t) = 0.06 Pr(|T| > |t|) = 0.11 Pr(T > t) = 0.94

The results of the t-test on FC (Table B.2e) show that the estimated mean of FE under the device installed configuration is 0.54 mpg larger than that of the baseline configuration. Also, the p-value (0.13) is larger. Therefore, we conclude that, at the conventional significance level of 0.05, there is no significant difference between the FE of these two test configurations.

To conclude, the t-tests neither show significant reduction in any of the emissions nor increase in fuel efficiency measures on the VW.

Ford Tests

Table B.3 presents test results for the Ford.

We ran several t-tests to define whether there was a statistically significant decrease or increase in emissions and efficiency measures between the two test configurations for Ford. Table B.4 provides the results. Note that, in these tables, *group 1* refers to the baseline test configuration and *group 2* refers to the device installed test configuration.

The results of the t-test on NO_X (Table B.4a) show that the estimated mean of NO_X emission of the device installed test configuration is 0.02 g/mi smaller than that of the baseline

Table B.2d
t-Test on CO_2: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	3	316	3	5	305	328
2	3	320	2	3	311	329
Combined	6	318	2	4	314	323
Difference		–3	3		–13	6

NOTE: diff = mean(1) – mean(2). t = –0.99. H_O: diff = 0. Degrees of freedom = 4.

H_A: diff < 0	H_A: diff ≠ 0	H_A: diff > 0
Pr(T < t) = 0.19	Pr(|T| > |t|) = 0.38	Pr(T > t) = 0.81

Table B.2e
t-Test on FE: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	3	35.67	0.25	0.43	34.60	36.74
2	3	36.21	0.13	0.23	35.63	36.78
Combined	6	35.94	0.17	0.43	35.49	36.39
Difference		–0.54	0.28		–1.32	0.25

NOTE: diff = mean(1) – mean(2). t = –1.90. H_O: diff = 0. Degrees of freedom = 4.

H_A: diff < 0	H_A: diff ≠ 0	H_A: diff > 0
Pr(T < t) = 0.07	Pr(|T| > |t|) = 0.13	Pr(T > t) = 0.93

Table B.3a
Test Results for Ford

Mark	Run	Configuration	THC (g/mi)	NO_X (g/mi)	CO (g/mi)	CO_2 (g/mi)	FE (mpg)
Ford	1	Baseline	5.77	0.10	81.50	624	21.94
Ford	2	Device	5.71	0.10	71.77	681	21.94
Ford	3	Baseline	6.60	0.13	91.73	622	21.59
Ford	4	Device	5.51	0.08	74.29	677	21.98
Ford	5	Baseline	6.38	0.08	88.77	604	22.53
Ford	6	Device	6.02	0.10	72.67	669	22.41
Ford	7	Baseline	6.01	0.14	80.84	607	22.63

Table B.3b
Summary of Test Results for Baseline Test Configuration

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
THC	4	6.19	0.37	5.77	6.60
NO_X	4	0.11	0.03	0.08	0.14
CO	4	85.71	5.39	80.84	91.73
CO_2	4	614	10	604	624
FE	4	22.17	0.49	21.59	22.63

Table B.3c
Summary of Test Results for Device Installed Test Configuration

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
THC	3	5.75	0.26	5.51	6.02
NO_X	3	0.09	0.01	0.08	0.10
CO	3	72.91	1.28	71.77	74.29
CO_2	3	676	6	669	681
FE	3	22.11	0.26	21.94	22.41

configuration. As apparent from Table B.4, however, the p-value (0.32) is very large. Therefore, we can conclude that, at the conventional significance level of 0.05, there is no significant difference between the NO_X emissions under these two test configurations.

The results of the t-test on THC (Table B.4b) show that the estimated mean of THC emission for the device installed configuration is 0.44 g/mi smaller than that of the baseline configuration. However, since the p-value (0.14) is larger than 0.05, at the conventional

Table B.4a
t-Test on NO_x: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	4	0.11	0.01	0.03	0.07	0.16
2	3	0.09	0.01	0.01	0.06	0.12
Combined	7	0.10	0.01	0.02	0.08	0.13
Difference		0.02	0.01722	0.12	–0.03	0.06

NOTE: diff = mean(1) – mean(2). t = 1.11. H_O: diff = 0. Degrees of freedom = 5.
H_A: diff < 0 H_A: diff ≠ 0 H_A: diff > 0
Pr(T < t) = 0.84 Pr(|T| > |t|) = 0.32 Pr(T > t) = 0.16

Table B.4b
t-Test on THC: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	4	6.19	0.19	0.37	5.60	6.78
2	3	5.75	0.15	0.26	5.11	6.39
Combined	7	6.00	0.14	0.38	5.65	6.35
Difference		0.44	0.25		–0.20	1.09

NOTE: diff = mean(1) – mean(2). t = 1.76. H_O: diff = 0. Degrees of freedom = 5.
H_A: diff < 0 H_A: diff ≠ 0 H_A: diff > 0
Pr(T < t) = 0.93 Pr(|T| > |t|) = 0.14 Pr(T > t) = 0.07

significance level of 0.05, there is no significant difference between the THC emissions under these two test configurations.

The results of the t-test on CO (Table B.4c) show that the estimated mean of CO emission under the device installed configuration is 12.8 g/mi smaller than that of the baseline configuration. Also, the p-value (0.01) is smaller than 0.05. Therefore, we conclude that, at the conventional significance level of 0.05, there is a significant difference between the CO emissions under these two test configurations.

The results of the t-test on CO_2 (Table B.4d) show that the estimated mean of CO_2 emission under the device installed configuration is –61 g/mi larger than that of the baseline configuration. Also, the p-value is very small. Therefore, we conclude that, at the conventional significance level of 0.05, there is a difference between the CO_2 emissions under these two test configurations.

The results of the t-test on FE (Table B.4e) show that, on average, the mean of FE under the device installed configuration is 0.06 mpg smaller than that of the baseline configuration. Also, the p-value (0.85) is larger than 0.05. Therefore, we conclude that, at the conventional significance level of 0.05, there is no significant difference between the FE of these two test configurations.

Table B.4c
t-Test on CO: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	4	85.71	2.69	5.39	77.14	94.28
2	3	72.91	0.74	1.28	69.74	76.08
Combined	7	80.22	2.97	7.87	72.95	87.50
Difference		12.80	3.25		4.46	21.14

NOTE: diff = mean(1) – mean(2). t = 3.94. H_O: diff = 0. Degrees of freedom = 5.
H_A: diff < 0 H_A: diff ≠ 0 H_A: diff > 0
Pr(T < t) = 0.99 Pr(|T| > |t|) = 0.01 Pr(T > t) = 0.01

Table B.4d
t-Test on CO_2: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	4	614	5	10	598	630
2	3	676	4	6	660	691
Combined	7	641	13	34	60	672
Difference		–61	7		–79	–44

NOTE: diff = mean(1) – mean(2). t = –9.14. H_O: diff = 0. Degrees of freedom = 5.
H_A: diff < 0 H_A: diff ≠ 0 H_A: diff > 0
Pr(T < t) = 0.00 Pr(|T| > |t|) = 0.00 Pr(T > t) = 1.00

Table B.4e
t-Test on FE: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	4	22.17	0.25	0.49	21.39	22.96
2	3	22.11	0.15	0.26	21.46	22.76
Combined	7	22.15	0.14	0.38	21.79	22.50
Difference		0.06	0.32		–0.75	0.88

NOTE: diff = mean(1) – mean(2). t = 0.20. H_O: diff = 0. Degrees of freedom = 5.
H_A: diff < 0 H_A: diff ≠ 0 H_A: diff > 0
Pr(T < t) = 0.57 Pr(|T| > |t|) = 0.85 Pr(T > t) = 0.43

To conclude, the t-tests show reduction in THC and NO_X emissions as well as a reduction in FE under the device installed configuration. However, these reductions are not statistically significant. The t-tests also show a significant reduction in the average CO emission under the device installed configuration. The t-tests also show a statistically significant increase in the average CO_2 emission under the device installed configuration.

Suzuki Tests

Table B.5 presents test results for the Suzuki.

The tests were performed on Suzuki Best 125 motorcycles and, as is apparent from Table B.5a, included three runs when the device was not installed and three runs after the device was installed. Tables B.5b and B.5c present summaries of these runs. Note that, in these tables, the unit of the emission measures is g/km and the unit of FC is L/100km.

We ran several t-tests to define whether there is a statistical significant decrease or increase in emissions and efficiency measures between the two test configurations. Table B.6 provides the results. Note that, in these tables, *group 1* refers to the baseline test configuration and *group 2* refers to the device installed test configuration.

The results of the t-test on NO_X (Table B.6a) show that, on average, the mean of NO_X emission of the device installed test configuration is 0.03 g/km larger than that of the baseline configuration. As apparent from Table B.6, the p-value is 0.04 (less than 0.05). Therefore, we can conclude that, at the conventional significance level of 0.05, there is a significant difference—but in the undesired direction—between the NO_X emissions of these two test configurations. The results of the t-test on THC (Table B.6b) show that, on average, the mean of THC emission for the device installed configuration is 0.01 g/km larger than that of the baseline configuration. However, since the p-value (0.61) is larger than 0.05, at the conventional significance level of 0.05, there is no difference between the THC emissions under these two test configurations.

The results of the t-test on CO (Table B.6c) show that the estimated mean of CO emission under the device installed configuration is 0.53 g/km smaller than that of the baseline configuration. Also, the p-value is very small. Therefore, we conclude that, at the conventional

Table B.5a
Suzuki Test Results from Thailand

Mark	Run	Configuration	THC (g/km)	NO_X (g/km)	CO (g/km)	CO_2 (g/km)	FC (L/100km)
Suzuki	1	Baseline	0.73	0.42	1.60	41	1.96
Suzuki	2	Device	0.77	0.43	1.01	39	1.86
Suzuki	3	Baseline	0.73	0.42	1.69	40	1.95
Suzuki	4	Device	0.71	0.47	1.14	39	1.84
Suzuki	5	Baseline	0.73	0.42	1.59	40	1.93
Suzuki	6	Device	0.75	0.46	1.14	39	1.85

Table B.5b
Summary of Test Results for Baseline Test Configuration

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
THC	3	0.73	0.00	0.73	0.73
NO_x	3	0.42	0.00	0.42	0.42
CO	3	1.63	0.05	1.59	1.69
CO_2	3	40	0	40	41
FC	3	1.95	0.02	1.93	1.96

Table B.5c
Summary of Test Results for Device Installed Test Configuration

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
THC	3	0.74	0.03	0.71	0.77
NO_x	3	0.45	0.02	0.43	0.47
CO	3	1.10	0.08	1.01	1.14
CO_2	3	38.90	0.26	38.70	39.20
FC	3	1.85	0.01	1.84	1.86

Table B.6a
t-Test on NO_x: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	3	0.42	0.00	0.00	0.41	0.43
2	3	0.45	0.01	0.02	0.40	0.50
Combined	6	0.44	0.01	0.02	0.41	0.46
Difference		–0.03	0.01		–0.07	–0.00

NOTE: diff = mean(1) – mean(2). t = –2.95. H_0: diff = 0. Degrees of freedom = 4.

H_A: diff < 0	H_A: diff ≠ 0	H_A: diff > 0
Pr(T < t) = 0.02	Pr(|T| > |t|) = 0.04	Pr(T > t) = 0.98

significance level of 0.05, there is a significant difference between the CO emissions of these two test configurations.

The results of the t-test on CO_2 (Table B.6d) show that the estimated mean of CO_2 emission under the device installed configuration is 1.47 g/km smaller than that of the baseline configuration. Also, the p-value is very small. Therefore, we have enough evidence to conclude that, at the conventional significance level of 0.05, there is a significant difference between the CO_2 emissions of these two configurations.

Table B.6b
t-Test on THC: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	3	0.73	0.00	0.00	0.73	0.74
2	3	0.74	0.02	0.03	0.67	0.82
Combined	6	0.74	0.01	0.02	0.72	0.76
Difference		–0.01	0.02		–0.06	0.04

NOTE: diff = mean(1) – mean(2). t = –0.55. H_O: diff = 0. Degrees of freedom = 4.
H_A: diff < 0 H_A: diff ≠ 0 H_A: diff > 0
Pr(T < t) = 0.30 Pr(|T| > |t|) = 0.61 Pr(T > t) = 0.70

Table B.6c
t-Test on CO: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	3	1.63	0.03	0.05	1.49	1.76
2	3	1.10	0.04	0.06	0.91	1.29
Combined	6	1.36	0.12	0.29	1.05	1.67
Difference		0.53	0.05		0.38	0.68

NOTE: diff = mean(1) – mean(2). t = 9.85. H_O: diff = 0. Degrees of freedom = 4.
H_A: diff < 0 H_A: diff ≠ 0 H_A: diff > 0
Pr(T < t) = 1.00 Pr(|T| > |t|) = 0.00 Pr(T > t) = 0.00

Table B.6d
t-Test on CO_2: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	3	40	0	0	40	41
2	3	39	0	0	38	40
Combined	6	40	0	1	39	41
Difference		1	0		1	2

NOTE: diff = mean(1) – mean(2). t = 6.96. H_O: diff = 0. Degrees of freedom = 4.
H_A: diff < 0 H_A: diff ≠ 0 H_A: diff > 0
Pr(T < t) = 1.00 Pr(|T| > |t|) = 0.00 Pr(T > t) = 0.00

The results of the t-test on FC (Table B.6e) show that the estimated mean of FC under the device installed configuration is 0.10 L/100km smaller than that of the baseline configuration.

Also, the p-value is very small. Therefore, we conclude that, at the conventional significance level of 0.05, there is a significant difference between the FC of these two test configurations.

To conclude, the t-tests show a significant reduction in average CO and CO_2 emissions as well as a significant reduction in the average FC when the device is installed. However, this conclusion does not hold for NO_X and THC emissions. The t-test shows a significant increase in the average NO_X emission when the device is installed and shows an increase in the average THC emission, although the latter is not significant.

Table B.6e
t-Test on FC: Two-Sample t-Test with Equal Variances

Group	Observations	Mean	Standard Error	Standard Deviation	95% Confidence Interval	
					Minimum	Maximum
1	3	1.95	0.01	0.02	1.91	1.98
2	3	1.85	0.01	0.01	1.83	1.87
Combined	6	1.90	0.02	0.05	1.84	1.96
Difference		0.10	0.01		0.07	0.13

NOTE: diff = mean(1) – mean(2). t = 9.17. H_O: diff = 0. Degrees of freedom = 4.
H_A: diff < 0 H_A: diff ≠ 0 H_A: diff > 0
Pr(T < t) = 1.00 Pr(|T| > |t|) = 0.00 Pr(T > t) = 0.00

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