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October 31, 2004

Final Report/Task 5B Report

Updated Assessment of Potential Emission Reductions of Prototype Diesel/Electric Hybrid Pickup/Delivery Vehicles in the Houston-Galveston Region

Deliverable for

Task 5: Regional Vehicle Estimates and Survey
Emissions Testing of Prototype Diesel/Electric Hybrid Commercial Pickup/Delivery Vehicles (PUDS) and Assessment of Potential Emission Reductions in the Houston-Galveston Non-Attainment Area from Widespread Use in Delivery Fleets

Prepared for

Texas Commission on Environmental Quality
New Technology Research and Development Program

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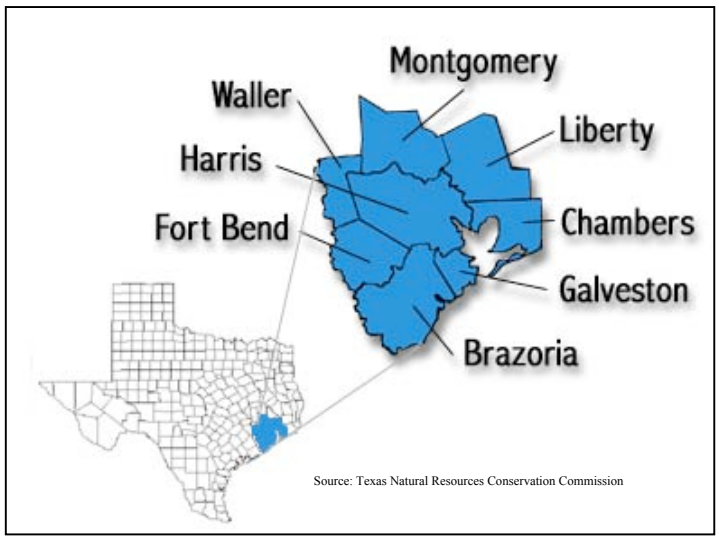
I. Introduction

Objective

This report provides estimates of the emission reductions possible under various scenarios involving the widespread use of diesel/electric hybrid commercial pickup/delivery vehicles (PUDs) in the eight-county Houston-Galveston Non-Attainment Area (Figure 1). An earlier report (*Task 3: Regional Vehicle Estimates and Survey*, August 13, 2003) from this project estimated the current fleet size of trucks of this type in the Houston-Galveston region.[1]

Figure 1
Houston-Galveston Non-Attainment Area



Trucks that are one class smaller (Class 3) and one class larger (Class 5) are also investigated since the diesel/electric hybrid propulsion technology of interest here can, in many cases, also be used in these other vehicles with accommodations made for different weight and performance requirements.

This report is the second deliverable of Task 5 of the Texas Council on Environmental Technology project entitled *Emissions Testing of Prototype Diesel/Electric Hybrid Commercial Pickup/Delivery Vehicles (PUDS) and Assessment of Potential Emission Reductions in the Houston-Galveston Non-Attainment Area from Widespread Use in Delivery Fleet*s. The first report included analysis of impacts of a prototype delivery truck. This report is an update of the November 2003 report and includes analysis of the pre-production vehicle with a 2004 certified engine.

[1] William G. Barker, David Hitchcock and Dan Matisoff, *Baseline Class 4 Truck Inventory for the Houston-Galveston Region*, prepared for the Texas Council of *Environmental Technology by the Houston Advanced Research Center, August 13, 2003.

Project Background

In August 2000, FedEx, the world's largest express transportation company, and the Alliance for Environmental Innovation, a project of the non-profit environmental organization Environmental Defense, entered into a partnership to create the next generation delivery truck. The project will fundamentally change the energy and environmental profile of FedEx's fleet of pick-up and delivery trucks, and will serve as a model for other companies to upgrade their fleets and continue to push for cleaner, more fuel-efficient technology. The FedEx-Alliance partnership leverages FedEx's purchasing power to signal a demand for new transportation options. The project is being conducted on an aggressive timeline designed to push technology development, support public policy, encourage replication, and ultimately, to put cleaner trucks on the road as soon as possible.

The project's goal has been to develop a FedEx Express pick up and delivery vehicle that significantly decreases particulate emissions and smog-causing emissions, increases fuel economy, functions equivalently and, over its lifetime, costs the same as the standard FedEx Express medium-duty W700 delivery truck (Figure 2) . Alternative technologies will be needed to meet these goals while minimizing emissions of particulate matter (such as $PM_{2.5}$), smog-causing emissions (such as oxides of nitrogen [NOx]) and greenhouse gases (such as CO_2).

Figure 2
FedEx Standard W700 Step Van

Recent research[2, 3, 4] shows that hybrid electric vehicles (particularly those with direct-injection engines) have similar projected ranges of "well-to-wheel" energy efficiency as fuel cells. They also have design advantages such as regenerative braking, which make them well suited for pickup and delivery trucks. Additionally, unlike electric or compressed natural gas engines, hybrid electric trucks use a widely available fuel and do not need dedicated fueling infrastructure. This is critical to FedEx which does not centrally fuel its fleet. This is also essential to encourage rapid, widespread adoption of the new truck by other fleets.

[2] General Motors Corporation, *et al*., *Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems, North America Analysis, Executive Summary Report*, June 2001.
[3] Frank Kreith and R. E. West, "Gauging Efficiency, Well to Wheel," *Mechanical Engineering Power*, June 2003, www.memagazine.org.
[4] Malcolm A. Weiss, John B. Heywood, Andreas Schafer & Vinod K. Natarajan, *Comparative Assessment of Fuel Cell Cars*, Laboratory for Energy and the Environment, Massachusetts Institute of Technology, MIT LFEE And 2003-001 RP, February 2003.

In tests of buses used in New York City, hybrid electric vehicles achieved dramatically better fuel economy than either standard diesel buses (65% improvement) or CNG buses (as much as 100% improvement). These fuel savings add to the economic incentive for using environmentally advanced technology.

Hybrid electric technology also significantly reduces other vehicle emissions, including greenhouse gases, particulates and air toxics.

Summary of Findings

Both the prototype and pre-production vehicles built by Eaton for FedEx reduced the emissions of NOx and PM significantly, as compared with the baseline vehicle. On the pre-production model NOx emissions were reduced by 65% and PM emissions by 96%.

Widespread adoption of the hybrid electric drive train for Class 3, 4, and 5 vehicles in the Houston region could reduce NOx emissions by 2.48 tons per day by 2010 through normal truck replacement schedules. These vehicles are normally replaced over a 10 to 12 year period.

Higher initial costs of hybrid vehicles would dampen market penetration and subsequent emission impacts, reducing the impacts to less than one-half ton per day of NOx emission reductions. Incentives that offset the purchase price difference would increase emission reductions by an estimated 30%. Similarly, rising fuel prices would increase market penetration as fuel savings offset initial purchase costs. (Fuel price scenarios were not analyzed in this study.)

Vehicle Description and Classification

The prototype FedEx Eaton Hybrid Electric Vehicle (shown in Figure 3), which was reported in the first version of this report, used the Freightliner Custom Chassis Model MT45 with a standard step van Utilimaster body. The baseline Cummins 5.9L diesel engine was initially replaced with a DaimlerChrysler OM904 4.3L diesel engine and the Allison automatic transmission was replaced with an Eaton Hybrid Drive Unit, containing the automatic clutch, electric traction motor, and AutoShift transmission. This **prototype vehicle** was tested by Southwest Research Institute in September 2002.

The **pre-production hybrid vehicl**e included in this report uses the Mercedes Benz OM904 I-4 EGR with 2004 certification. In addition, the Fleetguard Diesel Particulate Filter is employed in the exhaust system for reducing particulate emissions. Testing of this pre-production vehicle took place in August 2004.

Figure 3
Eaton Hybrid Electric Truck

A comparison of the standard, baseline FedEx delivery step van, the prototype Eaton Hybrid Electric Truck and the pre-production Eaton Hybrid Electric Truck is shown in Table 1.

The hybrid vehicle is powered by a smaller diesel engine in combination with an electric motor. As can be seen in Table 2, both the prototype and pre-production vehicles are able to achieve better fuel economy, lower emissions, and greater acceleration all at the same time.

Table 1
Vehicle Description – Baseline and Eaton Hybrid Trucks
Source: Environmental Defense, *FedEx-Alliance Future Vehicle Program Eaton Hybrid Electric Vehicle Description & Measured Performance* March 24, 2003 updated by HARC based on private communication with Elizabeth Sturcken, October 22, 2004

	Baseline Truck	Prototype Hybrid Electric Truck	Pre-Production Hybrid Electric Truck
Model	W700 Step Van	W700 Step Van	W700 Step Van
Body	Utilimaster	Utilimaster	Utilimaster
Chassis	Freightliner MT45	Freightliner MT45	Freightliner MT45
Cargo Area	700 cubic feet	700 cubic feet	700 cubic feet
Engine	5.9L Cummins I6 Diesel	2002 4.3L Mercedes OM904 I4 Diesel	2004 4.3L Mercedes OM904 I4 Diesel EGR
Transmission	Allison AT542FE	Eaton FO-8406A-ASX	Eaton FO-8406A-ASX
Rear Axle Ratio	4.10	3.31	3.31
Tires Front:	Goodyear G647 225/70R19.5	Goodyear G647 225/70R19.5	Goodyear G647 225/70R19.5
Rear:	Goodyear G159	Goodyear G159	Goodyear G159

	Baseline Truck	Prototype Hybrid Electric Truck	Pre-Production Hybrid Electric Truck
	225/70R19.5	225/70R19.5	225/70R19.5
Wheels	19.5 inch, steel	19.5 inch, steel	19.5 inch, steel
Brakes	Hydraulic	Hydraulic	Hydraulic
Weight:			
GVWR (lbs.)	16,000	16,000	16,000
Payload (lbs.)	5,720	5,390	5,390
Test Weight (lbs.)	13,200 (includes 3,000 lbs. of payload)	13,800 (includes 3,000 lbs. of payload)	13,800 (includes 3,000 lbs. of payload)

Table 2
Summary of Southwest Research Institute FTP Test Results

Source: Environmental Defense, *FedEx-Alliance Future Vehicle Program Eaton Hybrid Electric Vehicle Description & Measured Performance* March 24, 2003 updated by HARC based on private communication with Elizabeth Sturcken, October 22, 2004

FedEx Requirements	FedEx FVP Program Targets	Comparison of Prototype Eaton Hybrid Truck to the Baseline Truck	Comparison of Pre-Production Eaton Hybrid Truck to the Baseline Truck
Fuel Economy Requirements			
Fuel Economy (MPG)	50% Increase	45% Increase	57% Increase
Environmental Requirements			
NOx (g/mile)	90% Reduction	54% Reduction	65% Reduction
PM (g/mile)	90% Reduction	93% Reduction	96% Reduction
Functional Requirements			
Payload Capacity - Weight (lbs.)	Same as baseline	within 330 lbs.	within 330 lbs.
Payload Capacity - Volume (ft.3)	Same as baseline	Unchanged - no intrusion to cargo area	Unchanged - no intrusion to cargo area
Cruise Speed (MPH)	Same as baseline	Unchanged	Unchanged
0-60 MPH Acceleration (seconds)	Same as baseline	16% improvement	16% improvement
Braking System	Same as baseline	Unchanged	Unchanged
Range (miles)	Same as baseline	Unchanged - downsized fuel tank for weight reduction	Unchanged - downsized fuel tank for weight reduction
Turning Radius (feet)	Same as baseline	Unchanged	Unchanged
Maximum Launch Grade (%)	Same as baseline	52% Improvement	52% Improvement
Maximum Grade at 55 MPH (%)	Same as baseline	28% Improvement	28% Improvement
Cost Requirements			
Lifetime Cost (Cents / Mile)	Cost competitive	Improved over baseline	Improved over baseline

FedEx Fleet in the Houston-Galveston Region

FedEx has a fleet of 443 vehicles of all model years in the Houston-Galveston Non-Attainment Area which account for 9.7 million vehicle miles each year. The most popular single model vehicle in the fleet is the W700 step van of which there are 294, or 66% of the total fleet, in the region. The W700 step van is the vehicle which is targeted to be replaced over time by the new diesel hybrid electric vehicle. The FedEx W700 trucks currently account for 6.2 million annual vehicle miles or 64% of the mileage of the FedEx fleet in the non-attainment area. FedEx reports that vehicles are kept in service for 10-12 years, which is consistent with standard industry practice.[5]

A Vehicle Classification

A comparison of the truck classes used in this inventory with those used in the MOBILE6 emissions estimation program is shown in Table 4. The 16,000 gross vehicle weight (gvw) of both the baseline and Eaton hybrid step vans put these vehicles in Class 4.

Because the hybrid propulsion technology can be applied to other classes of trucks, information was collected on Class 3 and 5 trucks in addition to the Class 4 of the vehicles under direct study. Photos of examples of Class 3, 4 and 5 trucks are shown in Figure 3.

Table 3
Vehicle Classification

Source: Based on Office of Transportation and Air Quality, *Technical Guidance on the Use of MOBILE6 for Emission Inventory Preparation*, U.S. Environmental Protection Agency, January 2002.

	EPA Description	R.L. Polk Truck Class
LDV	Light-Duty Vehicles (Passenger Cars)	
LDT1	Light-Duty Trucks 1 (0-6,000 lbs. GVWR, 0-3750 lbs. LVW)	1C
LDT2	Light Duty Trucks 2 (0-6,001 lbs. GVWR, 3751-5750 lbs. LVW)	
LDT3	Light Duty Trucks 3 (6,001-8500 lbs. GVWR, 0-5750 lbs.	2
LDT4	Light Duty Trucks 4 (6,001-8500 lbs. GVWR, >5750 lbs.	
HDV2B	Class 2b Heavy Duty Vehicles (8501-10,000 lbs. GVWR)	2C
HDV3	Class 3 Heavy Duty Vehicles (10,001-14,000 lbs. GVWR)	3
HDV4	Class 4 Heavy Duty Vehicles (14,001-16,000 lbs. GVWR)	4
HDV5	Class 5 Heavy Duty Vehicles (16,001-19,500 lbs. GVWR)	5
HDV6	Class 6 Heavy Duty Vehicles (19,501-26,000 lbs. GVWR)	6
HDV7	Class 7 Heavy Duty Vehicles (26,001-33,000 lbs. GVWR)	7
HDV8A	Class 8a Heavy Duty Vehicles (33,001-60,000 lbs. GVWR)	8
HDV8B	Class 8b Heavy Duty Vehicles (>60,000 lbs. GVWR)	
HDBS	School Buses	
HDBT	Transit and Urban Buses	
MC	Motorcycles (All)	

[5] FedEx information provided by Ms. Alison Bird, Project Manager, Environmental Engineering, FedEx in Memphis, TN through personal communications in 2003.

Figure 4
Examples of Class 3, 4 and 5 Trucks
Source: http://www.trucktraderonline.com/index.html

Class 3 (10,001-14,000 gvw)

Class 4 (14,001-16,000 gvw)

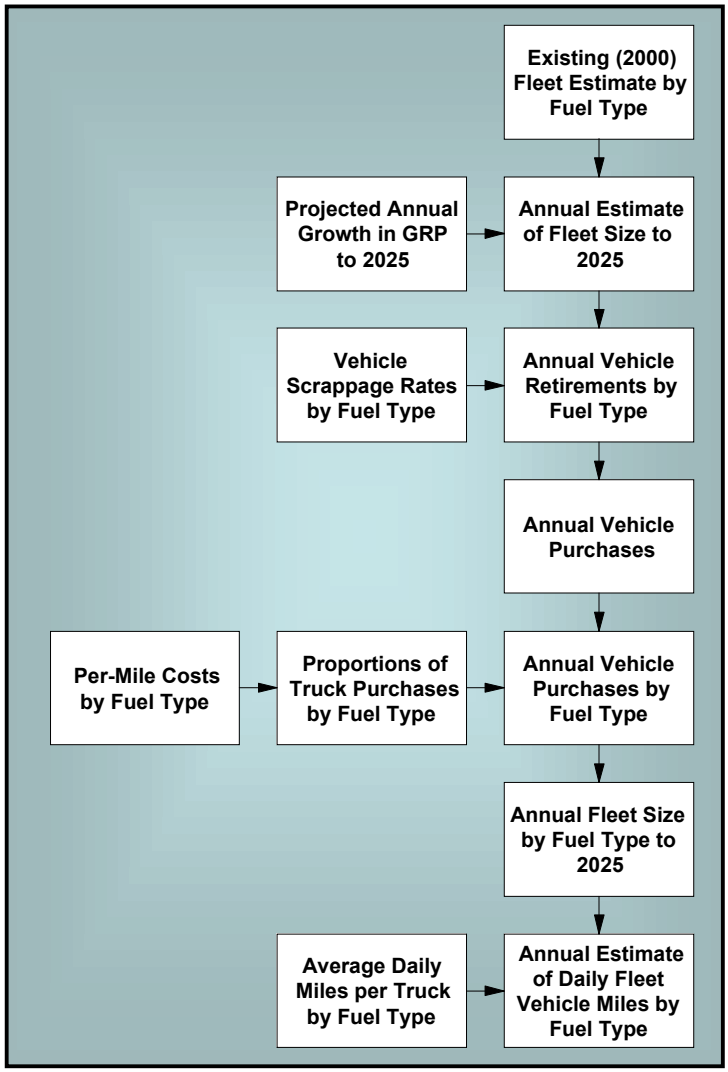
Class 5 (16,001-19,500 gvw)

II. Projected Baseline Fleet Inventory, Use and Emissions

To estimate the emissions from trucks in the eight-county Houston-Galveston Non-Attainment Area, projections must be made of the numbers of trucks by type and the amount of vehicle miles generated by these vehicles. These projections are presented in this section and are based upon the previous report in this project (*Task 3: Regional Vehicle Estimates and Survey*, August 13, 2003).

The approach to making these estimates is illustrated in Figure 5. The year 2000 fleet estimates made previously as part of this project are factored by the expected growth in the gross regional product in order to estimate the total number of vehicles in the fleet for each year from 2000 to 2025.

Figure 5
Fleet Size and Activity Estimation Methodology



With the total number of vehicles in the region set, the number of vehicles being retired each year is estimated based on the number of vehicles in the previous year's fleet. Subtracting the scrapped vehicles from the total estimated fleet size provides the number of features purchased in the year of interest.

The percentage of the purchased vehicles that are diesel, gasoline, or hybrid propulsion is estimated by a model based on the cost per mile to own and operate the truck. It is assumed that the cheaper it is to own and operate a truck, the more likely it is that the propulsion technology will be purchased compared to other choices.

Per truck mileage rates are assigned to the fleet in order to estimate the total vehicle mileage.

Current Fleet Inventory and Use

Estimates were documented for the year 2000 base year in the previous report and are summarized here in Table 7.

Table 7
Total Class 3, 4 & 5 Trucks in Houston-Galveston Non-Attainment Area, 2000
Source: HARC tabulations of VMT data provided by the Houston-Galveston Area Council for August 30, 2000 and national averages for Metropolitan Statistical Areas of the miles per vehicle and percent locally based trucks in the 1997 U.S. Census Vehicle Inventory and Use Survey

Truck Class	Fuel	Daily VMT	Daily Miles/Vehicle	Number of Vehicles	Percent Local Vehicles	Number of Local Vehicles	Number of Non-Local Vehicles
Class 3	Gasoline	742,626.6	54.84	13,542	39.1%	5,300	8,242
	Diesel	904,178.0	70.11	12,897	36.0%	4,645	8,252
	Total	979,004.6	68.65	26,439	36.3%	9,945	16,494
Class 4	Gasoline	342,453.6	52.85	6,479	41.8%	2,707	3,773
	Diesel	527,437.9	72.00	7,325	36.5%	2,677	4,649
	Total	869,891.5	63.01	13,805	39.0%	5,383	8,421
Class 5	Gasoline	146,218.0	22.76	6,424	65.2%	4,187	2,238
	Diesel	342,491.8	67.19	5,097	55.7%	2,840	2,257
	Total	488,709.8	42.42	11,522	61.0%	7,026	4,495

Growth in the Vehicle Fleet

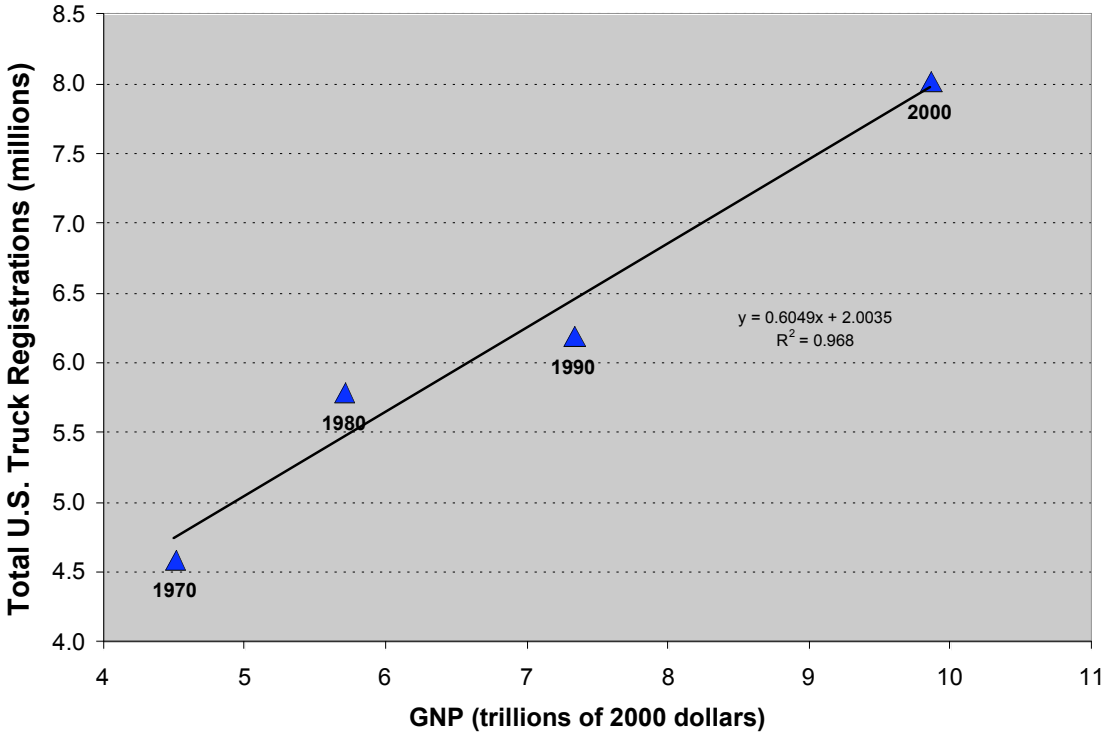
There is a direct relationship between the United States Gross National Product (GNP) and the total national truck fleet as shown in Figure 6. The number of trucks operating in the Houston-Galveston Non-Attainment area is assumed to be largely dependent on the Gross Regional Product (GRP) of the area. The gross product for a region is conceptually the same as estimates of gross national product: it is the value of all goods produced for final sale in an accounting period and originates from a particular geographic region.[6]

Houston's GRP grew by 2.74% per year during the period 1977-1991 which was about 12% higher rate than the annual growth rate of 2.45% in the GNP during the same period.[7] The Perryman Group has predicted a 2.8% average growth of the Houston area's annual real gross regional product until the year 2025.[8] This is a realistic, if not conservative, estimate given that the reference, or midpoint, estimate of the GNP growth assumed in the Annual Energy Outlook is 3.0% per year during 2001-2025.[9]

[6] Robert W. Gilmer, "Gross Regional Product: Another View of Houston's Economy," *Houston Business*, Federal Reserve Bank of Dallas, Houston Branch, April 1995.
[7] Ibid.
[8] Houston Mayor Lee Brown speech before the Houston Hispanic Architects and Engineers Monthly Seminar, HESS Club, September 17, 2001.
[9] Energy Information Administration, *Assumptions for the Annual Energy Outlook 2003,* U.S. Department of Energy, DOE/EIA-0554(2003), January 2003

Assuming an annual growth rate of 2.8%, the projected number of vehicles operating in the Houston-Galveston Non-Attainment Area is shown in Figure 7. These estimates assume no changes in the proportions of vehicles by class or fuel type.

Figure 6
Gross National Product and National Truck Fleet
Source: HARC analysis of data in National Transportation Statistics 2000[10]



The distribution of the national fleet of Class 3, 4 and 5 trucks in 1997 was assumed to be the distribution of the ages of the trucks operating in the Houston-Galveston Non-Attainment Area in 1999. These age distributions are shown in Figure 8.

Projected Vehicle Scrappage

To project the number of vehicles purchased, the number of vehicles which are scrapped each year is estimated based on heavy truck survival rates published by Greenspan and Cohen.[11] Figure 9 shows how the probability of a vehicle remaining in operation falls during the useful life of the vehicle. These rates are based on observation and there is no consideration as to the reason the vehicle is taken out of service.

[10] U.S. Department of Transportation, Bureau of Transportation Statistics, *National Transportation Statistics 2000* BTS01-01 (Washington, DC, U.S. Government Printing Office, April 2001)
[11] Alan Greenspan and Darrel Cohen, "Motor Vehicle Stocks, Scrappage, and Sales." Federal Reserve Board, Washington, D.C., October 30, 1996

Approximately 2,000 to 3,000 Class 3, 4 and 5 trucks will be scrapped each year within the first few years of this analysis (see Figure 10). By 2010, the annual scrappage of these trucks approaches 4,000 per year and increases by about an additional 500 trucks each five years. By 2025, the annual scrappage of Class 3, 4 and 5 trucks is about 5,500 vehicles per year.

Projected Vehicle Purchases

With the scrappage estimated, the number of vehicles purchased each year can be calculated from:

$$N_{n+1} = V_{n+1} + S_{n+1} - V_n$$

where:

N_{n+1} is the number of vehicles purchased in year n+1;
V_{n+1} is the number of vehicles operating in year n+1;
S_{n+1} is the number of vehicles scrapped in year n+1; and
V_n is the number of vehicles operating in year n.

Total purchases of Class 3, 4 and 5 trucks are shown in Figure 11. Total truck purchases are approximately 4,000 per year in the beginning of this analysis. The purchases climb to nearly 9,000 vehicles annually by 2025.

Figure 7
Baseline Vehicle Forecasts, 2000-2025
Source: HARC

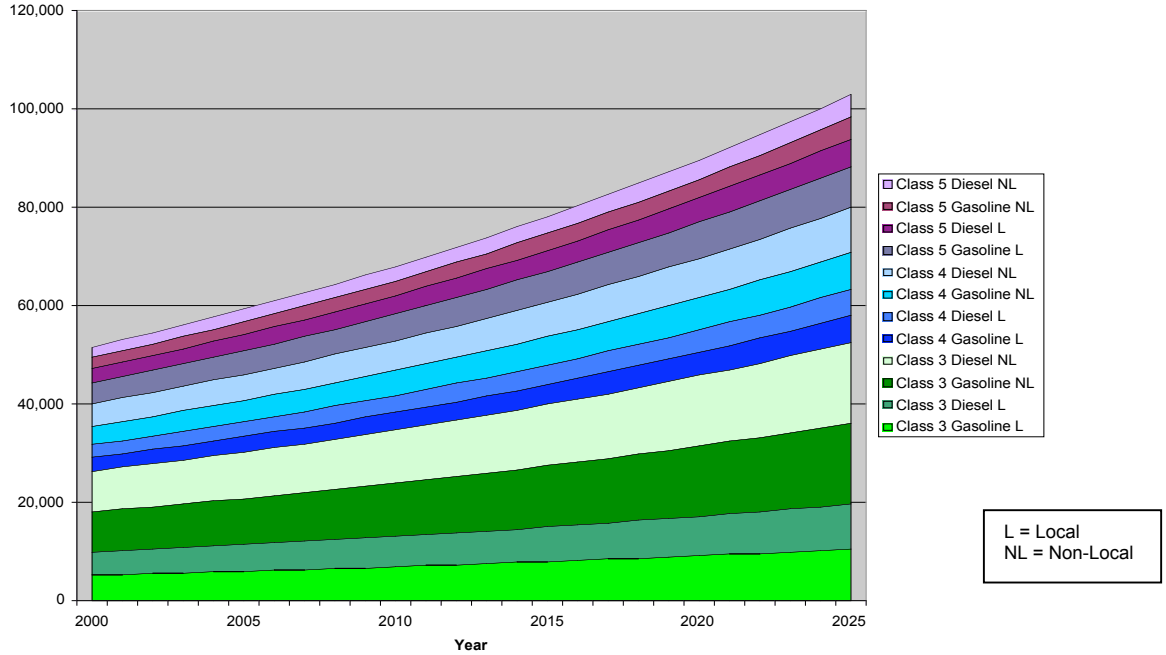


Figure 8
National Vehicle Age Distribution, 1997

Source: HARC tabulations of U.S. Census Bureau, 1997 Vehicle Inventory and Use Survey

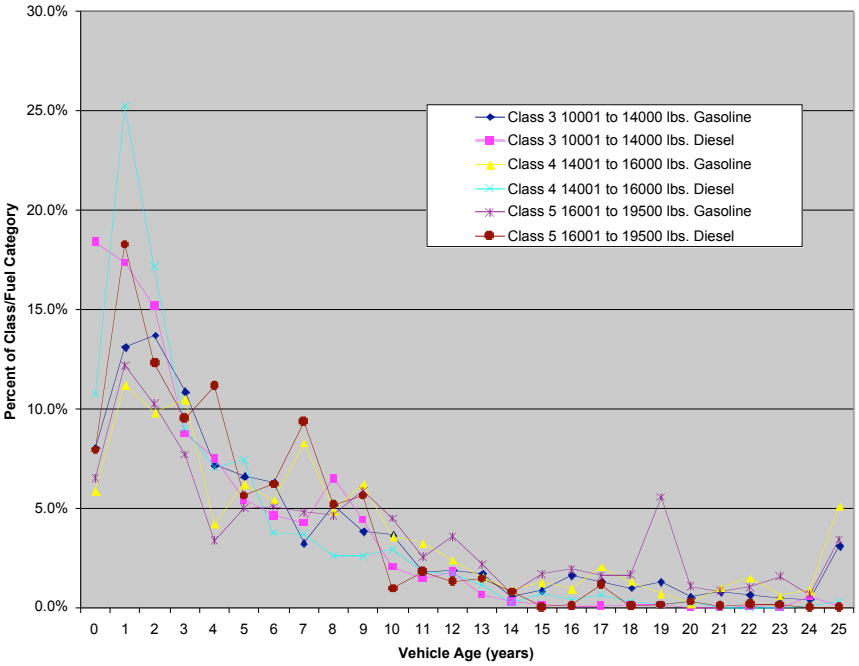


Figure 9
National Heavy Vehicle Scrappage Rate

Source: Alan Greenspan and Darrel Cohen, "Motor Vehicle Stocks, Scrappage, and Sales." Federal Reserve Board, Washington, D.C., October 30, 1996

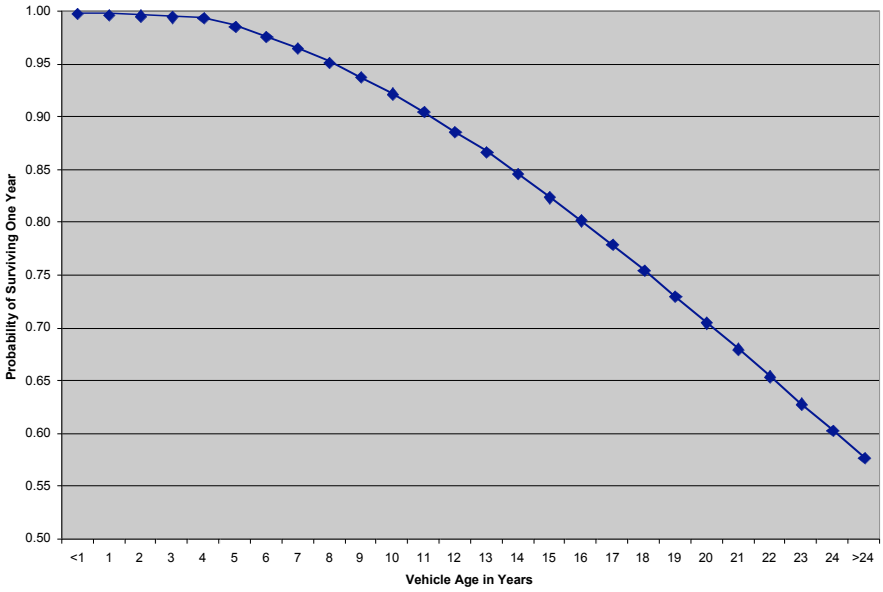


Figure 10
Annual Class 3, 4 and 5 Vehicles Scrapped, 2000-2025
Source: HARC estimates, 2003

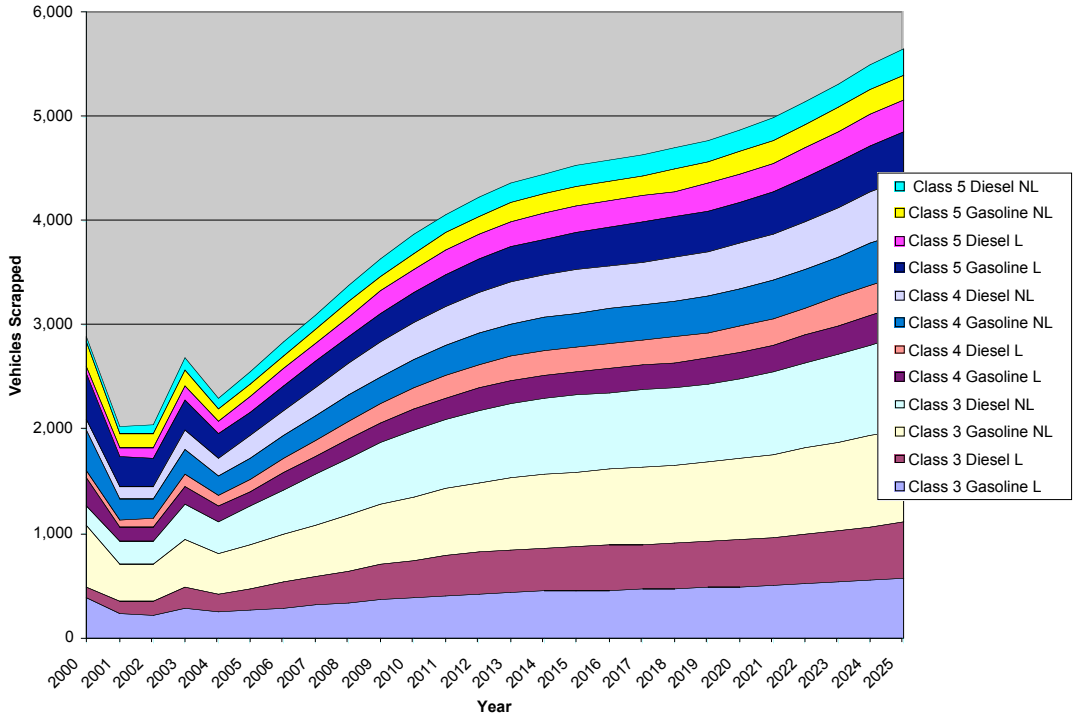
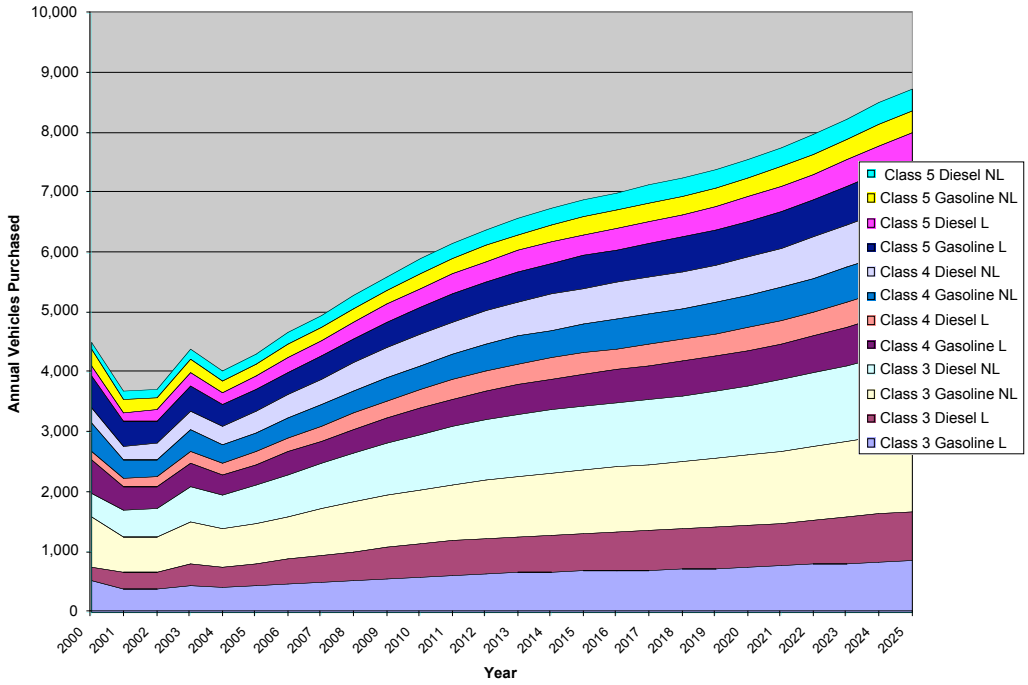


Figure 11
Annual Class 3, 4 and 5 Vehicles Purchased, 2000-2025
Source: HARC estimates, 2003



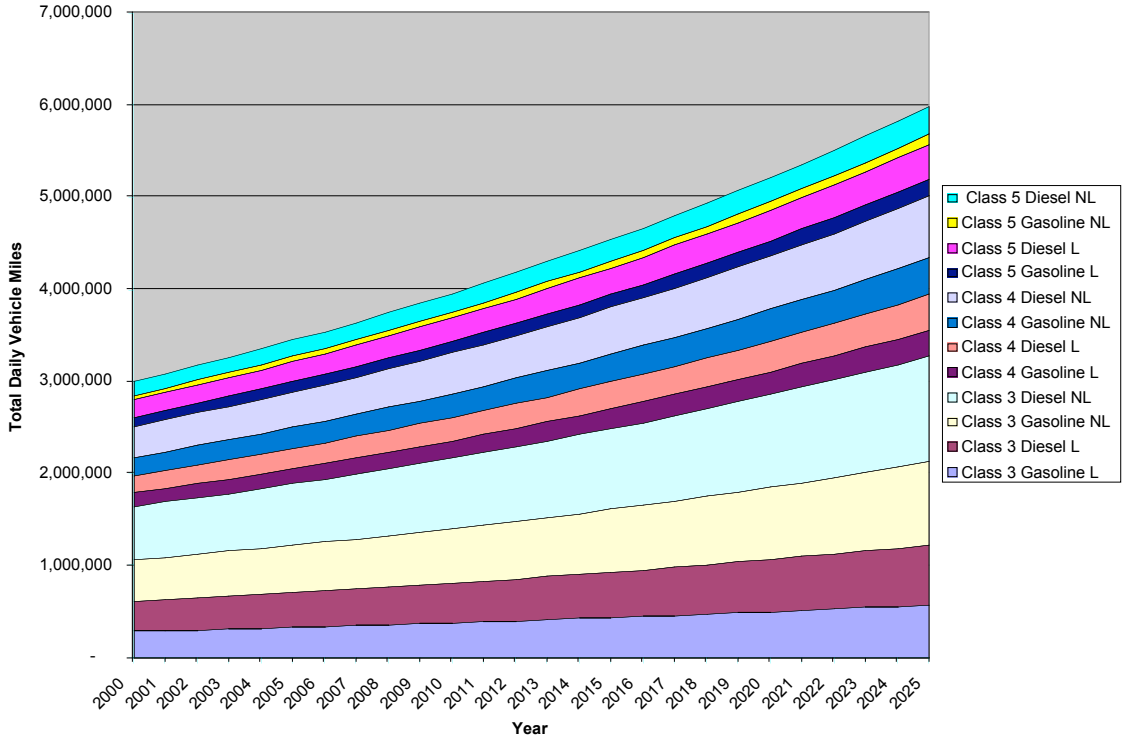
Projected Vehicle Miles of Travel (VMT)

To estimate the vehicle miles of travel, observed values of the number of miles per vehicle by class and fuel type are used. These values are for the national fleet of trucks operating in urban areas. The derivation of these values is documented in the first report from this project.[12]

Will trucks continue to operate the same number of miles per unit in the years ahead? A sprawling metropolitan area suggests that trucks will need to operate more miles to achieve the same productivity level. On the other hand, a slower, congested roadway system would result in fewer miles per truck hour. For the purposes of this analysis, it is assumed that the vehicle miles per truck unit remain the same over the forecast period.

Estimated daily vehicles miles of travel (VMT) are shown for the years 2000-2025 in Figure 12. Total daily vehicle miles generated by all Class 3, 4 and 5 trucks double from 3 million miles in 2000 to 6 million miles in 2025.

Figure 12
Average Daily Class 3, 4 and 5 Vehicles Miles Traveled, 2000-2025
Source: HARC estimates, 2003



[12] William G. Barker, David Hitchcock and Dan Matisoff, op. cit.

Projected Baseline Emissions

Emission rates used for these estimates made here are based upon the Houston-Galveston area's application of the latest release of the U.S. Environmental Protection Agency's MOBILE6 model.[13] The MOBILE6 model estimates emission factors, i.e., grams of pollutant emissions per vehicle mile, based on the characteristics of the vehicle, vehicle speed, and local climate. Specifically, the model estimates motor vehicle emission rates for hydrocarbons (HC or VOC for volatile organic compounds), oxides of nitrogen (NOx) and carbon monoxide (CO).

In the Houston-Galveston area, the Texas Transportation Institute applies the MOBILE6 model to directional traffic flows on roadway network links on an hourly basis for each of the 28 vehicle types.[14, 15] These disaggregate estimates are then combined to provide aggregate emission rates for VOC, CO and NOx. While MOBILE6.2 will provide emission rates for particulate matter, carbon dioxide and air toxics, the most recent Houston-Galveston area applications for transportation conformity purposes do not compute or publish these values.

Two separate years are of interest: 2000 and 2007. Daily emission factors have been tabulated for both years and are summarized in Table 8. The day of Wednesday, August 30, 2000 was used as the analysis day.

Table 8
Aggregate Emission Factors for Class 3, 4 & 5 Trucks in Houston-Galveston Non-Attainment Area, 2000 and 2007
Source: HARC tabulations of TTI data posted on Monday, August 18, 2003, to the Texas Council on Environmental Quality website:
http://ftp.tnrcc.state.tx.us/pub/OEPAA/TAD/Modeling/NearNonattainmentAreas/MobileEI/temp/

		Class 3		Class 4		Class 5	
Year	Rate	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel
2000	VOC lbs/1000 VMT	2.751090	0.550423	2.600746	0.632557	5.195334	0.708677
	CO lbs/1000 VMT	43.591019	2.162313	35.760503	2.498481	75.547212	3.027388
	NOx lbs/1000 VMT	12.052912	12.898283	11.163025	15.160705	14.010664	16.429726
2007	VOC lbs/1000 VMT	2.792924	0.520583	2.776435	0.608602	7.115403	0.705710
	CO lbs/1000 VMT	45.589398	2.142720	38.460393	2.505887	101.113406	3.051752
	NOx lbs/1000 VMT	12.000109	12.507382	11.203270	14.941475	15.207430	16.127977

[13] The U.S. Environmental Protection Agency released an updated version of the MOBILE model on November 12, 2002 named MOBILE6.2 on its website http://www.epa.gov/otaq/m6.htm.
[14] Texas Transportation Institute, *2000 On-Road Mobile Source Episode-Specific Emissions Inventories for the Houston-Galveston Ozone Nonattainment Area*, sponsored by the Texas Natural Resource Conservation Commission, March 2002
[15] Texas Transportation Institute, *2007 On-Road Mobile Source Episode-Specific Emissions Inventories for the Houston-Galveston Ozone Nonattainment Area*, sponsored by the Texas Natural Resource Conservation Commission, March 2002

The emission rates in Table 8 were applied to the daily vehicle miles estimated previously to project the total daily tons of VOCs, CO and NOx. The 2000 rates were used for the years from 2000 to 2006 and the 2007 rates were used for that and subsequent years.

It is clear from Figures 13, 14 and 15 that the substitution of diesel-electric propulsion for a diesel-only powertrain will have the biggest impact on NOx emissions. This will be the focus of the remainder of this report.

Figure 13
Average Daily Class 3, 4 and 5 Vehicles VOC Baseline Emissions, 2000-2025
Source: HARC estimates based on TTI data, 2003

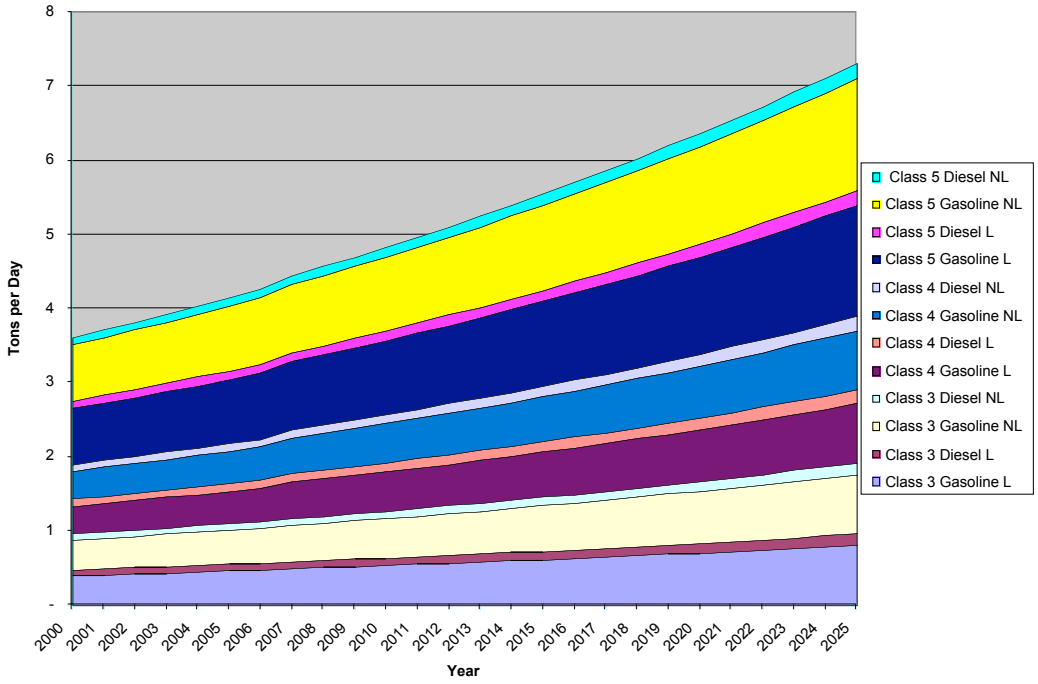


Figure 14
Average Daily Class 3, 4 and 5 Vehicles CO Baseline Emissions, 2000-2025
Source: HARC estimates based on TTI data, 2003

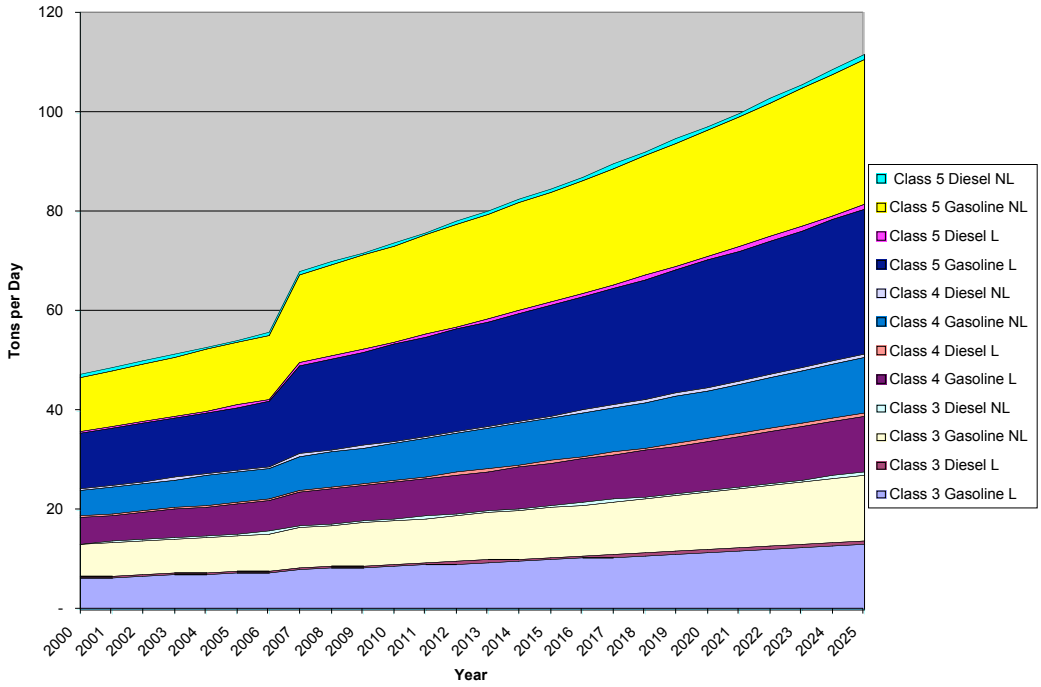
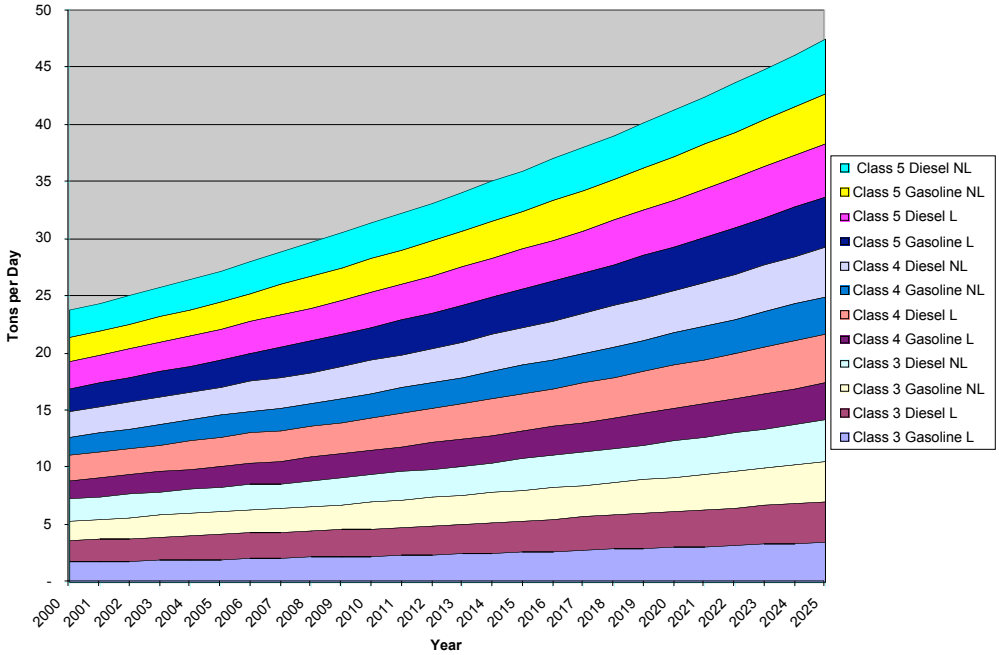


Figure 15
Average Daily Class 3, 4 and 5 Vehicles NOx Baseline Emissions, 2000-2025
Source: HARC estimates based on TTI data, 2003



IV. Emissions Reductions from Diesel-Electric Trucks

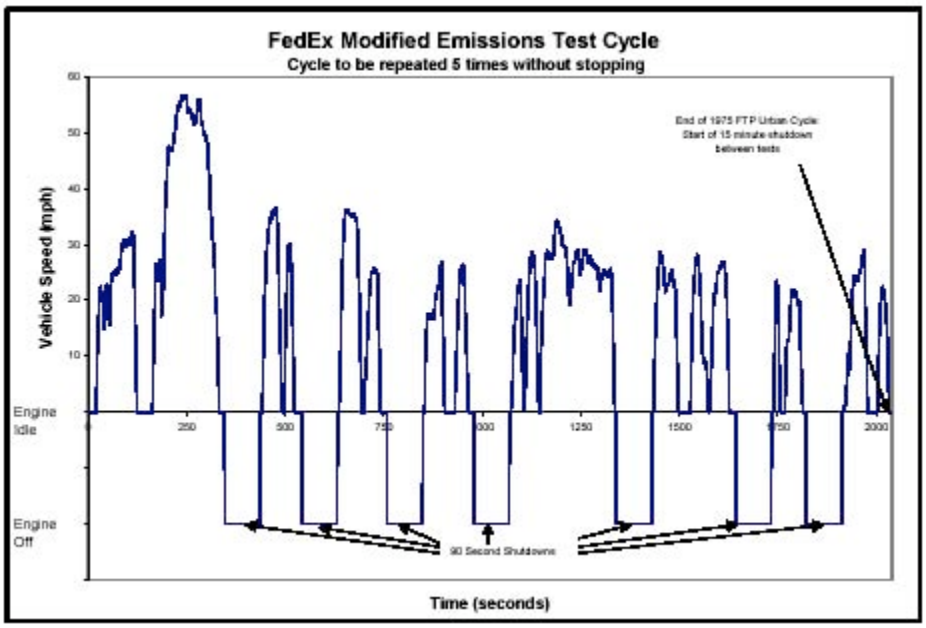
The potential emissions reductions in the Houston-Galveston Non-Attainment Area from the widespread use of diesel/electric hybrid commercial vehicles is estimated here by substituting the emissions from the prototype Eaton diesel electric hybrid truck for the emissions from conventional trucks under various scenarios. Section VI, which follows, adjusts these emission estimates to reflect the August 2004 testing of the pre-production hybrid truck.

Emissions from the FedEx Eaton Hybrid Electric Vehicle

The FedEx Eaton Hybrid Electric Vehicle was tested by Southwest Research Institute (SwRI) in San Antonio, Texas. The 1999 baseline W700 vehicle was also tested at the same time to provide a comparison.

The test cycle used by Southwest Research was the modification of the 1975 Federal Test Procedure (FTP) as defined in SAE Information Report J1506. This modified cycle uses only the first 1,372 seconds of the 1975 urban cycle and includes an engine shutdown at every other vehicle stop. This test cycle is representative of the average daily drive cycle of the vast majority of FedEx trucks. The cycle is shown below in Figure 16.

Figure 16
FedEx Modified Emissions Test Cycle, 2003
Source: FedEx, Alliance for Environmental Innovation and Southwest Research



Emissions from the Southwest Research tests were reported in terms of grams per vehicle mile (g/mi). Compared to the baseline vehicle, the prototype hybrid emitted 54% less

NOx and 93% less particulates.[16] The pre-production hybrid increased these to 65% for NOx and 96% for particulates. While the reduction in particulate emissions is significant, the focus of this analysis is on the NOx emission reductions.

Possible Scenarios

The following scenarios were examined as part of this assessment:

1. Baseline (for comparison purposes)
2. Substitution for all new diesel Class 4 step vans (12.6% of Class 4 diesel trucks)[17]
3. Substitution for new diesel Class 4 step vans based on a vehicle choice model
4. Scenario 3 above with grants available to offset the additional capital cost of a hybrid vehicle
5. Substitution for all new Class 4 diesel trucks
6. Substitution for all new Class 3, 4 and 5 diesel vehicles

Scenario 3 is considered to be the most realistic estimate of the application of the specific vehicle being developed by FedEx and Eaton without any governmental incentives. The other scenarios suggest the potential impact of this technology through widespread application.

Vehicle Choice Model

A simple model of vehicle choice was used to estimate the expected purchases of a production version of a vehicle similar to the FedEx Eaton Hybrid Electric Vehicle.

A logit model[18] was assumed:

$$P(h) = \exp(\Delta) / (1 + \exp(\Delta))$$

where:

P(h) is the probability of a new vehicle purchase being a diesel-electric hybrid; and

Δ is the value of the net present value of the cost of owning and operating a diesel vehicle less the net present value of the cost of owning and operating a diesel-electric hybrid vehicle all divided by $10,000. In other words,

[16] FedEx-Alliance Future Vehicle Program Eaton Hybrid Electric Vehicle Description & Measured Performance, March 24, 2003

[17] According to HARC tabulations of the *1997 Vehicle Inventory and Use Survey*, 26.1% of all Class 3 diesel trucks in metro areas are step vans. The same percentage for Class 4 trucks is 12.6%, and, for Class 5, the percentage is 6.3%.

[18] J.S. Cramer, "The Origins and Development of the Logit Model," August 2003 based on Chapter 9 in *Logit Models from Economics and Other Fields*, Cambrodge University Press, 2003.

Δ = (NPV(owning/operating diesel truck)-NPV(owning/operating hybrid truck))/$10,000

where:

NPV is the net present value;

and

owning/operating costs include purchase price, fuel cost, maintenance costs, less the estimated scrappage value of the vehicle. The operating costs include neither the costs of driver labor nor overhead.

By using the net present value, capital and operating costs are combined with discounted values for costs and revenues in the future.[19]

The logit model will estimate the probability of selecting a hybrid truck as 0.5 during a truck purchase if the net present value of the ownership and operation of the hybrid truck equals that of the diesel truck. The probability of selecting a hybrid truck increases as the net present value of the hybrid becomes relatively more attractive compared to the diesel truck.

A sample output of the vehicle choice model is shown in Figure 17. This assumes that the diesel truck costs $40,000 and the hybrid vehicles costs 30% more. The fuel economy of the diesel truck was set at 7 miles per gallon with the hybrid truck set at a 45% higher fuel economy. Maintenance costs of the diesel vehicle were assumed to be $0.16 per vehicle mile with the hybrid truck costing 10% less.[20] The price of diesel fuel was assumed to be $1.50 per gallon.[21] The vehicles were assumed to travel 26,000 miles per year and last for 12 years. Vehicles depreciate in value at 19% per year.[22] A 3% discount rate was assumed.

The point on the curve highlighted in Figure 17 matches the assumptions above assuming a 12-year lifetime of both vehicles. At this point, the hybrid vehicle has a life cycle cost or net present value of nearly $10,000 less than a conventional diesel vehicle. The model predicts a 73% chance of a hybrid vehicle being purchased under these assumptions. This simple model used here assumes rational, informed purchase behavior based solely on costs on the part of firms buying trucks and further assumes that there is no supply constraint on the production of the hybrid vehicles.

[19] Borg & Company, *Harnessing the Power of the Public Purse: Final report from the European PROST study on energy efficiency in the public sector*, prepared for the European Council for an Energy Efficient Economy, 2002

[20] Evin Chandler, Kevin Walkowicz and Nigel Clark, *United Parcel Service (UPS) CNG Truck Fleet: Final Results*, U.S. Department of Energy, August 2002.

[21] Energy Information Agency, "Gasoline and Diesel Fuel Update," U.S. Department of Energy, October 21, 2003

[22] Rand Corporation, *Fighting Air Pollution in Southern California by Scrapping Old Vehicles*, prepared for the Institute for Civil Justice, 2001

Figure 17
Simple Logit Model of Vehicle Choice with No Grants
Source: HARC

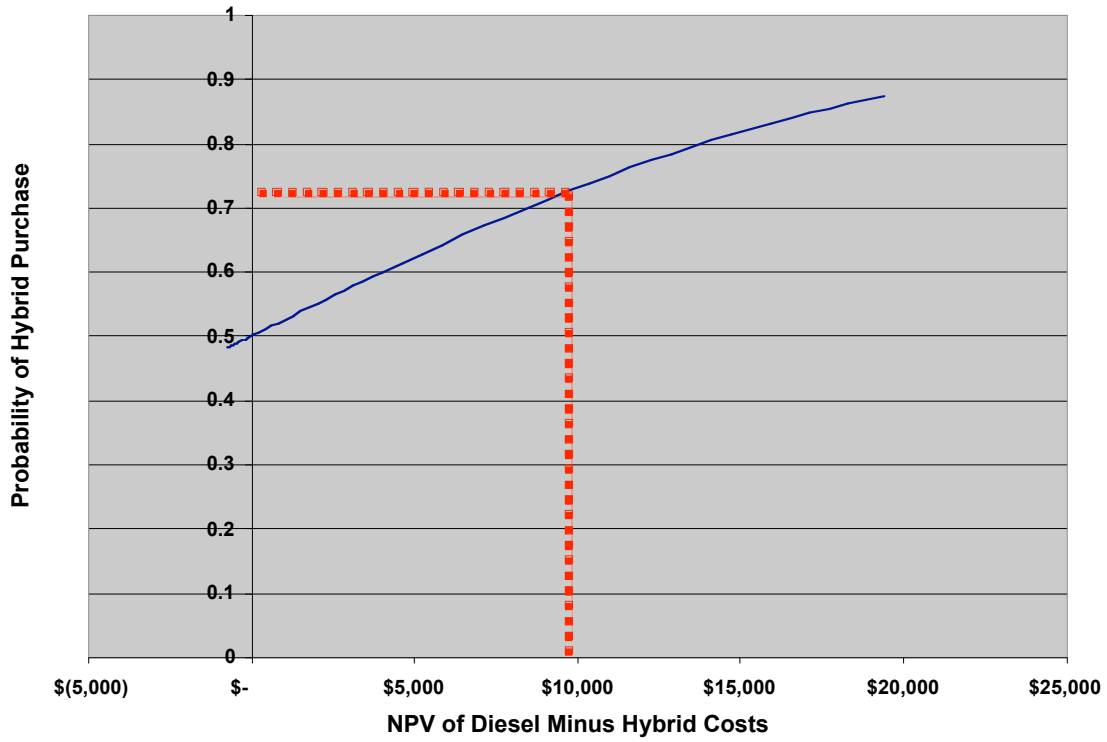


Figure 18 shows the potential impact of a capital grant to offset the assumed 30% premium on the purchase price of a hybrid truck. The difference in the net present value (to the truck purchaser) between the hybrid and diesel-only vehicles becomes approximately $20,700 in favor of the hybrid vehicle with 12-year lifetimes assumed for both vehicles. The model predicts that 89% of the new vehicle purchases would be hybrids under this scenario.

Projected Number of Hybrid Vehicles

Assuming that the production hybrid vehicles are available in 2005, Figure 19 shows the purchases of new diesel-electric hybrid trucks in the Houston-Galveston Non-Attainment Area for Scenarios 2-6. Scenario 1 does not include hybrid vehicles.

Note the relative size of the diesel step van market in Scenarios 2-4 when compared to the total Class 3, 4 and 5 diesel vehicle fleets.

Figure 18
Model of Vehicle Choice with Purchase Price Premium Offset Grant
Source: HARC

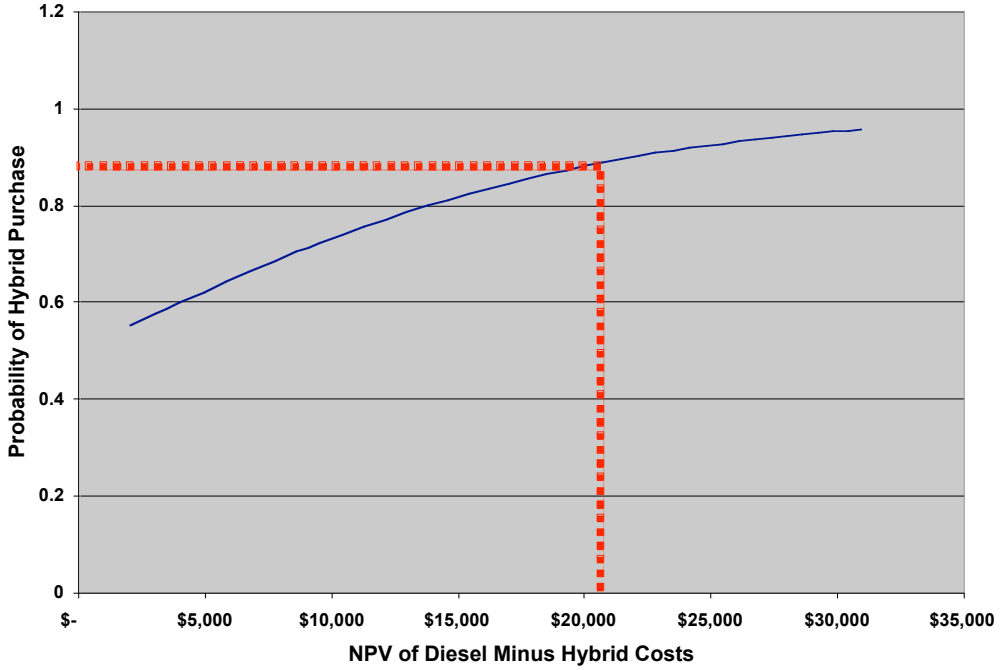


Figure 20 indicates the total number of hybrid trucks operating under Scenarios 2-6. The hybrid vehicles are assumed to be subject to the same scrappage rates as conventional trucks.

Figure 21 summarizes the daily NOx emissions reduced from the baseline projection in Scenario 1. Assuming that production diesel-electric step vans can be on the road in 2005, by 2010 the NOx savings from these step vans would save between 0.10 and 0.15 tons of NOx emissions per day assuming the prototype vehicle characteristics. Using the emissions characteristics of the pre-production vehicle tested in August 2004, daily NOx savings are estimated between 0.11 and 0.17 tons The capital grant scenario, Scenario 4, would increase NOx reductions by 30% based on the September 2002 prototype truck emissions compared to expected implementation of the hybrid technology without the grant program. Assuming the more recent August 2004 pre-production emissions characteristics, Scenario 4 would increase NOx reductions by 34%.

As hybrid trucks are assumed for all Class 4 diesel trucks in Scenario 5 and all Class 3, 4 and 5 trucks in Scenario 6, the NOx reductions are increased significantly. By 2010, for example, the NOx reductions in Scenario 6 are estimated to be 2.25 tons per day assuming the September 2003 prototype truck characteristics. NOx reductions in Scenario 6 are increased to 2.48 tons per day with the improved emissions of the pre-production model truck tested in August 2004.

Figure 19
Purchases of Hybrid Vehicles by Scenario
Source: HARC

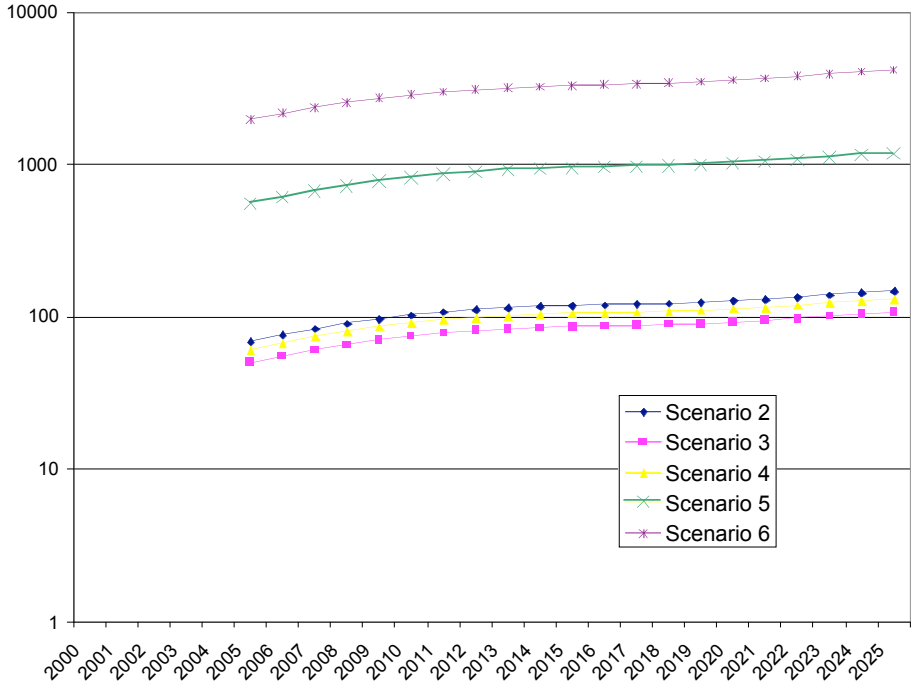


Figure 20
Total Operating Hybrid Vehicles by Scenario
Source: HARC

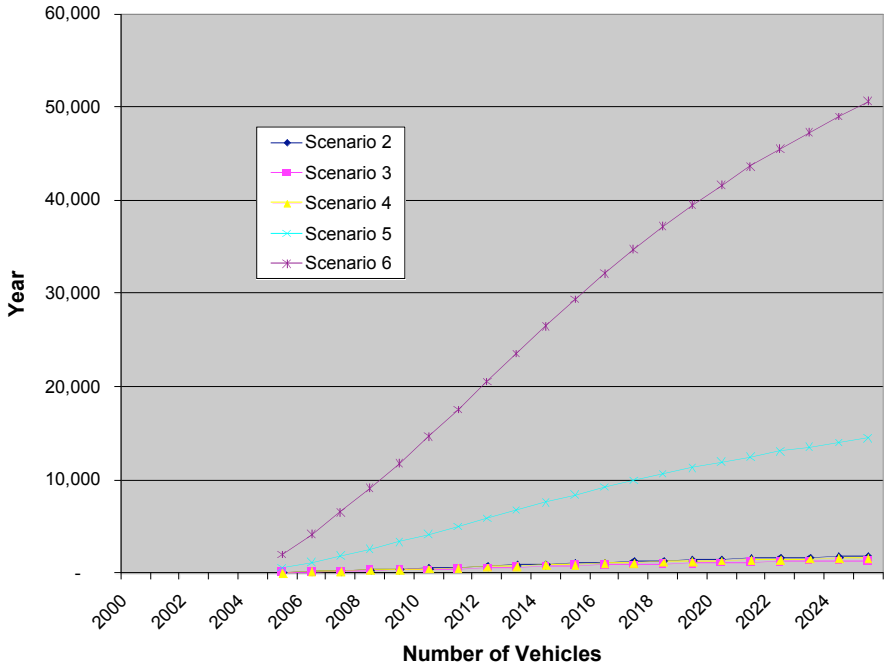
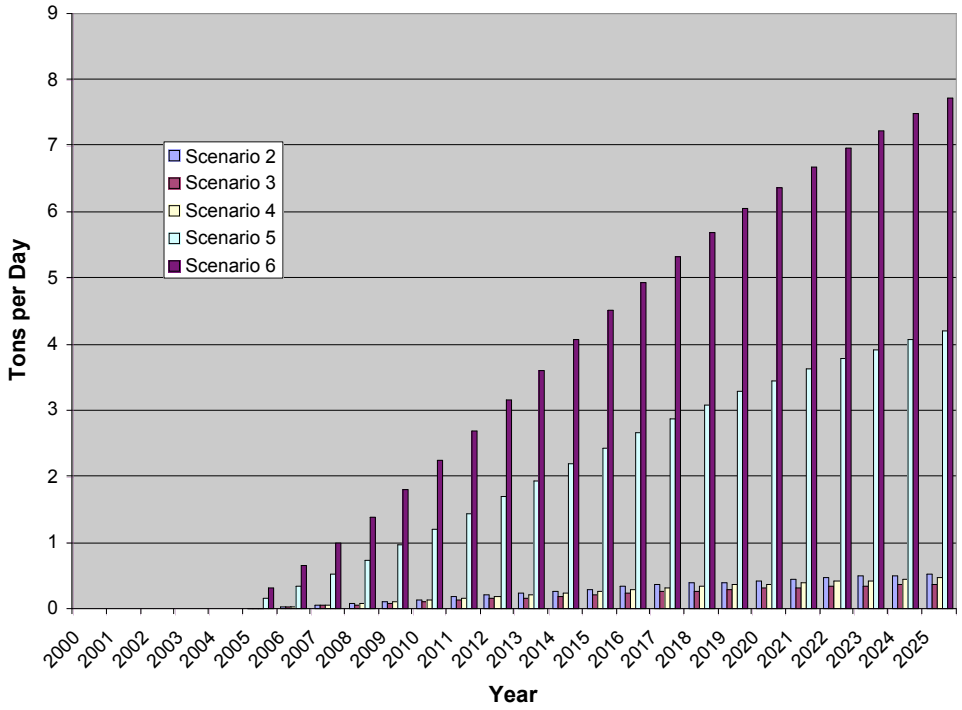


Figure 21
Daily NOx Reductions (Tons) from Hybrid Vehicles by Scenario
Source: HARC



V. Update from Emissions Tests of Pre-Production Vehicle

This section of the report provides a summary update on the potential impact of the program by incorporating the findings from the August 2004 testing of a new pre-production truck. By September 2004, a total of 18 pre-production model trucks were delivered to Sacramento, New York City, Washington, DC, and Tampa and were put in revenue service. In August 2004, one of these 18 new trucks was sent to Southwest Research Institute in San Antonio, Texas where the same tests were conducted as those on the baseline truck and the prototype.[23] Figure 22 shows the truck mounted on the chassis dynamometer.

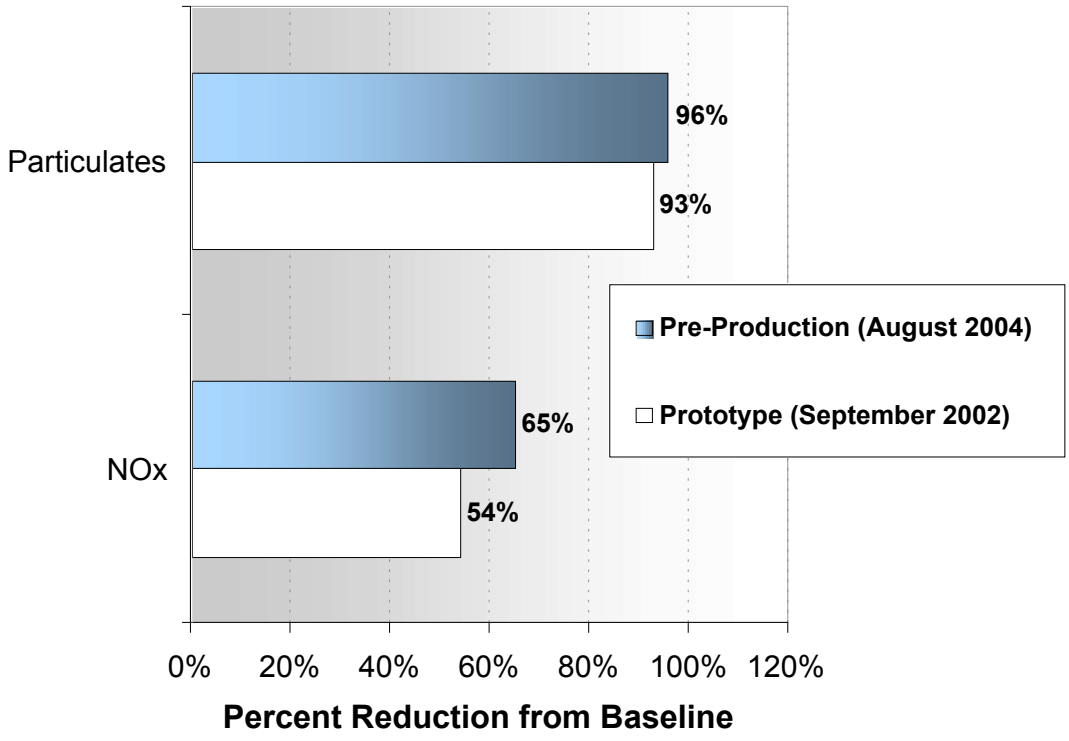
Figure 22
Hybrid-Drive Walk-In FedEx Delivery Truck Mounted on Chassis Dynamometer at Southwest Research Institute
Source: Environmental Defense

[23] Environmental Defense, *Final Report to the Houston Advanced Research Center & the Texas Commission on Environmental Quality*, Contract No. 02-R01-23G for Air Pollutant Emissions Reduction Technology Environmental Defense & FedEx Hybrid Truck Project. September 13, 2004.

The testing was essentially the same as previous testing on the base and prototype vehicle and as described in Section IV, Emissions Reductions from Diesel-Electric Trucks of this report. Additional testing was accomplished to determine the size distribution of the particulates emitted in the exhaust of the pre-production vehicle with a diesel particulate filter.[24]

Information provided by Environmental Defense[25] and the Southwest Research Institute were combined to document the reduction in emissions, in terms of grams per vehicle mile, for the 2002 prototype truck and the 2004 pre-production vehicles as compared to the baseline vehicle. This information is shown in Figure 23.

Figure 23
Reductions in Emissions (grams/mile)
Source: Houston Advanced Research Center analysis of data from Environmental Defense and Southwest Research Institute



[24] Imad A. Khatek, *Particle Size and Number Characterization of the Exhaust from a Baseline Diesel and a Diesel Hybrid FedEx W700 Delivery Truck Equipped with a Diesel Particulate Filter*, prepared for Environmental Defense by Southwest Research Institute, San Antonio, Texas, September 2004.

[25] Elizabeth Sturcken, Environmental Defense, personal communication, October 22, 2004.

As expected due to continuing improvements, the pre-production vehicle was found to have lower emissions than the prototype vehicle. Emissions of particulates were reduced an additional 3% to 96% while emissions of NOx were reduced an additional 12% to 65% when compared to the baseline vehicle.

These new values are more representative of what production vehicle emissions will be. They do not affect the projections of the number of vehicles and vehicle miles of travel for the Houston region as set forth in this report. The reductions in emissions are, however, greater than previously estimated.

The following scenarios were used earlier in the report to perform the impact assessment:

1. Baseline (for comparison purposes)
2. Substitution for all new diesel Class 4 step vans (12.6% of Class 4 diesel trucks)[26]
3. Substitution for new diesel Class 4 step vans based on a vehicle choice model
4. Scenario 3 above with grants available to offset the additional capital cost of a hybrid vehicle
5. Substitution for all new Class 4 diesel trucks
6. Substitution for all new Class 3, 4 and 5 diesel vehicles

Assuming that production diesel-electric step vans can be on the road in 2005, by 2010 the NOx savings from these step vans would save between 0.11 and 0.17 tons of NOx emissions per day. The capital grant scenario, Scenario 4, would increase NOx reductions by 34% (0.15 to .23 tons/day) compared with expected implementation of the hybrid technology without the grant program.

As hybrid trucks are assumed for all Class 4 diesel trucks in Scenario 5 and all Class 3, 4 and 5 trucks in Scenario 6, the NOx reductions are increased. By 2010, for example, the NOx reductions in Scenario 6 are estimated to be 2.48 tons per day.

[26] According to HARC tabulations, 26.1% of all Class 3 diesel trucks in metro areas are step vans. The same percentage for Class 4 trucks is 12.6%, and, for Class 5, the percentage is 6.3%.

VI. Conclusions

This report provides estimates of the emission reductions possible under six different scenarios involving increasingly widespread use of diesel-electric hybrid commercial pickup/delivery vehicles (PUDs) and other similar trucks in the eight-county Houston-Galveston Non-Attainment Area.

Based primarily on the Texas Transportation Institute application of the MOBILE6.2 model in the Houston-Galveston region, baseline, i.e., without hybrid vehicle, daily Class 3, 4, and 5 truck emissions of VOC, CO and NOx were made. Then, using the Southwest Research testing of the prototype Eaton Hybrid Electric Truck NOx emissions, estimates of NOx reductions were made. These estimates were made from 2005, the year that production hybrid trucks are expected to be available, to the year 2025.

Assuming that production diesel-electric step vans, like the Eaton Hybrid Electric Truck with the emissions of the pre-production model tested in August 2004, can be on the road in 2005, by 2010 the NOx savings from these step vans would save between 0.11 and 0.17 tons of NOx emissions per day assuming the emissions rates of the pre-production vehicle. A capital grant program to eliminate the expected premium purchase price of the hybrid vehicle would increase NOx reductions by 34% compared to expected implementation of the hybrid technology without the grant program.

Since step vans represent only about 13% of all Class 4 diesel trucks, the application of the technology to other truck applications and Class 3 and 5 trucks will increase NOx reductions. For example, if all new Class 3, 4 and 5 diesel trucks purchased after 2004 were hybrid trucks, the NOx reductions are estimated to be 2.48 tons per day for the Houston-Galveston Non-Attainment Area based on the findings from the August 2004 tests of the pre-production hybrid truck.