



# SmartWay Applications for Drayage Trucks

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by

*Monica Beard-Raymond*

Assistant Research Scientist

Center for Air Quality Studies, Texas Transportation Institute

Tel.: (512) 467-0946 Email: [mbraymond@tamu.edu](mailto:mbraymond@tamu.edu)

*Mohamadreza Farzaneh, Ph.D.*

Assistant Research Scientist

Center for Air Quality Studies, Texas Transportation Institute

Tel.: (512) 467-0946 Email: [mfarzaneh@tamu.edu](mailto:mfarzaneh@tamu.edu)

*Carlos Duran*

Graduate Research Assistant

Research and Implementation Division, Texas Transportation Institute

Tel.: (915) 532-3759 Email: [c-duran@tamu.edu](mailto:c-duran@tamu.edu)

*Josias Zietsman, Ph.D., P.E.\**

Center Director

Center for Air Quality Studies, Texas Transportation Institute

Tel.: (979) 458-3476 Email: [zietsman@tamu.edu](mailto:zietsman@tamu.edu)

*Doh-Won Lee, Ph.D.*

Assistant Research Scientist

Center for Air Quality Studies, Texas Transportation Institute

Tel.: (979) 862-2232 Email: [leedw@tamu.edu](mailto:leedw@tamu.edu)

and

*Jeremy Johnson.*

Associate Research Specialist

Center for Air Quality Studies, Texas Transportation Institute

Tel.: (979) 862-7253 Email: [j-johnson@ttimail.tamu.edu](mailto:j-johnson@ttimail.tamu.edu)

*\* Principal Investigator and Corresponding Author*

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# 1. EXECUTIVE SUMMARY

Drayage trucks operating daily across the border between the U.S. and Mexico can be a significant source of emissions, which negatively impact air quality. The U.S. Environmental Protection Agency's (EPA) SmartWay Transport Partnership program helps to reduce fuel usage and emissions from freight operations through the use of technologies and best practices. SmartWay strategies are primarily touted for long-haul trucking and not the short haul operations found in drayage vehicles. This project tests the applicability of three SmartWay strategies (use of lighter trailers, modified driving behavior, and the use of diesel oxidation catalysts) for border drayage operations.

This project studies the availability, use, and effect of SmartWay technologies on emissions and fuel use from drayage trucks traveling between the U.S. and Mexico. The overall goal of this project is to provide a broad range of stakeholders (drayage truck owners and operators and public and private sector organizations) with information on effective SmartWay technologies for drayage trucks.

The study focuses on the El Paso-Ciudad Juárez border area. The area has a significant drayage truck circulation that is typical of other drayage activities along the U.S./Mexico border. El Paso is currently categorized as nonattainment for particulate matter (PM<sub>10</sub>), and border-crossing activities directly impact El Paso's air quality and attainment status.

Three different SmartWay strategies were tested and evaluated for their emissions and fuel consumption impacts. Based on their costs, potential emissions benefits and applicability to drayage operations, the study tested the emissions and fuel economy performance of lighter trailers, driving behavior, and diesel oxidation catalysts (DOCs). Five drayage trucks representing common makes and models were tested with portable emissions measurement systems (PEMS) units before and after implementation of a SmartWay strategy. PEMS collected second-by-second emissions of oxides of nitrogen (NO<sub>x</sub>), hydrocarbons (HC), carbon monoxide (CO), PM, and carbon dioxide (CO<sub>2</sub>). CO<sub>2</sub> emissions served as a proxy for fuel consumption testing.

This project required a funding match from another source – for this, testing of a fuel combustion enhancer from Carbon Chain Technologies Limited was performed in addition to the emissions measurement of the three selected SmartWay technologies. The company's 2ct® product was tested in light duty gasoline vehicles and heavy-duty diesel vehicles for fuel economy and emissions, and may have potential for future applicability for emissions reduction efforts and for Smartway. The abstract from this project is included in Appendix B.

The Texas Transportation Institute (TTI) compared the emissions results from baseline tests with results from tests performed with a SmartWay strategy deployed. The EPA's Motor Vehicle Emissions Simulator (MOVES) model approach was employed, which uses vehicle-specific power (VSP) and operating mode bins to evaluate emissions.

The research team developed and implemented a data collection and data analysis methodology based on the EPA's MOVES model's analysis framework. The methodology is

based on the concept of second-by-second modal emissions rates based on VSP. Driving patterns were developed to cover broad range of drayage trucks operational modes. The methodology significantly reduces the duration of the data collection effort compared to using regular drive cycles.

The gaseous ( $\text{CO}_2$ , CO,  $\text{NO}_x$ , and total HC [THC]) and PM emissions rates were measured using two PEMS units. Using the previously-mentioned VSP-based approach, the collected emissions data were grouped into operating mode bins according to criteria used in EPA's MOVES model and average emissions rates for each bin were calculated from all the observations that fall within that operating mode bin.

The research team found that the operating mode bins provide satisfactory estimates for drayage operation at the U.S./Mexico border. A cycle-based analysis was performed using the drayage operation speed profiles that were collected using a Global Positioning System (GPS) technology. The results show that DOCs provide major THC and CO reduction benefits for drayage operations. Lightweight trailers and Eco Driving were also found to decrease CO and THC emissions moderately. Only Eco Driving appeared to have a positive impact on  $\text{CO}_2$ , fuel consumption, and  $\text{NO}_x$  emissions. All the investigated strategies resulted in lowering PM emissions compared to the baseline.

## 2. BACKGROUND INFORMATION

Vehicle emissions measurement is a highly technical endeavor. This section provides the background information necessary to understand the significance of the project and the reasoning behind the project team's approach and methodology for evaluating the effectiveness of key SmartWay strategies on drayage operations. The section on drayage operations highlights why understanding and mitigating these emissions are important. The remaining sections on border crossings, SmartWay strategies, in-use testing, and EPA's MOVES model methodology all serve to provide the background information necessary to understand the scientific approach underlying the project's methodology.

### DRAYAGE OPERATIONS

In 2007, more than \$347 billion worth of goods were traded between the U.S. and Mexico.<sup>1</sup> Most of this trade is conducted through container transport across the international boundary between the two countries via truck or rail. These goods must enter or exit the U.S. through one of 29 commercial truck ports of entry (POE) along the U.S.'s southern border. International shipments crossing the border via truck have a significant impact on both the economy and the environment in the areas where the goods cross.

An estimated 90 percent of truck traffic between the U.S. and Mexico is comprised of drayage trucks used for short haul trucking.<sup>2</sup> With few exceptions, Mexico-domiciled carriers are limited to the commercial zone that generally extends from 3-to-25 miles north of the border. This results in the vast majority of shipments crossing the border by short hauls, in which Mexican cargo destined for the U.S. is dropped off near the border, loaded onto a drayage truck, taken across the border and then unloaded at a location within the U.S. commercial zone.

The border crossing at El Paso, Texas and Ciudad Juárez, Mexico is one of the busiest border crossings in the state. Ciudad Juárez is El Paso's sister city across the border and is the largest city in the state of Chihuahua and the fifth largest city in Mexico. The metropolitan area of Ciudad Juárez and El Paso comprises of more than 2.2 million people, making it the largest bi-national metropolitan area in the world.<sup>3</sup> El Paso is currently the sixth largest city in Texas and the 21<sup>st</sup> largest city in the U.S. In 2007, more than 780,000 trucks from Mexico entered the U.S. from one of El Paso's two international bridges for commercial trade.<sup>4</sup>

Following the implementation of the North American Free Trade Agreement (NAFTA), trade between the U.S. and Mexico increased substantially. Northbound commercial movements through the Ciudad Juárez-El Paso gateways have continuously risen over the past 10 years.<sup>5</sup> The overall growth of northbound commercial movements between Ciudad Juárez and El Paso

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<sup>1</sup> U.S. Census Bureau. *Top Ten Countries with which U.S. Trades*, <http://www.census.gov/foreign-trade/top/dst/2007/12/balance.html>, accessed December 2008.

<sup>2</sup> *Mexican Truck Idling Emissions at the El Paso-Ciudad Juarez Border Location*. Texas Transportation Institute, The Texas A&M University System, College Station, TX, November 2005.

<sup>3</sup> El Paso. *El Paso Information and Links*, <http://www.elpasoinfo.com/>, accessed November 2008.

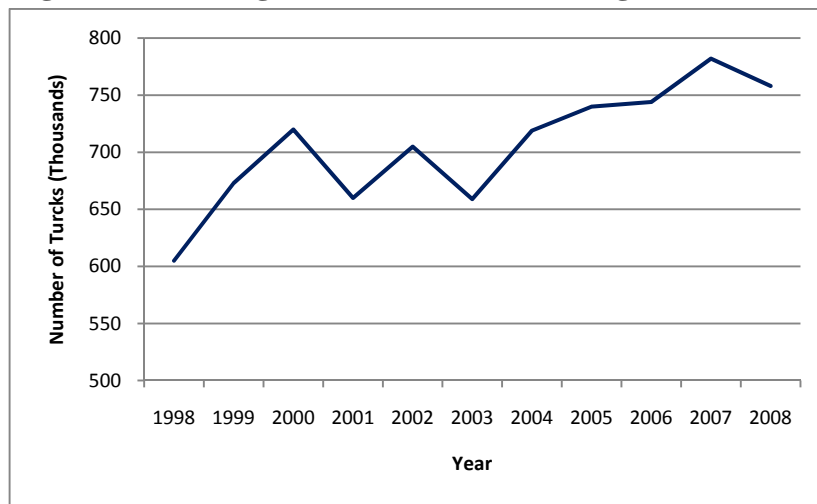
<sup>4</sup> Texas A&M International University, Texas Center for Border Economic and Enterprise Development. [http://texascenter.tamiu.edu/texcen\\_services/truck\\_crossings.asp?framepg=datatruck](http://texascenter.tamiu.edu/texcen_services/truck_crossings.asp?framepg=datatruck), accessed November 2008.

<sup>5</sup> US Customs and Border Protection, <http://www.cbp.gov/>, accessed October 2008.

increased by more than 153,000 crossings over the past decade, as Figure 1 shows. The effect of the economic slowdown is seen in a significant reduction in the number of trucks crossing the US-Mexico border at the ports of El Paso in 2008.

More than 40 percent of Mexican exports can be traced to maquiladoras.<sup>6</sup> Maquiladoras are foreign owned factories in Mexico that import raw materials, assemble them into products and then export the manufactured goods back into the originating country (typically the U.S.). Many of these manufacturing facilities receive raw materials from the U.S. and ship assembled goods back across the U.S./Mexico border in significant volumes.

**Figure 1. Incoming Truck Movements through El Paso, TX.**



SOURCE: U.S. Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics, Border Crossing/Entry, accessed October 2009

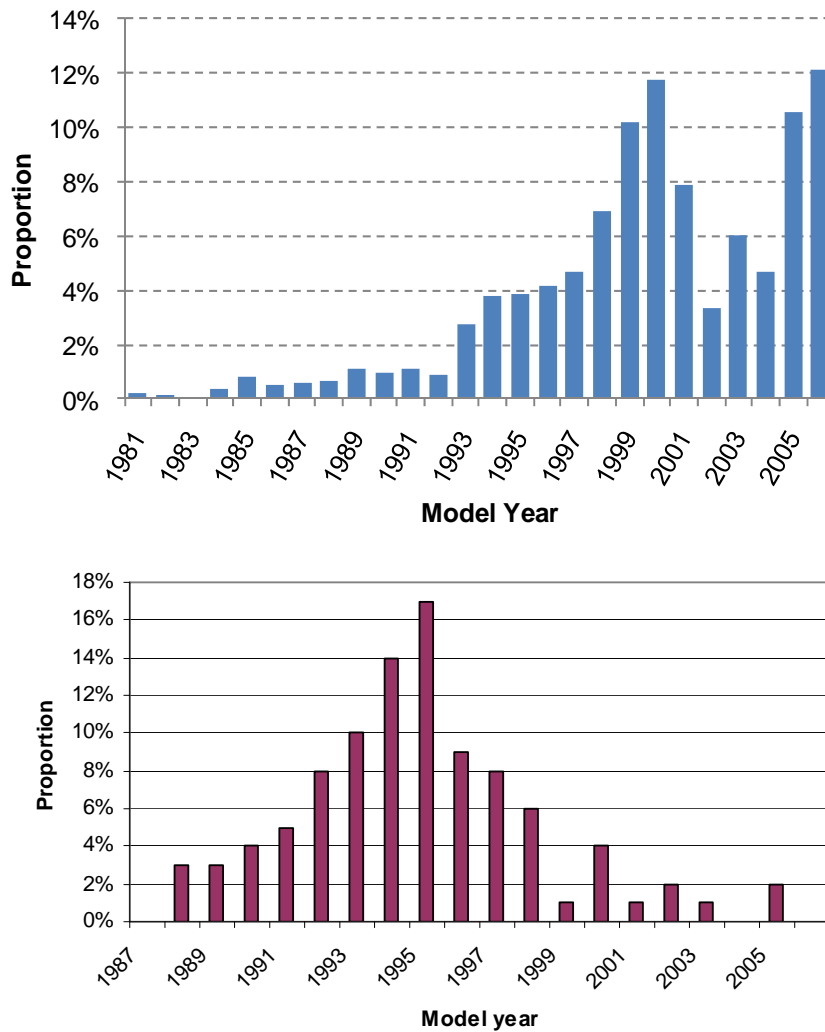
Despite much controversy, the U.S. has made proposals and plans for opening up the border to Mexican trucks and allowing them to operate beyond the U.S. commercial zone. If the U.S. border is opened to Mexican trucks, then current drayage operations could be altered significantly. However, the scale and impact of this potential change is unknown. A report evaluating the safety performance of Mexican trucks found insufficient Mexican participation in the study, which may indicate that significant barriers exist beyond legally opening the border for Mexican long-haul trucking in the U.S.<sup>7</sup> More definitive studies on the safety implications of opening the southern border are underway, and it will be a minimum of one year before the federal government will make a decision regarding whether Mexican trucks will be allowed to operate within the interior U.S.

<sup>6</sup> Dallas Federal Reserve. *NAFTA and Maquiladoras: Is Growth Connected?*, [http://www.dallasfed.org/research/border/tbe\\_gruben.html](http://www.dallasfed.org/research/border/tbe_gruben.html), accessed November 2008.

<sup>7</sup> Downey III, Mortimer L., et. al. *Independent Evaluation Panel Report to the U.S. Secretary of Transportation: U.S.-Mexico Cross-Border Trucking Demonstration Project*. October 31, 2008. <http://www.dot.gov/affairs/PanelReport.pdf>, accessed November 2008.

Drayage trucks are typically older and less well maintained than long-haul trucks and therefore can emit more pollution than their newer, long-haul counterparts<sup>8</sup>. Figure 2 shows the age distribution of a sample of drayage trucks and the Texas fleet age distribution from registration data. The drayage fleet age distribution belongs to Laredo border crossing and is based on a border survey performed by TTI in 2006. It is expected that drayage fleet operating in the El Paso region would have similar characteristics. As shown in Figure 2, approximately 55 percent of U.S. class 8b trucks registered in Texas in 2006 were newer than model year 2000 (with 85 percent newer than 1995) while only 10 percent of drayage fleet was newer than 2000 ( and only 40 percent newer than 1995).

**Figure 2. Age Distribution of Drayage Fleet and Long-Haul Fleet Trucks.**



<sup>8</sup> Note: The research team could not find any other documentation of the maintenance level of the drayage fleet at El Paso; however, the field observations by the research team indicated a poor level of maintenance compared to other long-haul trucks.



A drayage truck's typical stop-and-go driving cycle contributes to increased emissions with more frequent stops and idling during border crossing times and load/unload periods. Drayage trucks typically make daily trips in fewer than 200 miles and do not idle overnight.<sup>9</sup> While drayage fleets are primarily comprised of small carriers, there are several carriers that dominate the El Paso-Juárez border crossing. A prior TTI study surveyed more than 200 different carriers crossing the border, but found that 16 account for approximately half of the total trips.<sup>10</sup> Presumably, this translates into a rather consistent fleet of trucks crossing the border.

## **DRAYAGE BORDER CROSSINGS**

El Paso is home to two of the largest commercial POEs along the U.S.'s southern border – the Bridge of the Americas (BOTA) and the Ysleta-Zaragoza Bridge. El Paso is second only to Laredo in the number of northbound truck shipments crossing along the U.S.'s southern border.<sup>11</sup> While the Ysleta-Zaragoza crossing has longer hours of operation, the facility charges a toll (approximately \$10), and therefore many drayage operators prefer the BOTA.

A previous TTI study evaluated drayage idling at both bridges. Outlined in Table 1, the study found that average percentage of time spent in idling and creep idling were in excess of 60 percent for both bridges. Creep idling or “queue” idling refers to the type of idling that occurs when trucks waiting in long lines idle and move very slowly. Normal type of idling is in excess of creep idling. This normal idling is very significant because creep idling is very difficult to control and most idle control technologies are not effective for creep idling applications. The Ysleta-Zaragoza crossing had higher travel and idling times than the BOTA crossing. The average normal idle time per truck per crossing for the BOTA was 9.5 minutes and 21.5 minutes for the Ysleta-Zaragoza crossing.

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<sup>9</sup> U.S. EPA. *DrayFLEET: EPA SmartWay Drayage Activity and Emissions Model and Case Studies*, <http://www.epa.gov/smartway/transport/documents/drayage/final-dray-fleet-report.pdf>, accessed November 2008.

<sup>10</sup> *Mexican Truck Idling Emissions at the El Paso-Ciudad Juarez Border Location*. Texas Transportation Institute, The Texas A&M University System, College Station, TX, November 2005.

<sup>11</sup> Bureau of Transportation Statistics. *U.S. Border Crossings*, <http://www.transtats.bts.gov/BorderCrossing.aspx>, accessed October 2008.

**Table 1. Summary of Travel Time, Normal Idling and Creep Idling.**

Section	BOTA			Ysleta-Zaragoza		
	Travel Time (min)	% Normal Idle	% Creep Idle	Travel Time (min)	% Normal Idle	% Creep Idle
1- Mexican customs booth to U.S. primary inspection station	8.5	41%	18%	11.1	36%	13%
2- Within U.S. federal compound	8.2	62%	13%	23.0	75%	8%
3- From federal compound to state Border Safety Inspection Facility (BSIF) exit	4.2	13%	29%	-	-	-
<b>Total</b>	<b>21.0</b>	<b>45%</b>	<b>18%</b>	<b>34.2</b>	<b>63%</b>	<b>9%</b>

Source: *Mexican Truck Idling Emissions at the El Paso-Ciudad Juárez Border Location*. Texas Transportation Institute, The Texas A&M University System, College Station, TX, November 2005.

TTI's study also examined idling times during peak and off-peak periods and for Free and Secure Trade (FAST) program and non-FAST trucks. The FAST program provides carriers an expedited border crossing in exchange for increased security measures. Table 2 provides a summary of idling and volume per travel mode.

**Table 2. Idling, Creep Idling and Volumes per Travel Mode.**

Travel Mode	BOTA			Ysleta-Zaragoza		
	Volume (veh/day)	Normal idle time (min)	Creep idle time (min)	Volume (veh/day)	Normal idle time (min)	Creep idle time (min)
Off-peak/FAST	90	4.1	4.2	89	7.1	2.3
Off-peak/Non-FAST	420	16.5	3.7	432	33.9*	5.1
Peak/FAST	140	8.5	3.2	141	20.8	1.7
Peak/Non-FAST	651	9.5*	5.2	683	11.4*	2.4*

\* These values are adjusted by providing different weights because only 1 percent of the cases represent extensively long crossing times (commonly from secondary inspections).

Source: *Mexican Truck Idling Emissions at the El Paso-Ciudad Juárez Border Location*. Texas Transportation Institute, The Texas A&M University System, College Station, TX, November 2005.

Contrary to expectations, the table suggests that FAST participation does not consistently reduce idle times. While normal idling was reduced for FAST participants at the BOTA and for off-peak idling at the Ysleta-Zaragoza crossing, the idling times actually increased for FAST members during peak times at the Ysleta-Zaragoza crossing. For creep idling, FAST participants had lower creep idling times compared to their non-FAST counterparts except during the off-peak period at the BOTA crossing.

The table also indicates that peak periods do not consistently increase idling times. For FAST program participants, normal idling increased during peak periods but creep idling was reduced at the Ysleta-Zaragoza crossing. For non-FAST trucks, peak period idling was reduced for normal idling and for creep idling at the Ysleta-Zaragoza crossing. However, creep idling increased during peak periods at the BOTA.

Together, these findings indicate that other factors may significantly affect truck idling times. However, consistency could be found in that for almost every category for each crossing, normal idling occurred for longer durations than creep idling. Also noteworthy is the observation that truck volumes were fairly similar between the two crossings with slightly more trucks utilizing the Ysleta-Zaragoza crossing presumably because of its longer operating hours.

#### **DRAYAGE EMISSIONS AND SMARTWAY STRATEGIES**

Emissions from drayage traffic crossing the border contributes to El Paso's air quality issues. A TTI study found that drayage idling alone at the border produced 24 tons/year of NOx and 600 pounds/year of PM.<sup>12</sup> These emissions account for a small percentage of the overall onroad emissions budget (which is a ceiling on emissions levels used in conformity determination), yet generate a high concentration of emissions in a small geographic area and do not include the whole of emissions contributed by drayage truck operations. El Paso is in moderate nonattainment for PM-10 and was just recently found to be in compliance with CO. Reducing idling and emissions from drayage trucks can help mitigate these emissions.

Fortunately, there are many options for reducing idling and emissions from heavy-duty diesel trucks. EPA's SmartWay Transport Partnership Program outlines options for reducing greenhouse gas (GHG) emissions and air pollution from freight movement. It should be noted that not all strategies uniformly decrease all emissions – some may decrease only certain types of emissions and may even increase certain others. Strategies can be divided into the following categories.

- Engine, tire and truck modifications- low rolling resistance tires, auto-tire inflation, aerodynamic improvements, low-viscosity lubricants, lighter tractors and trailers, and SmartWay certified trailers.
- Idle reduction technologies- bunker heaters, auxiliary power units (APUs), automatic shut down and start up systems, and electrified parking spaces.

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<sup>12</sup> *Mexican Truck Idling Emissions at the El Paso-Ciudad Juarez Border Location*. Texas Transportation Institute, The Texas A&M University System, College Station, TX, November 2005.

- Diesel retrofit and advanced technologies- hybrid power-train technology, DOC, diesel particulate filter (DPF), selective catalytic reduction (SCR), and replacing engine and trucks with newer models complying with new emission certification standards.
- Cleaner fuels- compressed natural gas (CNG) and biodiesel.
- Operational strategies- speed reduction, driver education, and improved freight logistics.

SmartWay certified trailers employ a combination of strategies to reduce fuel consumption and emissions, and contain components that overlap with the more itemized options on the list. SmartWay provides a list of specific model trailers on their website. These certified trailers include:

- side skirts;
- weight-saving technologies (optional);
- gap reducer on the front or trailer tails (either extenders or boat tails); and
- options for low-rolling resistance tires (single wide or dual). Weight-saving aluminum wheels are optional.

SmartWay also has a certification program for tractors that requires a host of aerodynamic devices, a 2007 or later model year engine, and an idle control device. For drayage operations, this strategy would often be incorporated as a truck replacement strategy.

## **IN-USE EMISSIONS MEASUREMENT**

Direct vehicle emissions measurements are either performed in a laboratory with a chassis or engine dynamometer or occur during in-use operation with a PEMS. This project used PEMS to test three different SmartWay strategies on five drayage trucks. CO<sub>2</sub> emissions are used as a proxy for fuel consumption. EPA and the Intergovernmental Panel on Climate Change (IPCC) estimate that 99 percent of carbon in the fuel is oxidized, which demonstrates that CO<sub>2</sub> emissions are appropriate for estimating fuel consumption.<sup>13</sup>

PEMS has a secure foothold within transportation and air quality science. PEMS testing has been used since the late 1990's for providing real-world emissions information. Several studies have confirmed the validity and reliability of PEMS testing, including EPA's large-scale study of light-duty vehicles in Kansas City, which found that PEMS compared favorably to the chassis dyno testing of 480 vehicles.<sup>14</sup> Both EPA and the California Air Resources Board (CARB) employ PEMS testing for in-use compliance of heavy-duty diesel vehicles for all

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<sup>13</sup> U.S. EPA. *Emission Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel*, <http://www.epa.gov/otaq/climate/420f05001.htm>, accessed August, 2009.

<sup>14</sup> T. Younglove, G. Scora, and M. Barth. Designing On-road Vehicle Test Programs for Effective Vehicle Emission Model Development. *Transportation Research Record: Journal of the Transportation Research Board*, No.1941, 2005, pp. 51-59.

criteria pollutants except PM.<sup>15, 16</sup> PEMS has several advantages for emissions measurement, including the technology's ability to:

- provide accurate data cost-effectively;
- capture real-world emissions;
- can supply data on emissions, activity and environmental data simultaneously<sup>17</sup>;
- test vehicles at any location, including where the emissions normally occur; and
- test large vehicles more easily.

EPA's In-Use Testing Program sets guidelines for PEMS testing, which are provided in 40 CFR Part 1065, Subpart J. The regulations provide exhaust flow measurement specifications, establish PEMS performance standards, and outline the procedures for system calibration, verification, and conducting the actual PEMS test. The regulations also specify the instrumentation components that are acceptable for PEMS emissions measurement. Table 3 outlines the instrument system for each pollutant, along with a column for TTI's SEMTECH-DS unit.

**Table 3: PEMS Emissions Measurement Instruments**

<b>Pollutant</b>	<b>EPA's Acceptable Instrument for Measurement</b>	<b>Description</b>	<b>TTI's SEMTECH-DS System<sup>18</sup></b>
NO <sub>x</sub>	Chemiluminescence detector (CLD) or non-dispersive ultra-violet detector (NDUV)	NO <sub>x</sub> is typically measured as the sum of nitrous oxide (NO) and NO <sub>2</sub> . CLDs convert NO <sub>2</sub> to NO and measure NO emissions. NDUV measures NO and NO <sub>2</sub> directly.	NDUV
CO	Non-dispersive infrared detector (NDIR)	Infra-red light is pulsed through a gas sample to alternately detect CO and CO <sub>2</sub> concentrations.	NDIR
NMHC*	Flame ionization detector (FID)	FID is a gas detector used to measure HC concentrations.	FID**

\* NMHC: Non-Methane Hydrocarbons

\*\* The SEMTECH-DS FID provides Total Hydrocarbon concentrations.

PM measurements have been more of a challenge for PEMS and thus have been delayed for use in the compliance program. The pilot program for PEMS PM measurement for compliance purposes and the determination of accuracy margins for PM are currently underway. Some

<sup>15</sup> On-Road Heavy-Duty Diesel Engine In-Use Compliance Program Homepage. California Environmental Protection Agency Air Resource Board. Updated July 18, 2007.

<http://www.arb.ca.gov/msprog/onroadhd/hdiut.htm>, accessed August, 2009.

<sup>16</sup> Heavy Trucks, Buses, and Engines Homepage. U. S. Environmental Protection Agency.

<http://www.epa.gov/otaq/hd-hwy.htm>, accessed on August, 2009.

<sup>17</sup> Note: The PEMS unit uses in this study, SEMTECH-DS, is equipped with GPS and engine data recording capability.

<sup>18</sup> U.S. Environmental Protection Agency. *In-Use Testing Program for Heavy-Duty Diesel Engines and Vehicles*. Technical Support Document, EPA420-R-05-006, June 2005.

PEMS units, such as TTI's Axion system manufactured by Clean Air Technologies International, do measure PM mass through light scattering detection technology. While these systems are not yet approved for in-use compliance purposes for PM measurement, they are commonly used in academic research.

A central advantage of PEMS is its ability to characterize in-use emissions. The systems capture second-by-second emissions data, operational and environmental data simultaneously, which allows for emissions studies to more closely link vehicle operations and road conditions to emissions behavior. Several PEMS studies have demonstrated that the importance of vehicle operation is a crucial component of emissions behavior.

TTI has conducted more than a dozen PEMS studies, some of which have challenged previous assumptions and provided interesting insights. For example, a study on Mexican trucks found that the tested Mexican trucks did not typically have elevated emissions when compared to their U.S. counterparts from same model year.<sup>19</sup> A separate study examining Mexican trucks emissions using various types of fuel also found that using Mexican fuel (PEMEX), which has higher sulfur levels than ultra-low sulfur diesel (ULSD) fuel, did not translate into the expected higher PM emissions or increased air toxic levels.<sup>20</sup>

One important aspect of PEMS testing is the drive cycle of the vehicle. Drive patterns differ by vehicle type, which greatly affects emissions.<sup>21</sup> While some tests have been conducted in traffic under real-world conditions, this method of testing can be particularly difficult for heavy-duty diesel vehicles due to the sensitive nature of the PEMS equipment.<sup>22</sup> An alternative option is to conduct testing on a track or in a low traffic area with a pre-determined drive cycle. Drive cycles are often created to mirror typical driving patterns by incorporating GPS data collected over a period of time.

Using a track with a pre-determined drive cycle provides three primary advantages. Pre-determined drive cycles reflect averaged driving patterns instead of reflecting the conditions of a single testing period that may prove to be an atypical day. A developed drive cycle can also allow for the replication of tests easily. Under real-world conditions, the timing of lights and flow of traffic would be a few factors that would make comparisons between tests difficult. In this study, traffic was diverted from one lane of a low-traffic roadway with no traffic lights to eliminate inconsistencies between tests.

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<sup>19</sup> J. Zietsman J. Villa, T. Forrest, and J. Storey. *Mexican Truck Idling Emissions at the El Paso - Ciudad Juarez Border Location*. Southwest Region University Transportation Center, Report No. SWUTC/05/473700-00033-1. The Texas A&M University System, College Station, Texas, November 2005.

<sup>20</sup> J. Zietsman, M. Farzaneh, J. Storey, J. Villa, M. Ojah, D. Lee, and P. Bella. *Emissions of Mexican-Domiciled Heavy-Duty Diesel Trucks Using Alternative Fuels*. Texas Transportation Institute, The Texas A&M University System, College Station, Texas, October 2007.

<sup>21</sup> M. Andre, R. Joumard, R. Vidon, P. Tassel, and P. Perret. Real-World European Driving Cycles, for Measuring Pollutant Emissions from High- and Low-Powered Cars. *Atmospheric Environment*, Vol.40, 2006, pp. 5944-5953.

<sup>22</sup> J. Zietsman J. Villa, T. Forrest, and J. Storey. *Mexican Truck Idling Emissions at the El Paso - Ciudad Juarez Border Location*. Southwest Region University Transportation Center, Report No. SWUTC/05/473700-00033-1. The Texas A&M University System, College Station, Texas, November 2005.

Probably the most important advantage of a developed drive cycle is the ability to test vehicles under a more complete variety of driving behavior and conditions. High-powered events are particularly recommended for testing because there is a general lack of emissions data for these high emitting events. One study recommends the use of air conditioning and a series of accelerations up to freeway speed at 50 percent throttle, 75 percent throttle, 90 percent throttle, and wide-open throttle to ensure that even atypical events are measured.<sup>23</sup> Many TTI studies have employed the use of drive cycles to ensure data quality and account for the full range of vehicle operation.<sup>24, 25</sup>

## DATA ANALYSIS USING METHODOLOGY FROM EPA'S MOVES MODEL

This project utilizes some of the concepts and methodologies used in EPA's MOVES model to analyze emissions data. The MOVES model will replace EPA's MOBILE 6.2 model for air quality planning, emissions inventories and regulatory efforts. By using the MOVES methodology framework to analyze data, this project is better able to analyze the operational characteristics of emissions data according to an established analysis protocol. The local data needs for MOVES are also significant and the results from this study can be used to enhance localized inputs into the MOVES model for the El Paso border area.

The MOVES model better characterizes in-use emissions by using second-by-second emissions rates that account for a vehicle's operating modes. This enables the model to provide a finer scale of analysis for use at the local level. MOVES incorporates VSP to capture modal emissions. EPA defines the term as "power per unit mass of the source" and is characterized in Equation 1.<sup>26, 27</sup> VSP accounts for the forces a vehicle must overcome when operating on the road, including acceleration, road grade, tire rolling resistance, and aerodynamic drag. For example, fast accelerations or driving up a steep hill would have a higher VSP bin, rather than coasting downhill.

$$VSP = \frac{A \times u + B \times u^2 + C \times u^3 + M \times u \times a}{M} \quad (1)$$

Where:

- $u$  is instantaneous speed of vehicle in m/s;
- $a$  is instantaneous acceleration of vehicle in m/s<sup>2</sup>;
- $A$  is a rolling resistance term;

<sup>23</sup> T. Younglove, G. Scora, and M. Barth. Designing On-road Vehicle Test Programs for Effective Vehicle Emission Model Development. *Transportation Research Record: Journal of the Transportation Research Board*, No.1941, 2005, pp. 51-59.

<sup>24</sup> J. Zietsman J. Villa, T. Forrest, and J. Storey. *Mexican Truck Idling Emissions at the El Paso - Ciudad Juarez Border Location*. Southwest Region University Transportation Center, Report No. SWUTC/05/473700-00033-1. The Texas A&M University System, College Station, Texas, November 2005.

<sup>25</sup> J. Zietsman, M. Farzaneh, J. Storey, J. Villa, M. Ojah, D. Lee, and P. Bella. *Emissions of Mexican-Domiciled Heavy-Duty Diesel Trucks Using Alternative Fuels*. Texas Transportation Institute, The Texas A&M University System, College Station, Texas, October 2007.

<sup>26</sup> *Draft Design and Implementation Plan for EPA's Multi-Scale Motor Vehicle and Equipment Emission System (MOVES)*. EPA420-P-02-006, U.S. Environmental Protection Agency, October 2002.

<sup>27</sup> *Draft Software Design and Reference Manual: Motor Vehicle Emission Simulator Highway Vehicle Implementation (MOVES-HVI) Demonstration Version*. MOVES Homepage. U.S. Environmental Protection Agency, February 2007. Available online at: <http://www.epa.gov/otaq/ngm.htm>.

$B$  is rotating resistance term;  
 $C$  is a drag term; and  
 $M$  is the vehicle's weight in metric tonne.

VSP is normalized by mass and placed into bins. There are 23 bins based on VSP and instantaneous speed. Table 4 shows the MOVES operating bins. A vehicle operating over a drive cycle would then spend different times in different bins depending on operation.

**Table 4. MOVES Operating Mode Bin Definitions for Running Emissions.**

<b>Braking (Bin 0)</b>			
<b>Idle (Bin 1)</b>			
<b>Instantaneous VSP (kW/tonne)</b>	<b>Instantaneous Speed (mph)</b>		
	<b>0-25</b>	<b>25-50</b>	<b>&gt; 50</b>
<b>&lt; 0</b>	Bin 11	Bin 21	
<b>0 to 3</b>	Bin 12	Bin 22	
<b>3 to 6</b>	Bin 13	Bin 23	
<b>6 to 9</b>	Bin 14	Bin 24	
<b>9 to 12</b>	Bin 15	Bin 25	
<b>12 and greater</b>	Bin 16		
<b>12 to 18</b>		Bin 27	Bin 37
<b>18 to 24</b>		Bin 28	Bin 38
<b>24 to 30</b>		Bin 29	Bin 39
<b>30 and greater</b>		Bin 30	Bin 40
<b>6 to 12</b>			Bin 35
<b>&lt; 6</b>			Bin 33

The VSP and bin approach is expected to be a clear indicator of emissions and provide the needed flexibility to provide analysis at meso and microscales of analysis.<sup>28</sup> MOVES' more disaggregated methodology is expected to more precisely estimate emissions based on the local activity data available. This approach is a better fit for incorporating operational data provided by in-use emissions testing.

<sup>28</sup> C. Lindhjem, A. Pollack., R. Slott., and R. Sawyer. *Analysis of EPA's Draft Plan for Emissions Modeling in MOVES and MOVES GHG*. CRC Project E-68. Final Report Prepared for Coordinating Research Council, Inc. Environ, Novato, California, May 2004.



### **3. IDENTIFICATION AND SELECTION OF SMARTWAY STRATEGIES**

As discussed in the background section on SmartWay strategies, there are several approaches recommended by the EPA program for reducing emissions and fuel usage from the freight sector. These strategies have been primarily focused on long-haul operations and are largely unevaluated for their applicability to the short-haul operations used by drayage fleets.

There are dozens of approaches for reducing emissions and fuel usage from freight movement. However, this project chose three key strategies for evaluation. With comments and recommendations from the Texas Commission on Environmental Quality (TCEQ) and EPA's SmartWay Transport program, the list of SmartWay strategies was reduced to the following approaches: DOCs, driver behavior, and lighter trailers.

The selected strategies were chosen based on a series of criteria. The sections below describe the criteria used for selection and how individual strategies fared when evaluated by those strategies.

#### **CRITERIA FOR SMARTWAY STRATEGY SELECTION**

There is no silver bullet solution to emissions reductions from heavy-duty trucks. Every option will have benefits and drawbacks depending on the situation and objective. Selecting the appropriate strategy will depend on a variety of factors. Key factors affecting strategy selection are outlined in the following sections along with a discussion about how this factor would apply to drayage trucks in the El Paso area.

##### **Cost of Strategy**

The cost of a strategy typically varies with the application. Some strategies, such as truck replacement, are very expensive. Other strategies, such as speed reduction, do not result in direct expenditures, but may affect trip travel times and logistics. Another variable concerns who pays for the strategy. Strategies that provide quantifiable emissions benefits, such as retrofit and idle reduction strategies, are often eligible for government funding, while owners or operators typically pay for other strategies.

Cost can be a significant factor for drayage trucks crossing the border. Reducing emissions from drayage operations has been called "one of the most challenging issues involving goods movement" in part because drayage operations are typically low-margin businesses with few capital resources.<sup>29</sup> Unlike other nonattainment areas in Texas, El Paso is not eligible for the state's Texas Emissions Reduction Plan (TERP) funds that can assist with the purchase of diesel retrofits and other emissions-reducing activities. However, grant programs, such as the Border 2012 program, could be a funding source for air pollution mitigation strategies.

Idle reduction technologies, improved freight logistics, and other fuel saving strategies will typically pay for themselves with time. Often, uncontrolled idling is the most expensive option

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<sup>29</sup> California Air Resources Board. "Goods Movement Action Plan," pg 93-4  
<http://www.arb.ca.gov/gmp/docs/gmap-1-11-07.pdf>, accessed December 2008.

for a trucker. Fuel estimates for a 2001 truck idling uncontrolled are between 0.77 (if heating) and 0.98 (if cooling) gallons per hour. For a 2008 truck, idling estimates are between 0.53 (if heating) and 0.72 (if cooling) gallons per hour.<sup>30</sup> Payback estimates for idle reduction devices typically range from two to three years depending on the extent of idling and the cost of diesel fuel.

However, idle reduction technologies such as APUs require an upfront capital investment. This study found that APUs (including installation) cost about \$10,000-to-\$12,000 per drayage truck. This upfront price can be a barrier for drayage fleets. In addition, the payback period is longer for drayage fleets than for many long-haul fleets because drayage trucks do not idle overnight.

### **Emissions Reduced**

Some strategies will reduce only a few pollutants, while others will reduce all emissions collectively through decreased use. For example, DOCs and DPFs will dramatically reduce PM, HCs, and CO, but will have no effect on NO<sub>x</sub> emissions. In contrast, engine, truck, and tire modifications will reduce all emissions, if only marginally for some strategies.

Tradeoffs between emissions reductions and costs are common. For example, truck replacement and repowers can dramatically reduce emissions but are also among the most expensive options. Low viscosity lubricants are cheap but may have only a marginal effect on emissions. Idle reduction technologies are an exception in that they can effectively reduce emissions at a reasonable cost that can be recouped through fuel savings. However, there is no idle reduction technology to address “creep” idling, which is common for drayage trucks passing through the border ports of entry.

For nonattainment areas such as El Paso, the ability to quantify and verify the emissions reduced for air quality plans is an important consideration. For a strategy to be included in a State Implementation Plan (SIP), the emission reduction activities must be quantifiable and verifiable. Diesel retrofits are frequently used in SIPs because the emissions reductions can be easily and reliably estimated and applied. EPA and CARB’s technology verification programs assign emissions reductions to verified technologies that can be used to calculate emissions credit for SIPs. However, other strategies, such as auto tire inflation, low viscosity lubricants, driver training, and improved freight logistics are difficult to quantify or have unknown emissions benefits and therefore have not been commonly used in air quality plans.

As mentioned before, El Paso is in nonattainment for PM-10 and therefore would benefit from technologies that reduce PM and can be incorporated into the SIP. These strategies would include DOCs, DPFs, cleaner fuels, engine replacement, and truck replacement (including replacement with SmartWay certified tractor/trailers and/or hybrid power-train technology).

### **Fuel Consumption**

Strategies that reduce fuel consumption without negatively impacting operations are more favorable to truck owner and operators. Fuel consumption, emissions reductions and costs are

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<sup>30</sup> Argonne National Laboratory. Handout: Which Idling Reduction Technologies are the Best? August 2008. Available at: <http://www.transportation.anl.gov/engines/idling.html>.

closely related in that most fuel saving strategies reduce emissions and pay for themselves through reduced fuel costs. Active DPFs are the only SmartWay strategy that can be expected to have a slightly negative impact on fuel consumption because some active particulate filters use small amounts of fuel to provide additional heat to oxidize the trapped PM. Other retrofit strategies are expected to have negligible impacts of fuel economy, if any. Truck operations and use will significantly affect a strategy's fuel savings, which will be discussed in the next section.

### **Applicability to Drayage Border Operations**

Drayage and border operation discussed previously in the background information section of this report lays the framework for assessing whether a strategy is applicable to drayage fleets operating at the border. Truck operation can significantly affect the utility of various emissions control and fuel-saving strategies. Aerodynamic devices and highway speed reductions provide the most benefit to long-haul driving cycles and could be expected to provide only marginal benefits to drayage trucks that operate at more variable and lower speeds. Since TTI's prior study found that idling at the border occurs at various locations and occurs in queues rather than rest stations, electrified parking spaces would not be appropriate for the El Paso border crossing. Passive DPFs require high operating temperatures that may not be sustained through a drayage truck's drive cycle, although data logging could confirm whether a truck's typical operation make it a candidate for a passive DPF system. DPF systems also require ULSD fuel, which is available in the Mexican border cities of Ciudad Juarez, Ensenada, Mexicali and Rosarito since January of 2007. Supply of ultra low sulfur diesel was to be introduced nationwide in Mexico in September 2009.<sup>31</sup>

Climate considerations also affect the utility of a strategy. Bunker heaters do not cool cabins, which is an important factor in the hot southern climates along the border. Low viscosity lubricants are also more effective in colder climates and automatic shut-down and start up devices are more effective in mild climates that do not see temperature highs found at the border.

While cleaner fuels, such as CNG and biodiesel, may be a viable option in the future, they are currently not readily available at the El Paso border area. A new CNG station is expected in the coming years, although there is currently no station available. The current supply of B20 is limited to a local supply of 500,000 gallons per year and is located 20 miles north of the border. Biodiesel is suspected to slightly increase NOx from diesel engines and thus is considered inappropriate for ozone non-attainment areas.

The high age of many drayage trucks also eliminates some SmartWay strategies from being applicable to drayage fleets. The research team talked to vendors of auto tire inflation systems and found that only some axles and wheel configurations are appropriate for this strategy. These systems are expected to acquire a mere 0.6 percent improvement in fuel savings for long-haul operations and such a small difference may not appear in the project's test results.<sup>32</sup>

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<sup>31</sup> PEMEX, [Investors Relations](http://www.ri.pemex.com/index.cfm?action=content&sectionID=23#Pregunta9). <http://www.ri.pemex.com/index.cfm?action=content&sectionID=23#Pregunta9>. Access in 10/20/2009.

<sup>32</sup> Ang-Olson, J., and W. Schroeer. Energy Efficiency Strategies for Freight Trucking: Potential Impact on Fuel Use and Greenhouse Gas Emissions. *Transportation Research Record*, No. 02-3877, 2002. p.13.

Similarly, it was found that single-wide tires can only be installed on newer rims, which became popular starting in 1999. An evaluation of two of the largest drayage operators in the El Paso- Ciudad Juárez area found that the vast majority believed that retrofitting their fleet with single-wide tires would not be cost effective.

### **Maintenance**

Strategies that require less maintenance or have maintenance benefits will be more acceptable to owner/operators than those requiring significant upkeep and care. For example, SCRs require periodic refilling of a reactant that necessitates a sufficient supply and monitoring for low levels. Conversely, several strategies have maintenance benefits such as automatic tire inflation, automatic shut down and start up devices, engine replacements, and truck replacements.

### **Driver Comfort**

Drivers often idle rather than shutting off their engines to maintain a comfortable cab environment. While many of the strategies on the list are neutral to driver comfort, APUs and electrified parking spaces provide air conditioning and electricity to the cabin while in use. However, driver comfort was not found to be a top priority among the drayage truck drivers in this project. Even if a drayage truck had a functioning air conditioning system, many drivers did not turn on the systems.

## **ASSESSMENT OF SMARTWAY STRATEGIES**

More than 20 SmartWay strategies were evaluated according to the criteria selection discussed previously. Table 5 provides a summary of the SmartWay strategies and their fit for drayage operations at the El Paso –Ciudad Juárez border. A plus sign (“+”) indicates an advantage and a minus sign (“-”) indicates a disadvantage. A blank indicates either neutrality or that not enough information about the strategy and how it applies to drayage trucks is known. Since every strategy reduces emissions, only those that significantly reduce emissions and are easily quantifiable and verifiable for SIPs are given a plus sign. Costs are given a plus sign if they pay for themselves within a short timeframe (two-to-five years) or are relatively inexpensive (< \$1,000 per truck). Applicability was judged on whether the strategy would be effective in drayage border operations along the southern border and not whether the strategy was applicable to all drayage operations nationwide.

Some common strategies for reducing emissions were eliminated for consideration. Alternative fuels, such as propane, are a SmartWay strategy but would require significant vehicle conversions or be would be covered under a truck replacement strategy. Closed crankcase ventilation and exhaust gas recirculation are omitted because these systems are not verified by EPA or CARB by themselves and are instead coupled with other diesel retrofit technologies that are included in the strategies considered. The strategies listed also do not include the SmartWay operational strategies recommended for drayage trucks serving ports, such as the EModal port community system, gate accessibility, and terminal appointment system. While some of these systems may be modified for border use, the multi-jurisdictional players involved in border operations could affect their application and would require more examination and study.

**Table 5. Summary of Benefits and Disadvantages of SmartWay Strategies Applied to Drayage at the El-Paso-Ciudad Juárez Border Crossing.**

<b>Strategy</b>	<b>Cost</b>	<b>Fuel Use</b>	<b>Emissions (sizeable and SIP credible)*</b>	<b>Applicability to Drayage Border Operations</b>	<b>Maintenance</b>	<b>Driver Comfort</b>
Auto-tire inflation	+	+		-	+	
Low-rolling resistance tires	+	+	+	-		
Aerodynamic improvements	+	+	+	-		
Low-viscosity lubricants	+	+		-	+	
Lighter tractors and trailers/		+				
SmartWay certified trailers		+				
Bunker heaters		+		-		+
APUs	-	+	+		+	+
Automatic shut down and start up systems	+	+	+	-	+	+
Electrified parking spaces		+	+	-	+	+
Hybrid power-train technology	-	+	+			
DOCs			+			
DOC + Closed Crankcase Filtration	-		+			
DPFs	-	-	+	-		
SCRs	-		+		-	
Engine replacement	-	+	+		+	
Truck replacement	-	+	+		+	
CNG	-		+	-		
Biodiesel			+	-		
Speed reduction	+	+				
Driver Behavior		+		+		
Improved freight logistics		+		+		

\* Assumes that local mandates and funding sources do not affect SIP eligibility.

## STRATEGY SELECTION FOR BORDER DRAYAGE OPERATIONS

Meetings were held with major drayage companies in the El Paso – Ciudad Juárez area to discuss the various options and to obtain their input on what might work best for their applications. Three strategies were selected for emissions testing on drayage trucks crossing the El Paso – Ciudad Juárez border. Technologies for testing were selected from the previous summary table by eliminating from consideration any technology with a significant drawback, indicating a “-” sign. Also eliminated from consideration are technologies that could not be tested in a reasonable time frame, such as improved freight logistics. While logistics strategies are promising for the drayage sector, testing them would involve analysis, time, and resources outside the scope of this project. Similarly, auxiliary power units are potentially a good strategy, but will be tested under another TTI project. Based on the analysis, the following technologies are selected for testing:

- DOCs;
- lighter tractors and trailers; and
- driver behavior (a.k.a. eco-driving)

DOCs are an established retrofit technology for the highway sector. In many cases, DOCs replace the muffler and require no maintenance in most applications. The devices work best with ULSD fuel, but can also tolerate the higher sulfur levels of Mexican fuel. EPA and CARB’s technology verification programs have several DOCs that are verified for heavy-duty on-road trucks.<sup>33, 34</sup>

Lighter trailers are another option for drayage companies. For long-haul trucks, reducing 3,000 pounds by using lighter-weight components could save up to 500 gallons of fuel annually and eliminate up to five metric tons of CO<sub>2</sub>.<sup>35</sup> This project examines whether a similar emissions benefit would apply to the short haul characteristics of drayage fleets.

Emissions and fuel benefits from lighter tractors and/or trailers are often calculated differently depending on whether truck loads are typically at the legal weight limit. Trucks are typically either maxed out on volume (“cubed out”) or maxed out on weight (“grossed out”). For trucks at the maximum weight limit, a lighter trailer allows more products to be transported, which can help eliminate truck trips. The fuel and emissions benefit would be calculated on avoided trips. For trucks that are cubed out and utilize the maximum volume available, the lighter trailer would reduce the weight transported and the fuel and emissions benefit would be based on difference in emissions between the normal heavier tractor and/or trailer and the lighter tractor and/or trailer. The research team collected weight data on trucks crossing the border to determine the typical drayage trailer loads and found that most drayage trucks were neither cubed out nor grossed out. Therefore, any emissions reductions from lighter tractors can be

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<sup>33</sup> U.S. EPA. “Diesel Retrofit Technology Verification: Verified Technology List”, <http://www.epa.gov/otaq/retrofit/verif-list.htm>, accessed March 2009.

<sup>34</sup> CARB. “Verification Procedure: Currently Verified”, <http://www.arb.ca.gov/diesel/verdev/vt/cvt.htm>, accessed March 2009.

<sup>35</sup> U.S. Environmental Protection Agency, SmartWay Transport Partnership. *Weight Reduction*, <http://www.epa.gov/smartway/transport/documents/tech/weightreduction.pdf>, accessed November 2008.

calculated from the difference between emissions measured from a standard trailer and a lighter trailer.

Driver behavior can also impact emissions and fuel consumption by using the vehicle more efficiently. Driver education aimed at reducing aggressive driving with frequent and rapid stops and starts have been shown to positively impact fuel economy and emissions for urban bus drivers and passenger vehicle drivers in Europe.<sup>36, 37</sup> One U.S. study estimated that driver education can result in a 5-10 percent fuel economy gain for long-haul trucking.<sup>38</sup> While promising, the research team did not locate any studies that examined the driving behavior of drayage operators or utilized in-use emissions measurement. While driving behavior can refer to a host of driving and maintenance practices, this study specifically examined the fuel and emissions impact of rapid starts and stops, which are often termed “jack rabbit driving.” For passenger vehicle drivers, it is estimated that gentle accelerations and braking can save more than \$1 per gallon.<sup>39</sup> While this estimate cannot be directly compared to heavy-duty diesel vehicles, rapid starts can be expected to produce a disproportionate amount of emissions and fuel use similar to any high-powered event.

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<sup>36</sup>Zarkadoula, M., G. Zoidis, and E. Tritopoulou. *Training Urban Bus Drivers to Promote Smart Driving: A Note on a Greek Eco-Driving Pilot Program*. Transportation Research Part D 12 (2007) 449-451.

<sup>37</sup> Beusen, B. and T. Denys, “Long-Term Effect of Eco-Driving Education on Fuel Consumption Using an On-Board Logging Device.” In *Urban Transport*, XIV 295, 2008.

<sup>38</sup> Ang-Olson, J., and W. Schroeer. Energy Efficiency Strategies for Freight Trucking: Potential Impact on Fuel Use and Greenhouse Gas Emissions. *Transportation Research Record*, No. 02-3877, 2002. p.13.

<sup>39</sup> EcoDriving USA. *Eco-Driving Practices*, <http://www.ecodrivingusa.com/#/ecodriving-practices/>, accessed August, 2009.

## 4. IN-USE TESTING: PREPARATION AND PROCEDURES

Successful in-use emissions testing is the result of good preparation and procedures. In this section, the procedures and approach taken to prepare and conduct the in-use testing are described.

### PREPARATION FOR IN-USE TESTING

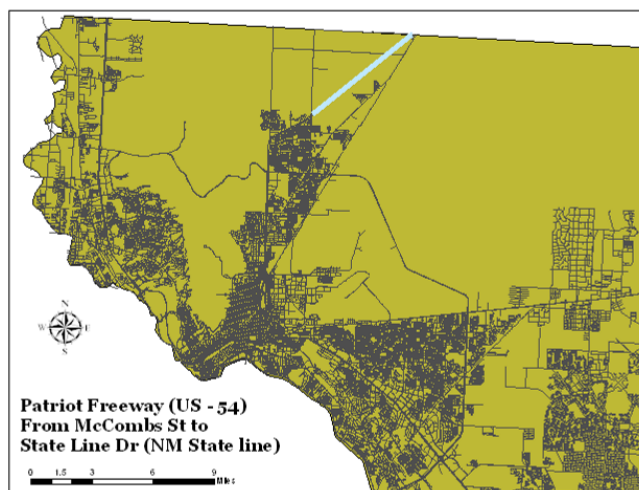
There are several preparatory steps necessary for conducting in-use emissions testing. A testing location and approved traffic management plan must be secured. SmartWay strategies have to be specifically defined and procured, and drayage vehicles and drivers must be selected. For this study, duty cycles also had to be developed from GPS data.

#### Testing Location and Traffic Management Plan

The research team selected a testing location that would allow for the safe operation of vehicles with minimal disruption to normal transportation operation. Since the study was replicating drive cycles that included idling at border POEs, the location had to allow for the idling and slow movement of vehicles as well as high speeds to simulate highway conditions. The road section on US 54 from McCombs Street to the border with New Mexico was found to have conditions that allow a safe maneuvering of vehicles during the emissions testing and represented a low hazard to local drivers. The area around the road has a low population density and there is minimal development in the surrounding area.

The testing location consisted of 6.27 miles of double-lane road with right and left shoulders 6 feet wide and four major U-turns 100 feet wide each. The stretch has no major driveways or connection to residential or commercial zones, and very little traffic. Figure 3 shows a map of the roadway with the roadway appearing as the blue line.

**Figure 3. Site Location of Road Testing, US 54.**



The Texas Department of Transportation (TxDOT) requires an approved traffic management plan for use of the roadway. The study team worked with TxDOT to create a plan following the agency's Traffic Control Plan Standards and the Texas Manual of Uniform Traffic Control



Devices. This included ensuring that proper signs were posted (Figure 4) and that the appropriate trail and shadow vehicles were used during use of the roadway.

**Figure 4. Photograph of Two Truck-Mounted Attenuators following a Drayage Truck during Testing to Warn Drivers of Atypical Conditions.**



In-use testing also requires space for equipment installation on vehicles and storage of testing equipment, supplies, and vehicles. TxDOT generously donated space for testing at one of their district offices located close to the roadway used for testing. The convenient location also included gate controlled access that provided the necessary security for storing test vehicles and testing equipment.

### **SmartWay Strategies**

The three SmartWay strategies selected for testing are DOCs, lighter trailers, and driver behavior. Each strategy required a unique process or procedure for effective emissions measurement.

#### ***DOCs***

The EPA and CARB both have a retrofit verification program that lists DOCs that have been evaluated for emissions performance. The verified technology lists specify expected emissions reductions for specific applications.<sup>40</sup> For this study, only EPA- or CARB-verified products

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<sup>40</sup> EPA verification list, <http://www.epa.gov/otaq/retrofit/verif-list.htm> and CARB verification list, <http://www.arb.ca.gov/diesel/verdev/verdev.htm>.

were considered. Based on price, availability, and time of delivery, the AZ Purimuffler and AZ Purifier systems manufactured by Engine Control Systems were selected for this project. Depending on the vehicle retrofitted, the systems are expected to reduce PM by 20-40 percent, CO by 40 percent, and HC by 50-70 percent. The systems require little, if any, maintenance.

DOCs replace a vehicle's muffler and are composed of a honeycomb-like structure coated with a catalyst that breaks down exhaust components into less harmful substances. The systems have to be sized correctly to fit the vehicles, but installation typically only took about three hours. There was no DOC installation or usage issues associated with this project.

### ***Lighter Trailers***

Lighter trailers translate into less work for the tractor engine and therefore reduced emissions. Some trailer manufacturers such as Great Dane, Utility, Wabash, Vanguard, New Life (formerly Trailmobile), and others have reduced the weight of some trailers through advanced designs and lighter materials. To determine the difference between a standard trailer and a lightweight model, the research team examined the weight specifications for new 53-foot trailers and the lower-weight models. The weight of a typical trailer averaged about 14,000 lbs., while the ultra-lightweight trailers weigh about 12,000 lbs. This 2,000 lb. difference may be a conservative estimate considering that most drayage fleets are using old trailers that are heavier than the new, standard trailers. The use of a lighter trailer was simulated during testing by removing 2,000 lbs. of load.

### ***Driver Behavior***

There are many aspects of driving behavior that could be tested, such as good maintenance practices and following the speed limit. The few academic studies performed on eco-driving have examined the impacts of driver education programs. This approach required more time than available and would not have indicated which aspects of driver behavior have a significant impact on emissions and fuel consumption. This project took a very specific approach that focused only the impact of rapid accelerations. Unlike long-haul trucking, drayage-operating cycles include a lot of starting and stopping, both at border crossings and through city traffic in between destinations. Accelerations are high emissions events with concentrated emissions in a short time span. Drayage vehicles may often be operating their engines at maximum loads to achieve rapid accelerations. Of the many eco-driving tools, it could be concluded that reducing rapid accelerations may be among the most promising tools for reducing drayage emissions.

To evaluate the impact of rapid accelerations, data was collected at baseline conditions where drayage drivers were told to operate the vehicles normally and then during test runs where drivers were told to deliberately accelerate at a relaxed pace.

### **Selection of Drayage Trucks**

Five drayage vehicles were selected from two of the largest drayage fleets operating in El Paso- Ciudad Juárez. Vehicles were selected based on the prevalence of make and model year as well as diversity of engine make and model. The selection of model years also spans several emissions standards established in 1988, 1990, 1991, 1994, 1998, and 2003. The selected sample covers almost 75 percent of the drayage fleet in terms of emissions standard classification with only the newest model years and MY 1990-1993 are not represented (the

latter category is only slightly different from post 1994 category). The 1998 International represented the most prevalent make and model and the Freightliner represented the second most popular model with 1999 being the most common model year for that vehicle make from one of the companies. A 1986 International truck was the most prevalent vehicle type from the other company, with the next two vehicles selected representing the next most common vehicle models and model years within the fleet (Table 6).

**Table 6. Drayage Trucks Selected for Testing.**

<b>Model</b>	<b>Model Year</b>	<b>Engine Manufacturer</b>	<b>Engine Model</b>	<b>Engine HP</b>
International	1986	Cummins	Big Cam	300
White GMC	1994	Detroit	S-60	360
Volvo	1996	Cummins	M11	330
International	1996	Detroit	S-60	330
Freightliner	1999	Cummins	ISM	330

### **Test Drive Cycles**

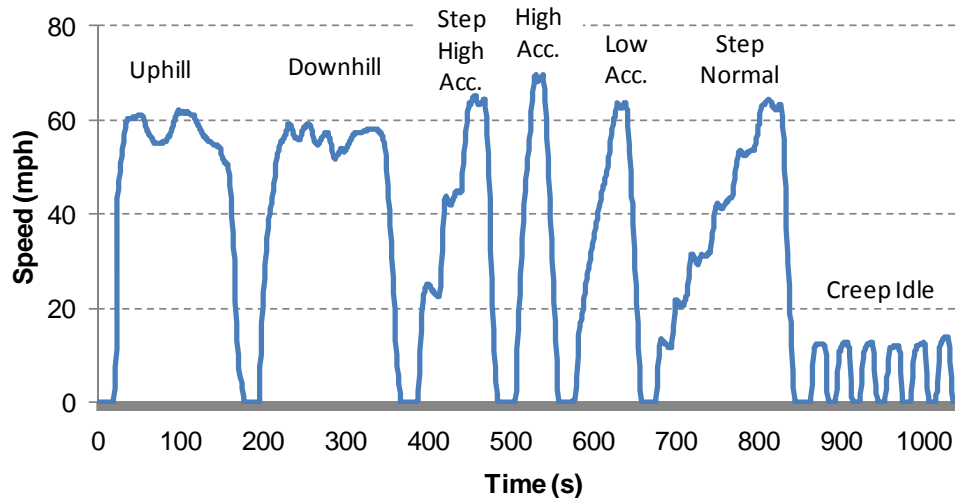
This study used a series of flexible driving cycles for collecting in-use data. Because the term “driving cycle” is usually used for fixed and inflexible speed profiles that the test vehicles must follow, the flexible drive cycles used in this study are referred to as “drive patterns” to distinguish this difference. The drive patterns used in this study consist of a series of driving guidelines and simple speed profiles to be loosely followed which cover a wide variety of a vehicle’s operation i.e. different combinations of instantaneous speeds and acceleration rates.

All test runs for each drayage vehicle followed the same established driving pattern. Using a drive pattern rather than just collecting data on a normal workday has three main advantages. First, the use of driving patterns enables tests to be comparable with each other, so that baseline tests can be more accurately compared to tests incorporating a SmartWay strategy. Drive patterns also allow tests to be repeated, which improves the quality of the data. For this project, each drayage truck repeated the normal driving pattern a minimum of five times. Finally, drive patterns can also incorporate all operation modes, even the high-emissions events that may occur on an atypical basis. If data was collected during a normal workday, then data reflecting high engine loads may not be adequately collected. For this study, a typical drive pattern was augmented with an uphill portion where the vehicle was forced to work at maximum load.

Figure 5 depicts the speed profile and driving events used for this project. The creep idle event was specifically included to reflect the emissions impacts of border crossings at U.S./Mexico POEs. Drayage vehicles repeated each event, except for the uphill portion, for a minimum of five repetitions. Depending on the running conditions of test vehicle, one-to-three runs of uphill data was collected. A period of at least 20 seconds of stop time was included in between

each run to let the engine stabilize to unloaded conditions and therefore minimize any possible effects of the previous run. A normal deceleration was considered for all events, except for the driver behavior testing that required gentle accelerations.

**Figure 5. Driving Event Speed Profiles used in the Study.**



## IN-USE TESTING

In-use testing involves a series of steps including PEMS installation, equipment calibration, data collection and monitoring and uninstallation. This section describes the in-use testing process conducted for this project and any anomalies that occurred in collecting the data. Since in-use testing is conducted in the field, it is subject to unforeseen and random events that can occur in normal drayage operations. There were few unexpected events for this study, with a one notable exception that is discussed in this section.

### Testing Equipment

This study used two PEMS units simultaneously to collect in-use emissions data. The SEMTECH-DS system was used to collect gaseous emissions NO<sub>x</sub>, HC, CO, and CO<sub>2</sub>, and TTI's Axion system manufactured by Clean Air Technologies International, Inc. was used to measure PM. The units are pictured in Figures 6 and 7, respectively. The following sections describe the two units.

#### *SEMTECH-DS*

The SEMTECH-DS system is manufactured by Sensors Inc. and includes a set of gas analyzers, an engine diagnostic scanner, a GPS, an exhaust flow meter (EFM) and embedded software. The gas analyzers measure the concentrations of NO<sub>x</sub> (NO and NO<sub>2</sub>), HC, CO, CO<sub>2</sub>, and oxygen (O<sub>2</sub>) in the vehicle exhaust. The SEMTECH-DS uses the Garmin International, Inc. GPS receiver model GPS 16 HVS to track the route, elevation, and ground speed of the vehicle on a second-by-second basis. TTI's SEMTECH-DS uses the SEMTECH EFM to measure the vehicle exhaust flow. Its post-processor application software uses this exhaust

mass flow information to calculate exhaust mass emissions for all measured exhaust gases. The unit meets all of EPA's in-use compliance equipment specifications.

**Figure 6. TTI's SEMTECH-DS Unit.**



### *Axion System*

The Axion system is comprised of a gas analyzer, a PM measurement system, an engine diagnostic scanner, a GPS, and an on-board computer. For this study only the PM measurement system was used. The PM measurement capability includes a laser light scattering detector and a sample conditioning system. The PM concentrations are converted to PM mass emissions using concentration rates produced by the Clean Air Technologies Inc. unit and the exhaust flow rates produced by the SEMTECH-DS unit.

**Figure 7. TTI's Axion Unit.**



## Testing Procedures

The EPA has an in-use testing program for demonstrating compliance with heavy-duty diesel emissions standards.<sup>41</sup> This program governs the standards for PEMS equipment and was followed for this project. Under this rule, the EPA's engine-testing procedures, 40 CFR Part 1065, describes PEMS testing procedure for gaseous sampling including NO<sub>x</sub>, CO, HC, CO<sub>2</sub> in a high level of detail, and specifies the instruments required for these tests. For example, a flame ionization detector (FID) must be used to measure HC emissions. EPA currently does not accept in-use testing data for PM for compliance purposes. However, the procedures used in this study for PM testing are largely the same as for other pollutants. For example, flow meter specifications met the provisions that should be used to measure exhaust flow. TTI's equipment complies with all the specifications of the EPA rules, and the research team followed the applicable testing procedures outlined in EPA's rules for this project. In general, the testing procedures include proper equipment installation, calibration, and verification, as well as calculation procedures. Pictures of equipment installation are shown in Figure 8.

Each drayage truck repeated the same drive cycle a minimum of five repetitions for each test. The trailer was loaded with the PEMS units and cement pallets to equal the typical drayage load. Weight data collected at the border crossing showed that drayage trucks are loaded with an average of 20,000 lbs. of cargo (Figure 9). Both of TTI's PEMS units were installed in front of the trailer as shown in Figure 9. The last pallets equaling 2,000 lbs. were removable with a forklift, which was removed to simulate a lighter trailer. A baseline test for each truck was followed by tests for lighter trailers and slower accelerations. DOCs were installed and then the truck was returned to the drayage fleet for a degreening period. The degreening process allows catalysts to stabilize. EPA recommends a minimum of 25 hours for DOCs. This project exceeded the minimum degreening thresholds by returning the drayage vehicles back to regular service for two or three weeks before performing the DOC in-use tests.

Since testing is conducted in the field under minimally controlled conditions, unexpected events can occur even with the best preparation, equipment and plans. For this project, one drayage truck suffered an engine failure and could not be tested with the DOC installed. This resulted in a loss of data for one test involving a DOC. However, test data on lighter trailers and driver behavior was collected on the vehicle before the vehicle breakdown.

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<sup>41</sup> U.S. EPA. *In-Use Testing Program for Heavy-Duty Diesel Engines and Vehicles*. EPA420-F-05-021, June 2005, <http://www.epa.gov/oms/regs/hd-hwy/inuse/420f05021.pdf>, accessed August, 2009.



**Figure 8. Photographs of Pre- and Post DOC installation (Left Photo Shows the Exhaust Flow Meter (EFM) Being Installed for the Baseline Test; Right Photo Shows the Same Vehicle with the DOC Installed).**



**Figure 9. Photograph of Inside Testing Trailer with TTI's PEMS Units installed in the Front of the Trailer and Concrete Pallets Used to Simulate a Typical Load (The last pallet was removable to simulate a lighter trailer).**



## 5. RESULTS

The data recorded by the two PEMS units were in second-by-second format. From the entire array of information that was recorded (emissions, ambient conditions, and vehicle parameters) the following information was extracted and used in this study:

- engine parameters (if recorded) such as engine speed, throttle position, and engine load for data quality checking;
- second-by-second vehicle speed from the GPS in mph; and
- emissions mass rates in grams per second (g/s).

Second-by-second emissions data were carefully aligned with the instantaneous speeds obtained from the GPS data. A linear smoothing was applied to speed and grade data to cancel out noise and fine-scale changes due to GPS accuracy limitations and other factors. The VSP value corresponding to each instance was calculated based on equation 1. Table 7 lists the values of parameters *A*, *B*, and *C* used for VSP calculation. These values were obtained from the MOVES source database.

**Table 7: MOVES' Vehicle Parameters Values.**

	Rolling Term A	Rotating Term B	Drag Term C	Vehicle Mass (tonne)
<b>Combination Short-Haul Truck</b>	1.96354	0	.00403054	29.3275 (28.4203*)

\* Light trailer results.

The second-by-second emissions rates were then grouped into operating mode bins according to Table 4. Modal average emissions rates for all the pollutants were then estimated for each bin using all the observations that fall into that modal bin. Chauvenet's criterion was applied to emissions rates of each bin to identify and filter out the outliers.<sup>42</sup> Not all the bins had enough data to determine their corresponding emissions rates. This is usually the case for high VSP bins, which barely occur during the normal operation of drayage trucks. For these bins, it was assumed that their emissions rates are equal to the bins that have immediate lower VSP limits in the same speed category. For example, if emissions rates were missing for bin 16, emissions rates of bin 15 were used instead. It is determined that the errors introduced by applying this assumption is minimal because the number of high VSP bins are very small compared to lower VSP bins that data were available for them.

### MODAL EMISSIONS

Figures 10 and 11 show the average base case emissions rated of all operating modes for the oldest (1986 International Truck) and newest (1996 Freightliner Truck) tested vehicles. As mentioned previously, due to an engine failure, no data was collected for the 1996 Volvo with the DOC installed. As Figure 10 shows, there was not any data for higher VSP bins, which corresponds to high engine load, and therefore they are assumed to be equal to their previous

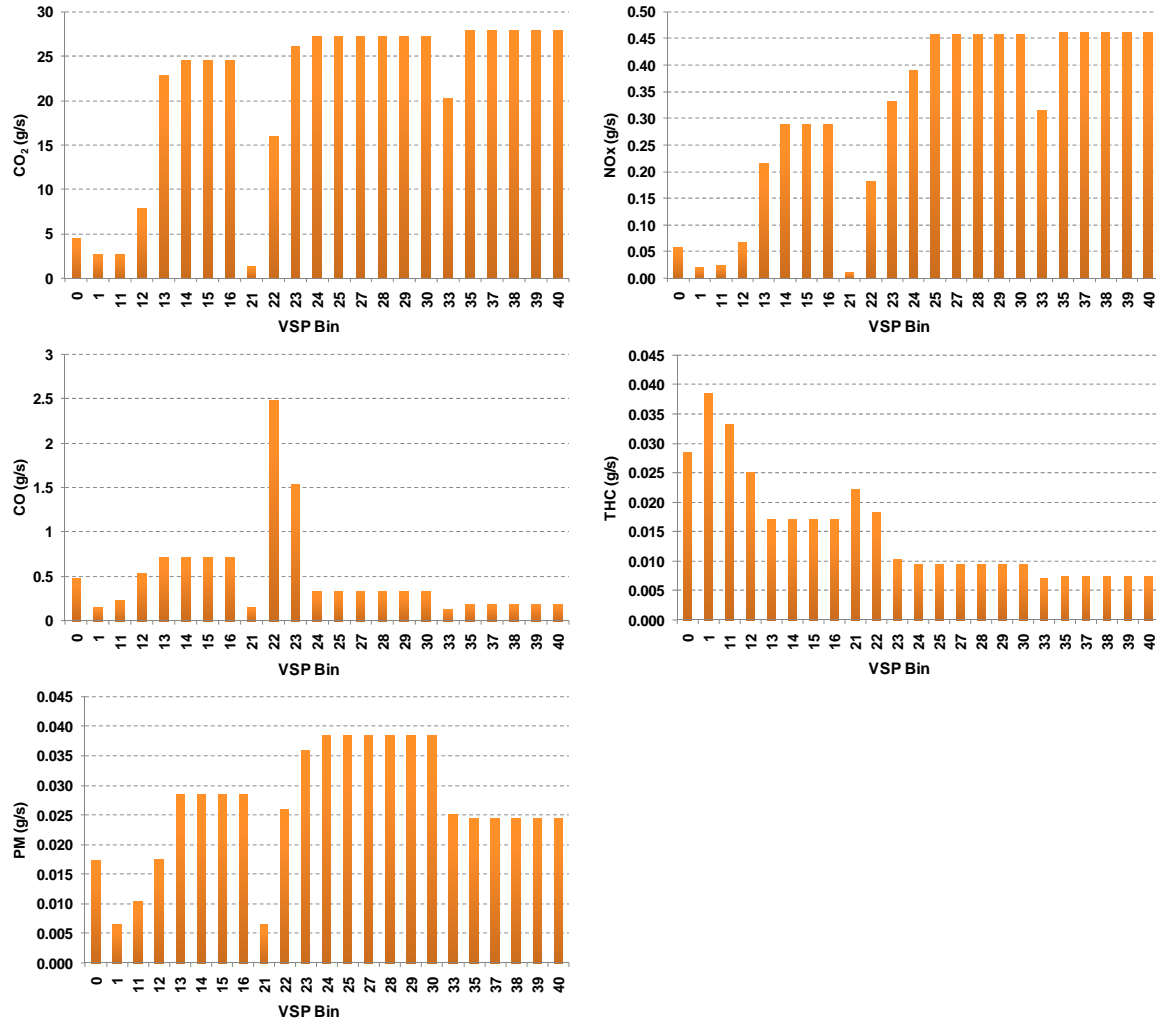
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<sup>42</sup> Taylor, J.R. *An Introduction to Error Analysis*. 2nd edition. University Science Books, Sausalito, CA, 1997.



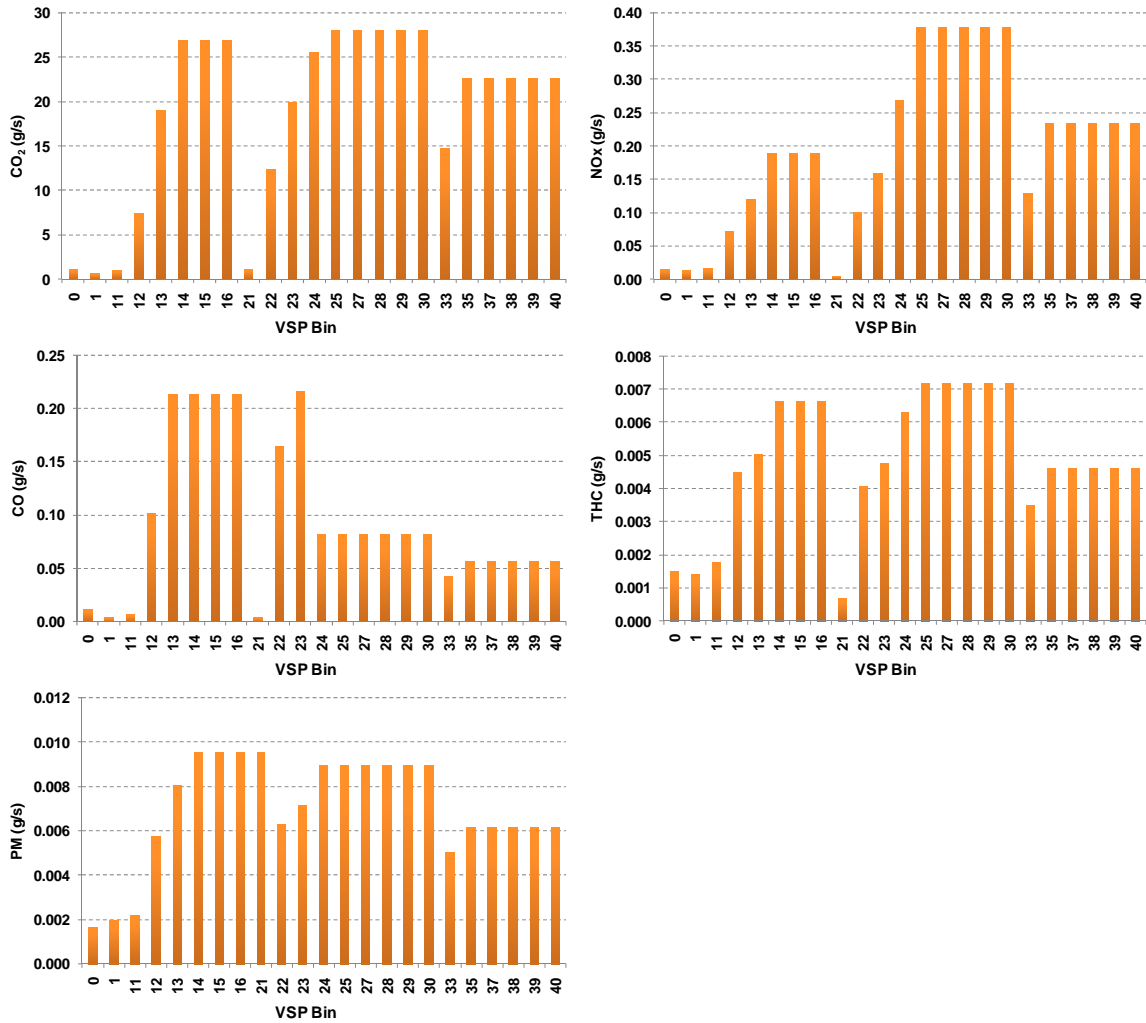
bins. The results for the other vehicles were qualitatively similar and therefore are not presented here.

**Figure 10. Average Modal Emission Rates for the 1986 International Truck.**



The emissions rates shown in Figure 11 indicate that the modal emissions rates of newer drayage trucks, which are in good running conditions, such as the 1999 Freightliner truck, generally increase as the VSP value increases. The exception to this trend is CO at speed between 25-to-50 mph, which has higher emissions rates for bins with medium VSP values than bins with higher VSP values. This could result from fewer observations being collected for these bins compared to lower VSP bins; however, the impact of this issue is minimal because very few instances of these high VSP bins occur during normal drayage operations.

**Figure 11. Average Modal Emission Rates for the 1999 Freightliner Truck.**



For the older vehicles, which are at poorer running conditions, such as 1986 International in Figure 10, the results show that THC emissions are higher in low VSP bins. This trend is a strong indication of incomplete combustion. This is also true to some extent for CO emissions as shown in Figure 10.

CO<sub>2</sub> and NO<sub>x</sub> show a consistent trend; higher VSP bins have higher emissions rates. CO<sub>2</sub> formation is the direct result of combustion and therefore a strong indicator of fuel consumption. Combustion temperature is the main factor determining the NO<sub>x</sub> formation rate. Higher engine load is equal to higher temperatures, and therefore more NO<sub>x</sub> is formed. Note that high load conditions are very small fractions of normal drayage driving patterns, and the vast majority of normal driving is under low and medium engine loads.

To validate the modal emissions rates, these average rates were applied to each corresponding instant of the observed data and the total emissions were calculated for highway section of testing. The highway section used in this validation effort includes various activities including

low and high acceleration, cruise driving, and creep idling. The results of this validation effort are demonstrated in Appendix A. The values in this table are the percentage difference between the estimated values and observed emissions.

The results of this validation effort show that in general the average modal rates provide satisfactory results for no-grade and uphill driving for all pollutants. The PM emissions of creep idling are generally overestimated, while the estimates for other emissions are near the observed values. This is because creep idle is a low-speed and low-power event and the mode bins describing it (bin 12 and 13) cover a wide speed range (0-25 mph), and therefore tends to overestimate PM emissions. Downhill has the lowest overall accuracy. This is because the engine is not working under constant load and load variability is higher than for the other modes. CO<sub>2</sub> rates provide the most accurate estimates for all modes while other pollutants show mixed results. Overall, it appears that the average modal emissions rates provide relatively accurate estimates for the majority of driving events; i.e. driving on zero-to-moderate grade roads. A sample of the operating modes results is provided in Table 8. The rest of the results are qualitatively the same and they are not included in the report.

**Table 8: Deviation of Estimated Modal Emissions from the Observation for the 1986 International Truck With Degreened DOC.**

	Deviation from Observation (%)				
	CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM
<b>Uphill</b>	-6.1%	175.5%	-21.4%	1555.9%	12.9%
<b>Downhill</b>	133.6%	61.4%	160.1%	-4.0%	83.2%
<b>Flat Road (highway 54)</b>	1.0%	4.1%	-2.4%	-1.7%	0.3%

## IMPACT ANALYSIS

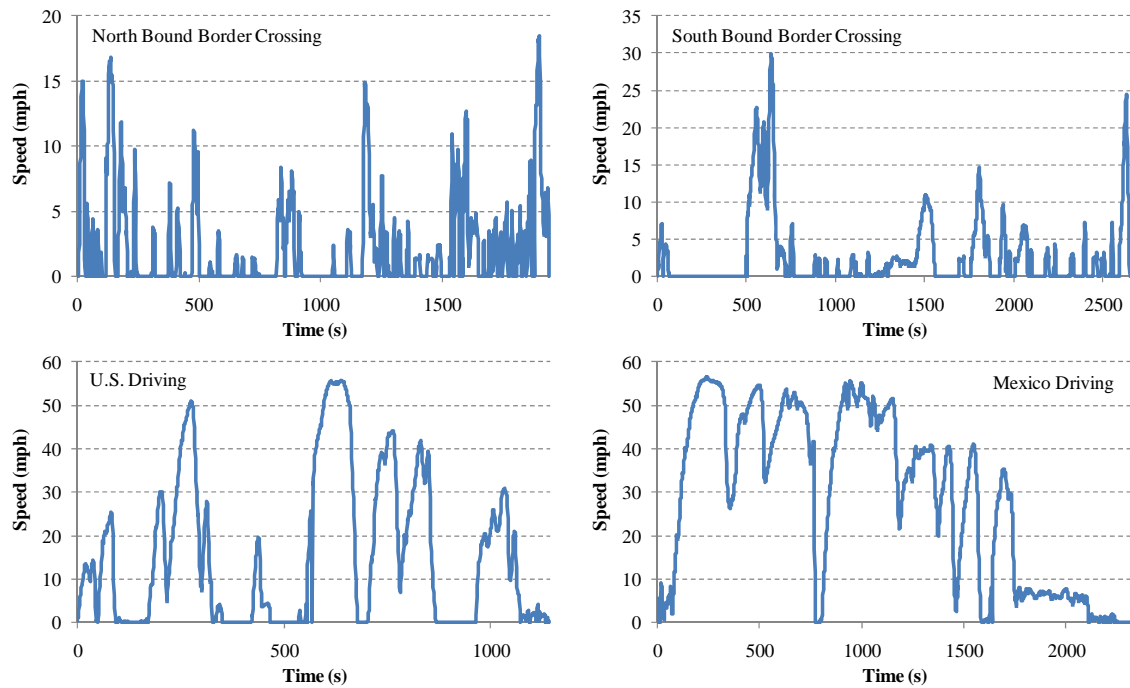
The main question for this study is whether the selected SmartWay strategies are effective in reducing emissions from drayage fleets operating at the U.S./Mexico border. For this purpose, the modal emissions rates for each vehicle were applied to a series of drive cycles that were collected using GPS. These emissions estimates were then used to investigate the impact of the selected strategies. To collect speed data for drive cycles, GPS units were installed on three different vehicles in Laredo, TX and second-by-second speed data were collected for an entire day of drayage operation including driving in the U.S. and Mexico, as well as north- and south-bound border crossings. A total of 35 drive cycles were examined in this effort. Figure 12 shows a sample of these analysis drive cycles.

The average total emissions for each scenario were calculated for each cycle. These estimates were then used to calculate the average impact of each strategy. All the statistical analyses were performed at 95 percent confidence level. Two scenarios were investigated for the eco-driving strategy. It was assumed that drivers will use lower acceleration rates, and therefore partial acceleration rates, 80 percent and 50 percent of the observed rates, were used for this purpose. New drive cycle operational mode distributions were calculated and total emissions were estimated based on these updated distributions and the base case emissions rates. It was determined that a 50 percent change in acceleration requires changing the drive cycles

significantly to accommodate for the dramatic distance and time differences, and therefore results of the 50 percent acceleration scenario should be treated only as general indications of the direction and amount of potential changes.

Figure 13 shows the results of this analysis in graphical form. These results are also presented in tabular format in Appendix A. The CO<sub>2</sub> results, which are a direct indicator of fuel consumption, show that the light trailer and eco-driving at 80 percent acceleration scenarios have no apparent impact on CO<sub>2</sub> emissions and fuel consumption for the drayage trucks; whereas, DOC causes a small increase in CO<sub>2</sub> emissions. The 8.1 percent CO<sub>2</sub> reduction from the eco-driving at 50 percent acceleration scenario should be considered carefully since the drive cycles were not updated to reflect the changes in duration and distance.

**Figure 12. Example Analysis Drive Cycles.**

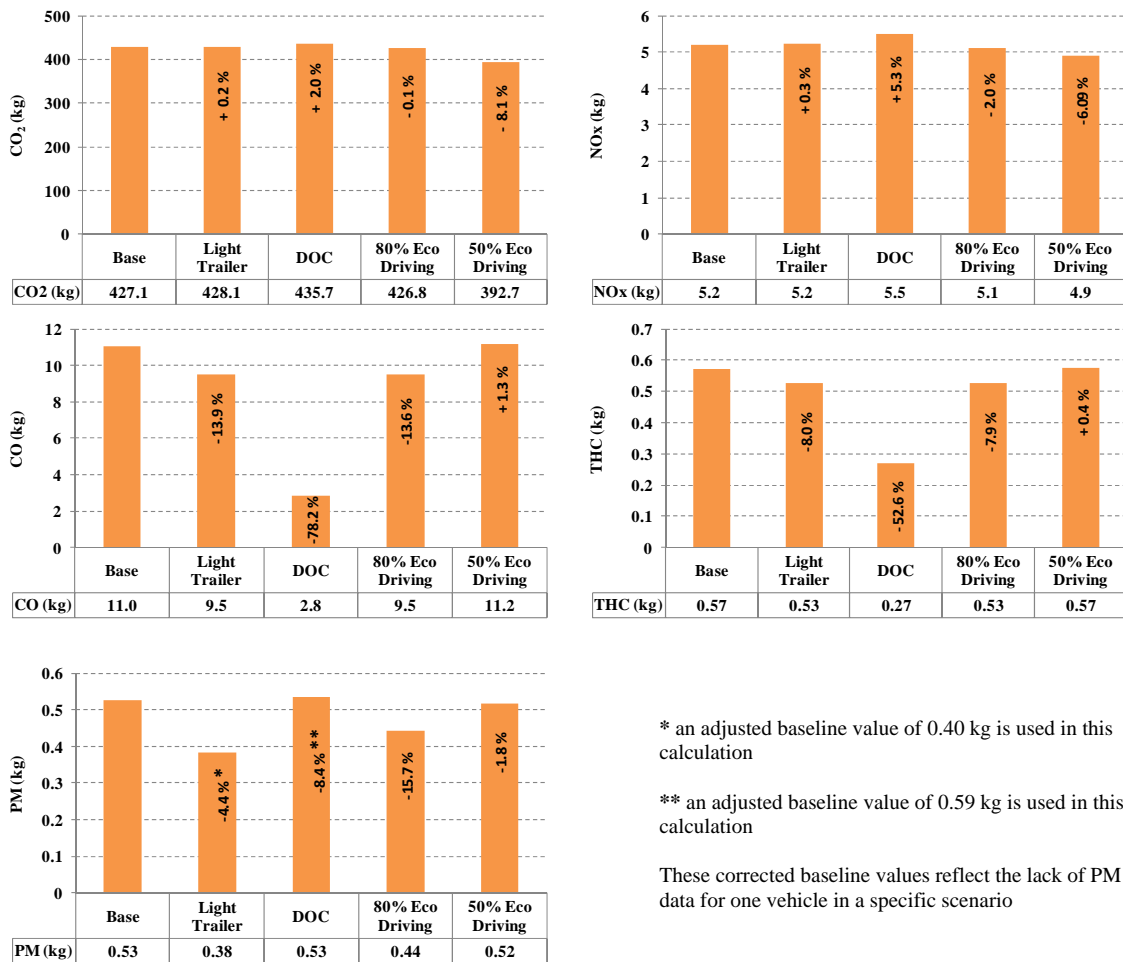


As expected, the CO results show a major (78.2 percent) reduction as the result of using DOCs. This is also true for the THC emissions with an average 52.6 percent reduction. Deploying DOCs also resulted in an 8.4 percent reduction in PM emissions and a 5.3 percent increase in NO<sub>x</sub> emissions. The DOCs used in this study were verified by the EPA to reduce PM by 20-40 percent, CO by 40 percent, and HC by 50-70 percent. While the retrofits in the study performed as expected for CO and THC, the small reduction in PM does not correspond to the technology’s EPA verification levels. This is because DOCs can potentially change the size distribution of PM emissions, and light scattering techniques, such as the one used in this study, usually cannot detect these changes. A gravimetric measurement (i.e., filter sampling

method) can more accurately show the changes regardless of changes in PM emissions size distribution.

The results indicate that using a lighter trailer can provide CO, THC, and PM reduction benefits, however it appears that it does not have a noticeable impact on NOx emissions for the drayage fleet. A modest reduction of all criteria emissions (CO, NOx, THC, and PM) is observed for the eco-driving at 80 percent acceleration scenario. PM and CO have the highest reduction at 15.7 percent and 13.6 percent, respectively; while NOx has the lowest with a 2 percent reduction.

**Figure 13. Total Emissions Results from Analysis Drive Cycles.**



Eco-driving at 50 percent acceleration rates appears to have no or lower emissions reduction benefits for CO, THC, and PM. This is because some of the modal bins with higher VSP values have lower emissions rates and therefore lowering the needed power increases these pollutants. As expected, lower acceleration and engine load in this scenario reduces NOx emissions. This is because NOx is formed under high load and engine temperatures, and therefore reducing these factors decreases the amount of NOx formed during combustion. It is

important to emphasize that the analysis drive cycles used in this analysis were not modified to reflect the impact of utilizing a 50 percent acceleration rate. The analysis is an attempt to investigate low-acceleration driving, and therefore the results should be interpreted as an indication of direction of the changes and not the final reduction or increase values.

## 6. CONCLUDING REMARKS

This research examined the air quality and GHG emissions impacts of three different SmartWay strategies for drayage fleets operating at the U.S./Mexico border. The following are the main findings and implications of this research.

- Drayage operations occurring along the southern border is an important source of emissions.
- This study evaluated the emissions and fuel impact of three promising SmartWay strategies with potential benefits for border drayage operations. The three SmartWay strategies were driver behavior (eco-driving), lighter trailers, and DOCs.
- Strategies were selected based on multiple criteria including cost, emissions reduced, and applicability to the short-haul operations used by drayage fleets. Five representative drayage vehicles were selected for testing.
- Installing single wide tires require newer rims than what are normally found on drayage trucks. Installing compatible rims is not a cost effective option, therefore this strategy was found to be ineffective for drayage fleets operating at the southern border. Auto air inflation had a similar issue in that the strategy requires a certain type of axel to be used cost effectively.
- Data collection and data analysis methodologies were proposed to estimate the emissions impact of drayage trucks and emissions reduction strategies. The proposed methodology reduces the duration of data collection and enables researchers to investigate broad operation modes.
- The selected drayage trucks were tested for emissions and fuel economy before and after the implementation of a SmartWay strategy. Second-by-second emissions of these five drayage trucks were collected for three different cases; baseline, lightweight trailers, and DOCs. The proposed methodologies are based on VSP factors as defined for the EPA's MOVES model.
- Data were analyzed based on MOVES' VSP-based approach. Eco-driving was analyzed by modifying the acceleration rates of the speed profiles that were used in the analysis. All the statistical analyses were performed at 95 percent confidence level.
- The results show statistically significant CO and THC reductions as the result of installing DOCs. Fuel consumption was found to be marginally affected by all the tested strategies.
- Using a lightweight trailer provided modest CO, THC, and PM reduction benefits, but no statistically significant impact on NOx.
- Eco-driving at an 80 percent acceleration rate provided statistically significant CO, THC, and notable PM reduction benefits; however, eco-driving at a lower acceleration rate (50 percent reduced acceleration rate) was not as effective. The results suggest that NOx and fuel consumption reduction are the major benefits of eco-driving at low acceleration rates.

Thus, the findings from this research provide the basis for assessing the air quality impacts of drayage freight operations at the border region, refining and improving data collection and analysis methodologies, and developing effective emissions reduction programs.



## 7. RECOMMENDATIONS

The research team recommends the following based on the results of the study:

- The results indicate that eco-driving is a promising strategy for reducing drayage emissions and fuel consumption cost effectively. The research team recommends consideration of an Eco Driving pilot program targeting the drayage fleet at major ports of entries in U.S.-Mexico border region.
- DOCs were found to be effective in reducing CO, THC, and PM from drayage operations. The research team recommends DOCs to be considered where PM, CO, and HC emissions reductions are desired. DOCs are relatively inexpensive and are a cost effective emissions option where funds and incentives are provided to drayage fleets.
- It is highly recommended that improvements to drayage operation logistics be studied and pursued. The load weight data collected at border crossings reveal that a significant portion of the drayage capacity is underutilized. Higher utilization of the existing capacity is anticipated to reduce the number of cross-border drayage trips and the associated emissions and fuel consumption.

The study revealed areas where further research is needed. Future projects that could effectively build off of the results of this study are below:

- Eco-driving is fairly a new concept in heavy-duty diesel truck operation. Different strategies such as progressive shifting and lower acceleration rates fall under eco-driving strategies. New research is needed to identify the most effective eco-driving strategies suited for drayage operations and for determining the overall effectiveness of the strategy and method of deployment.
- The EPA verified PM emissions reduction levels for DOCs were much higher than the results found in this study. Further research is needed to explain these results. While this study primarily estimated PM number, the pollutant can also be measured by size distribution and mass. One possible explanation for this study's findings is that DOCs in drayage fleets change the size distribution and/or mass of PM emissions. In order to investigate the complete impact of DOCs on PM emissions, in-depth PM characterization studies using particle size distribution and filter mass measurement instruments are required.
- The overall vehicle sample size of five is relatively small compared to the diversity of the in-use fleet. Having a larger sample size would increase the statistical confidence and applicability of the results. A sample that includes at least three vehicles per emissions standard class would provide a better picture of the average emissions characteristics of heavy-duty drayage trucks.
- This study could be replicated for the northern U.S. border or for other types of fleets and operations. Vehicle class and operating conditions vary widely among applications and should be studied separately in order to develop applicable conclusions for those classes.

## **8. ACKNOWLEDGEMENTS**

This research effort was funded by the Texas Commission on Environmental Quality with funding from the EPA, Region 6 through the U.S./Mexico Border Air Quality Program. The authors would like to thank Ross Pumfrey and Ed Moderow of TCEQ and Eduardo Calvo of TxDOT for their guidance and support during the project. The authors would like to thank TxDOT's El Paso District for use of their facilities during emissions testing. The authors would also like to thank the following TTI researchers for their contributions without which this study would not have been possible – Juan Villa, Rafael Aldrete, Edward Brackin, Melisa Finley, Noel Chavez, Luis David Galicia and Osiris Vidana. Finally, the team appreciates the insight and essential input from Cheryl Bynum from the EPA SmartWay Transport Program for her assistance in the selection of SmartWay strategies for emissions testing.

## APPENDIX A

**Table A.1. Validation Results: Total Emissions Change from Observation.**

		Change (%)				
		CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM
<b>Vehicle 1</b>	<b>Base</b>	10.5%	-2.1%	-3.4%	-1.1%	-1.3%
	<b>Light Trailer</b>	0.4%	-2.4%	0.8%	-1.6%	-2.1%
	<b>DOC</b>	0.2%	-43.2%	0.2%	-3.9%	-2.4%
<b>Vehicle 2</b>	<b>Base</b>	0.4%	5.2%	0.0%	4.1%	-5.5%
	<b>Light Trailer</b>	3.1%	3.0%	2.4%	7.9%	N/A
	<b>DOC</b>	1.0%	4.1%	-2.4%	-1.7%	0.3%
<b>Vehicle 3</b>	<b>Base</b>	-13.1%	0.1%	0.0%	23.1%	N/A
	<b>Light Trailer</b>	0.0%	-4.2%	0.2%	-1.6%	N/A
	<b>DOC</b>	N/A	N/A	N/A	N/A	N/A
<b>Vehicle 4</b>	<b>Base</b>	-0.3%	-2.3%	3.9%	4.3%	5.3%
	<b>Light Trailer</b>	1.1%	5.8%	1.6%	1.7%	5.6%
	<b>DOC</b>	1.1%	0.3%	3.0%	N/A	1.3%
<b>Vehicle 5</b>	<b>Base</b>	0.0%	4.9%	5.4%	-0.8%	2.2%
	<b>Light Trailer</b>	-0.2%	2.4%	7.5%	5.1%	1.0%
	<b>DOC</b>	0.8%	2.6%	9.8%	-1.5%	16.8%

**Table A.2. Total Emissions Results from Analysis Drive Cycles.**

		Emissions (kg)				
		CO <sub>2</sub>	CO	NO <sub>x</sub>	THC	PM
		(kg)	(kg)	(kg)	(kg)	(kg)
<b>Base</b>		427.1	11.0	5.2	0.57	0.53
<b>Light Trailer</b>	Value	428.1	9.5	5.2	0.53	0.38
	Change from Baseline (%)	0.2%	-13.9%	0.3%	-8.0%	-4.4%*
<b>DOC</b>	Value	435.7	2.8	5.5	0.27	0.53
	Change from Baseline (%)	2.0%	-74.2%	5.3%	-52.6%	-8.4%**
<b>EcoDriving at 80% Acceleration</b>	Value	426.8	9.5	5.1	0.53	0.44
	Change from Baseline (%)	-0.1%	-13.7%	-2.0%	-7.9%	-15.7%
<b>EcoDriving at 50% Acceleration</b>	Value	392.7	11.2	4.9	0.57	0.52
	Change from Baseline (%)	-8.1%	1.3%	-6.1%	0.4%	-1.8%

\* based on an adjusted baseline value of 0.40 kg

\*\* based on an adjusted baseline value of 0.59 kg

**These corrected baseline values reflect the lack of PM data for one vehicle in a specific scenario**

**APPENDIX B**

**Summary Fuel Consumption and Emissions Report  
for  
CARBON CHAIN TECHNOLOGIES LIMITED  
  
Testing 2ct® Treated Gasoline and Diesel Fuels**

Prepared by the  
Texas Transportation Institute

March, 2009

TEXAS TRANSPORTATION INSTITUTE  
The Texas A&M University System  
College Station, Texas 77843-3135

## SUMMARY

This report summarizes the results of collaborative testing performed by team members from the Texas Transportation Institute, Clean Air Technologies Inc. and Sensors, Inc (the research team) in 2008. The tests were performed at the Pecos Research and Testing Center (RTC) outside Pecos, Texas. The research team used well-known industry standard test procedures, details of which are fully documented together with the specific test procedures and conditions in separate full reports published by TTI, entitled “*Fuel Consumption and Emissions Report for CARBON CHAIN TECHNOLOGIES LIMITED - Testing 2ct® Treated Gasoline Fuel*” and “*Fuel Consumption and Emissions Report for CARBON CHAIN TECHNOLOGIES LIMITED - Testing 2ct® Treated Diesel Fuel*”.

In summary, the results presented in these reports demonstrate that gasoline and diesel fuels that were treated with 2ct® combustion enhancer improved the fuel consumption of the tested vehicles by 7.3% and by 13.7% respectively.

The results also show statistically significant changes of carbon dioxide (CO<sub>2</sub>) and gasoline carbon monoxide (CO). For treated gasoline, CO<sub>2</sub> was reduced by 6.9% and CO was reduced by 27.1%. For treated diesel fuel, CO<sub>2</sub> was reduced by 5.4% and CO increased by 6% (although the latter was statistically insignificant).

## INTRODUCTION

Recent increases in the cost of petroleum-based fuels have resulted in an unprecedented interest in products that have the potential to improve fuel economy. At the request of Carbon Chain Technologies Limited (CCT), the Texas Transportation Institute (TTI) in conjunction with Sensors Inc. (the research team) recently conducted a series of fuel economy and in-use emissions tests of light-duty gasoline vehicles (LDGVs) and class 8b Heavy-Duty Diesel Vehicles (HDDV-8bs). The purpose of this testing program was to evaluate the performance of CCT’s combustion enhancer<sup>43</sup>, trade marked as 2ct®, on an LDGV and HDDV-8b truck.

A test procedure based on the TMC<sup>44</sup>/SAE<sup>45</sup> Type II test procedure (SAE J-1321) was developed and used to evaluate the product’s effectiveness in improving the fuel economy of the test vehicles. A similar procedure was developed and utilized to evaluate the impact of 2ct® on the exhaust emissions. SAE J-1321 is primarily designed for heavy-duty diesel vehicles (HDD trucks and buses) and cannot be directly applied to LDGVs. The research team therefore developed a protocol closely assimilating SAE J-1321 to be used for LDGVs.

To facilitate the tests, fuel consumption in a test vehicle was compared to fuel consumption in an identical control vehicle before and after 2ct® combustion enhancer treatment at the recommended dose rate of 1:500 vol/vol. CCT claims that the product will improve fuel economy and reduce exhaust emissions after two tanks full of treated fuel. For this test, the

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<sup>43</sup> The client defines its 2ct® combustion enhancer as a petroleum fuels technology comprising hydrocarbon components that is mixed with fuel to improve the combustion burn, of all grades of petroleum fuel.

<sup>44</sup> Technology and Maintenance Council (TMC) of American Trucking Association (ATA).

<sup>45</sup> Society of Automotive Engineers (SAE).

research team ran the test vehicles for a notional 1,000 miles each to ensure that there was no question of conditioning not having been achieved. This report deals with the two pertinent test segments according to SAE J-1321: - untreated baseline testing, and – post treatment. Each segment of testing consisted of a gravimetric fuel consumption testing followed by emissions testing using SEMTECH-DS manufactured by Sensors Inc. and Montana-2100 and Axion manufactured by Clean Air Technology International Inc. (CATI) portable emissions measurement units.

## **TEST PROTOCOL**

### **FUEL CONSUMPTION TESTING**

SAE J-1321 is currently the only approved standardized testing procedure in the U.S. for comparing the in-service fuel consumption of two conditions of a test vehicle when the tested component (in this case a fuel technology) requires a period of time for replacement or modification (e.g. on-road conditioning). Based on SAE J-1321, fuel consumption can be measured by using a portable weigh tank method (gravimetric method) or utilizing a fuel flow meter (flow meter method).

The fuel consumption method determines the overall accuracy achievable with this procedure. The gravimetric method provides an accuracy of  $\pm 1\%$  (i.e. the actual improvement is within  $\pm 1\%$  of what is observed). The gravimetric method is by far the most widely used fuel consumption measurement method because of its relative simplicity and consistency

SAE J-1321 is primarily designed for heavy-duty diesel vehicles (HDD trucks and buses). Due to this characteristic, it cannot be directly applied to other types of vehicles such as LDGVs. The research team proposed a series of test protocols for this vehicle type to address this issue. These protocols closely assimilate SAE J-1321 with some modifications to make them suitable for LDGVs.

#### *SAE J-1321*<sup>46</sup>

The Joint TMC/SAE fuel consumption test procedure – Type II – SAE J-1321 is the proposed test protocol for these vehicle classes. Major elements of the procedure are:

- Two vehicles are used for the test — a control vehicle (“Vehicle C”) and a test vehicle (“Vehicle T”). Vehicle C is the control vehicle and is not modified in any way during the entire test and is dedicated to the test until the entire test process is complete. This includes load, trailer, and driver.
- The gravimetric method uses a portable auxiliary tank of at least 16 gallons to measure the fuel consumption. The tank is topped off and weighed before the test run and weighed again after the completion of the test run during which the vehicles perform the same driving pattern.

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<sup>46</sup> SAE International, Joint TMC/SAE Fuel Consumption Test Procedure – Type II, SAE Surface Vehicle Recommended Practice J1321, 1986.

- The fuel consumption calculations are based on T/C ([vehicle T]/[Vehicle C]) ratios. A T/C ratio is the ratio of the quantity of fuel consumed by the test vehicle (vehicle T) to the quantity of fuel consumed by the control vehicle (vehicle C) during one test run.
- The testing consists of two sets of tests — baseline and treatment. Each set is composed of a minimum of three valid T/C ratios according to SAE J-1321.
  - Baseline: to establish baseline fuel consumption of the test vehicle running on untreated fuel (vehicle T); and
  - Treatment: to establish the fuel consumption of the test vehicle after modification.

*Modified Test Protocol for Light Duty Gasoline Vehicles.*

SAE J-1321 requires using a portable tank of at least 16 gallons, however, this could not be achieved for LDGVs due to the following characteristics of gasoline vehicles: fuel pump is located inside the fuel tank; there is a sensor on the fuel pump assembly that sends information to vehicle's computer; and a gasoline vapor recovery system is mounted on the fuel tank. To account for these issues, the original tank of the truck was placed inside the cargo bed of the truck and was used as an auxiliary tank

After the baseline tests were completed, the test vehicles were each subjected to a period of approximately 1,000 miles running on the treated fuel. CCT representatives monitored the conditioning at 250-mile increments and confirmed the completion of conditioning.

**TEST PROCEDURE FOR EMISSIONS TESTING**

Emissions of total hydrocarbons (THC), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), oxides of nitrogen (NO<sub>x</sub>), and particulate matter (PM) were measured using two Portable Emissions Measurement System (PEMS) units. The SEMTECH-DS was used to measure CO, CO<sub>2</sub>, and NO<sub>x</sub> emissions, and PM emissions were measured using the OEM-2100 Montana system for the LDGV and the Axion system for the HDDV.

Currently, there is no standard test procedure for on-road emissions measurement. Therefore, a test procedure was developed by the research team to capture on-highway operational conditions. This procedure follows the preparation and calculation methods of J-1321.

The emissions testing was performed directly after completing the fuel efficiency testing

Two sets of tests were performed — baseline and treatment. Each set was composed of a minimum of three valid emissions reading: Baseline – to establish baseline emissions rates of the test vehicle running on untreated fuel (vehicle T); and Treatment – to establish the emissions rate of the test vehicle after treatment.

**TESTING INFORMATION**

**TEST FACILITY**

The test was conducted at the Pecos Research and Testing Center (RTC) outside Pecos, Texas. The 5,800-acres facility has a nine-mile, three-lane circular high speed track for speeds up to

200 mph. Figure B.1 shows the location of the Pecos facility as well as an aerial view of the test tracks.



**Figure B.1. Location and Layout of the Test Track.**

## **TEST FUELS**

Regular gasoline and diesel was purchased and stored in the Pecos facility prior to the testing. These fuels were used as “base fuel.” A specific portion of these fuels were mixed with 2ct® combustion enhancer at the recommended ratio of 1:500 (volume-to-volume) and were used as “treated fuel.” The mixing was performed by representatives of TTI under supervision of CCT. Treated fuel was used for conditioning and treatment testing.

## **TEST VEHICLES**

Two 2005 model year Toyota Tacoma trucks and two 2008 International / Pro Star 1351 HDDVs were selected for testing.

## **MODIFICATIONS TO TEST VEHICLE**

The following modifications were made to the Toyota Tacoma test vehicle’s exhaust line (Vehicle T) and emissions sampling procedure for this vehicle in order to demonstrate that 2ct® is a combustion enhancer:

- The oxygen sensor on the test vehicle was disabled. This was performed to make the engine work under “real conditions” by preventing the engine’s computer from modifying the combustion condition through changing the fuel flow based on the inputs of oxygen sensor. The oxygen sensor was disabled for the entire duration of fuel consumption and emissions testing.



- For the test vehicle, the “engine-out” emissions sample was used instead of the regular “tailpipe-out” sample. This was performed to eliminate the effect of the catalytic converter on the emissions of test vehicle. The gaseous emissions sample line was connected to the exhaust line before the catalytic converter. The PM emissions sample was taken from the tailpipe.

Note that the above modifications were applied only to test vehicle (Vehicle T). The control vehicle (Vehicle C) was used in its original state (unmodified state) for the entire duration of the study and the emissions samples were all tailpipe-out samples.

## **TEST CARGO**

According to SAE J-1321, the vehicles under test should have a cargo with weights representative of the fleet operations and within the capability of the vehicles. To comply with this criterion, both LDGV control and test vehicles were loaded with QUIKRETE® cement bags to reach the gross vehicle weight of 3,820 lbs, and both HDDVs were loaded with concrete barriers to reach the gross vehicle weight of 68,000 lbs.

## **DRIVE CYCLES**

Both control and test vehicles were tested according to the explained test procedures. In order to maintain the consistency between test runs, the vehicles were driven to fixed drive cycles at constant speeds and distances. Prior to testing, a warm-up driving period of 45 miles was executed for all vehicles.

### TEST DRIVE CYCLES

A separate drive cycle was developed for emissions measurement components for each of the gasoline and diesel tests.

### ANALYSIS DRIVE CYCLE

A synthetic drive cycle was used for emissions data analysis for each of the gasoline and diesel tests.

## **RESULTS**

### **FUEL CONSUMPTION**

The T/C ratios for all test runs were calculated and the first three ratios that fell within the SAE J-1321 prescribed 2 percent filtering band were used to compute an average value representing each segment of testing.

	GASOLINE	DIESEL
FUEL SAVED	6.8%	12.1%
IMPROVEMENT	7.3%	13.7%

Results show that the addition of 2ct® combustion enhancer to the base fuels produced an improvement of 7.3 percent under the modified J1321 test procedure and test vehicle modification (i.e. disabled oxygen sensor) for the gasoline test and 13.7 percent for the diesel test. The *fuel saved* and *improvement* values are calculated according to SAE J-1321 as following:

$$\% \text{ Fuel Saved} = (\text{Ave. Baseline T/C} - \text{Ave. Treatment T/C}) \div \text{Ave. Baseline T/C} \quad [2]$$

$$\% \text{ Improvement} = (\text{Ave. Baseline T/C} - \text{Ave. Treatment T/C}) \div \text{Ave. Treatment T/C} \quad [3]$$

## EMISSIONS

The improvement percentages are calculated according to the J-1321 calculation method. Positive improvement values mean a decrease in the total emissions for the cycle while a negative value indicates an increase of the pollutant.

	GASOLINE	DIESEL
CO <sub>2</sub>	6.9%	5.4%
CO	27.1%	-6.6%
NO <sub>x</sub>	-13.3%	-2.1%

Results show a statistically significant improvement of 6.9 and 5.4 percent respectively for CO<sub>2</sub> emissions. The results also indicate a statistically significant 27.1 percent improvement for CO emissions for gasoline and a statistically insignificant increase of 6.6% for diesel. The results show a 13 and 2 percent increase in NO<sub>x</sub> emissions of the already low readings for the post 2007 Class 8b trucks. These differences are statistically significant at the 95 percent degree of confidence level for gasoline and are not statistically significant for diesel.

From the gasoline emissions tests PM emissions differences were found to be statistically insignificant. Both diesel vehicles were equipped with Exhaust Gas Recirculation (EGR) and Diesel Particulate Filters (DPF). EGR is a NO<sub>x</sub> emissions control device working by recirculating a portion of exhaust gas back to the engine cylinders. EGR can reduce NO<sub>x</sub> emissions as high as 50 percent. DPF is a device developed to reduce PM emissions in diesel engines' exhaust gases. The PM emissions rates were found to be very low and close to the detection limit of Axion emissions measurement unit. Because of this, the collected data were inconclusive and not reported here.

*A full copy of the report can be obtained from: [2ct@carbonchaintech.com](mailto:2ct@carbonchaintech.com)*