OPTIMAL DEPLOYMENT PLAN OF EMISSION REDUCTION TECHNOLOGIES FOR TxDOT'S CONSTRUCTION EQUIPMENT

A Thesis

by

MUHAMMAD EHSANUL BARI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2009

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	Luca Quadrifoglio
Committee Members,	Mark W. Burris
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ABSTRACT

Optimal Deployment Plan of Emission Reduction

Technologies for TxDOT's Construction Equipment. (August 2009)

Muhammad Ehsanul Bari, B.Sc., Bangladesh University of Engineering and Technology

Chair of Advisory Committee: Dr. Luca Quadrifoglio

The purpose of this study was to develop and test an optimization model that will provide a deployment plan of emission reduction technologies to reduce emissions from non-road equipment. The focus of the study was on the counties of Texas that have nonattainment (NA) and near-nonattainment (NNA) status.

The objective of this research was to develop methodologies that will help to deploy emission reduction technologies for non-road equipment of TxDOT to reduce emissions in a cost effective and optimal manner. Three technologies were considered for deployment in this research, (1) hydrogen enrichment (HE), (2) selective catalytic reduction (SCR) and (3) fuel additive (FA). Combinations of technologies were also considered in the study, i.e. HE with FA, and SCR with FA. Two approaches were investigated in this research. The first approach was "Method 1" in which all the technologies, i.e. FA, HE and SCR were deployed in the NA counties at the first stage. In the second stage the same technologies were deployed in the NNA counties with the remaining budget, if any. The second approach was called "Method 2" in which all the technologies, i.e. FA, HE and SCR were deployed in the NA counties along with

deploying only FA in the NNA counties at the first stage. Then with the remaining budget, SCR and HE were deployed in the NNA counties in the second stage. In each of these methods, 2 options were considered, i.e. maximizing NOx reduction with and without fuel economy consideration in the objective function. Thus, the four options investigated each having different mixes of emission reduction technologies include Case 1A: Method 1 with fuel economy consideration; Case 1B: Method 1 without fuel economy consideration; Case 2A: Method 2 with fuel economy consideration; and Case 2B: Method 2 without fuel economy consideration and were programmed with Visual C++ and ILOG CPLEX. These four options were tested for budget amounts ranging from $500 to $1,183,000 and the results obtained show that for a given budget one option representing a mix of technologies often performed better than others. This is conceivable because for a given budget the optimization model selects an affordable option considering the cost of technologies involved while at the same time maximum emission reduction, with and without fuel economy consideration, is achieved.

Thus the alternative options described in this study will assist the decision makers to decide about the deployment preference of technologies. For a given budget, the decision maker can obtain the results for total NOx reduction, combined diesel economy and total combined benefit using the four models mentioned above. Based on their requirements and priorities, they can select the desired model and subsequently obtain the required deployment plan for deploying the emission reduction technologies in the NA and NNA counties.

DEDICATION

To

Dad and Mom

and

All My Family Members

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NOMENCLATURE

CO_2	Carbon Dioxide
CO	Carbon Monoxide
DOC	Diesel Oxidation Catalysts
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
FHWA	Federal Highway Administration
HC	Hydrocarbon
HDDV	Heavy-Duty Diesel Vehicle
LSD	Low Sulfur Diesel
NOx	Nitrogen Oxides
PM	Particulate Matter
$PM_{2.5}$	Fine Particulate Matter
SCR	Selective Catalytic Reduction
TxDOT	Texas Department of Transportation
TTI	Texas Transportation Institute
ULSD	Ultra Low Sulfur Diesel

TABLE OF CONTENTS

CHAPTER Page

Page

LIST OF FIGURES

Page

Page

Page

Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

Background

Pollutant emission is a big concern as breathing polluted air is injurious to health. Air pollution causes damage to trees, crops, plants, lakes, and animals. Therefore, air pollution is indeed a big concern for the environment (EPA 2008a).

Impacts of Emissions

Air pollution has significant health, environmental, and economic impacts. Inhaling polluted air irritates the throat and makes breathing difficult and causes burning sensations in the eyes and nose. Respiratory problems are triggered especially for people with asthma due to pollutants like tiny airborne particles and ground level ozone. Approximately 30 million adults and children in the United States have been identified with asthma. Air pollution worsens the health problem especially for the elders and others having respiratory or asthma problems.

This thesis follows the style of *Journal of Transportation Engineering*.

Highly toxic chemicals like benzene or vinyl chloride released in the air can cause cancer, birth defects, long term injury to the lungs, brain and nerve damage and can even cause death. Some pollutants deplete the protective ozone layer in the upper atmosphere and lead to changes in the environment and dramatic increase in skin cancers and cataracts. Toxic air pollutants and chemicals contribute to environmental damages through forming acid rain and ground-level ozone that can damage trees, crops, wildlife, lakes and other water bodies. Fish and other aquatic life are also affected by these pollutants. Economic losses are also associated with air pollution. Air pollution causes illnesses leading to lost days at work and school and inhibits the agricultural crop and commercial forest yields worth billions of dollars each year (EPA 2008a).

Major Sources of Emissions

The U.S. Environmental Protection Agency (EPA) (2009) categorized air pollution sources as stationary and mobile sources. Sources that are fixed in place are called stationary sources. These sources include facilities such as oil refineries, chemical processing facilities, power plants, and other manufacturing facilities. There are federal and state air pollution controls permitting requirements for most stationary sources.

Mobile sources are non-fixed sources of air pollution including a wide variety of vehicles, engines and equipment that can move or can be moved from place to place and can generate air pollution. Mobile sources are divided into two groups, on-road and non-road sources. On-road sources are vehicles used on roads for movement of passengers or freight. On-road sources include light-duty vehicles, light-duty trucks, heavy-duty vehicles, medium duty passenger vehicles, and motorcycles. Non-road sources comprise of engines, aircraft, marine vessels, locomotives, and equipment that are used for construction, agriculture, transportation, and recreational purposes (EPA 2007).

Mobile sources contribute pollutants such as carbon monoxide (CO), volatile organic compounds (VOCs), nitrogen oxides (NOx), and particulate matter (PM). They also emit hazardous air pollutants/air toxics like benzene, formaldehyde and acetaldehyde. Mobile sources' nationwide air pollution contribution is large and these are the primary cause of air pollution in many urban areas (EPA 2009).

Legislature Actions to Control Emissions

Thick clouds of air pollution above the industrial town of Donora, Pennsylvania in 1948 and events like London's "Killer Fog" in 1952 killed many people. These events alerted everyone to the dangers of air pollution to public health. To reduce the polluted air, several federal and state laws were passed, including the original Clean Air Act of 1963. Later Congress passed a much stronger Clean Air Act in 1970 (EPA 2008b). In the same year, Congress created the Environmental Protection Agency (EPA). The Congress gave the federal government authority to reduce air pollution in this country. Since then, EPA and states have established a variety of programs to reduce air pollution levels nationwide (EPA 2008a).

The Clean Air Act was dramatically revised and expanded in 1990 and it provided EPA with even broader authority to implement and enforce regulations to reduce pollutant emissions. EPA sets limits on certain air pollutants in order to ensure basic health and environmental protection from air pollution. The Clean Air Act gives EPA the authority to limit emissions from sources like chemical plants, utilities, and steel mills. EPA provides research, expert studies, engineering designs, and funding to assist state, tribal and local agencies to support clean air progress. Since 1970, several billion dollars were granted to the states, local agencies, and tribal nations by Congress and EPA to support these programs (EPA 2008b).

Specific Concern with Non-Road Sources

Based on the U.S. Environmental Protection Agency's report from 1999 regarding National NOx emissions, it was seen that on-road and non-road sources contributed 34 percent and 22 percent of total NOx emissions, respectively. Among the non-road sources, 49 percent of NOx came from diesel equipment. For fine particulate matter ($PM_{2.5}$) emissions, on-road and non-road sources contributed 10 percent and 18 percent of $PM_{2.5}$ respectively, and diesel equipment contributed 57 percent of $PM_{2.5}$ among the non-road sources (EPA 2007). Therefore, emissions from the non-road sector, especially diesel equipment are very significant.

Non-road diesel engines such as construction and agricultural equipment emit huge amounts of NOx and PM and contribute to air pollution and health related problems significantly (EPA 2008c). The diesel exhaust is considered a probable human carcinogen. According to the EPA (2006), emissions from non-road sources will continue to increase, contributing large amounts of particulate matter and ozone precursor emissions such as NOx. EPA is concerned with this growth in emissions from non-road sources and therefore issued 14 regulations to control pollutants from non-road engines, especially NOx and PM.

Congress directed EPA to study the contribution of non-road sources to ozone and other pollutants in the 1990 Clean Air Act Amendments. But until the mid-1990s, non-road emissions were largely unregulated. A study conducted by EPA in 1991 revealed that emission levels were higher than expected across a broad spectrum of engines and equipment (EPA 1996). According to EPA (2006), non-road engines contribute about 66 percent of the nation's fine particulate matter ($PM_{2.5}$) from all mobile sources. These non-road engine emissions affect about 88 million Americans in areas violating $PM_{2.5}$ air quality standards. NOx emissions from non-road engines are about 36 percent from all mobile sources and affect about 159 million Americans living in areas exceeding EPA's 8-hour ozone standard.

TxDOT's Motivation to Reduce Emissions

The Clean Air Act established standards for air quality and these standards are regulated by EPA. EPA defined 20 counties in Texas as nonattainment (NA) counties since these areas at times experience unhealthy air quality. Figure 1 presents the NA and near-nonattainment (NNA) counties in Texas. According to Texas Department of Transportation (TxDOT) (2008), federal funding will be at risk if Texas violates the EPA standards. That is why Texas Commission on Environmental Quality (TCEQ), TxDOT and their local partners have focused the majority of their emission reduction programs on these NA areas. TxDOT has one of the largest construction equipment fleets in the USA and they own and operate approximately 3,200 pieces of non-road diesel equipment (Lee et al. 2008). In Texas, the total estimated average NOx emissions was 461 tons over FY 2005-2007 for a total of 3,170 pieces of diesel construction equipment (Lee et al. 2008). Emissions from the fleet are significant and therefore, TxDOT wants to focus on the non-road fleet for emission reduction.

Problem Statement

Texas has a total of 254 counties of which 20 are NA and 3 are NNA counties. Figure 1 shows all the counties and the NA and NNA counties in Texas. TxDOT has divided Texas into 25 districts and these districts oversee the construction and maintenance of state highways within their jurisdiction. Figure 1 presents the districts of Texas having the 8-hour ozone NA and NNA counties. The different districts are marked with solid border line, and the NA and the NNA counties are shown with different shadings. These NA and NNA counties have different types and numbers of construction equipment.

Given a certain budget, TxDOT can utilize the budget to deploy emission reduction technologies to minimize emissions from the equipment in these NA and NNA counties. Reducing the emission levels from the equipment fleet is a benefit to society through improved health, and to public agencies through reaching conformity and attainment. However, purchasing these emission reduction technologies is a cost to TxDOT. Therefore, it is essential for TxDOT to use their budget effectively to deploy the emission reduction technologies optimally to reduce emissions from their fleet in a cost effective manner.

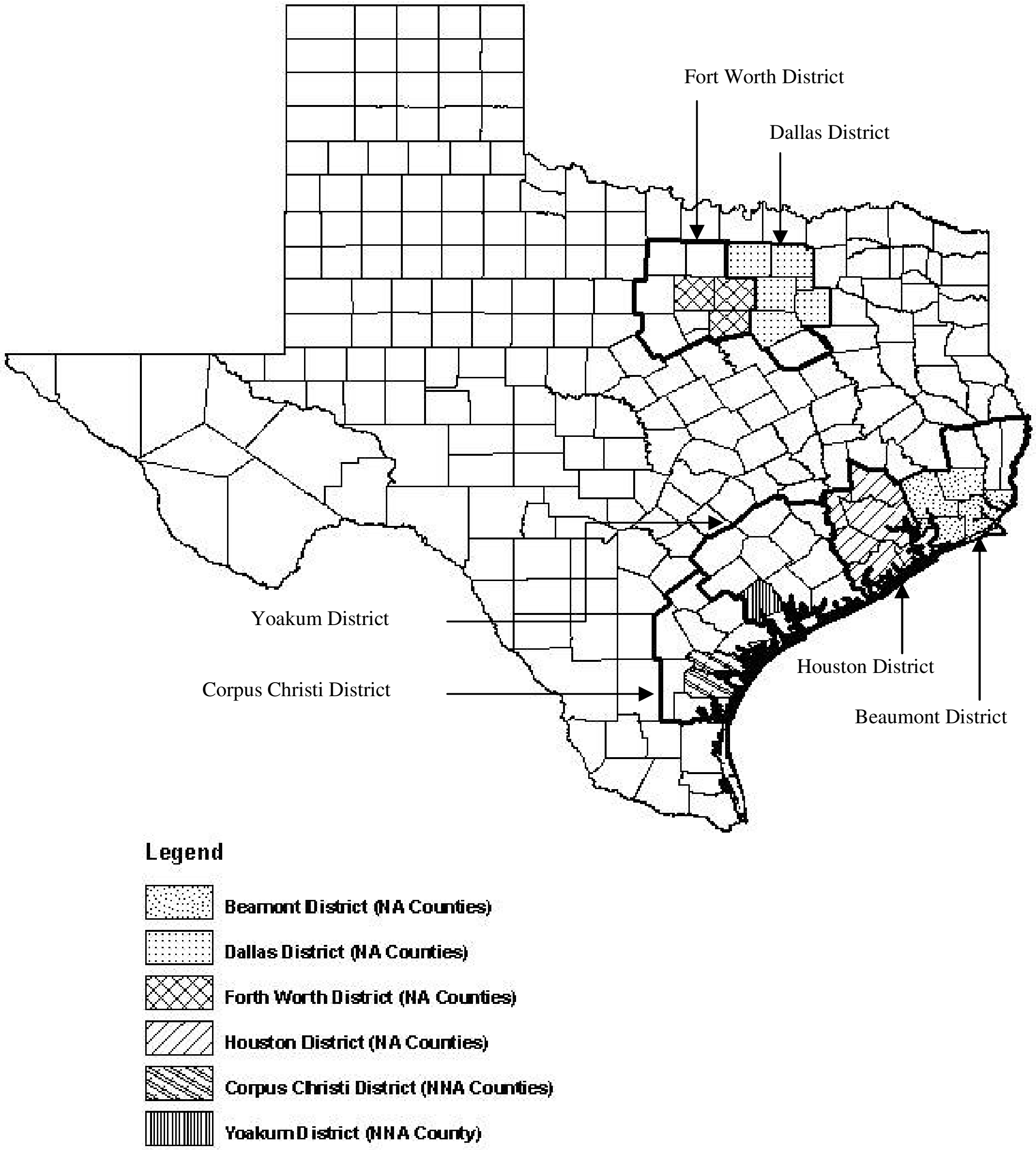

Figure 1. NA and NNA Counties of Texas

Texas has many ozone nonattainment counties (TCEQ 2008b). NOx is a precursor of ozone, and ozone causes adverse health effects like respiratory problems.

Therefore, the primary target pollutant in this study is NOx. Typical NOx reduction technologies are

- Selective catalytic reduction,
- Lean NOx catalysts,
- Hydrogen enrichment,
- Exhaust gas recirculation, and
- Fuel additives.

Research Goal

The purpose of the study was to develop a model for optimal deployment of emission control technologies. The goal was primarily to reduce emissions from construction equipment fleet with and without considering fuel economy for a given budget based on relevant economic, operational and technical constraints. The model will enable TxDOT to decide how to utilize the budget effectively to reduce the emissions from the construction equipment in a cost effective and optimal manner. The optimization model focused on deploying a limited set of emission reduction technologies for the construction equipment in the NA and NNA counties. The model was demonstrated through utilizing TxDOT's construction equipment fleets of NA and NNA counties. For demonstration purpose, several emission reduction technologies were considered such as hydrogen enrichment (HE), fuel additive (FA) and selective catalytic reduction (SCR). The target pollutant to be reduced was NOx.

The objective function was composed of two components namely NOx reduction benefit and increased fuel economy benefit. The final objective function of the model was maximization of emission reduction from the fleet with and without optimizing fuel economy benefit. The model formulated is flexible so that it can be applied to other types of emission reduction technologies for optimal deployment in other places. The steps involved in developing this model were:

- Define the objective functions and constraints.
- Development of the optimization model.
- Testing and refining the model.
- Development of a deployment plan to deploy emission reduction technologies optimally to achieve emission reduction cost effectively.

TxDOT provided some criteria for developing the model which are described later in the thesis. One criterion is giving higher priority to NA counties over NNA counties for technology deployment (called Method 1). An alternative approach of deploying emission control technologies was developed and proposed (called Method 2) in excess of the deployment pattern based on TxDOT's requirements. The definition of Method 1 and Method 2 are explained in Chapter IV. The models solutions corresponding to Method 1 and Method 2 are presented and compared in Chapter V.

Research Methodology

Firstly, the research involved an extensive review of relevant literature. The purpose of this step was to gain a better understanding of appropriate optimization methods, optimal deployment analysis and review of different emission control technologies, method of estimating emissions from construction equipment, the cost of different pollutants and details of TxDOT's construction equipment fleet database. Description of various emission control technologies was acquired though reviewing available literature and relevant websites. The emission reduction efficiency and cost of these technologies were obtained through consultations with vendors.

The next step was to identify several important factors that should be considered for deploying the emission reduction technologies among the NA and NNA counties. These factors were used for developing the optimization model. Some of the potential factors were horsepower of the equipment, remaining operational hours and remaining age of the equipment, location preferences, costs associated with the technologies, available budget for purchasing the technologies, fuel economy/ penalty of using the technologies and applicability of the technologies for different construction equipment.

The objective function and the constraints were then identified based on the previous tasks and the optimization model was developed. The model was then further tested and refined with the required data to obtain an optimal deployment plan. For testing the model, a small sample of equipment was taken for which the optimal deployment was known. The results from the model were then compared with it and the accuracy of the model was verified. The model was solved by mathematical programming with the state of the art optimization software CPLEX along with Microsoft Visual C++.

After developing the model, the model was demonstrated by applying selected control technologies and categories of equipment. Three technologies (Hydrogen Enrichment, Fuel Additive and Selective Catalytic Reduction) were selected for demonstration purpose. These three emission reduction technologies were selected since data regarding these technologies were available. Also the selected technologies have variations among them in terms of costs, emission reduction efficiencies and properties and thus capturing variability of technologies in the model would increase the flexibility of application of the model. After the application of the model, deployment plan was generated. A sensitivity analysis was performed afterwards by changing the budget constraint and different levels of emission reduction benefits were obtained. The results obtained through these steps are presented and discussed in this thesis later.

Research Benefit

This model will help TxDOT to prepare an optimal deployment strategy of emission control technologies for their non-road diesel fleets. It will help TxDOT to decide how to spend their resources optimally. By changing the different parameters, such as cost and emission reduction components, the results can be obtained for different combination of technologies.

Thesis Overview

This document is divided into six chapters. Chapter I presents an introduction, the problem statement, and an overview to the research. Chapter II is the literature review that discusses the emission estimation methodology, different emission reduction strategies, cost of pollutants and a few studies involving optimization analyses. Chapter III provides a brief description of data collection procedure. The collected data are summarized and presented subsequently. TxDOT's criteria for deployment of emission reduction technologies are discussed in this chapter. Chapter IV deals with model formulation. The overall approaches, the description of the problem, the two different methods with a total of four different alternatives to be tested are presented here. After that, the formulation of the model is described. Chapter V presents and discusses the model solutions. All the different alternatives in consideration are discussed and compared with each other in this section. Chapter VI provides the concluding remarks and scope for future research.

CHAPTER II

LITERATURE REVIEW

In this chapter, emission estimation methodology based on EPA's guidelines and procedure will be discussed. Different emission reduction strategies such as aftertreatment devices, engine technologies, and fuel technologies are briefly presented. Costs of several potential pollutants are also discussed based on studies conducted by McCubbin and Delucchi (1996a) and U.S. DOT (2002). At the end of this chapter, a few studies incorporating optimization analyses are also presented.

Emission Estimation Methodology

The United States Environmental Protection Agency (EPA) (2004) provided procedures and guidelines for estimating different pollutants such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO_x), hydrocarbon (HC) and particulate matter (PM) from compression ignition(CI) engines. This section describes the methodology for estimating pollutant emissions from construction equipment fleet. The guidelines are described in EPA (2004).

For calculating emissions from the construction equipment fleet, information regarding zero hour steady state emission factor (EF_{ss}), transient adjustment factor (TAF) and deterioration factor (DF) are required. This information can be acquired from the EPA's guideline (EPA 2004).

The emissions tiers of different equipment are determined from the guideline based on model year and horsepower. The steady-state emission factor (EF_{ss} in g/hp-hr) for NO_x for each piece of equipment is determined based on engine horsepower and tier. Transient Adjustment Factor (TAF) for NO_x is collected based on EPA's Source Category Code (SSC) and tier.

The Deterioration Factor (DF) for each pollutant and tier type is calculated based on the data from the guideline and two NONROAD input file (activity.dat and us.pop input file). The deterioration factor, DF is calculated using the following equation.

$$DF = 1 + A \times A_f^{\ b} \qquad \text{for Age Factor} \leq 1 \qquad (1)$$

$$DF = 1 + A \qquad \text{for Age Factor} > 1 \qquad (2)$$

where:

$A_{f=}$Age Factor =

$(\text{cumulative hours} \times \text{load factor} \div \text{median life at full load in hours})$

A= Relative Deterioration Factor depending upon pollutant and tier

b= a constant, for compression ignition b is always equal to 1

The final emission factor (EF_{adj} in g/hp-hr) for HC, CO and NO_x (to be used in the model after adjustments to account for transient operation and deterioration) is calculated as follows.

$$EF_{adj} = EF_{ss} \times TAF \times DF \qquad (3)$$

However, PM emission depends upon the sulfur content of the fuel. Therefore, an adjustment factor (S_{PMadj}) is provided in the guideline to account the variation of sulfur content in fuel. The equation for calculating $EF_{adj(PM)}$ is slightly modified from equation (3).

$$EF_{adj(PM)} = EF_{ss} \times TAF \times DF - S_{PMadj} \quad (4)$$

The emission of different pollutants from equipments can then be calculated using horse power, usage hour and adjusted emission factor.

$$\text{Emission E, grams} = EF_{adj} \times \text{Horsepower} \times \text{Usage Hours} \quad (5)$$

Therefore, emission from non-road equipment can be estimated by following the EPA methodology described above.

Emission Reduction Options

Retrofit, Rebuild, Replace and Repower are some strategies to reduce emissions from mobile sources. *Retrofit* means installing an emission control device on the equipment, *Rebuilding* is rebuilding some core engine components of the equipment, *Repowering* is replacing the older diesel engines with a newer engine and *Replacing* is replacing the entire older equipment or vehicle (Diesel Technology Forum 2006).

MECA (2008), Hansen (2007), EPA (2008d), CARB (2008), Genesis Engineering Inc. and Levelton Engineering Ltd (2003) and Lee et al. (2008) provided description on some emission reduction options that are briefly presented below. The emission reduction options are divided into three categories, (1) exhaust gas aftertreatment technologies, (2) engine technologies and (3) fuel technologies according to Hansen (2007) and Genesis Engineering Inc. and Levelton Engineering Ltd (2003).

Table 1 presents the different emission reduction options under the three categories mentioned above.

Table 1. Emission Reduction Options under Different Categories

Category	**Emission Reduction Options**
Exhaust Gas Aftertreatment Technologies	Diesel Oxidation Catalysts Diesel Particulate Filter Selective Catalytic Reduction Lean NOx Catalysts
Engine Technologies	Engine Repower and Rebuild Exhaust Gas Recirculation Crankcase Emission Control
Fuel Technologies	Low-Sulfur and Ultra Low-Sulfur Diesel Natural Gas Biodiesel Hydrogen Fuel Additive Hydrogen Enrichment

Exhaust Gas Aftertreatment Technologies for Emissions Reductions

Diesel Oxidation Catalysts (DOCs). According to MECA (2008), a diesel oxidation catalyst contains a substrate or catalyst support, a honeycomb structure, contained in a stainless steel canister. The interior surface having large amount of surface areas are coated with catalytic metals such as platinum or palladium. Through chemical oxidation, the device converts exhaust gas pollutants into harmless gases. In case of diesel exhaust, carbon monoxide (CO), hydrocarbons (HC) and liquid hydrocarbons absorbed on carbon particles are oxidized by the catalysts. In the engine exhaust liquid hydrocarbon absorbed on carbon particles are referred to as soluble organic fraction (SOF) i.e. the soluble part of the particulate matter in the exhaust. Diesel oxidation catalysts convert the soluble organic fraction of diesel particulate matter into carbon dioxide and water efficiently. Oxidation catalyst retrofits effectively reduce particulate and smoke emissions from older vehicles. The device also contributes substantial reduction in CO and HC emissions. Under the CARB and EPA retrofit technology verification processes, it is verified that diesel oxidation catalysts can provide at least a 25 percent reduction in PM emissions. But the total NOx emission remains unchanged for DOC. Platinum-based DOC enhances the proportion of NO_2 in the total NOx due to catalytic oxidation of NO which may present air quality problem in occupational health environment (Hansen 2007).

Diesel Particulate Filter (DPF). This device physically traps diesel particulates and prevents their release into the atmosphere. It is required to remove the trapped particulates periodically or continuously through the process called filter regeneration

(Hansen 2007). Diesel particulate filters are of different types depending upon the level of filtration required. There are partial flow through devices and wall flow designs which achieves highest filtration efficiency (MECA 2008). Hansen (2007) stated that there are different types of filter substrates of which wall-flow monoliths have most widely been used for retrofitting heavy-duty engines. Monolithic diesel filters consist of many parallel small squared channels running axially through the part. Diesel filter monoliths are obtained by plugging the channels of flow through filter that are used in catalytic converters and the adjacent channels are alternately plugged at each end. This arrangement forces the diesel aerosols through the porous substrate walls which act as a mechanical filter. Ceramic materials are commonly used for filters. Two materials mostly used for commercial filters are cordierite and silicon carbide. MECA (2008) mentioned that to regenerate the filter, a means of burning off or removing the accumulated particles inside the porous wall should be provided. A convenient way of disposing the accumulated particulate matter is to oxidize or burn it on the filter when the exhaust temperature is sufficient. The filter is cleaned or regenerated to its original state after burning the retained material. The frequency of regeneration is determined by the increased back pressure due to soot accumulation. According to Hansen (2007), particulate systems can be divided into two categories e.g. passive filter and active filter. Passive filters depend on the temperature of the exhaust gas whereas active filters rely on external heat source for regeneration. The single biggest challenge in the DPF application is the filter regeneration process. Manual cleaning of the filters do not regenerate thus drastically increases the maintenance cost. Poorly regenerated filters overloaded with soot are prone to uncontrolled regeneration. This can lead to rapid burning of soot releasing large amount of heat leading to filter failure through melting of substrate. Wall flow type DPFs are required to meet the stringent particulate emissions standards that are required for the heavy-duty diesel vehicle (HDDV) engines starting with the 2007 model year. Several manufacturers verified that at least 25 percent PM emission reduction is possible with DPF (Lee et al. 2008). Currently EPA and CARB verified DPF for non-road applications. EPA verified one product (EPA 2008b) and CARB verified nineteen products (CARB 2008).

Selective Catalytic Reduction (SCR). According to MECA (2008), these systems convert nitrogen oxides to molecular nitrogen and oxygen in oxygen-rich exhaust streams utilizing a metallic or ceramic wash-coated catalyzed substrate, or a homogeneously extruded catalyst and a chemical reductant. An aqueous urea solution is usually the preferred reductant in mobile source application. Urea decomposes thermally in the exhaust to ammonia which serves as the reductant. Sometimes ammonia can be used as the reductant in mobile source retrofit applications. NOx emissions are reduced to nitrogen and water as the exhaust and reductant pass over the SCR catalyst. In order to reduce both PM and NOx, SCR catalysts can be combined with a particulate filter. Open loop SCR systems are capable of reducing NOx emissions by 75 to 90 percent and closed loop systems on stationary engines can reduce NOx emissions by more than 95 percent. SCR systems can reduce HC emissions up to 80 percent and PM emissions by 20 to 30 percent. SCR performance can be enhanced by the use of low sulfur fuel, like all catalyst-based emission control technologies.

Lean NOx Catalysts (LNC). MECA (2008) mentioned that diesel engines are designed to run lean; therefore controlling NOx emissions from a diesel engine is inherently difficult. It is difficult to chemically reduce NOx to molecular nitrogen in the oxygen-rich environment of diesel exhaust. A reductant (HC, CO or H_2) is required for the conversion of NOx to molecular nitrogen in the exhaust stream and sufficient quantities of reductant are not present under the typical engine operating conditions to facilitate the conversion of NOx to nitrogen. According to MECA (2008), some LNC systems use diesel fuel as a reductant under lean conditions. The diesel fuel is injected into the exhaust gas to reduce NOx over a catalyst. Then nitrous oxide (N_2O), carbon dioxide (CO_2), and water (H_2O) are converted from the NOx (Lee et al. 2008). There are other systems that operate passively without any added reductant and have reduced NOx conversion rates. A porous material made of zeolite is often included in a lean NOx catalyst along with either a precious metal or base metal catalyst. Reduction reactions take place at fuel/hydrocarbon rich microscopic sites provided by the zeolites. Reduction reactions converting NOx to N_2 would not take place without the added fuel and catalyst because of excess oxygen present in the exhaust. At reasonable levels of diesel fuel reductant consumption, peak NOx conversion efficiencies are typically around 10 to 30 percent.

Engine Technologies for Emissions Reduction

Engine Repower and Rebuild. Hansen (2007) stated that repowering engine with cleaner engine technology might be an effective means of reducing emissions. NOx and PM emissions can be reduced by more than 50% by replacing a Tier 0 engine with a Tier 3 unit. The emission reductions can be easily quantified since the engines are emission certified. However, mechanical and electronic engine technology may present a limitation in re-powering equipment. Replacing a mechanical engine by an electronic one may not be possible. This drawback limits the repower of mechanical engines, such as Tier 2 to newest generation. Replacing a Tier 0 engine with a Tier 1 engine may be more cost effective since the engine block is often the same. The cost for emission reduction on a dollar per ton basis is lower even though the overall emission benefit is less.

Higher emission reductions can be achieved by repowering Tier 0 to Tier 1 than by repowering Tier 0 with Tier 2/3 engines if the fund is limited. In some cases, replacing the entire machine with a new one can be even more cost-effective than to repower with a Tier 2/3 engine. Engine rebuild kits are being developed by engine manufacturers to upgrade the engine to a cleaner emission standard. These kits are usually emission certified and allows quantifying the achieved emission reductions.

Exhaust Gas Recirculation (EGR). According to Hansen (2007), the EGR system operates by recirculating a portion of engines exhaust gas to its combustion chambers via the inlet system in order to reduce NOx emissions. The EGR method displaces some of the oxygen introduced into the engine as part of its fresh charge air with inert gases. This enables the reduction of the rate of NOx formation. An EGR cooler is implemented to cool the EGR stream before mixing with the intake air. Two principles are responsible for effective NOx reduction by EGR.

- Dilution of intake air with inert gas and
- Heat absorbed by EGR stream.

Though EGR reduces NOx emission, it increases emission of PM, HC, and CO, as well as causes fuel economy penalty. The introduction of soot laden gas into the combustion chamber introduces engine wear and durability issues. By drawing the EGR stream from downstream of a particulate filter can control the engine wear issue and the increased PM emissions (Hansen 2007). Currently two systems combined of EGR and DPF are verified by CARB, and they capable of reducing NOx by 50% and 40%, and PM by 85% (CARB 2008).

Crankcase Emission Control. Hansen (2007) pointed out that traditionally open crankcase breather systems were incorporated into diesel engines. Measuring crankcase emission during emission certification testing is required for future emission standards and that measured emission needs to be added to the exhaust emissions. For 2007 highway engines, and Tier 4 non-road engines, closed crankcase ventilation systems were introduced.

The open crankcase is responsible for blow-by emissions. Blow-by emissions result from pressure leaks through the piston rings during their reciprocating motion. Components of these blow-by emissions are aerosol and coalesced droplets made of lubricating oil, carbon soot, and wear debris.

Retrofit closed crankcase ventilation (CCV) systems control blow-by emissions. The systems filter the gas and route it back into the turbocharger inlet. The CCV unit is composed of an integrated filter and pressure regulator. The pressure regulator maintains pressure balance between the crankcase and the intake system and the filter prevents the fouling of turbocharger and intercooler. The filter separates the emitted oil and sends it to the engine oil sump. The serviceable filter element needs periodic maintenance. EPA and CARB verified several CCV and closed crankcase filtration systems. Some of them are coupled with DOCs. These systems are capable of reducing at least 25 % PM emissions (EPA 2008b, CARB 2008).

Fuel Technologies for Emissions Reductions

Clean fuels and fuel additives might be another option for reducing emission from non-road equipment. Clean fuel includes low-sulfur diesel, ultra-low sulfur diesel, natural gas (compressed or liquefied), biodiesel and other alternative fuels such as methanol, ethanol and hydrogen. Genesis Engineering Inc. and Levelton Engineering Ltd. (2003) provided a brief description about clean fuel options which are depicted below.

Low-Sulfur Diesel (LSD) and Ultra-Low Sulfur Diesel Fuel (ULSD). The usage of LSD and ULSD help to reduce the emission of inorganic sulfate particulates ($PM_{2.5}$) and SOx. These two elements are converted to acidic, $PM_{2.5}$ (respirable) sulfate aerosol in the atmosphere. ULSD enables to apply catalytic particulate-filter technology to the off-road equipment which further helps to minimize emission. More than 90% reduction of emission of fine particles and toxic air particles are possible by combing this system with ULSD. This leads to emission of hydrocarbon to an undetectable level. Even without implementing any reduction technologies, ULSD helps to minimize emission of harmful sulfate pollutants.

Natural Gas. Natural gas reduces emissions and provides potential operating cost savings. However, it requires higher up-front infrastructure cost. LNG can be produced from stranded natural gas resources. It can also be imported from low-cost producers.

Biodiesel. Biodiesel fuels are derived from renewable sources like vegetable oil, animal fat and cooking oil. Biodiesel fuels are esters that are oxygenated organic compounds. They can be used for compression ignition engines since their properties are comparable to diesel fuels. Biodiesel is compatible for using with high efficiency catalytic emission–reduction technology since it does not contain sulfur. It is more expensive than ULSD and emits more NO_x than off-road diesel. Its production cost is very high and producing on a larger scale might cause significant environmental impact.

Hydrogen. Hydrogen has low energy density in the gaseous form. Hence, if cheap and liquefied hydrogen become readily available then it can be used practically for non-road equipment sector. In petroleum refineries, hydrogen is used in large scale to produce low sulfur gasoline, diesel and ultra low sulfur diesel.

Fuel Additive. Fuel additives can reduce engine emissions and/or improve the fuel economy. Additives can also be used is to facilitate the regeneration of diesel particulate filters. It might also improve the performance of other emission controls such as oxidation catalysts (Hansen 2007). According to Lee et al. (2008), some of the fuel additives manufacturers claim that their products can reduce emissions of NOx, HC, PM and/or CO up to 25 percent, 25 percent, 50 percent, and 30 percent, respectively. Manufacturers also clam that fuel additives can decrease fuel consumption by up to 15 percent. Some of the products might increase emissions of one or more pollutants while reducing emissions of other pollutants and increasing fuel efficiency. Fuel Additives have not been verified yet by EPA or CARB.

Hydrogen Enrichment. Lee et al. (2008) stated that hydrogen enrichment systems create a better flame front in the engine that helps to reduce the emissions. Hydrogen gas (H_2) is generated from a small amount of water or diverted fuel using an on-board hydrolysis device or catalytic fuel reformer. The enriched H_2 is added into the fuel intake manifold. Then, it is delivered to the cylinder along with fuel. The mixture is more flammable and thus the hydrogen-rich intake charge creates a better flame front. This helps to produce lower engine-out emissions. Hydrolysis process generates oxygen (O_2) and the H_2-O_2 combination provides a better combustion on the power stroke. This helps to reduce the emission also. The combination provides higher energy value and helps to burn the fuel more completely in the combination chamber with little or no wastage. The complete burn of fuel reduces the amount of diesel/gasoline required to power the engine and thus reduce the fuel consumption. Manufacturers claim that their products can reduce NOx and CO emissions up to 25 percent and 35 percent, respectively and fuel consumption by about 10 percent. However, the hydrogen enrichment systems have not been yet verified by EPA or CARB.

Air Pollution Damage Costs

This section describes the studies associated with cost estimates of pollutants such as human health costs, damage costs and cost effectiveness of reducing pollutants. Human health costs of pollutants are estimated by McCubbin and Delucchi (1996b). Damage costs of pollutants are obtained from the Highway Economic Requirements System (HERS) model developed for the Federal Highway Administration (FHWA). The cost effectiveness of reducing per ton of NOx is acquired from a program called Texas Emissions Reduction Plan (TERP) established by the Texas Legislature.

McCubbin and Delucchi (1996b) estimated the human health cost of motor vehicle air pollution in all the urban and rural areas of the U.S. They estimated the total dollar costs, dollar costs per vehicle-mile of travel, and dollar costs per kilogram (kg) of pollutant emitted. They presented the costs per kilogram (kg) of emission by pollutants, emission sources, and geographic regions. This information makes it possible to calculate costs of emissions from other sources such as petroleum refineries or motor vehicles having different emission rates from the national-average rates used in their study. They calculated the dollar costs per kilogram ($/kg) value by dividing the total health damages attributable to the pollutant and sources by the emissions of the pollutant from the sources. Advantages of using $/kg estimate is that it can be applied to future emission rates. The cost estimate is proportional to the exposed population i.e. if the population increases by 10% over 1990 levels, the pertinent $/kg values should be increased by 10%.

The Highway Economic Requirements System (HERS) is a computer model developed for the Federal Highway Administration (FHWA). It was designed to simulate improvement selection decisions based on the relative benefit-cost merits of alternative improvement options. HERS employs damage costs for different pollutants. The pollutants are carbon monoxide, volatile organic compound, nitrogen oxides, sulfur dioxides, fine particulate matter and road dust. The estimates were derived from the study performed by McCubbin and Delucchi (1996a). The damage cost for NOx used in the HERS is presented in Table 2. The total annual costs for health and property damages caused by highway vehicles' contribution to atmospheric levels of each individual pollutant were estimated from McCubbin and Delucchi's study (1996a). The total amount of each pollutant emitted by highway vehicles annually was calculated. Then, the damage cost in dollars per ton of each pollutant was derived by dividing the total annual cost from health and property damages by the respective pollutant emitted annually. These values are assumed to give acceptable estimates of damage costs of each pollutant (U.S. DOT 2002).

Table 2. Air Pollutant Damage Costs Used in HERS

Pollutant	**Damage Costs ($/ton)**
NOx	3,625

Texas Emissions Reduction Plan (TERP) is a program established by the Texas Legislature and the purpose of the program is to provide monetary incentives for projects to improve the air quality in the state's nonattainment areas. There are eligibility criteria for projects that involve non-road equipment activities. Some activities that are allowed under the project are purchasing/ leasing, replacing, and repowering the non-road equipment, and applying retrofit or add-on emission reduction technologies. All the activities mentioned above are eligible for funding provided that these activities meet the certain requirements established by TCEQ under TERP. The cost effectiveness of a project must not exceed $ 15,000 per ton of NOx emission reduced in the eligible counties for which the project is proposed (TCEQ 2008a).

Studies Involving Optimization Analysis

This section provides a brief description of some studies involving optimization analysis. The six studies described below involved multiobjective mixed integer programming, linear programming with fuzzy coefficients, integer programming, combinatorial optimization, linear programming, and best-fitted resource methodology.

Chang and Wang (1996) analyzed solid waste management systems by utilizing multiobjective mixed integer programming model. In research programs for solid waste management system planning, the conflict between economic optimization and environmental protection had received wide attention. The purpose of this analysis was to apply multiobjective mixed integer programming techniques for reasoning the potential conflict between environmental and economic goals and for evaluating sustainable strategies for waste management in a metropolitan region. In the analytical framework, they considered four objectives: economics, noise control, air pollution control, and traffic congestion limitations. Economic impacts were characterized by operational income and cost for waste management, air quality impacts were due to discharges of target pollutants due to waste incineration, noise impacts were from various types of facilities operation, and traffic congestion was due to flow increments by garbage truck fleets. The constraint set consisted of mass balance, capacity limitations, operation, site availability, financial, traffic congestion and related environmental quality constraints. For demonstration purpose, a case study was performed in the city of Kaohsiung in Taiwan.

Eshwar and Kumar (2004) used linear programming with fuzzy coefficients for optimal deployment of construction equipment. The objective of the study was to identify the optimum number of pieces of equipment required to complete the project in the targeted period with fuzzy data. Their proposed model incorporated both technical and economical aspects for deploying optimal numbers of construction equipment. They performed a case study at Nizamabad district, Andhra Pradesh, India. The objective was to identify the exact number of equipments to be bought or rented. The required minimum number of each type of equipment, the cost of equipment, the rent of the equipment, the number of equipment that could be hired and the duration of service were considered in the constraint function. The model helped to deploy the equipment optimally and was able to handle the uncertainty successfully.

Swersey and Thakur (1995) developed an integer programming (IP) model for locating vehicle emissions testing stations. They developed a set covering model of the inspection station location problem and applied the model to Connecticut data. The constraints used were maximum travel distance from each town to its nearest station and average waiting time at the station. The maximum distance specified by the State was 20 miles and average waiting time must not exceed 20 minutes. The state also specified the maximum hours of operations and maximum number of lanes at each station. The integer programming model reduced the estimated cost of the objective function by at least $ 3 million. The station configuration at that time had more stations than IP solution and they were not well distributed. Even though the model provides least cost solution, it would be more appropriate for the decision makers to explore the tradeoffs between the system costs and specifications of travel distance and waiting time to choose a station configuration and the model was ideally suited for this purpose.

Zoka et al. (1995) formulated optimal deployment of fuel cell in a radial distribution system as a combinatorial optimization problem. Optimization problem that involves discrete variables are called combinatorial (Papadimitriou and Steiglitz 1998). The objective function was to minimize cost associated with power generation, installation and operation of fuel cells and thermal demand produced by electricity. They set an upper and lower limit of voltage at each node to restrict the voltage fluctuation in the distribution system. As the objective function was nonlinear and had to be minimized, optimal solutions could only be obtained through exhaustive search. Therefore, they applied genetic algorithm to obtain solution within reasonable computation time. They were successful in applying their algorithm on distribution systems having 69 and 111 nodes. The accuracy of the solutions and the computation time had satisfied the requirements for practical use of this kind of problem.

Fung et al. (2003) focused on an operational Quality Function Deployment (QFD) planning problem with resource allocation. QFD is customer oriented methodology to help decision making regarding product design and production development. To attain higher level of customer satisfaction regarding a product, certain characteristics or technical attribute (TA) are to be achieved. The aim of this research was to achieve maximum overall customer satisfaction by attaining TAs through allocating resources among the TAs. Technical, resource constraint and the impact of the correlation among the TAs were taken into account in order to formulate the operational QFD planning with resource allocation as a linear program. The model was solved by a heuristic-combined Simplex Method.

Otero et al. (2008) proposed a systematic approach, Best-Fitted Resource (BFR) methodology, to determine the suitability between the complete set of available skills from a candidate and required skills for tasks. Their proposed model helps to assign resources to tasks effectively even though the most desirable skills may not be available from the workforce. The proposed methodology was developed through considering the capabilities of candidates in the required skills, required level of expertise and relative priorities of required skills for tasks. They did a sample case study to demonstrate the capability of the model.

Summary

Among all the emission reduction technologies described in this chapter HE, SCR and FA were selected for the model application, since data were available for these technologies. Also, these technologies have differences among them in terms of costs, emission reduction efficiencies and properties, and thus capturing variability of technologies in the model would increase the flexibility of application of the model. Also, the model can be applied for other sets of emission reduction technologies by changing the relevant data such as cost, emission reduction efficiencies, etc.

Under TERP, the cost effectiveness of per ton of NOx reduction depends on the maximum amount of reductions to be achieved with the available budget, while at the same time ensuring that a good number of projects are funded. It also depends on the duration of the project. Therefore, the cost per ton of NOx reduce varies from project to project. In the HERS model, the estimation of damage cost of NOx is based on McCubbin and Delucchi's (1996b) study with some adjustment and thus the value used in HERS model is more recent. Also, the value is assumed to give acceptable estimates of damage cost of NOx and therefore, the damage cost of NOx was obtained from HERS model and used in this research.

All the studies involving optimization analyses described in this section were helpful to gain knowledge about optimal deployment problem, integer programming model, and multiobjective mixed integer programming model. The problems to be solved in this research required the concepts of optimal deployment, and the knowledge of integer programming model and multiobjective integer programming model.

Therefore, integer programming model and multiobjective integer programming model were the most suitable models considering the nature of the problems to be solved in hand.

CHAPTER III

DATA COLLECTION

This section specifies the important data required for the study and provides a brief description of the procedures that are followed for collecting the required data. Data collection procedures involved communicating with TxDOT officials and different technology vendors through questionnaire survey, telephone interview and emails. Appendix A provides the sample database of TxDOT's construction equipment fleet with emission estimation from the equipment. The letters and questionnaires that were used for collecting information are provided in Appendix B.

TxDOT's Construction Equipment Database

TxDOT has one of the largest construction equipment fleets in the USA owning and operating approximately 3,200 pieces of non-road diesel equipment (Lee et al. 2008). Types of equipment in use include graders, loaders, excavators, pavers, rollers, trenchers, cranes, and off highway tractors. TxDOT has prepared a very well organized database of their non-road fleet containing different characteristics of the equipment such as horsepower, fuel consumption, model year, age, usage hours, and location of the equipment, etc. This database with all this information is helpful for estimating the emissions from the construction equipment fleet using EPA's guidelines and procedure described in Chapter II. In Appendix B, a sample of TxDOT's construction equipment database is provided with emission estimation from the pieces of equipment.

Emission Reduction Technologies

Three emission reduction technologies were considered in this study for demonstrating the model. The technologies were HE, SCR, and FA. These three technologies were selected since data for these technologies were available. The model is flexible enough to apply it for other sets of emissions reduction technologies. A survey was conducted with the technology vendors' in order to assess the characteristics and properties of the technologies. The main purpose of the questionnaire surveys was to acquire information regarding the availability of the technologies, the different costs associated with them, requirements, fuel economy, and emissions reduction efficiencies. The different categories of costs included purchasing cost, installation cost, operation cost, and maintenance cost.

The purchasing cost for the SCR system varied with horsepower of the equipment. The purchasing cost varied from $14,000-$15,000 for horsepower varying from 101-300 hp. The installation cost was $3,000 for that horsepower range. The operation cost varied with both the horsepower and the tier classification of the equipment. The operation cost varied from $0.1 - $0.56 per hour depending upon the horsepower (101~300 hp) and tier classification (Tier 0~Tier3). The maintenance cost was in the range of $0.5 to $1.00 per hour for all horsepower ranges and tier classifications. The NOx reduction efficiency of the SCR system was 80%. The SCR system had 1% fuel economy penalty. The system represented an extra load on the engine due to the electrical power to operate it as well as the small exhaust restriction from the catalysts. This extra load caused the fuel penalty.

The purchasing and installation cost for HE system did not vary with horsepower and tier classification of the equipment. The purchasing cost was $8,000 and the installation cost was $400. The maintenance cost was $100 per year for each piece of equipment. The NOx reduction efficiency of the HE system was 36%. The fuel efficiency of the system was 8%, i.e. the system reduced fuel consumption by 8%. The fuel efficiency of 8% was achieved at around 240 hours of operation after installing the HE unit on the piece of equipment. For a piece of equipment having HE unit installed on it, the fuel efficiency was considered to be zero if it operated less than 240 hours after installation.

The cost of the FA was $18 per gallon. The dosage rate of FA was 4.25 ml per gallon of diesel fuel. The dosage rate did not vary with different equipment categories and different horsepower ranges. The NOx reduction efficiency of the FA system was 5.8%. The fuel efficiency of the FA was considered to be zero, since the additive had not been tested to determine the fuel efficiency. The Energy Information Administration (EIA) (2009) updates the gasoline and diesel price and the current cost of diesel was $2.216 per gallon.

The combination of the HE and FA, and SCR and FA were considered in the model. The combined NOx reduction efficiencies were estimated based on consultation with the HE and SCR vendors. HE vendor mentioned that the combination of HE and FA systems will have an additive effect in NOx reduction efficiency, i.e. 41.8% NOx reduction efficiency. Consultation with the SCR vendor revealed that the NOx reduction efficiency due to combination of SCR and FA systems will not be additive but will have a combined effect and the combined efficiency will be 81.16%.

The SCR vendor mentioned that SCR was not available for equipment having horsepower less than100 hp. They stated that the cost of the SCR system and size of the components made the system impractical to retrofit on such a small mobile engines. From TxDOT's construction equipment database, it was observed that the horsepower range for graders, loaders and excavators was within 300 hp. Therefore, a weighted average of purchasing cost of SCR system was estimated based on the horsepower distribution of the equipment. The operation cost for SCR varied with horsepower and tier classification of the equipment. Therefore, a weighted average estimation of operation cost was determined based on the distribution of both the tier and horsepower of the equipment. The maintenance cost of SCR varied from $0.5 to $1.0 per hour and an average value of this range was used in the study. Table 3 provides the horsepower and tier distribution of equipment (having horsepower >100 hp) that were used for the weighted average estimation of purchasing and operating cost of SCR. Table 4 summarizes the information that was used in this research.

Table 3. Horsepower and Tier Distribution of Equipment

Horsepower	Tier	Total
101~200 hp	Tier 0	46
	Tier 1	61
	Tier 2	44
	Tier 3	15
Greater or equal to 201 hp	Tier 1	16
	Tier 2	2

Table 4. Data Regarding the Selected Emission Reduction Technologies

Technology	Purchasing, Installation Cost ($)	Operation Cost ($)	Maintenance Cost ($)	Dosage Rate (ml)	Fuel Efficiency (%)	Reduction Efficiency (%)		Combined Reduction Efficiency (%)
						NOx	$PM_{2.5}$	NOx
HE	8400	-	100[a]	-	8[b]	36	-	41.8
SCR	17100[c]	0.25[d]	0.75[d]	-	-1	80	-	81.16
FA	18[e]	-	-	4.25[f]	-	5.8	-	-

(a)Per year
(b)After 240 hours of operation
(c)Within horse power 101 to 300
(d)Per hour
(e)Per gallon of FA
(f)Per gallon of diesel

TxDOT's Criteria for Deployment of Emission Reduction Technologies

TxDOT's preferences were obtained regarding the deployment criteria through consultation with TxDOT's officials. They proposed some requirements for selecting a piece of equipment for being eligible to be retrofitted. They mentioned about location preferences among the NA and NNA counties regarding deploying the emission reduction technologies.

They proposed that in order to retrofit a piece of equipment, it must have a remaining age and remaining usage hours of at least equal to 50 percent of its expected age and expected usage hours before disposal. The data regarding the usage hours and the age at disposal of equipment were obtained from TxDOT.

In order to deploy the emission control technologies, TxDOT wanted to allocate their budgets first in the NA counties. Then the remaining budgets were to be allocated in the NNA counties. They also suggested including Austin district and San Antonio district as NA status and NNA status accordingly especially in the analysis. All these considerations were incorporated while formulating the optimization model.

All the preferences stated by TxDOT are listed below.

- Location Preference: Give preference to NA counties over NNA counties for allocating budgets for technology deployment. About 77 percent of the fleet was in the NA counties and 23 percent was in the NNA counties.
- Age and Usage Hour Requirement: To be eligible for retrofitting, the selected piece of equipment should have remaining age and remaining usage hours equal to at least half of its expected age and expected usage hour before disposal. About 25 percent of the equipment had sufficient remaining age and remaining usage hour for satisfying the above requirement.

CHAPTER IV

MODEL FORMULATION

This chapter presents the overall approach for formulating the model. After that, a brief description of the problem is presented. The different variables, the objective function, and the constraints to be considered in the model are discussed subsequently. Then the following section provides descriptions regarding formulating the model.

Overall Approach

The overall approach involved several steps that ranged from development of the model to development of deployment plan of emission control technologies. The steps involved were development, testing and refinement of the model, and developing the deployment plan. Figure 2 presents the flow diagram of the overall process.

The first stage of the overall process was the development stage. In this stage, the different variables and the important factors were identified for formulating the model. The objective function and the constraints were also identified side by side. After that, the model was developed by mathematically translating the objective function and the constraints. The data requirements were also determined in this stage for model application.

The second stage of the process was evaluating the model on a range of input. The collected data were assembled in this step for suitable application of the model. After that the model was applied on TxDOT's equipment fleet, and output was generated subsequently. After analyzing the output, it might be necessary to refine the model. If necessary, the refinement of the model was done in this step.

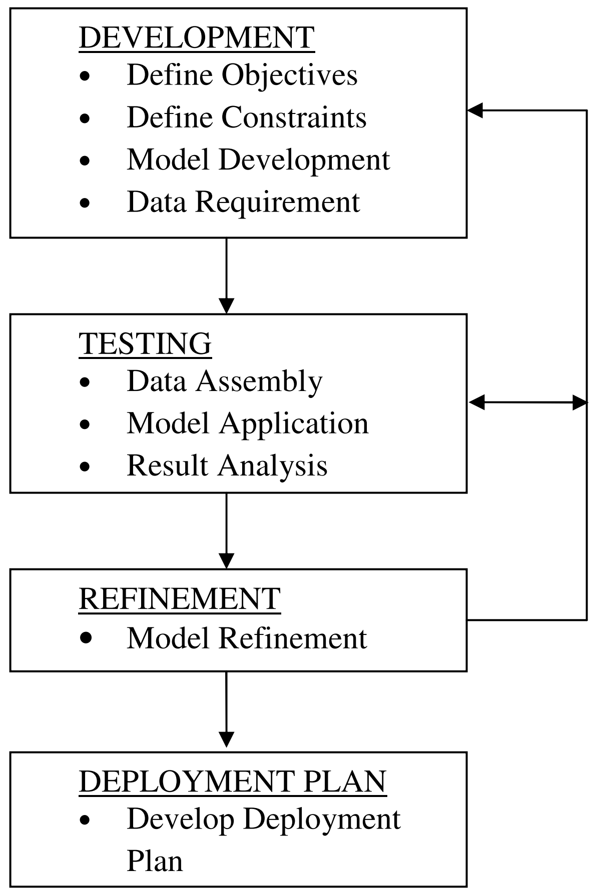

Figure 2. Flow Diagram of the Overall Approach

After completion of all the above mentioned steps, the deployment plan was generated. The deployment plan proposed the pieces of equipment that should have the specific emission control technology to reduce NOx emissions within a given budget. By varying the budget, it was possible to have a set of deployment plans with subsequent NOx reductions with and without consideration of fuel economy in the objective function. The model will help the decision maker to select the appropriate deployment plan based on the budget.

Description of the Problem

TxDOT has the largest construction equipment fleet in USA consisting of about 3200 pieces of construction equipment. The purpose of this study was to develop a model that will propose a deployment plan of emission control technologies for the selected categories of construction equipment, namely graders, loaders and excavators. These categories of equipment were selected since they were the highest NOx emitting equipment in Texas (Lee et al. 2008).

TxDOT proposed some equipment selection criteria and the location preferences for developing the deployment plan. It was recommended that for a piece of equipment to be retrofitted, it must have a remaining age and remaining usage hours equal to at least half of its expected age and expected usage hours before disposal. In terms of location preferences, TxDOT intended to focus on allocating the budgets in the NA counties first. Afterwards, the remaining funds were to be allocated in the NNA counties.

Three emission reduction technologies: HE, SCR and FA were selected for deployment. According to the SCR vendor, the SCR system was not available for equipment having horsepower less than 100 hp. According to TxDOT, each county has a diesel tank from which all the equipment located in that county are fueled. Therefore, FA had to be deployed in the county as a whole. In other words, if a piece of equipment of a particular county was selected for having FA, the rest of the equipment of that county would also receive FA i.e. either the whole county receives fuel additive or it does not receive it at all. In order to estimate the total FA additive requirement of a county, the diesel requirement for other categories of equipment ("Others") in excess of graders, loaders and excavators were considered in the analysis. All the other categories of equipment were fallen under "Other" category.

Combinations of technologies were also considered in this problem. That is, a piece of equipment could have either HE or SCR along with fuel additive. Combination of SCR and HE were not considered in this study. Combined reduction efficiencies of the technologies were estimated based on the recommendations of the respective vendors.

Figure 3 shows the schematic representation of the possible ways the emission reduction technologies can be deployed among different counties. Description of the notations is provided below the figure. The oval shape object represents the different counties. The circles contained in each oval shape object represents different categories of construction equipment and at the bottom the rectangular shape objects represents the several emission reduction technologies to be deployed among each of the counties. The path shows the possible ways the technologies can be deployed. The model developed in this study helps to identify which path to select for optimal deployment of technologies.

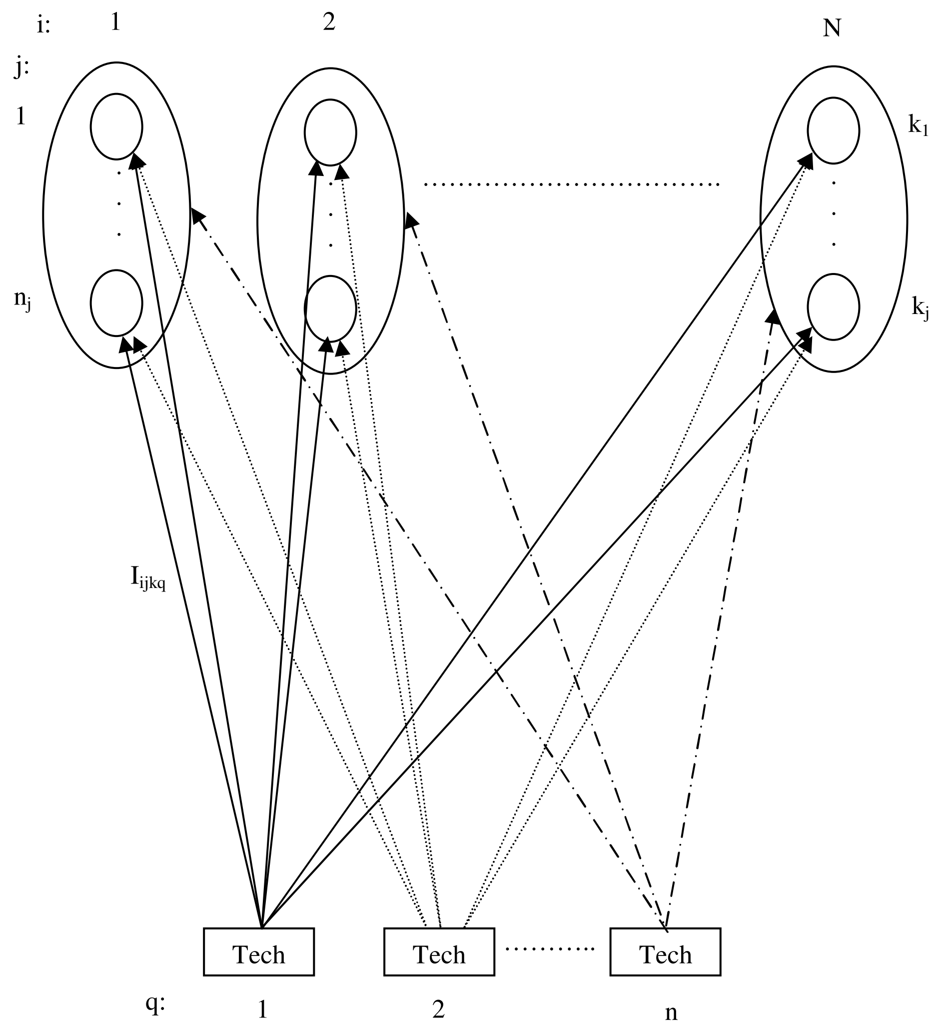

Figure 3. Possible Ways of Deploying Emission Reduction Technologies

Where,

i= different counties; i=1, 2…N (here N=32).
j= different categories of construction equipment at each counties; j=1, 2, 3, 4. (grader, loader, excavator and others)
k=total unit number of j-type equipment at each county
q= different types of emission reduction technologies; q=1, 2…..n (here n=3).
I_{ijkq}= binary variable

For each potential budget amount, the corresponding total benefit is plotted as shown in Figure 4. Total benefit is composed of total NOx reduction and total fuel economy benefit. As expected, the total benefit generally increases with increasing budget. However, it can be seen that there are some drops in the total benefit with increasing the budget amounts. For example, it is seen that at a certain budget B1, the overall benefit is less than that for a budget B2 which is less than B1. This occurs because of TxDOT's requirement of giving priority to NA counties over NNA counties. The NA counties receive expensive technology such as HE or SCR at budget B1 and therefore, less money is available for NNA counties. Thus the benefit for NA counties go up and the benefit for NNA counties go down and as a result, the total benefit goes down. At budget B2, the NA counties do not receive any expensive technology like HE or SCR since the budget is insufficient and, hence, a higher amount of budget is available for NNA. This causes the overall benefit to increase for B2 compared to that of B1.

Therefore, another approach of deploying technologies was considered for comparison purpose. In this arrangement, firstly all technologies, i.e. HE, SCR and FA were deployed in the NA counties and only FA was deployed in the NNA counties. Then, with the remaining budget available, SCR and HE were additionally deployed in the NNA counties.

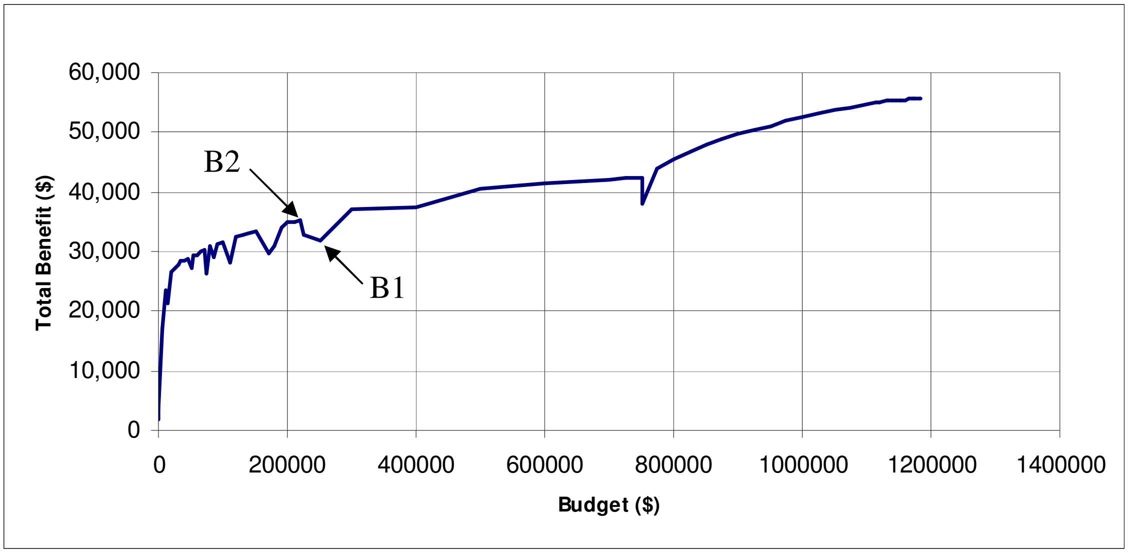

Figure 4. Total Benefit at Different Budgets

Fuel efficiency/penalty is another consideration that can be included in the model. HE increases fuel efficiency whereas SCR causes a fuel penalty. The two different approaches, as mentioned above, can be used with and without considering the fuel economy benefit in the objective function. The first approach will be called "Method 1" in which all the technologies, i.e. FA, HE and SCR are deployed in the NA counties at the first stage. After that, in the second stage the same technologies are deployed in the NNA counties with the remaining budget, if any. The second approach will be called "Method 2" in which all the technologies, i.e. FA, HE and SCR are deployed in the NA counties along with deploying only FA in the NNA counties at the first stage. Then with the remaining budget, SCR and HE are deployed in the NNA counties in the second stage. The analysis scheme is summarized in Table 5.

Table 5. Analysis Scheme of the Study

Approach	Options	Case
Method 1 (In first stage deploy FA, HE & SCR in NA counties; in second stage, deploy same technologies in NNA counties with remaining budget, if any)	NOx reduction with fuel economy	Case 1A
	NOx reduction without fuel economy	Case 1B
Method 2 (In first stage, deploy FA, HE & SCR in NA and FA in NNA counties; in second stage deploy either SCR or HE on any given equipment in the NNA counties with remaining budget, if any)	NOx reduction with fuel economy	Case 2A
	NOx reduction without fuel economy	Case 2B

Figures 5 and 6 present the schematic diagram of Method 1 and Method 2 respectively. The boxes without shading in each stage of both the figures represent the activated options while the dark shaded boxes of each stage represent the deactivated options. Figures 7 and 8 present the flow diagrams of the two different approaches of deploying technologies.

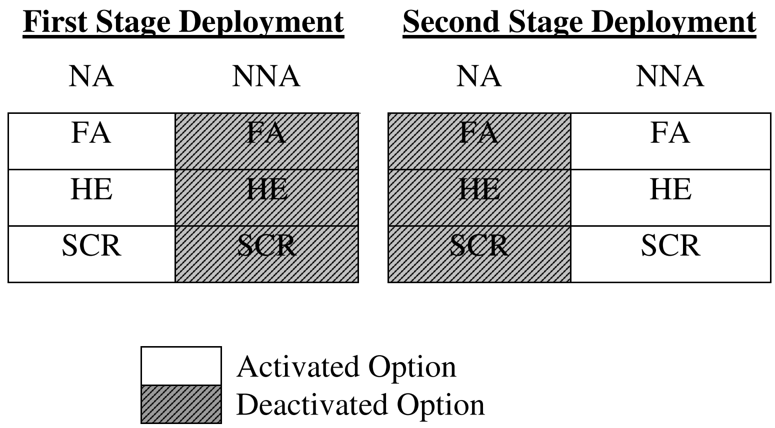

Figure 5. Schematic Diagram of Method 1

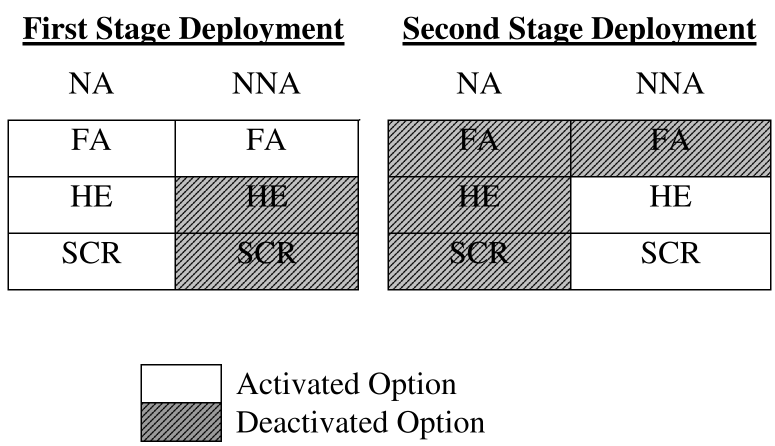

Figure 6. Schematic Diagram of Method 2

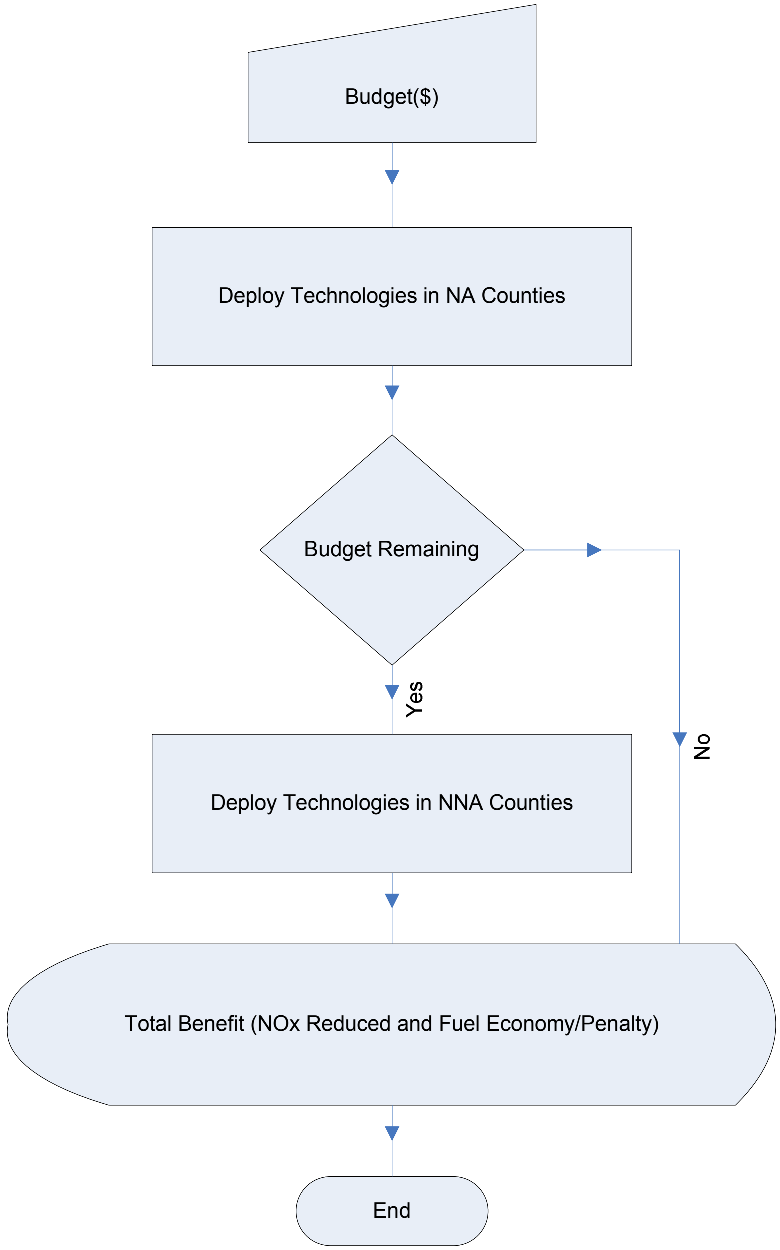

Figure 7. Flow Diagram of Method 1 (With/Without Considering Fuel Economy in the Objective Function)

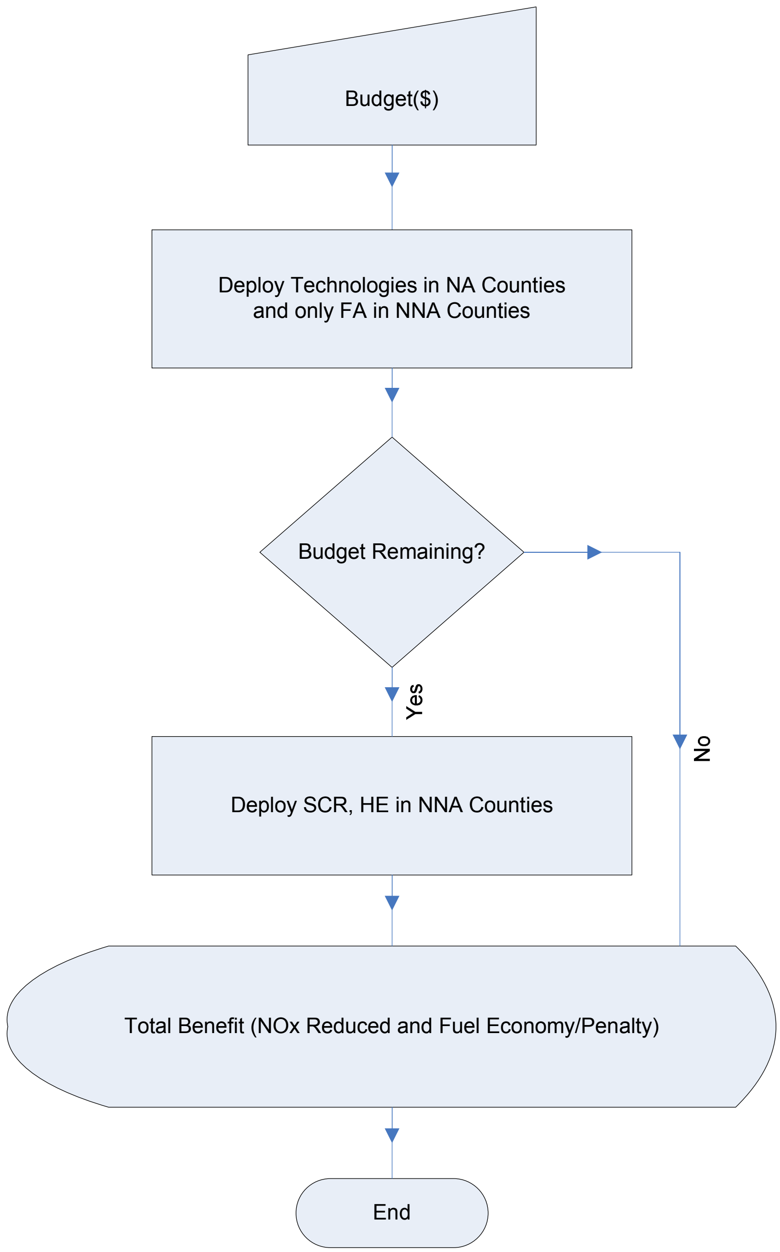

Figure 8. Flow Diagram of Method 2 (With/Without Considering Fuel Economy in the Objective Function)

Model Variables and Parameters

There were several variables that were considered during the formulation of the model. The variables were NA and NNA counties, different categories of equipment (e.g. graders, loaders, excavators and others), usage hour and age of the equipment, horsepower of the equipment, pollutant (NOx), and several emission reduction technologies (HE, SCR and FA). The parameters were the cost of NOx, emission reduction efficiencies of the technologies, different costs associated with the technologies, and the budget for deploying the emission reduction technologies.

Objective Function

The primary goal of TxDOT was to reduce NOx emissions from the construction equipment fleet. Fuel Economy was also another consideration in the objective function. Therefore, the objective function was to maximize the NOx emission reduction benefit along with and without considering fuel economy benefit in the objective function.

Model Constraints

There were several constraints that were considered in the model. In short, the objective function was subjected to a variable budget amount, a certain minimum remaining age and usage hours of the equipment, availability of technologies, location preferences, and the requirement that the FA be applied to all or none of the equipment within a county. Combination of emission control technologies such as “FA and HE” or “FA and SCR” were also considered in the model.

Formulation of Deployment Plan

After combining the objective function and the constraints, the model was formulated. The model was programmed and solved using Visual C++ and ILOG CPLEX. The output of the model was the required optimal deployment plan.

Model Formulation

The set C is defined as the set containing the nonattainment and near nonattainment counties, indexed by c. Let n_c be the total number of counties in consideration. In this case, n_c is equal to 32 considering all the NA and NNA counties. The set E is the set of different categories of construction equipment indexed by e and let n_e be the total categories of construction equipment to be considered. In this study, n_e is equal to 4, i.e. grader, loader, excavator and others. Let n_{ce} be the total number of equipment of category e in county c and each piece of equipment is indexed by i. Set P represents the set of different pollutants indexed by p and n_p represents the total number of pollutants to be considered. In this case, n_p is equal to 1. Set T represents the set of emission reduction technologies indexed by t and let n_t be the total number of emission control technologies to be considered. In this study n_t is equal to 3.

Let Em represent the emissions from a particular piece of equipment. C_p is the cost of pollutant p and R_{pt} represents the emission reduction efficiency of technology t for pollutant p. The variable I represents a binary variable and its value is 0 or 1. If a particular technology is selected for a piece of equipment, the value of I will be 1 otherwise 0.

The cost of emissions of pollutant p from ith equipment of category e of county c is $Em_{c,e,i,p}C_{p.}$ If technology t is applied on that piece of equipment, the emission reduction benefit would then be $Em_{c,e,i,p}C_pR_{p,t}I_{c,e,i,t.}$ The final expression for total emissions reduction benefit is $\sum_{c\in C}\sum_{e=1}^{n_e}\sum_{i=1}^{n_{ce}}\sum_{p=1}^{n_p}\sum_{t=1}^{n_t} Em_{c,e,i,p}C_pR_{p,t}I_{c,e,i,t}$.

Let the fuel consumption of a piece of equipment be $F_{c,e,i.}$ Let the cost of per gallon of fuel be C_F and let the fuel efficiency of technology t be $FE_{t..}$ If the technology selected causes fuel penalty, the value of $FE_{t.}$ will be negative. Therefore the expression for fuel efficiency/penalty is $F_{c,e,i}\, C_F\, FE_t\, I_{ceit.}$ The final expression for total fuel efficiency/penalty is $\sum_{c\in C}\sum_{e=1}^{n_e}\sum_{i=1}^{n_{ce}}\sum_{t=1}^{n_t} F_{c,e,i}C_F FE_t I_{c,e,i,t}$.

Objective Function

Therefore, the final expression of the objective function optimizing both emissions reduction benefits and fuel economy benefit, and only optimizing emission reduction benefit is given in Eq. (6).

$$\text{Maximize } Z = w_1 \sum_{c\in C}\sum_{e=1}^{n_e}\sum_{i=1}^{n_{ce}}\sum_{p=1}^{n_p}\sum_{t=1}^{n_t} Em_{c,e,i,p}C_pR_{p,t}I_{c,e,i,t} + w_2 \sum_{c\in C}\sum_{e=1}^{n_e}\sum_{i=1}^{n_{ce}}\sum_{t=1}^{n_t} F_{c,e,i}\, C_F\, FE_t\, I_{c,e,i,t} \qquad (6)$$

In the above equation w_1 and w_2 are the weights associated with emission reduction benefit and fuel economy benefit respectively. The value of w_1 and w_2 can vary from zero to one depending upon which Case (see Table 5) is considered. The values of w_1 and w_2 for different Cases are summarized below.

Case 1A: w_1=0.5 and w_2= 0.5

Case 1B: w_1=1 and w_2= 0

Case 2A: w_1=0.5 and w_2= 0.5

Case 2B: w_1=1 and w_2= 0

Model Constraints

Let, the cost of the technology t is represented by C_t. The cost C_t includes purchasing cost, installation cost, operation cost and maintenance cost. The cost associated with the technology t is $C_t\, I_{c,e,i,t}$. Therefore, the expression for the budget constraint is given in Eq. (7).

$$\sum_{c\in C}\sum_{e=1}^{n_e}\sum_{i=1}^{n_{ce}}\sum_{t=1}^{n_t} C_t I_{c,e,i,t} \leq Budget\ \ (\$) \tag{7}$$

TxDOT preferred that for a piece of equipment to be retrofitted, it must have remaining age and remaining usage hours of at least equal to half of its expected age and expected usage hours before disposal. The remaining usage hour and the expected usage hours at disposal of a piece of equipment are represented by $ru_{d,c,e,i}$ and $U_{e,i}$ respectively. Similarly the remaining age and the expected age at disposal of a piece of equipment are represented by $ra_{d,c,e,i}$ and $A_{e,i}$ respectively. The expression for the remaining usage hours and remaining age constraints are provided in Eq. (8) and (9).

$$ru_{c,e,i} \geq 0.5U_{e,i} \qquad \text{(Remaining usage hours)} \qquad (8)$$

($c=1$ to n_c, $e=1$ to n_e, $i=1$ to n_{ce})

$$ra_{c,e,i} \geq 0.5A_{e,i} \qquad \text{(Remaining age)} \qquad (9)$$

($c=1$ to n_c, $e=1$ to n_e, $i=1$ to n_{ce})

SCR systems (t=2) are not available for equipment of horsepower less than or equal 100 hp. Hence, the value of the variable I for a particular piece of equipment having horsepower less than or equal to 100 hp will be zero.

Combination of technologies e.g. HE (t=1) & FA (t=3) and SCR (t=2) & FA (t=3) are considered and the expressions of the constraints are as follows. Combination of HE and SCR are not considered in the study. The constraints are provided in Eq. (10) and (11).

$$\sum_{t=1}^{n_t} I_{c,e,i,t} \leq 2 \qquad (10)$$

($c=1$ to n_c, $e=1$ to n_e, $i=1$ to n_{ce}, $t=1$ to 3)

$$\sum_{t=1}^{2} I_{c,e,i,t} \leq 1 \qquad (11)$$

($c=1$ to n_c, $e=1$ to n_e, $i=1$ to n_{ce}, $t=1$ to 3)

Another requirement regarding FA is that the FA must be applied either to all or none of the equipment within a county. The expression related to this constraint is given in Eq. (12).

$$I_{c,e,i=1,t=3} = I_{c,e,i=2,t=3} = \ldots\ldots = I_{c,e,i,t=3} \qquad \forall c, e \qquad (12)$$

TxDOT has set a priority to NA counties over NNA counties in terms of allocating budget for the emission control technologies. After the nonattainment counties are served, the remaining budget is utilized in the near nonattainment counties. The expressions for the above constraints corresponding to NA and NNA counties are provided in Eq. (13) and (14).

With the entire budget amount making available for the NA counties at the beginning:

$$I_{c_{NA},e,i,t} \geq 0 \text{ and } I_{c_{NNA},e,i,t} = 0 \qquad \forall e,i,t \tag{13}$$

With the remaining budget amount making available for the NNA counties after serving the NA counties:

$$I_{c_{NNA},e,i,t} \geq 0 \qquad \forall e,i,t \tag{14}$$

The equation 14 and 15 for the approach called Method 2 (as described in Figure 6) will be slightly different. Under Method 2, all the technologies are deployed in the NA counties along with deploying only FA in the NNA counties at first. After that, SCR and HE are deployed in the NNA counties with the remaining available resources. The expressions for these constraints are given in Eq. (15) and (16).

With the entire budget amount available at the beginning:

$$I_{c_{NA},e,i,t} \geq 0\text{, and } I_{c_{NNA},e,i,t=3} \geq 0\text{, and } I_{c_{NNA},e,i,t=1} = 0\text{, } I_{c_{NNA},e,i,t=2} = 0 \quad \forall e,i \tag{15}$$

With the remaining budget amount available after the above step:

$$I_{c_{NNA},e,i,t=1} \geq 0\text{, } I_{c_{NNA},e,i,t=2} \geq 0 \qquad \forall e,i \tag{16}$$

Therefore, the final optimization model is an integer program. In linear programming (LP) in which all or some of the variables are required to be non-negative integers are called integer programming problem (IP) (Winston and Venkataramanan 2003). Under Method 1, the objective function is expressed by equation (6) which is subjected to the constraints expressed through equation (7) to (14). Under Method 2, equation (6) is subjected to constraints expressed through equation (7) to (12), (15) and, (16). The model result will be a deployment plan of emission control technologies with a view to maximize the emissions reduction benefit with/without considering fuel efficiency.

CHAPTER V

RESULTS AND DISCUSSIONS

This chapter presents the results of model applications prescribing a mix of technologies to be deployed for emission reduction of non road equipment. Two approaches or methods have been tested, each having two options (with and without fuel economy) and thus making four cases as stated earlier.

Some useful definitions of selected terms that are used frequently in this chapter are presented below.

First and second stage deployment: The definitions of first and second stage deployment are provided in Figures 5 and 6.

Total benefit (first stage): The total benefit (first stage) is defined as the monetary value of the total fuel economy/penalty and the total NOx reduced in the first stage.

Total NOx reduced (first stage and second stage): The total NOx reduction includes the total NOx reduced from both the NA and NNA counties.

Combined fuel/diesel economy (first stage and second stage): It is defined as the total fuel economy obtained from both the NA and NNA counties.

Total combined benefit (first stage and second stage): The total combined benefit includes the total NOx reduced and the total fuel economy from both the NA and NNA counties.

Graphs are plotted in the following sections, such as total NOx reduced (first stage), total benefit (first stage), total NOx reduced (first and second stage) and total combined benefit (first and second stage) for budgets ranging from about $500 to $1,183,000 in order to present the sensitivity of the above mentioned variables with budgets. The model solutions are obtained up to budget $1,183,000, since, both NA and NNA counties receive the maximum possible units of HE, SCR and FA coverage at this budget, and the total NOx reduction and total benefit at the first and second stage becomes constant with further increasing the budgets.

The technology deployments for different cases are also plotted for specific budgets. For a given budgets, the variables, such as total NOx reduced (first stage), diesel economy (first stage), total benefit (first stage), total NOx reduced (first and second stage), diesel economy (first and second stage) and total combined benefit (first and second stage) show variations while comparing between respective cases. Therefore, several specific budgets are selected for comparison of the above mentioned variables and for comparing the deployment patterns between respective cases. Explanations are provided for the reasons of variations, subsequently.

In the following sections, the results for different cases and comparison between cases are discussed.

Case 1A: Method 1 with Consideration of Fuel Economy

In Case 1A, fuel economy is considered along with reducing NOx in the objective function. Figures 9, 10 and 11 present the NOx reduction at the first stage, the total NOx reduction (first stage and second stage) and the total combined benefit (first stage and second stage) for Case 1A at different budget amounts, respectively.

The NOx reduction at the first stage (Figure 9) shows an increasing trend with increasing budget amounts but there are some drops in NOx reduction at certain budgets. The NOx reduction (first stage) shows a steep increase (approximately up to budget $12,500) followed by a smooth increase (approximately for budgets within $12,500 ~ $73,000) with increasing budget amounts. Beyond this (approximately $730,000), the trend becomes flat indicating that maximum NOx reduction benefit at the first stage has been obtained. Both the total NOx reduction at the first and second stage (Figure 10) and the total combined benefit at the first and second stage (Figure 11) for Case 1A follow a similar pattern. Both the graphs show an increasing upward trend with some drops at some budget amounts. The initial steep portion of the graphs presented in Figures 9, 10 and 11 indicate that the investment is beneficial. The graphs indicate that the total NOx reductions and total combined benefit are huge at lower budget levels. As FA is inexpensive and at lower investment or budget levels more expensive technologies are not affordable, FA use become beneficial making both total NOx reduction benefit and total combined benefit higher.

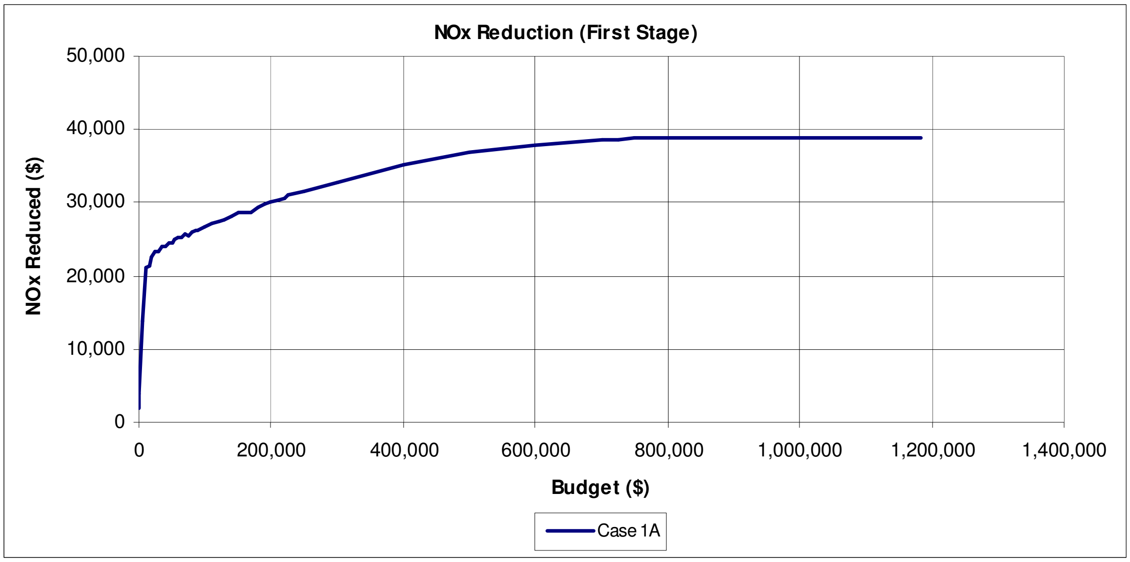

Figure 9. Total NOx Reduction at the First Stage at Different Budget Amounts (Case 1A)

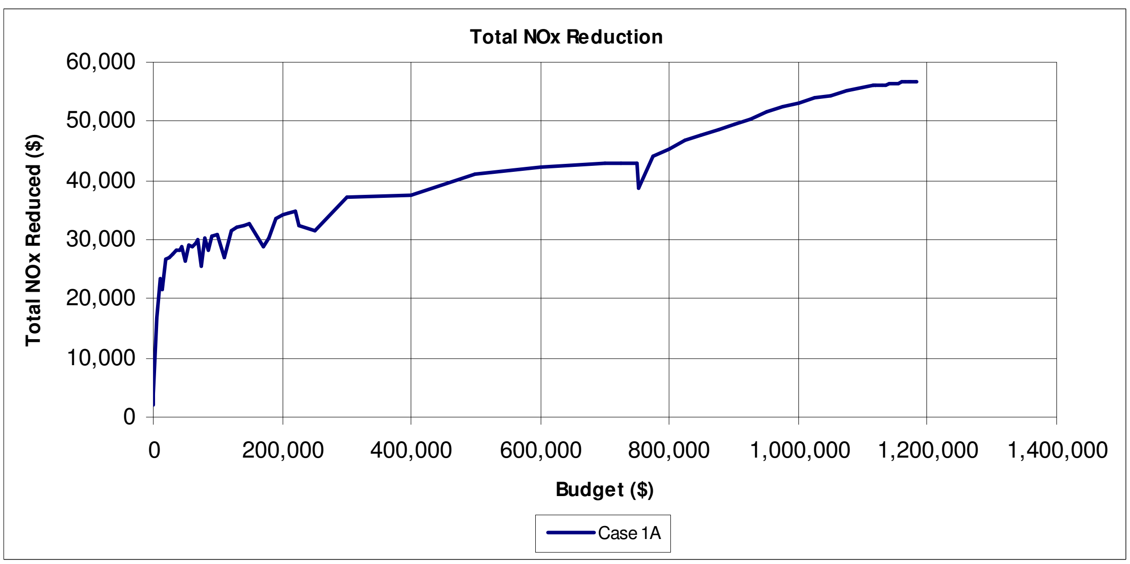

Figure 10. Total NOx Reduction at the First and Second Stage at Different Budget Amounts (Case 1A)

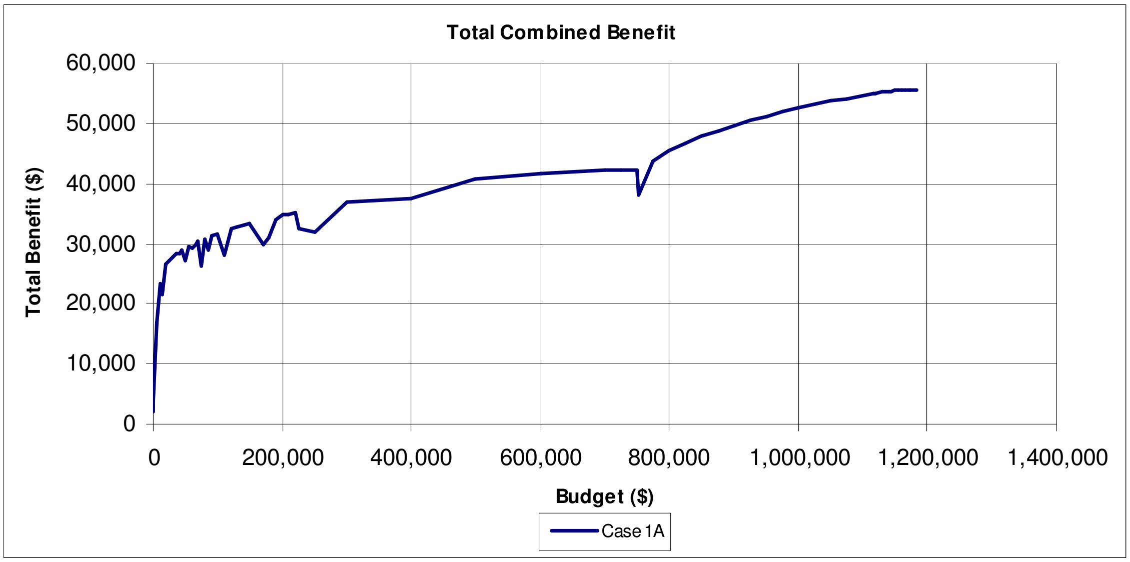

Figure 11. Total Combined Benefit at the First and Second Stage at Different Budget Amounts (Case 1A)

Case 1B: Method 1 without Consideration of Fuel Economy

In Case 1B, fuel economy is not considered along with reducing NOx in the objective function. Figures 12, 13 and 14 present the total NOx reduction at the first stage, the total NOx reduction (first stage and second stage) and the total combined benefit (first stage and second stage) for Case 1B at different budget amounts, respectively. The NOx reduction (first stage) shows a steep increase (approximately up to budget $12,500) followed by a smooth increase (approximately for budgets within $12,500 ~ $73,000) with increasing budget amounts. Then approximately at $730,000, the graph becomes flat indicating that maximum NOx reduction benefit at the first stage has been obtained. Both the total NOx reduction at the first and second stage (Figure 13) and the total combined benefit at the first and second stage (Figure 14) for Case 1B follow a similar trend, i.e. both the graphs show an increasing upward trend with some drops at some budget amounts. Similar to Case 1A, the initial steep portion of the graphs presented in Figures 12, 13 and 14 indicate that the total NOx reductions and total combined benefit are huge at lower budget levels. This is because at lower investment level, expensive technologies are not affordable, FA use becomes more beneficial as this is inexpensive with consequent higher total NOx reduction benefit and higher total combined benefit.

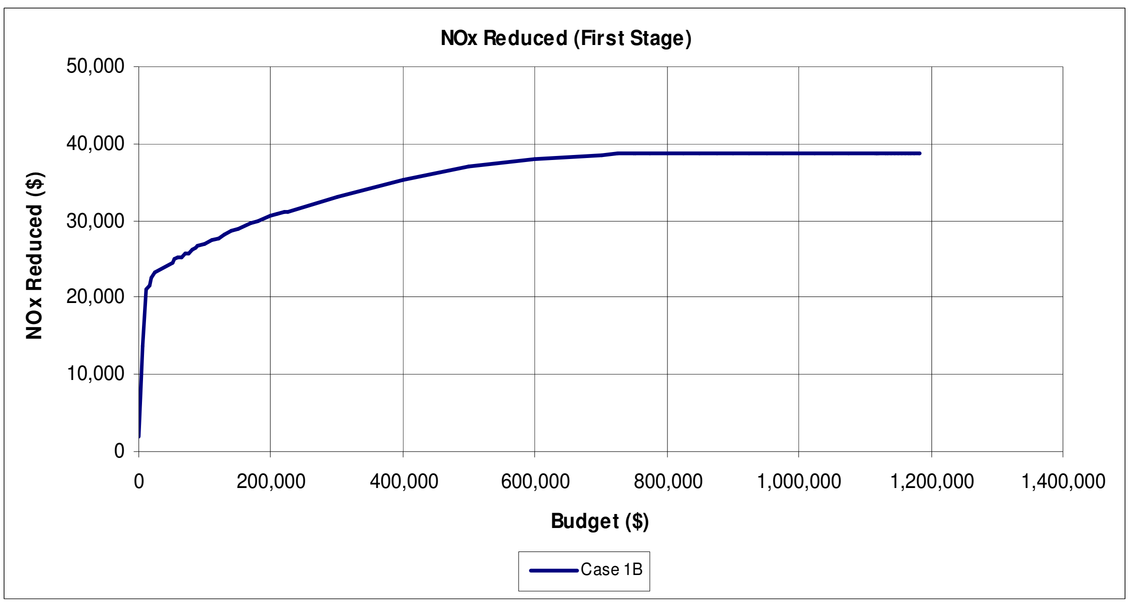

Figure 12. Total NOx Reduction at the First Stage at Different Budget Amounts (Case 1B)

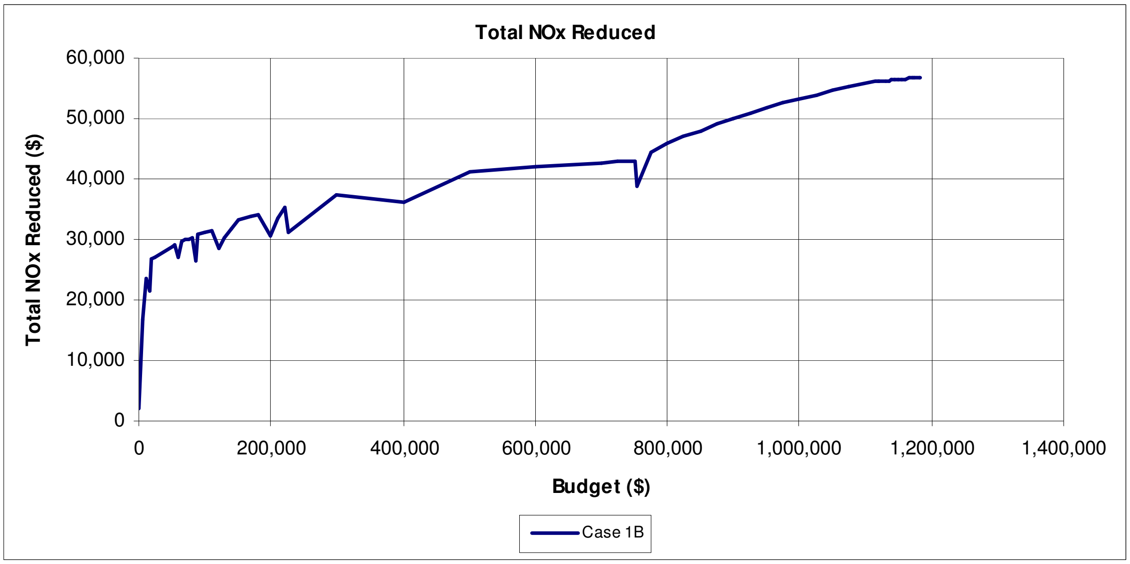

Figure 13. Total NOx Reduction at the First and Second Stage at Different Budget Amounts (Case 1B)

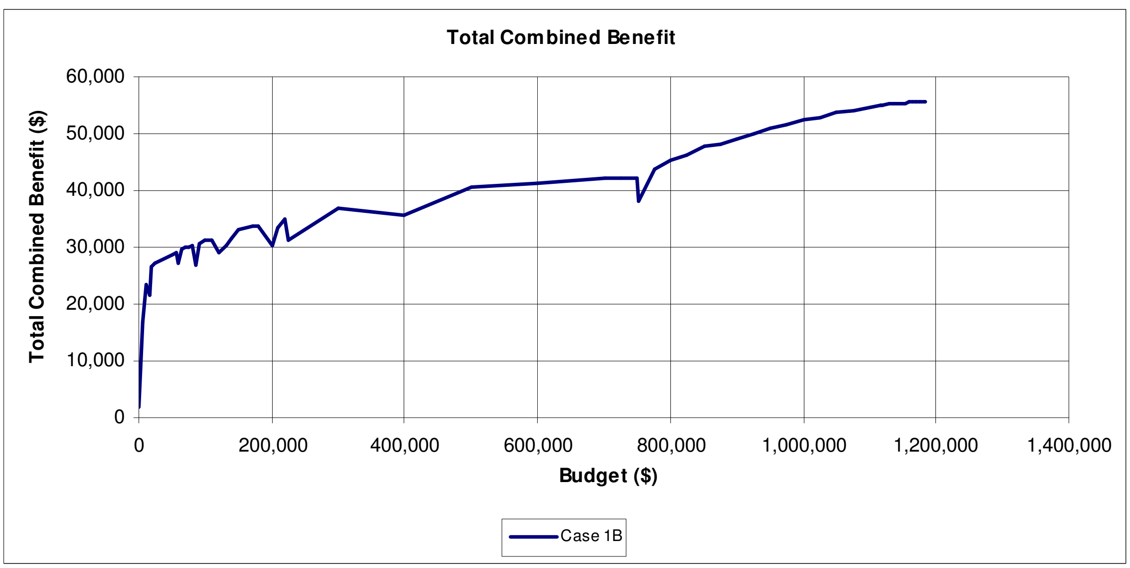

Figure 14. Total Combined Benefit at the First and Second Stage at Different Budget Amounts (Case 1B)

Case 2A: Method 2 with Consideration of Fuel Economy

In Case 2A, fuel economy is considered along with reducing NOx in the objective function. Figures 15, 16 and, 17 presents the total NOx reduction at the first stage, the total NOx reduction (first and second stage) and the total combined benefit (first and second stage) for Case 2A at different budget amounts, respectively. The NOx reduction at the first stage (Figure 15) shows a sharp increase (up to approximately $25,000) followed by a smooth increase (approximately within budgets of $25,000~$730,000) with increasing budget amounts. There are also some drops in NOx reduction at certain points. When budget amount exceeds this (approximately $730,000), the trend becomes flat reaching the maximum NOx reduction benefit at the first stage. Both the total NOx reduction at the first and second stage (Figure 16) and the total combined benefit at the first and second stage (Figure 17) for Case 2A follow a similar trend. Both the graphs show an increasing upward trend with some drops at some budget amounts. Both the graphs (Figures 16 and 17) have three distinct regions. The first region (up to budget of approximately $25,000) is the rapid increasing portion; the second region (approximately within budget range of $25,000~$750,000) is the smooth upward increasing portion and the third region (approximately with budgets higher than $750,000) is the smooth upward increasing portion at a higher slope than the second region. Both the graphs of Figures 15 and 16 have some drops at some points since the model is also focusing on optimizing the fuel economy along with NOx reduction. However, the total combined benefit (first and second stage) presents no drop at any point.

The first region (the steep portion) of Figures 15, 16 and 17 indicate that the total NOx reduction and total combined benefit is higher at lower budget levels. As FA is inexpensive and at lower investment or budget levels, more expensive technologies are not affordable, FA use become beneficial making both total NOx reduction benefit and total combined benefit higher.

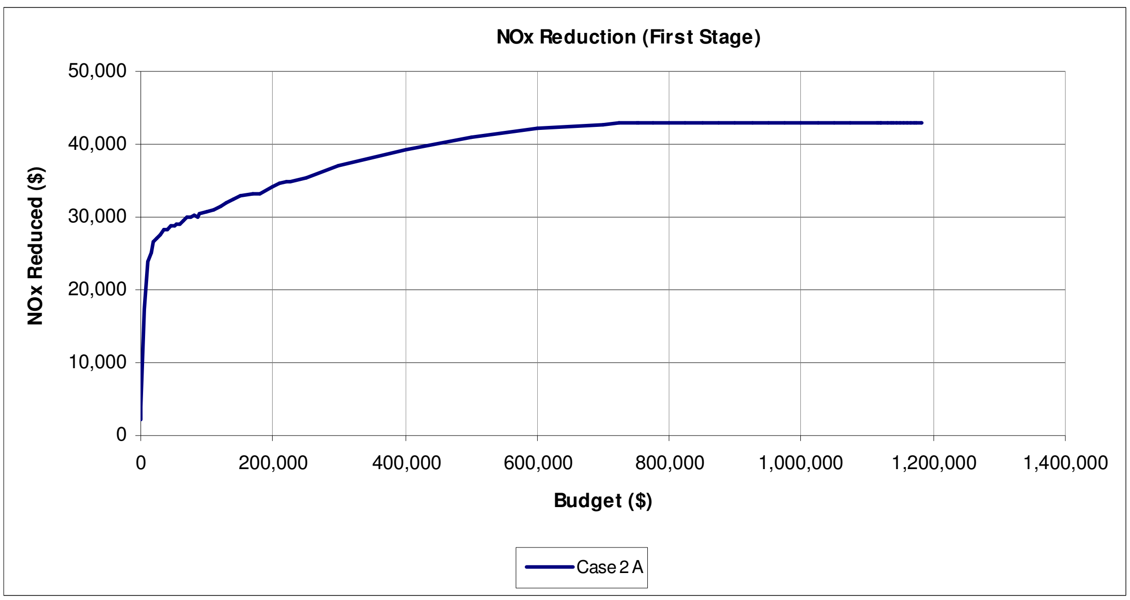

Figure 15. Total NOx Reduction at the First Stage at Different Budget Amounts (Case 2A)

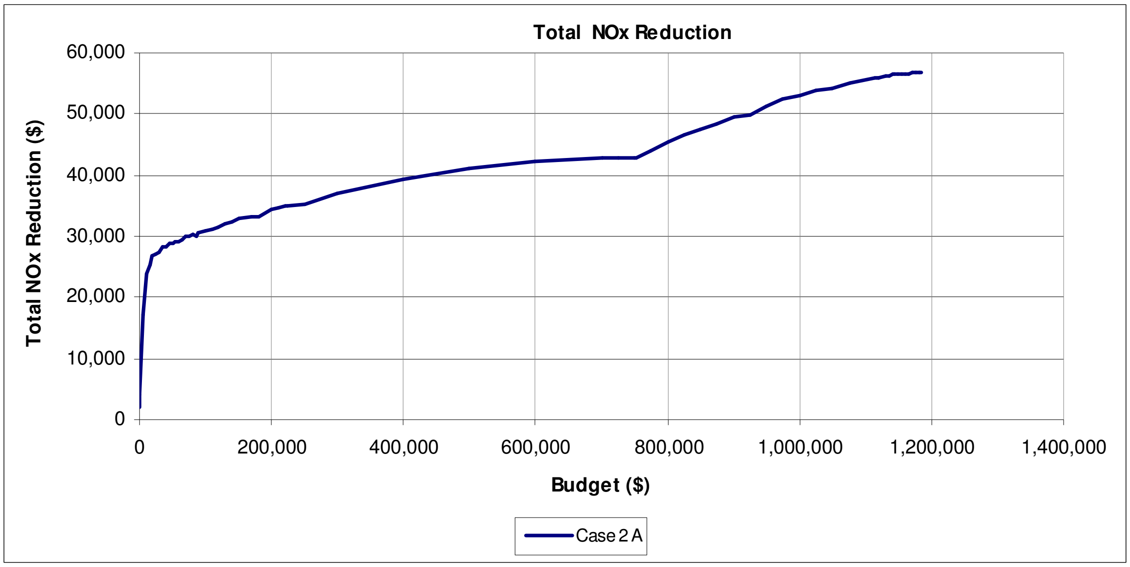

Figure 16. Total NOx Reduction at the First and Second Stage at Different Budget Amounts (Case 2A)

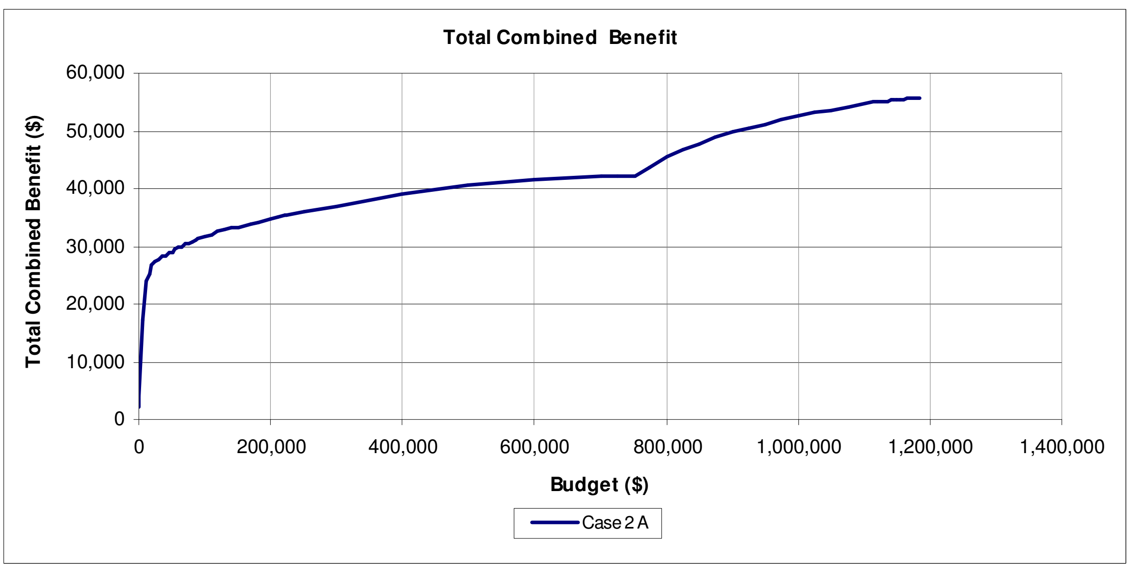

Figure 17. Total Combined Benefit at the First and Second Stage at Different Budget Amounts (Case 2A)

Case 2B: Method 2 without Consideration of Fuel Economy

Case 2B does not consider fuel economy along with NOx reduction in the objective function. Figures 18, 19 and 20 present the total NOx reduction at the first stage, the total NOx reduction (first and second stage) and the total combined benefit (first and second stage) for Case 2B at different budget amounts, respectively. The NOx reduction at the first stage (Figure 18) presents a sharp increase (up to a budget of approximately $25,000) followed by a gradual smooth increase (approximately within $25,000~$730,000) with increasing budget amounts. After a budget of approximately $730,000, the graph for NOx reduction becomes flat attaining the maximum NOx reduction benefit (first stage). Both the graph for the total NOx reduction at the first and second stage (Figure 19) and the total combined benefit at the first and second stage (Figure 20) for Case 2B follow a similar pattern to that of Case 2A and both graphs show an increasing upward trend. Both Figures 19 and 20 have three distinct regions. The first region (approximately up to budget of $25,000) is the rapid increasing portion; the second region (approximately between $25,000~$750,000) is the gradual smooth upward increasing portion and the third region (approximately for budgets higher than $750,000) is the smooth upward increasing portion with a higher slope than that of the second region.

Similar to Case 2A, Figures 18, 19 and 20 indicate that the total NOx reduction and total combined benefit is higher at lower budget levels. At lower budget levels (the first region) the NOx reduction and total combined benefit are obtained predominantly due to higher FA coverage. As FA is inexpensive and at lower investment or budget levels, more expensive technologies are not affordable, FA use become beneficial making both total NOx reduction benefit and total combined benefit higher.

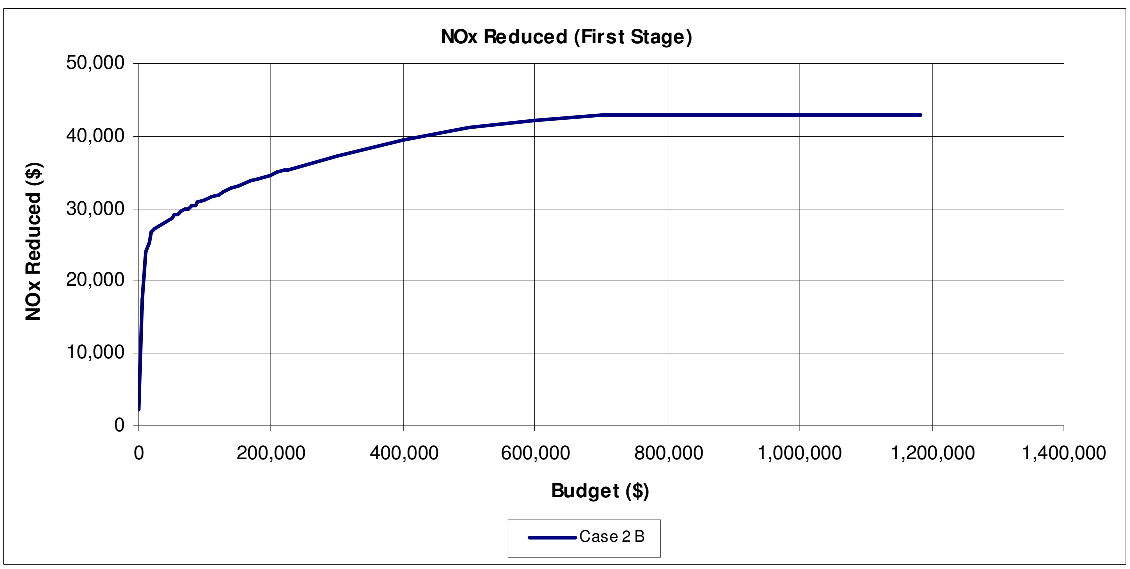

Figure 18. Total NOx Reduction at the First Stage at Different Budget Amounts (Case 2B)

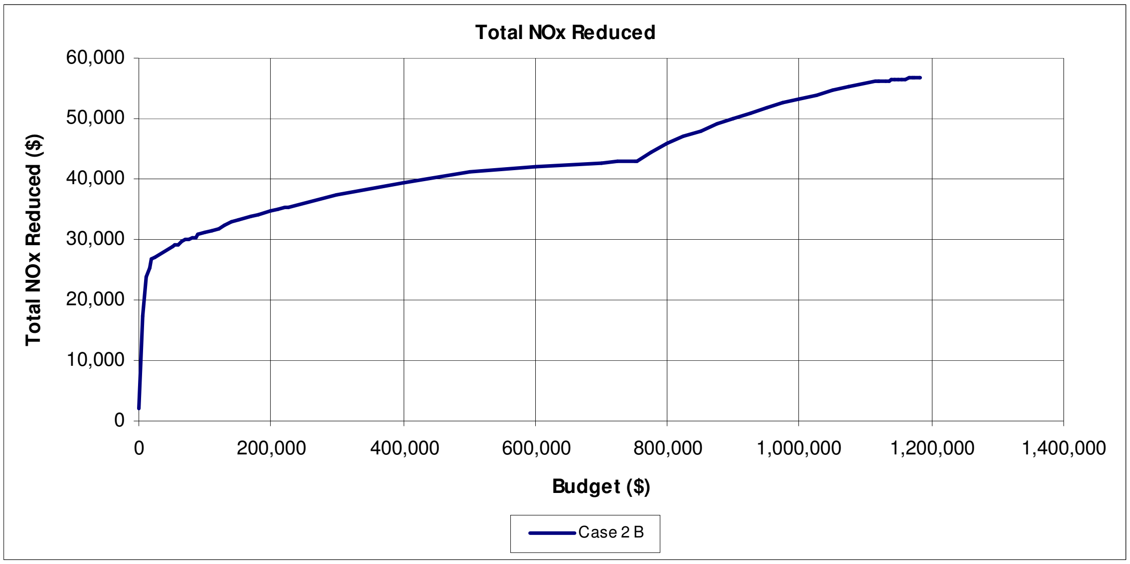

Figure 19. Total NOx Reduction at the First and Second Stage at Different Budget Amounts (Case 2B)

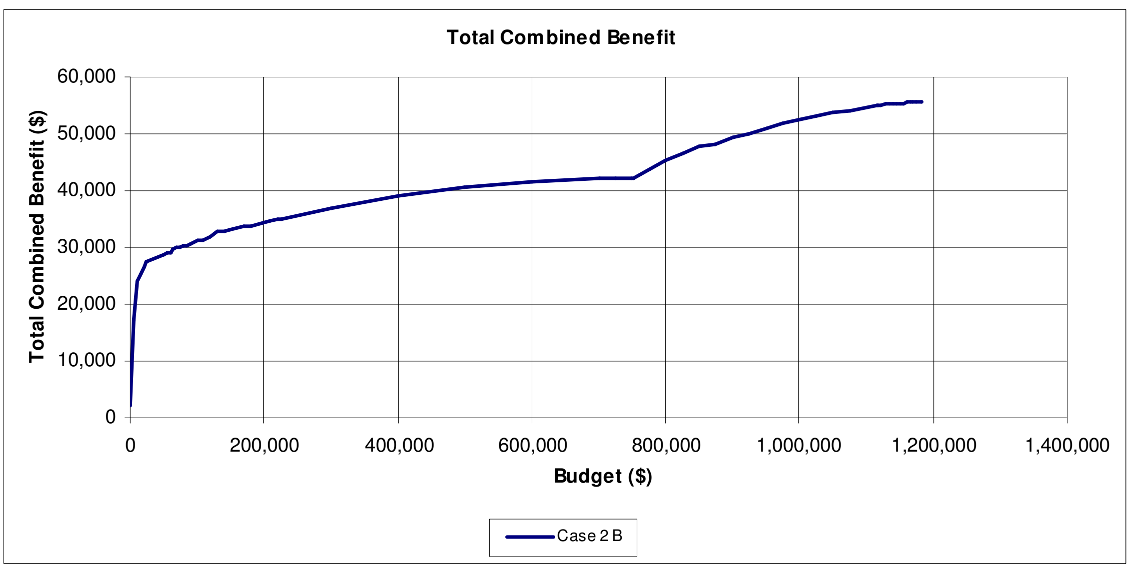

Figure 20. Total Combined Benefit at the First and Second Stage at Different Budget Amounts (Case 2B)

Comparison Between Case 1A and Case 1B

Case 1A and Case 1B are compared for NOx reduction (first stage). Case 1B shows higher NOx reduction than Case 1A for budgets ranging from $50,000 to $600,000 and the difference ranges from about $13 to $831. There is no difference between the cases for the other budget amounts (Figure 21).

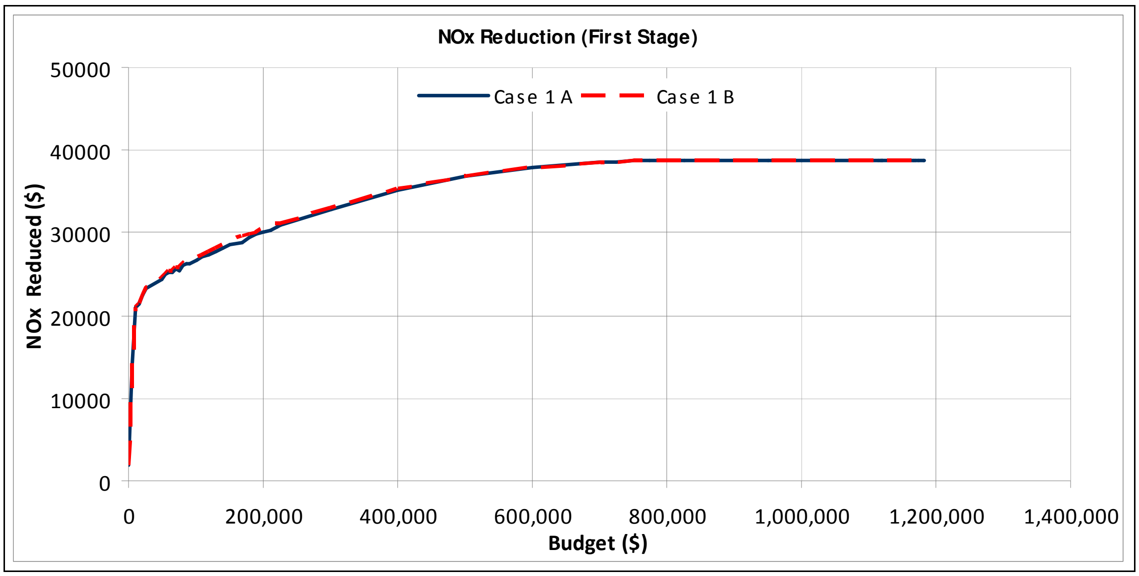

Figure 21. Total NOx Reduction at the First Stage (Case 1A vs Case 1B)

The comparison between Case 1A and Case 1B for total benefit in the first stage shows that at a budget range of $50,000 to $ 600,000, Case 1A exceeds Case 1B with a difference ranging from about $0.25 to $898. There is no difference for the rest of the budget amounts (Figure 22).

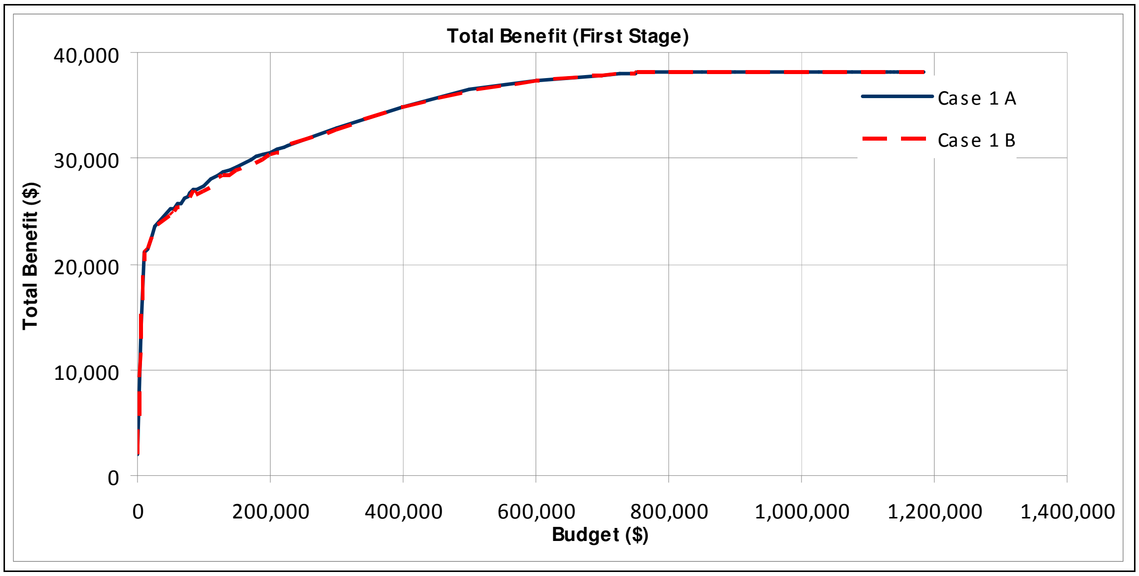

Figure 22. Total Benefit at the First Stage (Case 1A vs Case 1B)

A comparison of total NOx reduction (first and second stage combined) between Case 1A and Case 1B reveals that Case 1B exceeds Case 1A for budgets ranging from $775,000 to $ 1,120,000 with a difference ranging from about $50 to $608. For other budget amounts, the differences are sometimes positive or negative, or zero (Figure 23).

A comparison of total combined benefit (first and second stage) between Case 1A and Case 1B reveals that Case 1A exceeds or equals Case 1B for a badget starting from $200,000. Case 1A exceeds Case 1B for a budget ranging from $200,000 to $600,000 and $775,000 to $1,120,000 with a difference ranging from about $76 to $4,440 and $6 to $610, respectively (Figure 24).

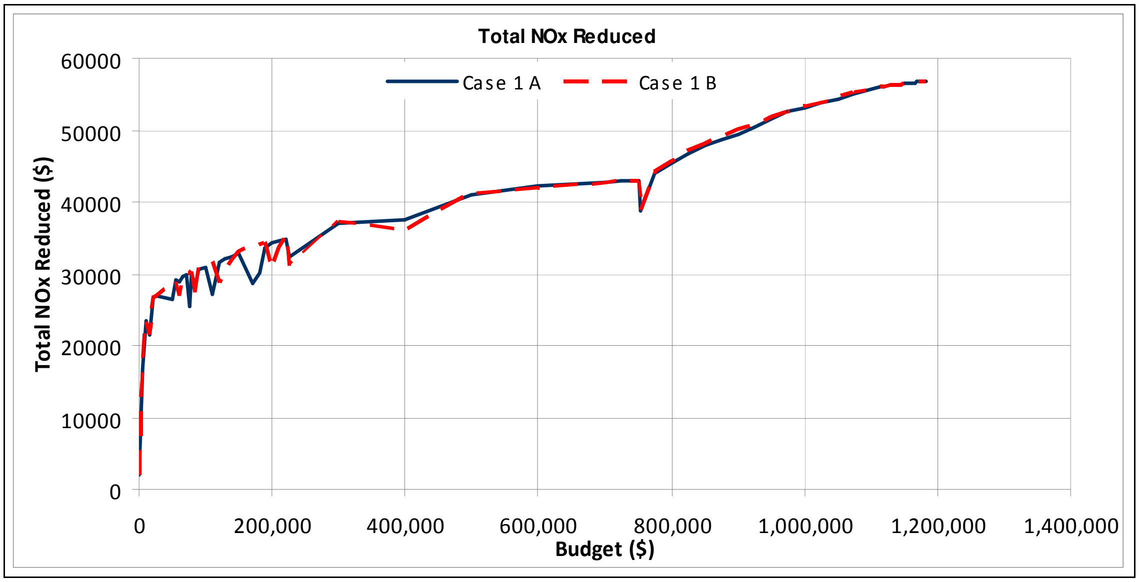

Figure 23. Total NOx Reduced at the First and Second Stage (Case 1A vs Case 1B)

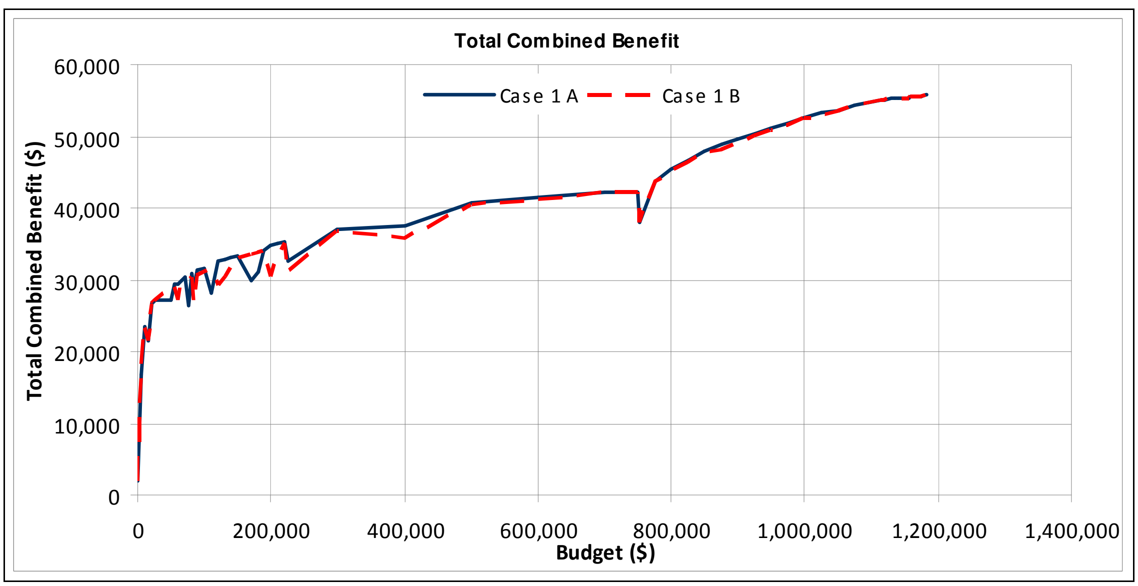

Figure 24. Total Combined Benefit at the First and Second Stage (Case 1A vs Case 1B)

Comparison between Case 1A and Case 1B at Given Budgets

The variation in the NOx reductions, benefits, and deployment of technologies for Case 1A and Case 1B are analyzed in this section. Tables 6 and 7 present the NOx reductions, fuel economy, and benefits for Case 1A and Case 1B respectively at different budget levels. Figures 25 and 26 are the graphical representation of Tables 6 and 7, respectively. The technology deployed at different budget amounts are presented in bar diagrams through Figures 27 to 31. The detailed information regarding technology deployment for Case 1A and Case 1B are provided in Appendices C and D, respectively. All the deployments produce optimal results at a given budget.

Table 6. NOx Reductions and Benefits at Different Budget Amounts (Case 1A)

	Budget ($)				
	110,000	170,000	400,000	752,791	1,150,000
NOx Reduced (1st Stage) ($)	27,117	28,735	35,159	38,732	38,732
Diesel Economy(1st Stage) ($)	963	1,105	-234	-639	-639
Total Benefit (1st Stage) ($)	28,081	29,840	34,925	38,093	38,093
Total NOx Reduced (1st and 2nd stage) ($)	27,117	28,735	37,645	38,732	56,510
Combined Diesel Economy (1st and 2nd stage) ($)	963	1,105	-234	-639	-1,081
Combined Total Benefit (1st and 2nd stage) ($)	28,081	29,840	37,411	38,093	55,429

Table 7. NOx Reductions and Benefits at Different Budget Amounts (Case 1B)

	Budget ($)				
	110,000	170,000	400,000	752,791	1,150,000
NOx Reduced (1st Stage) ($)	27,349	29,566	35,276	38,732	38,732
Diesel Economy(1st Stage) ($)	-167	-172	-368	-639	-639
Total Benefit (1st Stage) ($)	27,182	29,394	34,908	38,093	38,093
Total NOx Reduced (1st and 2nd Stage) ($)	31,567	33,783	36,127	38,731	56,510
Combined Diesel Economy (1st and 2nd Stage) ($)	-167	-172	-368	-639	-1,081
Combined Total Benefit (1st and 2nd Stage) ($)	31,400	33,611	35,759	38,093	55,429

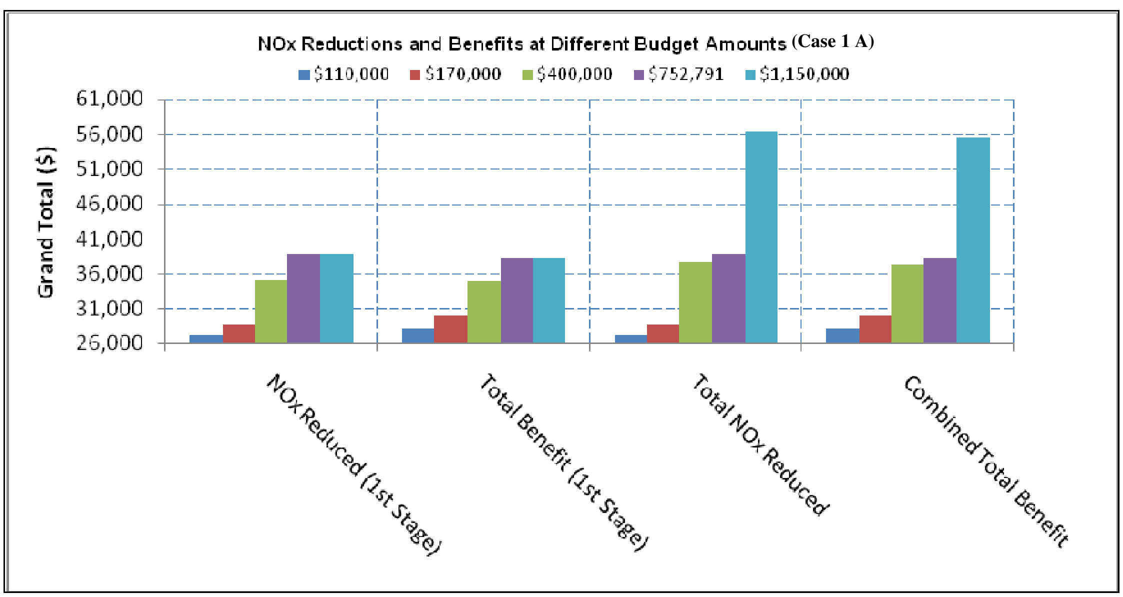

Figure 25. NOx Reductions and Benefits at Different Budgets (Case 1A)

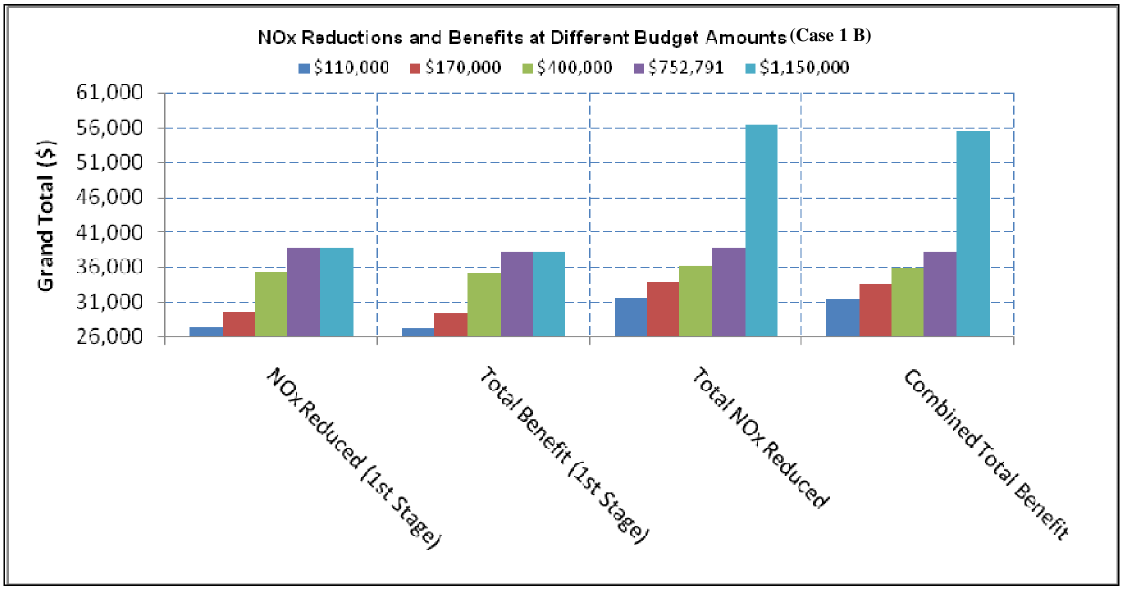

Figure 26. NOx Reductions and Benefits at Different Budgets (Case 1B)

From Figure 27, it can be seen that at a budget of $110,000, Case 1A has higher combined HE and FA (HE-FA) than Case 1B, whereas Case 1B has higher combined SCR and FA (SCR-FA) than Case 1A. Case 1B also has higher number of equipment (both NA and NNA counties) having FA than that of Case 1A. Case 1A considers fuel economy along with NOx reduction in the objective function. Since HE unit is capable of reducing fuel consumption and SCR causes fuel penalty, Case 1A deploys more HE than that of Case 1B. It is evident from Tables 6 and 7 that the combined fuel economy (first and second stage combined) is greater for Case 1A than that of Case 1B. Case 1B focuses on NOx reduction only and does not consider fuel economy in the objective function. Hence, Case 1B has higher number of SCR units deployed than that of Case 1A since SCR is capable of reducing more NOx than HE. Therefore, the NOx reduction at the first stage and the total NOx reduction (first and second stage combined) are higher for Case 1B (Table 7) than that of Case 1A (Table 6). Since the diesel fuel economy for Case 1A is higher than that of Case 1B, the total benefit at the first stage is greater than that of Case 1B. But considering the total NOx reduction (first and second stage combined) and the total fuel economy (first and second stage combined), the total combined benefit (first and second stage combined) is greater for Case 1B than that of Case 1A.

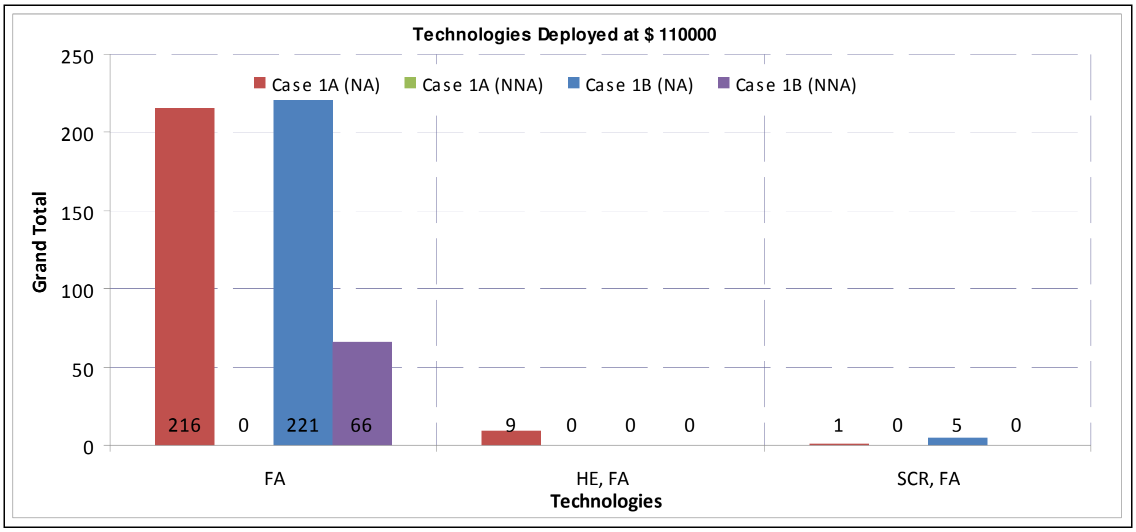

Figure 27. Technology Deployed at $110,000

It can be observed that at a budget of $170000, Case 1B has higher number of equipment having FA (both NA and NNA counties) than that of Case 1A (Figure 28). Case 1A has greater number of HE-FA in NA counties than Case 1B since Case 1A considers fuel economy also. Case 1B has higher SCR unit deployed in NA counties since it considers NOx reduction only. Therefore, the NOx reduction at the first stage is greater for Case 1B because of having more FA and SCR-FA. Case 1A has higher total benefit at the first stage because of having fuel economy due to having more HE units. The total NOx reduction (first and second stage combined) is greater for Case 1B because of having wide coverage of FA and having more SCR units than that of Case 1A. The total combined benefit (first and second stage combined) is greater for Case 1B because of the total NOx reduction (first and second stage combined).

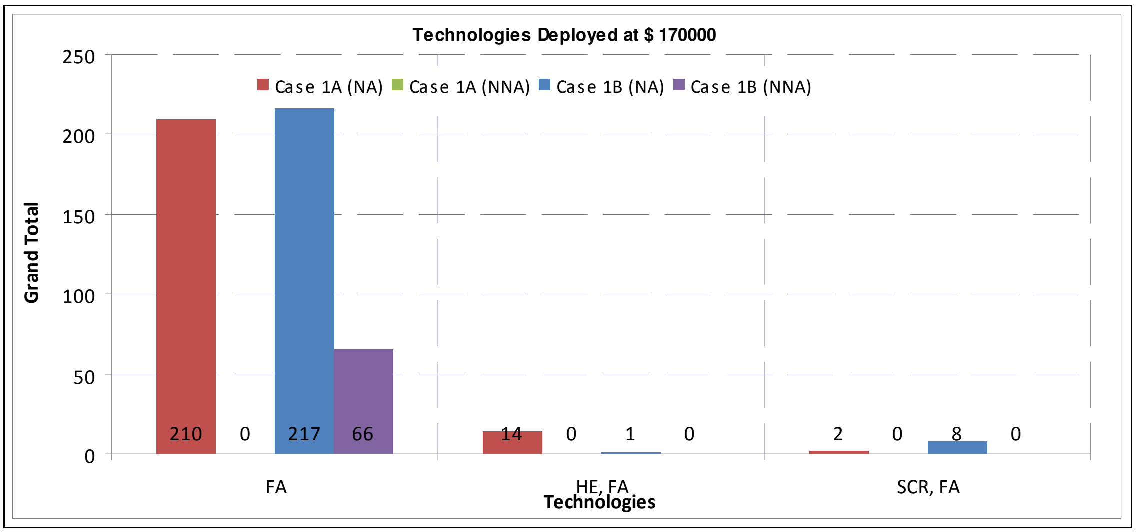

Figure 28. Technology Deployed at $170,000

It can be seen form Tables 6 and 7 that at a budget of $400,000, Case 1B has higher NOx reduction (first stage) because of having an extra SCR-FA and FA (Figure 29). Case 1B has higher fuel penalty (first stage) than Case 1A since Case 1B has greater number of SCR units and lesser HE units in the NA counties. The NNA counties do not have any SCR or HE unit. This causes the total benefit (first stage) for Case 1A to be higher than that of Case 1B. In terms of total NOx reduction (first and second stage combined), Case 1A exceeds Case 1B essentially because of having wider coverage of

FA in the NNA counties than Case 1B. As a result, the total combined benefit (first and second stage combined) for Case 1A is higher than that of Case 1B.

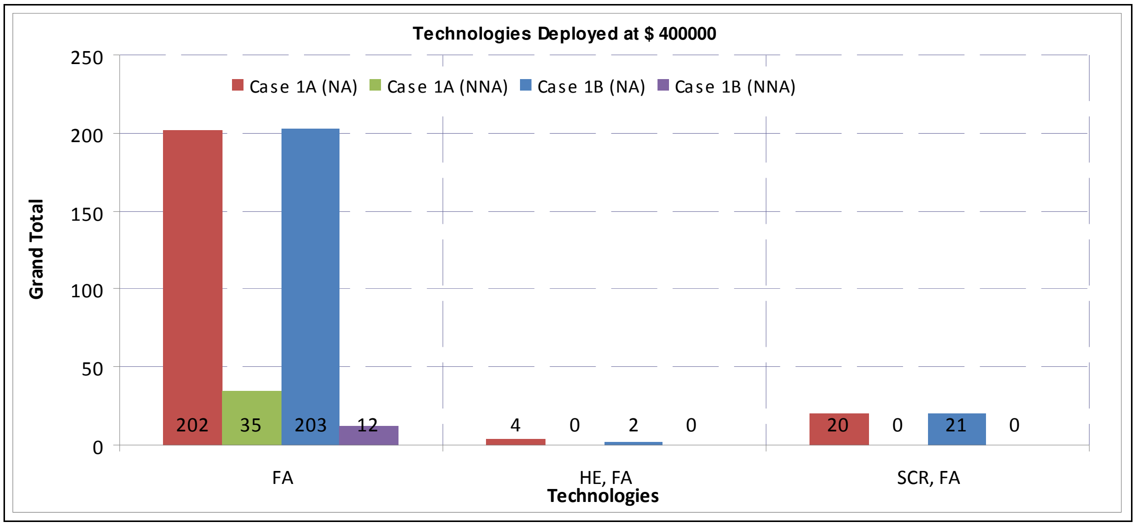

Figure 29. Technology Deployed at $400,000

From Figures 30 and 31, it can be observed that at budgets $752,791 and $1,150,000, the total number of HE-FA and SCR-FA and total amount of FA deployed are equal for both Case 1A and Case 1B for the respective budget and thus having equal total NOx reduction (first and second stage combined) and total combined benefit (first and second stage combined). At budget $752,791, both Case 1A and Case 1B has maximum possible units of SCR, HE and FA coverage in the NA counties.

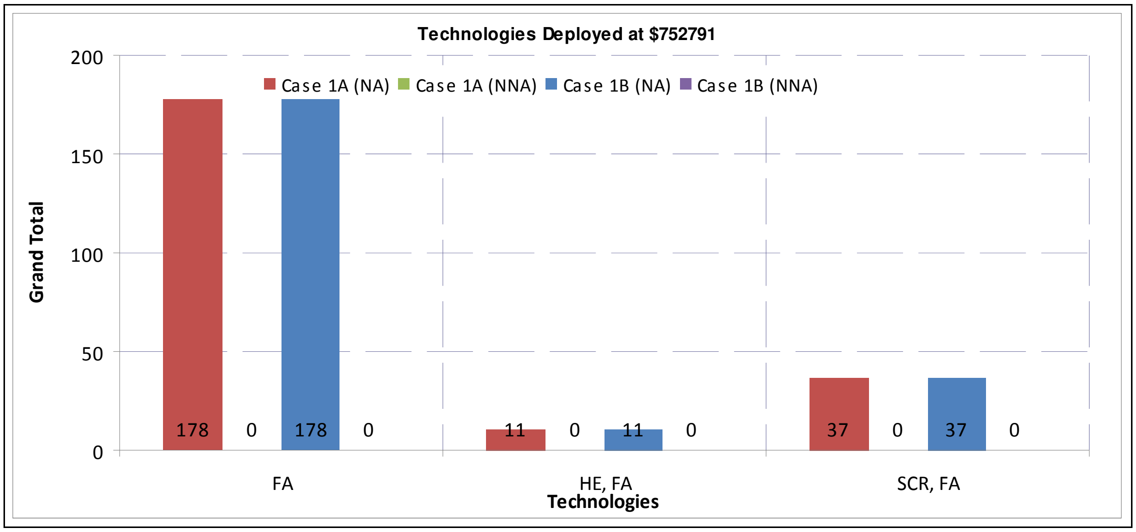

Figure 30. Technology Deployed at $752,791

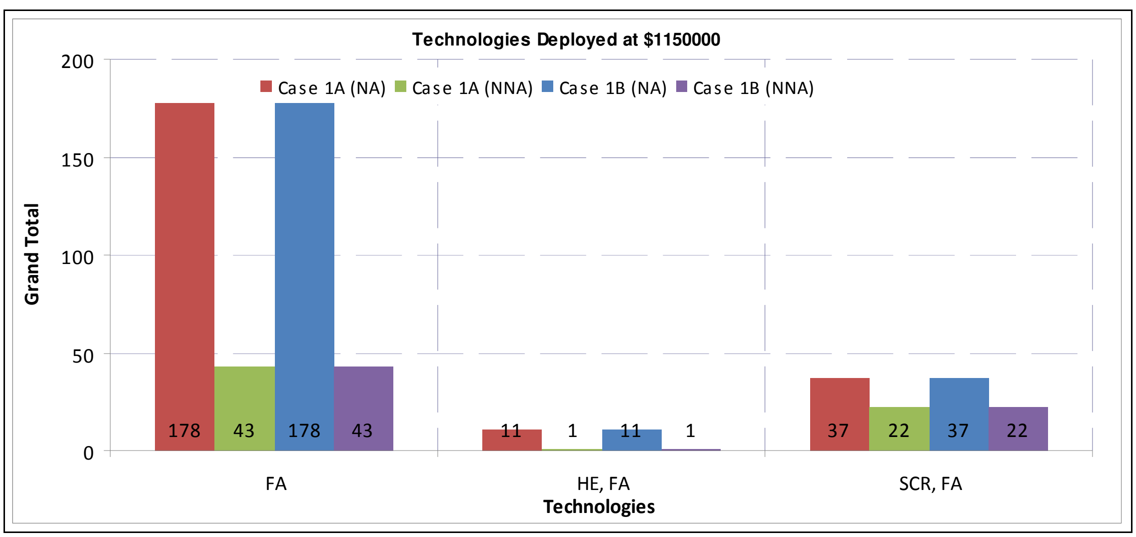

Figure 31. Technology Deployed at $1,150,000

Comparison between Case 2A and Case 2B

A comparison of NOx reduction (first stage) between Case 2A and Case 2B reveals that Case 2B has higher NOx reduction than Case 2A for the budget range of $45,000 to $600,000 and the difference ranges from about $6 to $869. There is no difference between the cases for the other budget amounts. The NOx reduction at the first stage for both cases is presented in Figure 32.

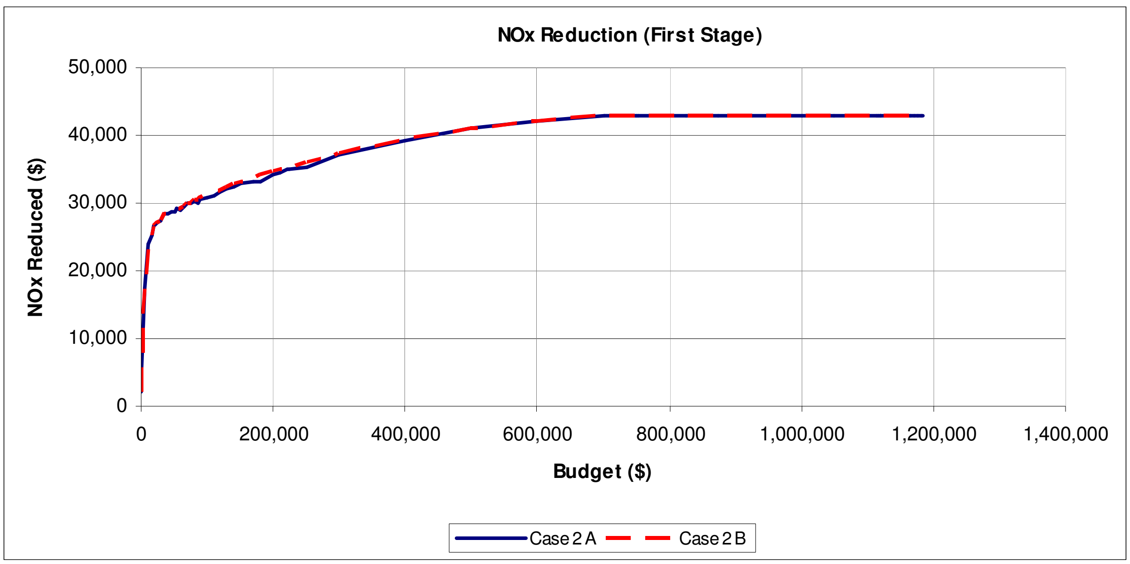

Figure 32. Total NOx Reduction at the First Stage (Case 2A vs Case 2B)

The comparison between Case 2A and Case 2B for total benefit (first stage) shows that at a certain budget range ($45,000 to $ 600,000), Case 2A exceeds Case 2B with a difference ranging from about $1 to $732. There are no differences between the cases for the rest of the budget amounts. The total benefit (first stage) for Case 2A and Case 2B are presented in Figure 33.

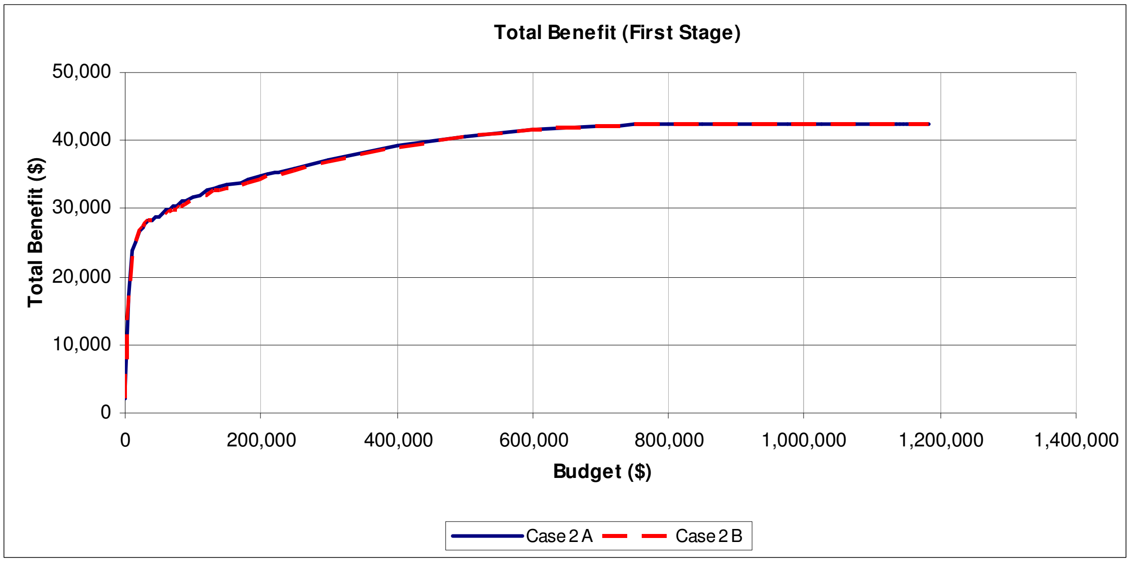

Figure 33. Total Benefit at the First Stage (Case 2A vs Case 2B)

Case 2A and Case 2B are compared for the total NOx reduction (first and second stage combined). Case 2B has greater total NOx reduction (first and second stage combined) for budgets ranging from $45,000 to $600,000 and $775,000 to $1,120,000 with a difference ranging from about $7 to $867 and $50 to $1,205, respectively. For other budget amounts, there are no differences in terms of total NOx reduction (first and second stage combined) between both the cases. Figure 34 presents the total NOx reduction (first and second stage combined) for both cases.

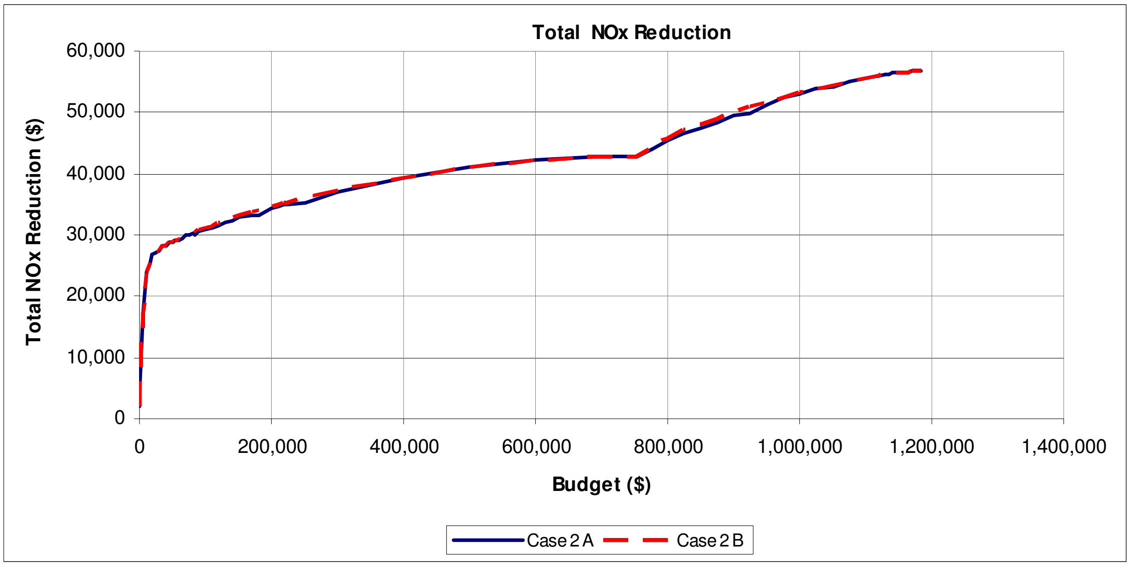

Figure 34. Total NOx Reduced at the First and Second Stage (Case 2A vs Case 2B)

A comparison of total combined benefit (first and second stage combined) between Case 2A and Case 2B reveals that Case 2A exceeds Case 2B for a budgets ranging from $45,000 to $6,00,000 and $775,000 to $1,120,000 with a difference ranging from $1 to $732 and $4 to $545, respectively. The only exception in this budget range is $975,000 at which Case 2B exceeds Case 2A. Figure 35 presents the total combined benefit (first and second stage combined) for both Case 2A and Case 2B.

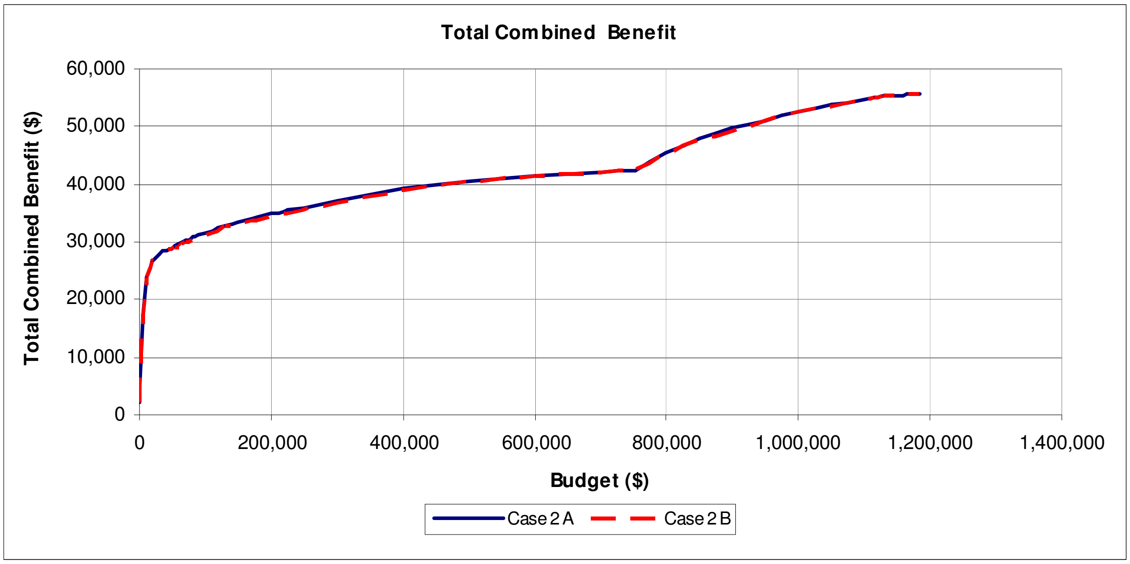

Figure 35. Total Combined Benefit at the First and Second Stage (Case 2A vs Case 2B)

Comparison between Case 2A and Case 2B at Given Budgets

The variation in NOx reductions, benefits, and deployment of technologies for Case 2A and Case 2B are introduced in this section. Tables 8 and 9 presents the data for NOx reductions, fuel economy, and benefits at different budget levels and Figures 36 and 37 presents Tables 8 and 9 graphically for Case 2A and Case 2B. The technology deployed at different budget amounts are presented through Figures 38 to 44. All the deployments produce optimal results at a given budget. Detailed information regarding technology deployment for Case 2A and Case 2B are provided in Appendices E and F, respectively.

Table 8. NOx Reductions and Benefits at Different Budget Amounts (Case 2A)

	Budget ($)						
	130,000	170,000	250,000	600,000	925,000	1,050,000	1,182,020
NOx Reduced (1st Stage) ($)	32,000	33,187	35,271	42,170	42,949	42,949	42,949
Diesel Economy (1st Stage) ($)	862	697	707	-597	-639	-639	-639
Total Benefit (1st Stage) ($)	32,861	33,884	35,978	41,574	42,311	42,311	42,311
Total NOx Reduced (1st and 2nd Stage) ($)	32,000	33,187	35,271	42,170	49,692	54,265	56,770
Combined Diesel Economy (1st and 2nd Stage) ($)	862	697	707	-597	618	-591	-1,086
Combined Total Benefit (1st and 2nd Stage) ($)	32,861	33,884	35,978	41,574	50,309	53,674	55,683

Table 9. NOx Reductions and Benefits at Different Budget Amounts (Case 2B)

	Budget ($)						
	130,000	170,000	250,000	600,000	925,000	1,050,000	1,182,020
NOx Reduced (1st Stage) ($)	32,337	33,783	35,974	42,176	42,949	42,949	42,949
Diesel Economy (1st Stage) ($)	410	-172	-354	-604	-639	-639	-639
Total Benefit (1st Stage) ($)	32,747	33,611	35,620	41,572	42,311	42,311	42,311
Total NOx Reduced (1st and 2nd Stage) ($)	32,337	33,783	35,974	42,176	50,897	54,589	56,770
Combined Diesel Economy (1st and 2nd Stage) ($)	410	-172	-354	-604	-841	-983	-1,086
Combined Total Benefit (1st and 2nd Stage) ($)	32,747	33,611	35,620	41,572	50,056	53,606	55,683

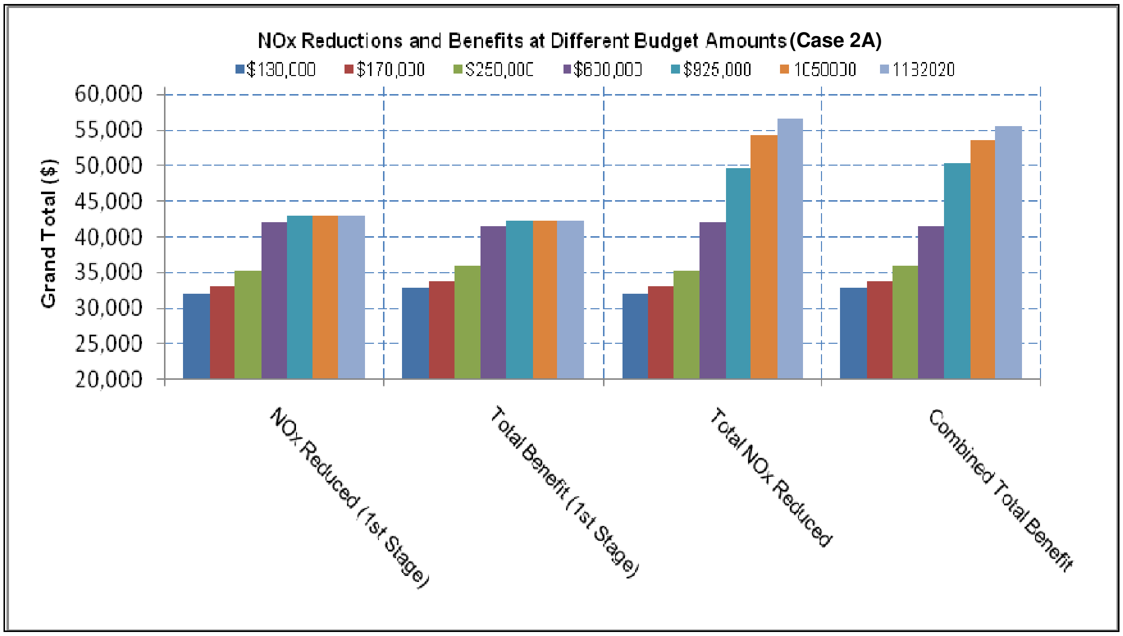

Figure 36. NOx Reductions and Benefits at Different Budgets (Case 2A)

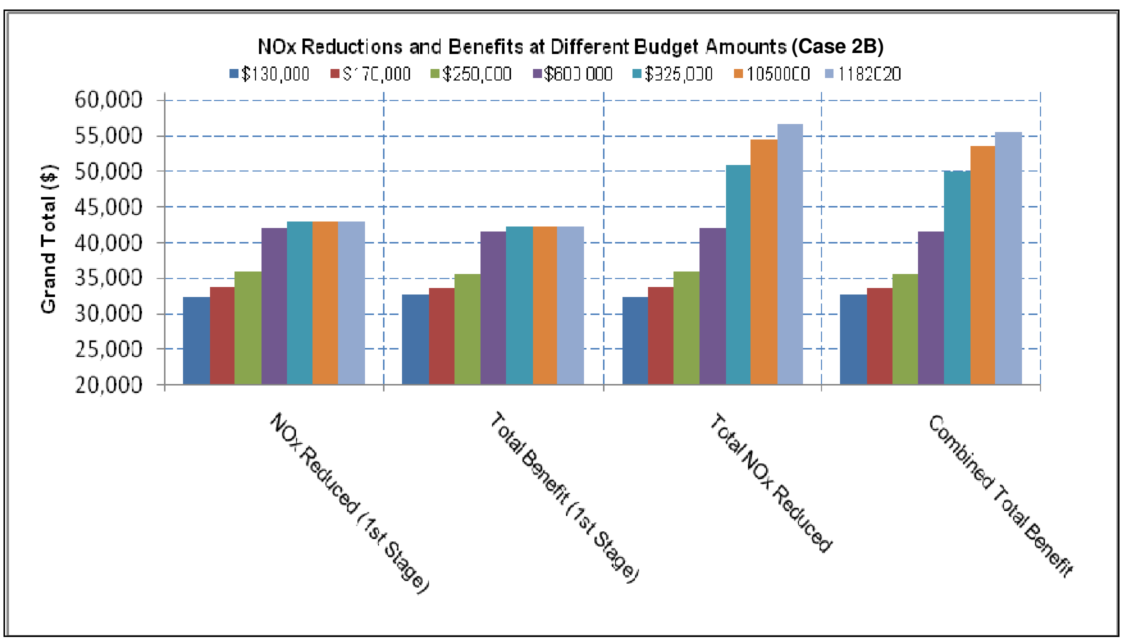

Figure 37. NOx Reductions and Benefits at Different Budgets (Case 2B)

It is observed that at a budget of $130,000, Case 2B has higher FA coverage and SCR-FA than that of Case 2A whereas Case 2A has more HE-FA than that of Case 2B. This is graphically presented at Figure 38. Case 2A has more HE because HE is more fuel efficient than SCR and since Case 2A considers fuel economy along with NOx reduction. Similarly, as Case 2B focuses only on NOx reduction, it has more SCR because SCR has higher NOx reduction efficiency than HE. Case 2B (Table 9) has higher NOx reduction (first stage) than that of Case 2A (Table 8). The diesel economy (first stage) is higher for Case 2A thus causing the total benefit (first stage) for Case 2A to be higher than that of Case 2B. The total NOx reduction (first and second stage combined) is higher for Case 2B. The combined diesel economy (first and second stage combined) is greater for Case 2A and as a result, the total combined benefit (first and second stage combined) is higher for Case 2A than that of Case 2B.

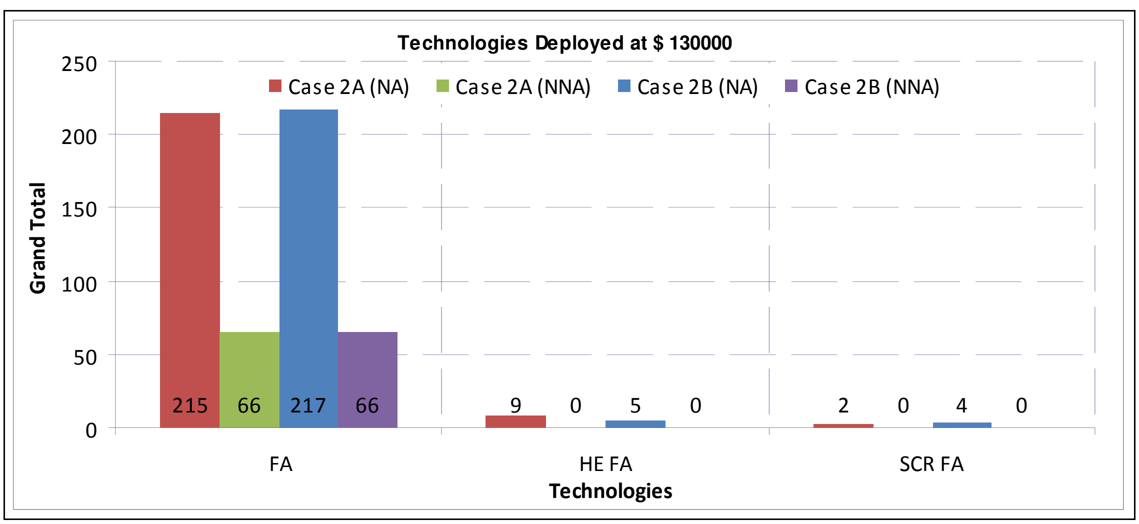

Figure 38. Technology Deployed at $130,000

The technology deployment pattern at $170,000 (Figure 39), $ 250,000 (Figure 40), and $600,000 (Figure 41) is similar to that of $130,000, i.e. higher FA and SCR-FA for Case 2B and higher HE-FA for Case 2A. The technology deployment at $170,000, $ 250,000, and $600,000 are presented in Figures 39, 40 and 41, respectively. Due to the nature of the technology deployment at the first stage, Case 2B has higher NOx reduction (first stage) than that of Case 2A. But the diesel economy (first stage) is higher for Case 2A and this elevates the total benefit (first stage) for Case 2A than that of Case 2B. Total NOx reduction (first and second stage combined) is higher for Case 2B but the combined diesel economy (first and second stage combined) is higher for Case 2A. As a result, the combined benefit (first and second stage combined) is higher for Case 2A than that of Case 2B.

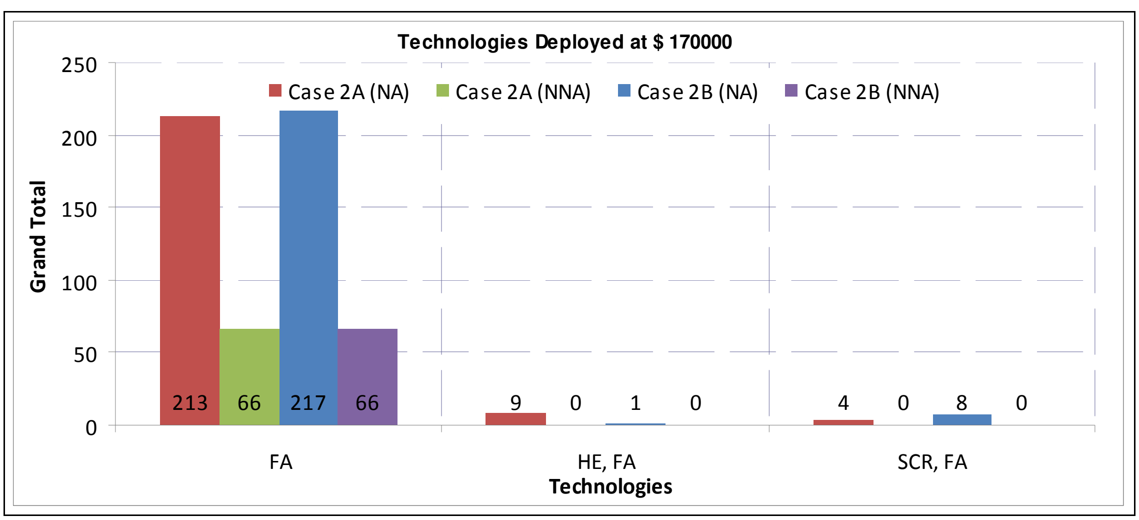

Figure 39. Technology Deployed at $170,000

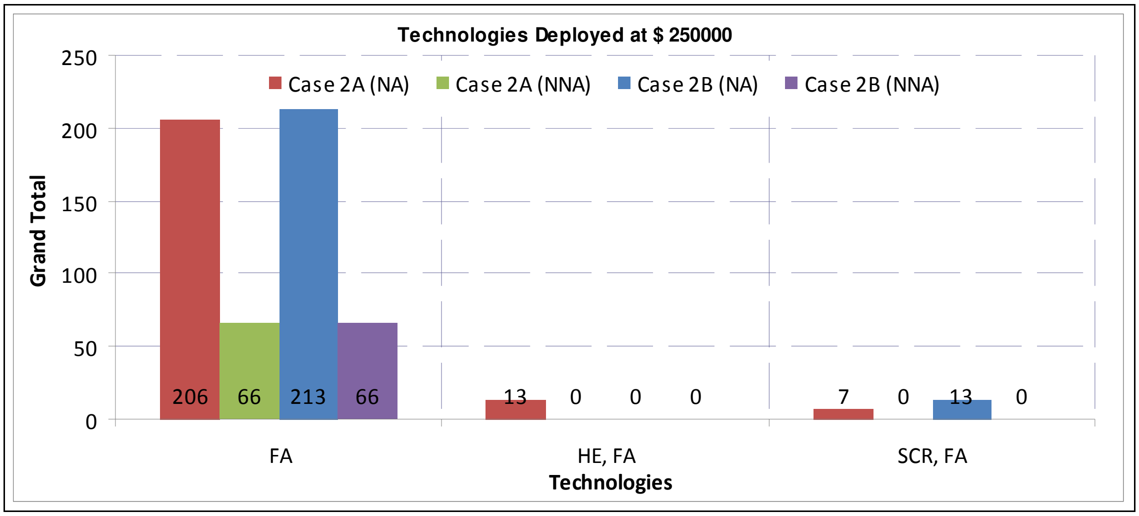

Figure 40. Technology Deployed at $250,000

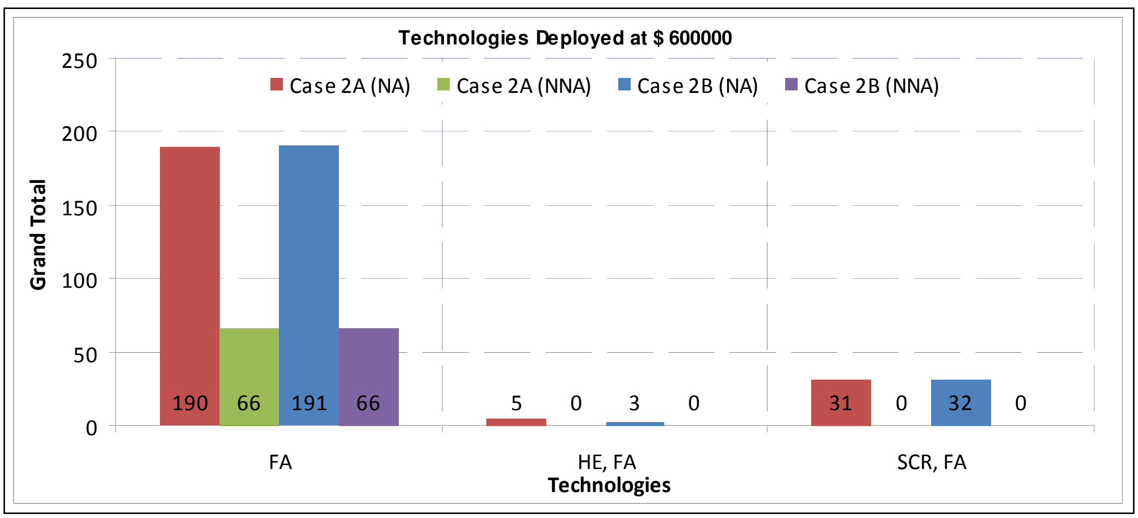

Figure 41. Technology Deployed at $600,000

It is observed from Figure 42 that at budget $925,000, deployment in the NA counties at the first stage has the maximum possible amount of FA, SCR-FA and HE-FA. The NOx reduction (first stage), the diesel economy (first stage), and the total benefit (first stage) are equal for both Case 2A and Case 2B. In the second stage of deployment, Case 2B has more SCR-FA and Case 2A has more HE-FA. Therefore, the total NOx reduction (first and second stage combined) is higher for Case 2B and the combined diesel economy (first and second stage combined) is higher for Case 2A. All these facts are causing the total combined benefit (first and second stage combined) for Case 2A to be greater than that of Case 2B.

The technology deployment in the NA counties at the first stage at $1,050,000 and $1,182,020 is same as that of $925,000 i.e. having the same amount of FA, SCR-FA and HE-FA. The technology deployment at $1,050,000 and $1,182,020 are presented in Figures 43 and 44, respectively. The NOx reduction (first stage), the diesel economy (first stage), and the total benefit (first stage) for both Case 2A and Case 2B are equal. The total NOx reduction (first and second stage combined), the combined diesel economy (first and second stage combined) and the total combined benefit (first and second stage combined) for Budget $1,050,000 follow a similar trend to that of budget $925,000, i.e. higher total NOx reduction (first and second stage combined) for Case 2B, and higher combined diesel economy (first and second stage combined) and higher total combined benefit (first and second stage combined) for Case 2A.

At a budget of $1,182,020, all the NA counties and NNA counties have the maximum possible amount of FA, SCR-FA and HE-FA. Thus the total NOx reduction (first and second stage combined), combined diesel economy (first and second stage combined) and combined total benefit (first and second stage combined) are equal for both Case 2A and Case 2B. The technology deployments at $1,182,020 are presented in Figure 44.

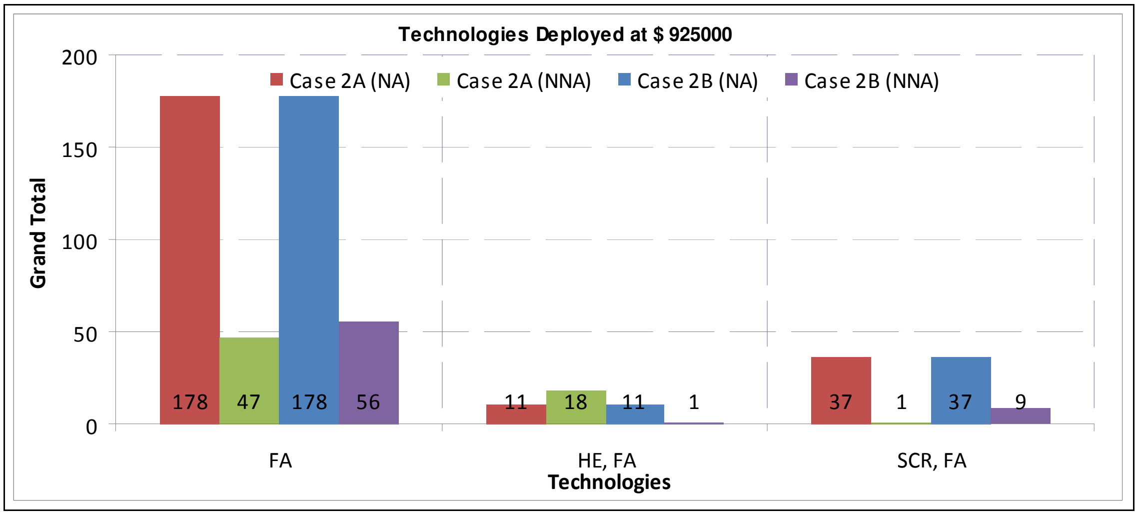

Figure 42. Technology Deployed at $925,000

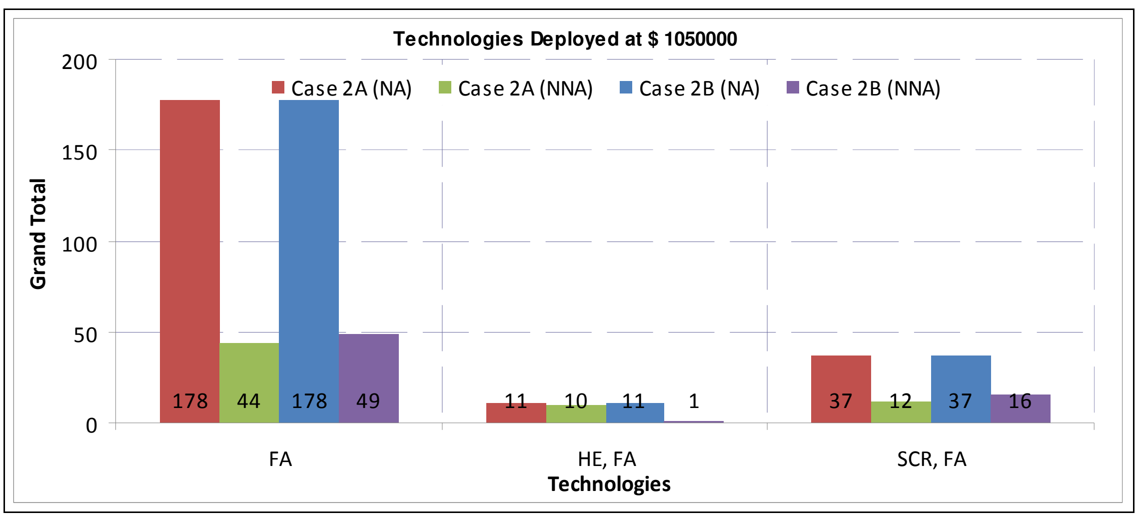

Figure 43. Technology Deployed at $1,050,000

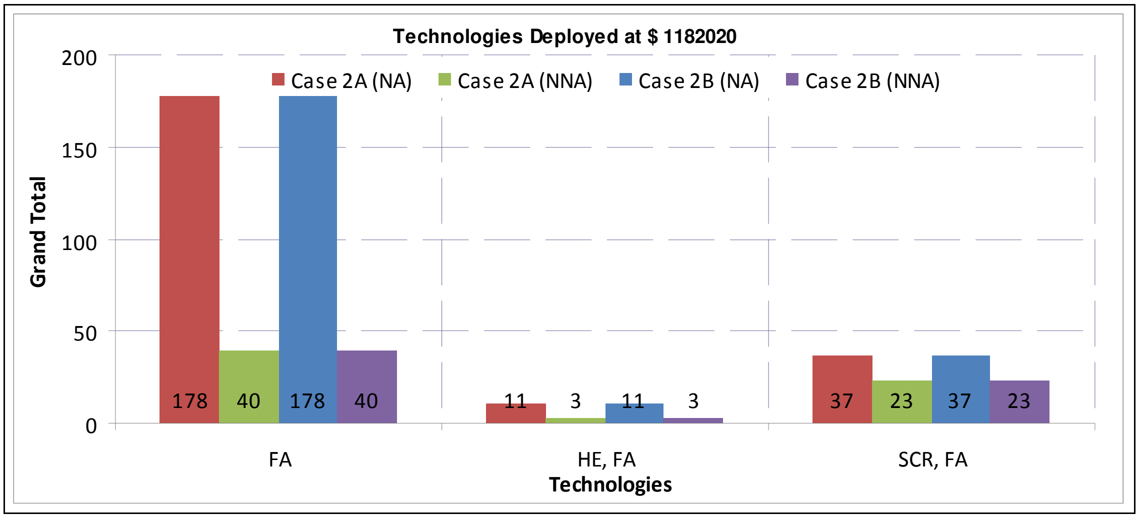

Figure 44. Technology Deployed at $1,182,020

Comparison between Case 1A and Case 2A

Camparison for NOx Reduction (first stage) and total benefit (first stage) between Case 1A and Case 2A are presented in Figures 45 and 46, respectively. The difference between Case 1A and Case 2A at the first stage is that deployment of FA in NNA counties is considered at the first stage of Case 2A while deployment of FA in NNA counties is not considered at the first stage of Case 1A. This casues the NOx reduction and the total benefit at the first stage of Case 2A to be elevated than that of Case 1A (Figures 45 and 46).

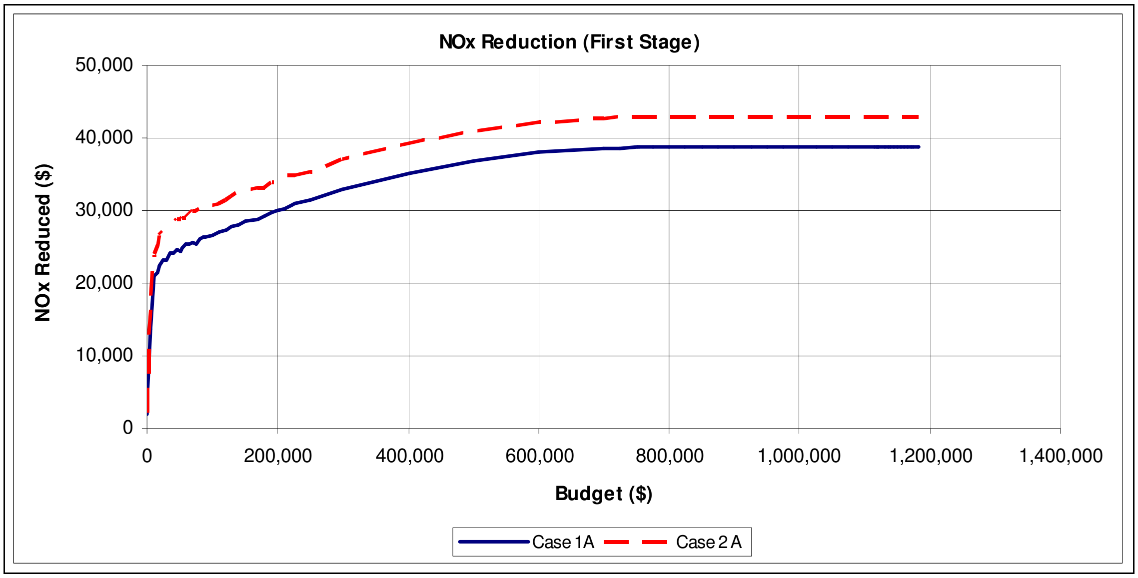

Figure 45. Total NOx Reduction at the First Stage (Case 1A vs Case 2A)

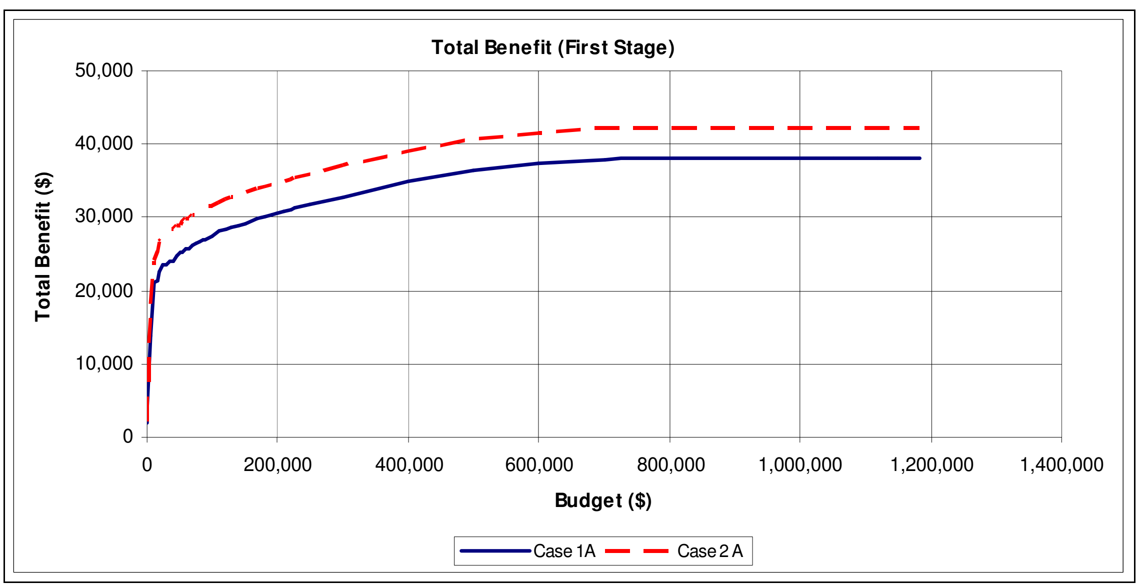

Figure 46. Total Benefit at the First Stage (Case 1A vs Case 2A)

The total NOx reduction (first and second stage combined) for Case 2A is greater or equal to Case 1A up to budget $752,791 with differences up to $4,207, while Case 1A is greater or equal to Case 2A starting from budget $850,000 and onwards with differences up to $702. There are no differences between them for the rest of the budgets. The total NOx reduction (first and second stage combined) for Case 1A and Case 2A are presented in Figure 47.

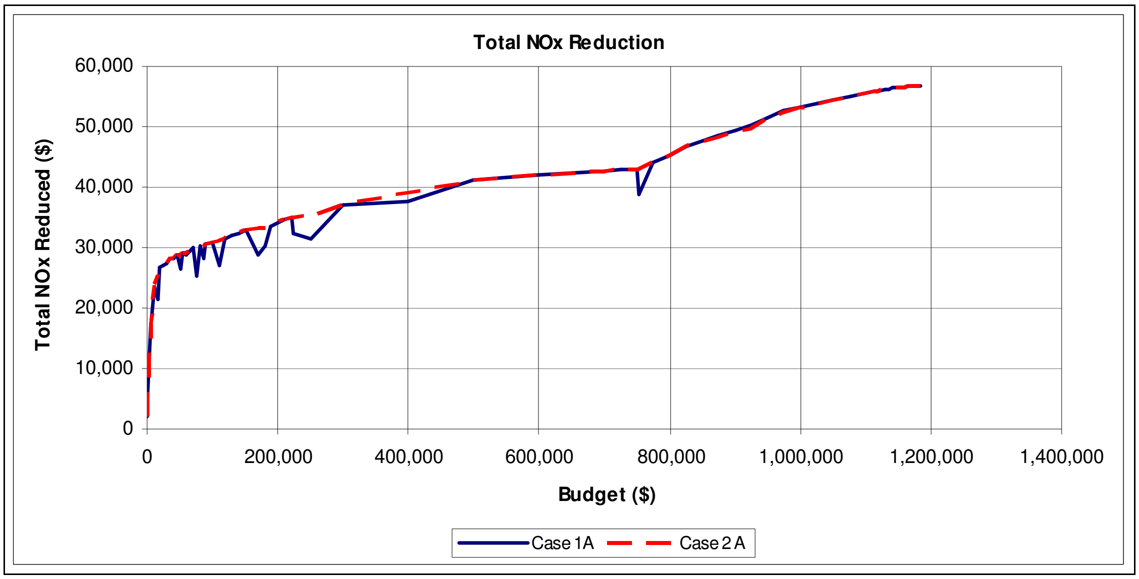

Figure 47. Total NOx Reduced at the First and Second Stage (Case 1A vs Case 2A)

The total combined benefit (first and second stage combined) for Case 1A is greater or equal to Case 2A for budgets ranging from $500 to $825,000 with differences up to $4,207. Case 2A again exceeds Case1A for budgets ranging from $850,000 to $1,075,000 with differences up to $0 to $90. For rest of the budgets, there are no differences between the cases. The graphs for Case 1A and Case 2A for the total combined benefit (first and second stage combined) are presented in Figure 48.

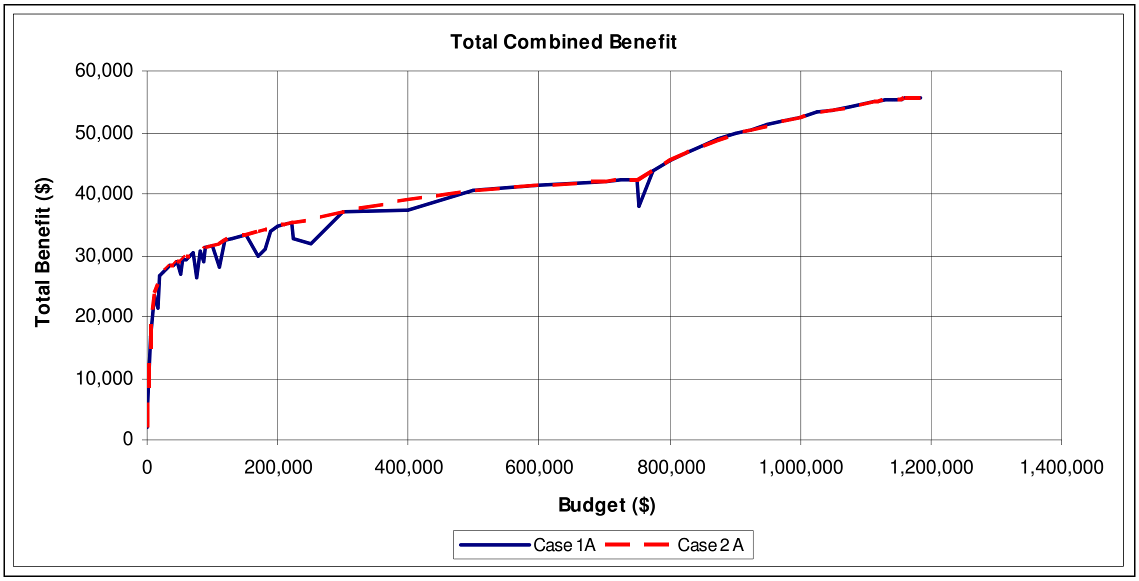

Figure 48. Total Combined Benefit at the First and Second Stage (Case 1A vs Case 2A)

From Figures 47 and 48, it can be observed that Case 2A (Method 2) avoids the drops occurred in Case 1A (Method 1) for variables such as total NOx reduction (first and second stage) and total combined benefit (first and second stage). The graphs for total NOx reduction (first and second stage) and total combined benefit (first and second stage) of Case 2A advances upward without any drop with further increasing the budget amounts.

Comparison between Case 1A and Case 2A at Given Budgets

The variation in NOx reductions, benefits, and deployment of technologies are investigated in this section. Tables 10 and 11 presents the data for NOx reductions, fuel economy, and benefits at different budget levels and , Figures 49 and 50 presents graphically Tables 10 and 11 for Case 1A and Case 2A, respectively. The technology deployed at different budget amounts are presented through Figures on pages 99-103. All the deployments produce optimal results at a given budget.

Table 10. NOx Reductions and Benefits at Different Budget Amounts (Case 1A)

	Budget ($)				
	170,000	250,000	400,000	752,791	925,000
NOx Reduced (1st Stage) ($)	28,735	31,444	35,159	38,732	38,732
Diesel Economy (1st Stage) ($)	1,105	386	-234	-639	-639
Total Benefit (1st Stage) ($)	29,840	31,831	34,925	38,093	38,093
Total NOx Reduced (1st and 2nd Stage) ($)	28,735	31,444	37,645	38,732	50,394
Combined Diesel Economy (1st and 2nd Stage) ($)	1,105	386	-234	-639	5
Combined Total Benefit (1st and 2nd Stage) ($)	29,840	31,831	37,411	38,093	50,399

Table 11. NOx Reductions and Benefits at Different Budget Amounts (Case 2A)

	Budget ($)				
	170,000	250,000	400,000	752,791	925,000
NOx Reduced (1st Stage) ($)	33,187	35,271	39,259	42,939	42,949
Diesel Economy (1st Stage) ($)	697	707	-122	-639	-639
Total Benefit (1st Stage) ($)	33,884	35,978	39,137	42,300	42,311
Total NOx Reduced (1st and 2nd Stage) ($)	33,187	35,271	39,259	42,939	49,692
Combined Diesel Economy (1st and 2nd Stage) ($)	697	707	-122	-639	618
Combined Total Benefit (1st and 2nd Stage) ($)	33,884	35,978	39,137	42,300	50,309

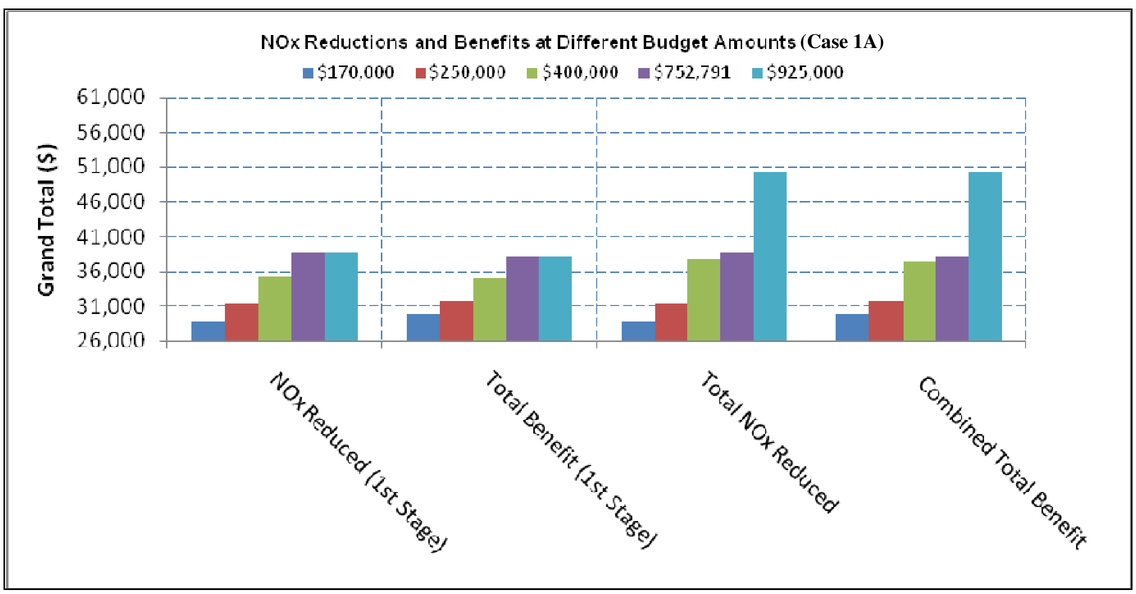

Figure 49. NOx Reductions and Benefits at Different Budgets (Case 1A)

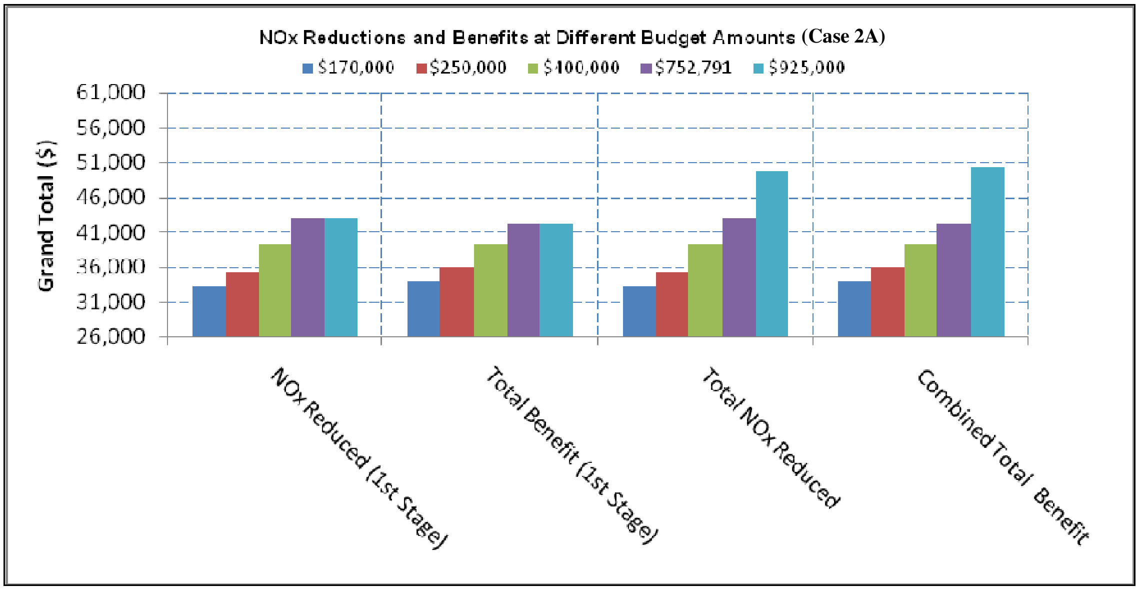

Figure 50. NOx Reductions and Benefits at Different Budgets (Case 2A)

As mentioned earlier, Case 1A and Case 2A have different patterns of deployment strategy at the first and second stage (Figures 5 and 6). Case 1A deploys technologies only in the NA counties at the first stage whereas Case 2A includes additionally NNA counties for FA deployment in the first stage. In both cases, fuel economy is considered in the objective function.

At a given budget of $170,000, Case 1A utilizes the total budget entirely in the NA counties. But Case 2A utilizes part of the budget for deploying FA in the NNA counties also at the first stage. Therefore, Case 2A has higher FA coverage than that of Case 1A. This can be observed from Figure 51. Case 1A has more HE-FA since it is not deploying any technology in the NNA counties at the first stage and thus utilizing the budget entirely to maximize both NOx reduction and fuel economy in the NA counties. Case 2A is having more SCR-FA since it is spending less on HE-FA than that of Case

1A. The total NOx reduction (first and second stage combined) is higher for Case 2A (Table 11) primarily because of having more FA coverage. The combined diesel economy (first and second stage combined) is higher for Case 1A (Table 10) essentially because of having more HE units. The combined total benefit (first and second stage combined) is higher for Case 2A predominantly because of having greater total NOx reduction.

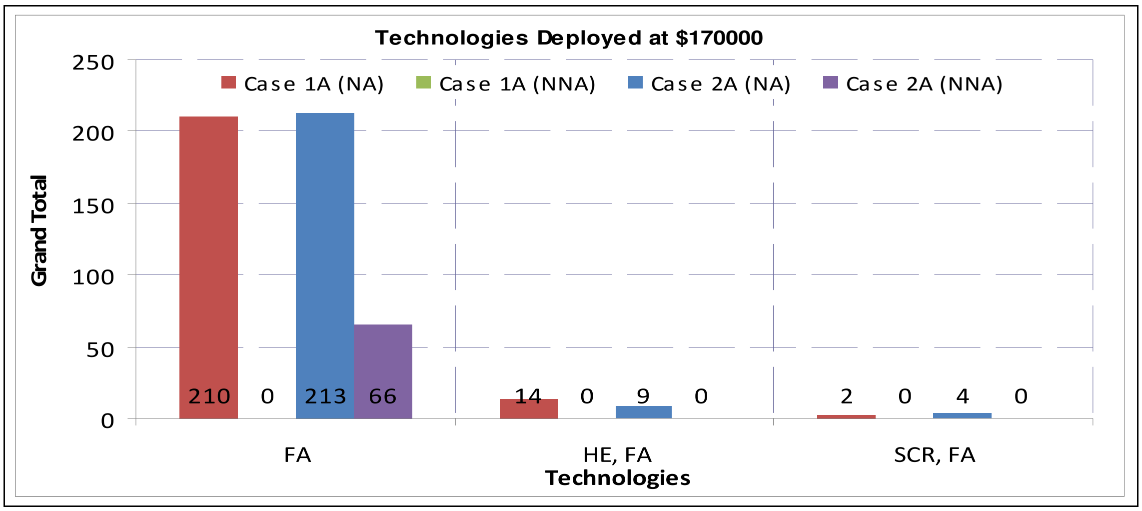

Figure 51. Technology Deployed at $170,000

At budget $250,000, Case 2A greater total NOx reduction (first and second stage combined), combined diesel economy (first and second stage combined) and combined total benefit (first and second stage combined) than that of Case 1A. Case 2A has higher FA coverage than that of Case 1A. The technology deployment pattern at $250,000 can be observed from Figure 52. Since Case 2A has full FA coverage in NNA counties, it is having less SCR and more HE than that of Case 1A. Hence, the combined NOx reduction (first and second stage combined), the diesel economy (first and second stage combined) and the benefits (first and second stage combined) for Case 2A are higher than that of Case 1A. Similar to budget $250,000, the total NOx reduction (first and second stage combined), the combined diesel economy (first and second stage), and the total combined benefit (first and second stage) are consistently higher for Case 2A than that of Case 1A at budget $400,000. The technology deployment pattern at $400,000 is also similar to that of $250,000, i.e. higher FA, HE-FA and less SCR-FA for Case 2A than that of Case 1A. The technology deployment pattern at $400,000 is presented in Figure 53.

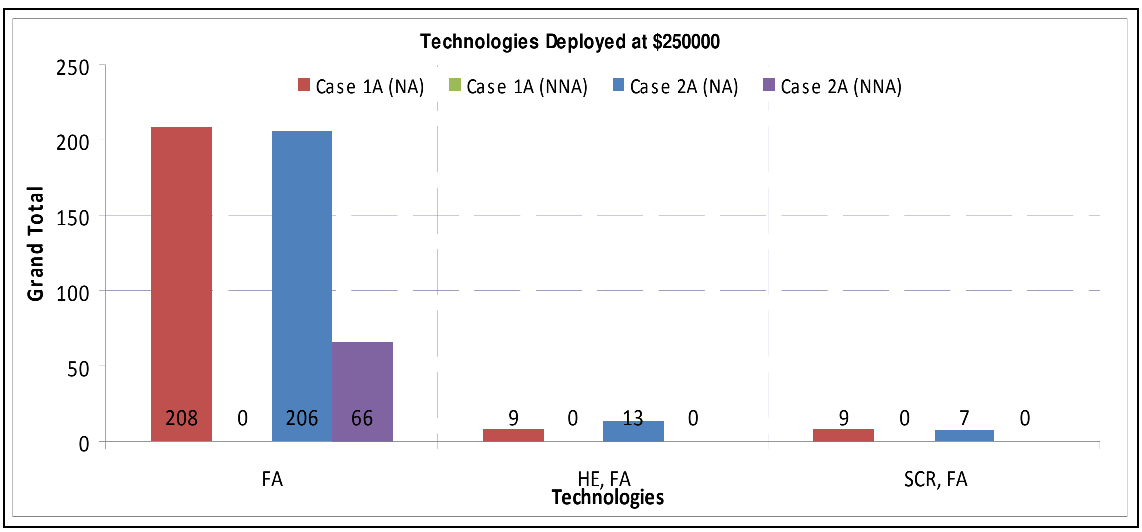

Figure 52. Technology Deployed at $250,000

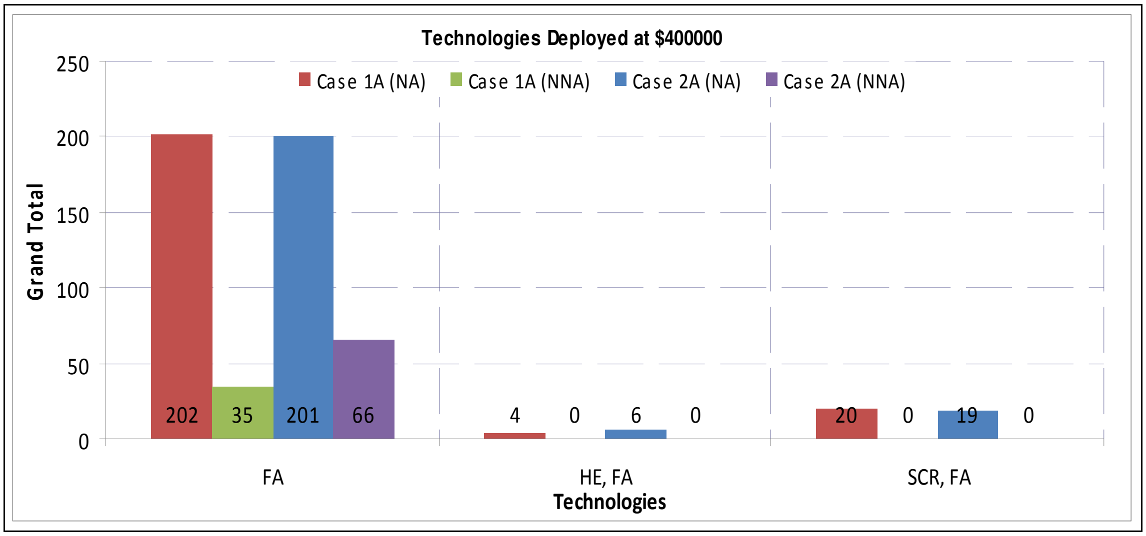

Figure 53. Technology Deployed at $400,000

At budget $752,791, Case 2A has greater FA coverage than that of Case 1A. The deployments are presented at Figure 54. The total HE units are less for Case 2A and the total SCR units are equal for both cases. The combined diesel economy is same for both cases. The total NOx reduction (first and second stage) and the total combined benefit (first and second stage) are higher for Case 2A than that of Case 1A.

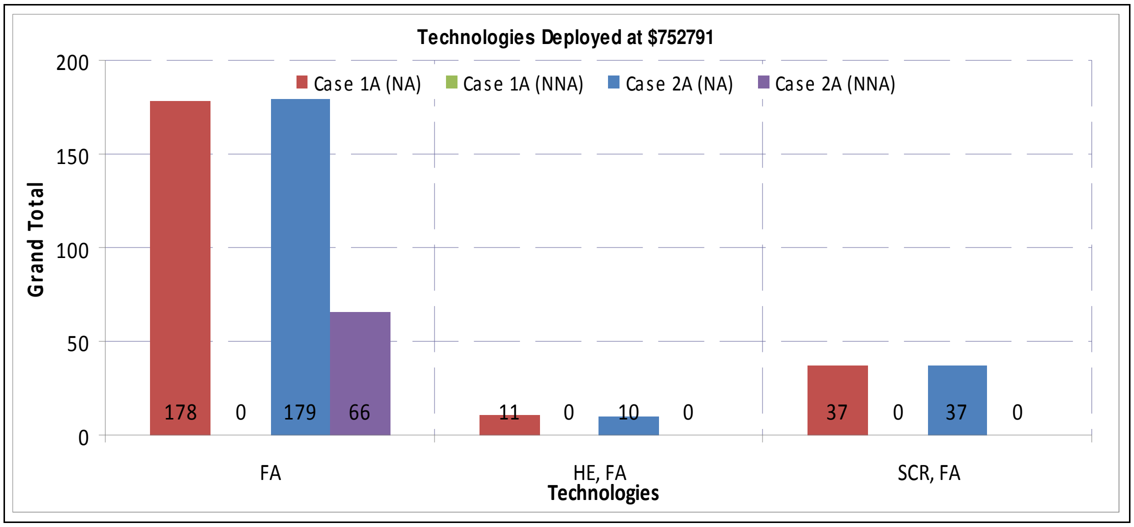

Figure 54. Technology Deployed at $752,791

At budget $925,000, the NA counties for both cases have equal amounts of FA, SCR-FA and HE-FA units and the deployments are presented at Figure 55. The differences in total NOx reduction (first and second stage combined), combined diesel economy (first and second stage) and total combined benefit (first and second stage combined) between the two cases is due to the differences in the technology deployed in the NNA counties. Case 1A has higher FA coverage and more units of SCR-FA and less units of HE-FA than that of Case 2A. The total NOx reduction (first and second stage combined) is higher for Case 1A because of having higher FA coverage and SCR units. The combined diesel economy (first and second stage) is higher Case 2A because of having more HE units and the combined total benefit (first and second stage combined) is higher for Case 1A than that of Case 2A.

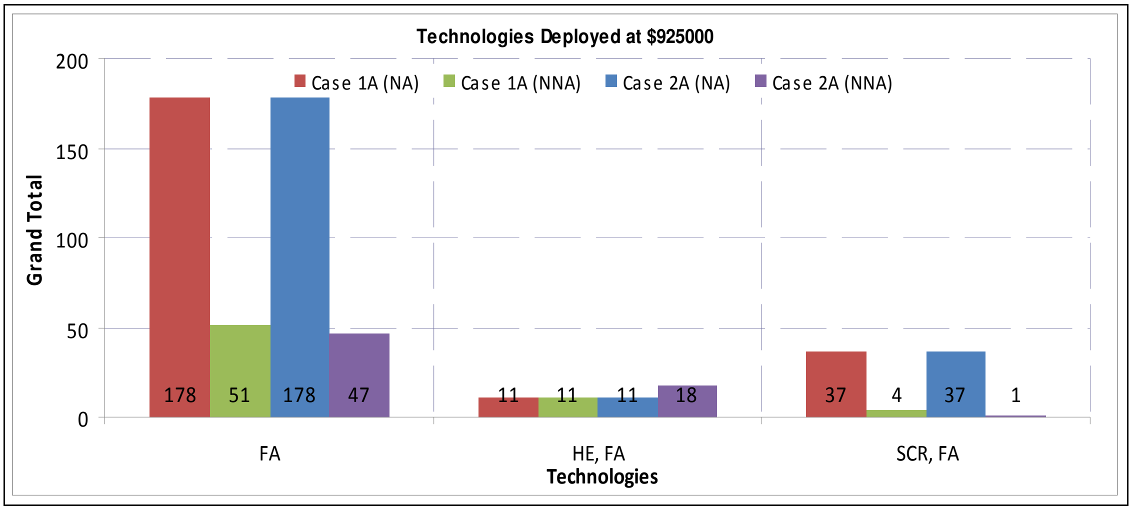

Figure 55. Technology Deployed at $925,000

Comparison between Case 1B and Case 2B

Comparison for NOx Reduction (first stage) and total benefit (first stage) between Case 1B and Case 2B follows a similar pattern like the comparison between Case 1A and Case 2A. In Case 2B deployment of FA in the NNA counties are considered in the first stage. Hence the both the graphs for Case 2B are elevated than that of Case 1B. The NOx reduction (first stage) and total benefit (first stage) for both cases are presented in Figures 56 and 57, respectively.

A comparison for total NOx reduction (first and second stage combined) between Case 1B and Case 2B reveals that Case 2B is greater or equal to Case 1B up to budget $800,000 with differences up to $ 4,207 . After that, Case 1B is greater or equal to Case 2B with differences up to $ 61. There are no differences between both the cases for rest of the budget amounts. The total NOx reduction (first and second stage combined) for both cases are presented in Figure 58.

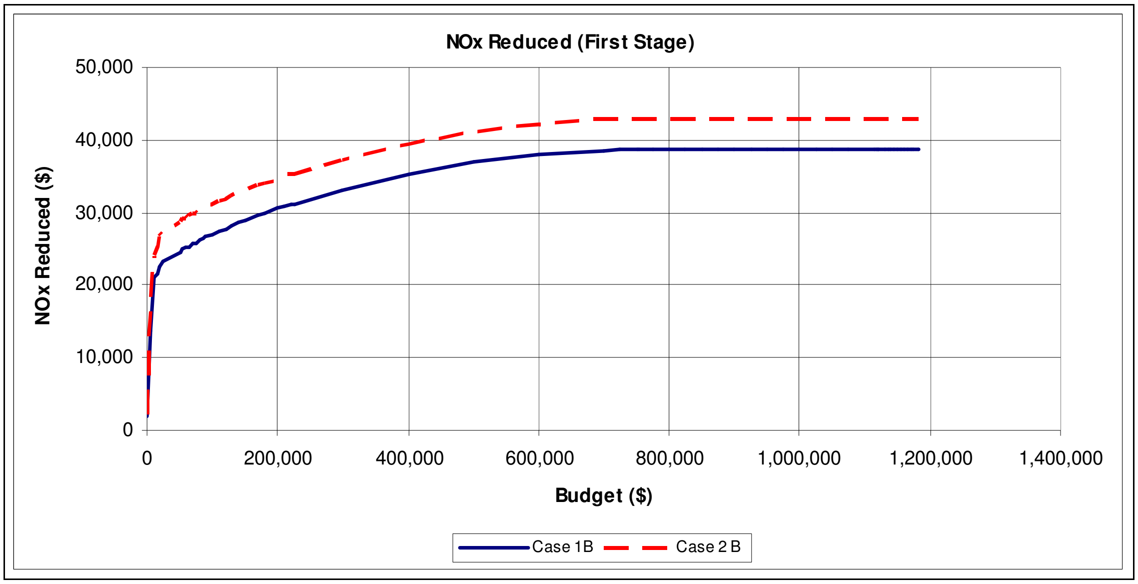

Figure 56. Total NOx Reduction at the First Stage (Case 1B vs Case 2B)

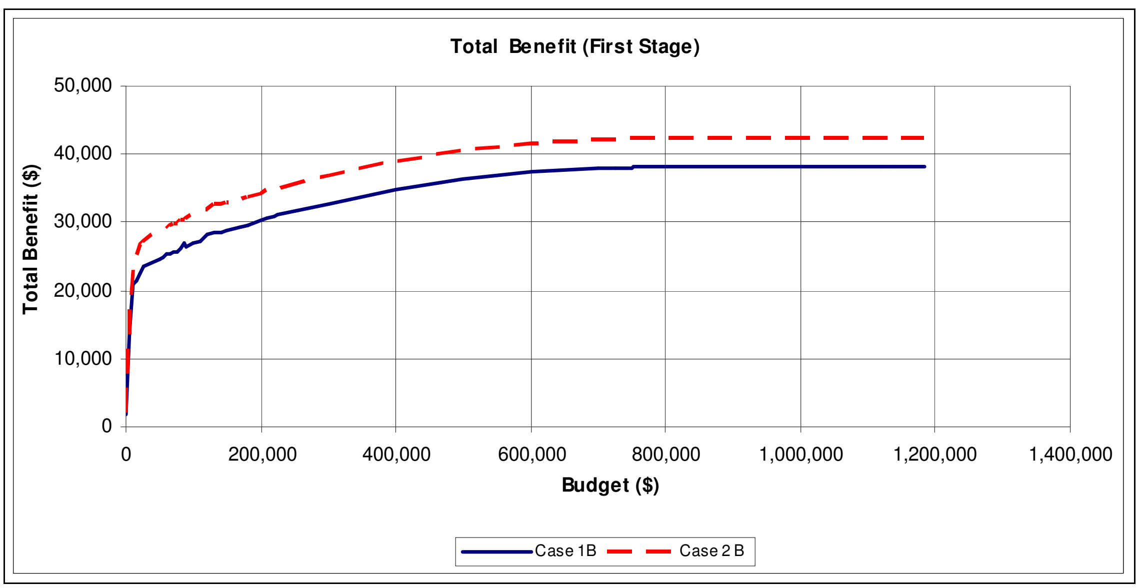

Figure 57. Total Benefit at the First Stage (Case 1B vs Case 2B)

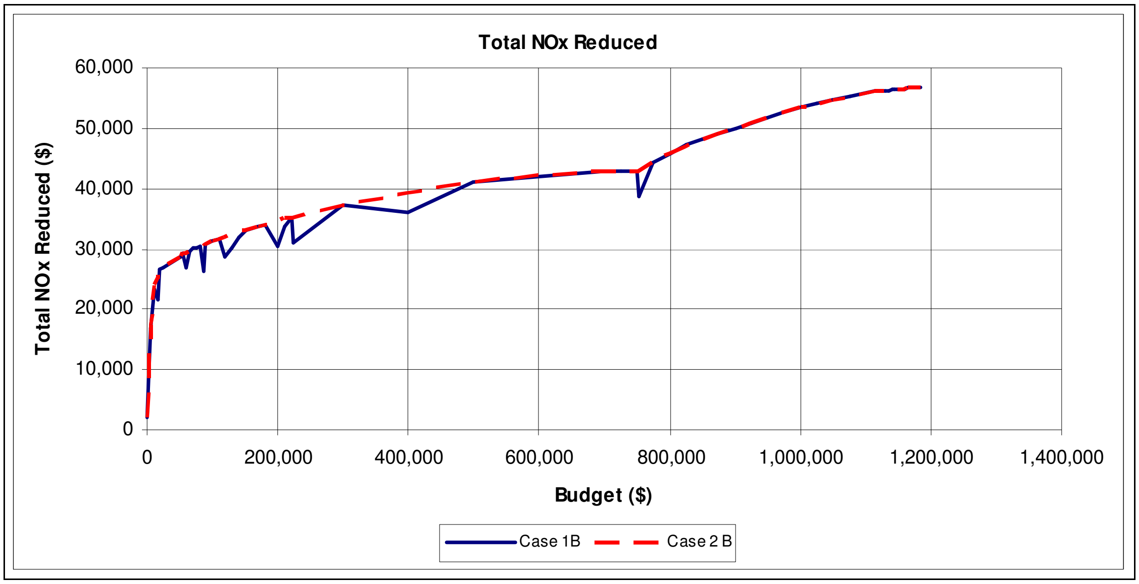

Figure 58. Total NOx Reduced at the First and Second Stage (Case 1B vs Case 2B)

The total combined benefit (first and second stage combined) for Case 2B, presented in Figure 59, is greater or equal to that of Case 1B for budgets up to $1,130,000 with differences up to 4207. At $1,135,000 Case 1B exceeds Case 2B. For rest of the budget amounts, there is no difference between both the cases.

From Figures 58 and 59, it can be observed that Case 2B (Method 2) prevents the drops occurred in Case 1B (Method 1) for variables such as total NOx reduction (first and second stage) and total combined benefit (first and second stage). The graphs for total NOx reduction (first and second stage) and total combined benefit (first and second stage) of Case 2B progress upward without any drop with further increasing the budget amounts.

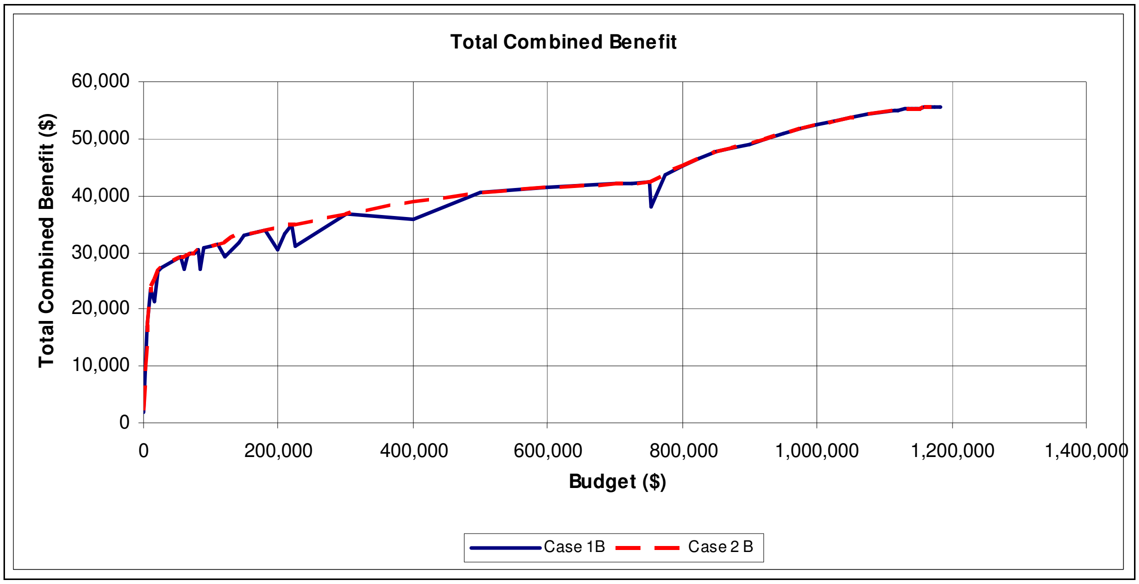

Figure 59. Total Combined Benefit at the First and Second Stage (Case 1B vs Case 2B)

Comparison between Case 1B and Case 2B at Given Budgets

The variation in NOx reductions, benefits, and deployment of technologies are analyzed in this section for Case 1B and Case 2B. Tables 12 and 13 present the NOx reductions, fuel economy, and benefits for Case 1B and Case 2B respectively at different budget levels. Figures 60 and 61 present the data of Tables 12 and 13, respectively. The technology deployed at different budget amounts are introduced graphically through Figures 62 to 66. All the deployments produce optimal results at a given budget.

Table 12. NOx Reductions and Benefits at Different Budget Amounts (Case 1B)

	Budget ($)				
	15000	120000	225000	752791	825000
NOx Reduced (1st Stage) ($)	21,467	27,745	31,124	38,732	38,732
Diesel Economy (1st Stage) ($)	0	493	54	-639	-639
Total Benefit (1st Stage) ($)	21,467	28,238	31,177	38,093	38,093
Total NOx Reduced (1st and 2nd Stage) ($)	21,467	28,609	31,124	38,732	47,147
Combined Diesel Economy (1st and 2nd Stage) ($)	0	493	54	-639	-767
Combined Total Benefit (1st and 2nd Stage) ($)	21,467	29,102	31,177	38,093	46,380

Table 13. NOx Reductions and Benefits at Different Budget Amounts (Case 2B)

	Budget ($)				
	15000	120000	225000	752791	825000
NOx Reduced (1st Stage)	25,224	31,911	35,292	42,939	42,949
Diesel Economy (1st Stage)	0	-31	-314	-639	-639
Total Benefit (1st Stage)	25,224	31,879	34,978	42,300	42,311
Total NOx Reduced (1st and 2nd Stage)	25,224	31,911	35,292	42,939	47,086
Combined Diesel Economy (1st and 2nd Stage)	0	-31	-314	-639	-519
Combined Total Benefit (1st and 2nd Stage)	25,224	31,879	34,978	42,300	46,566

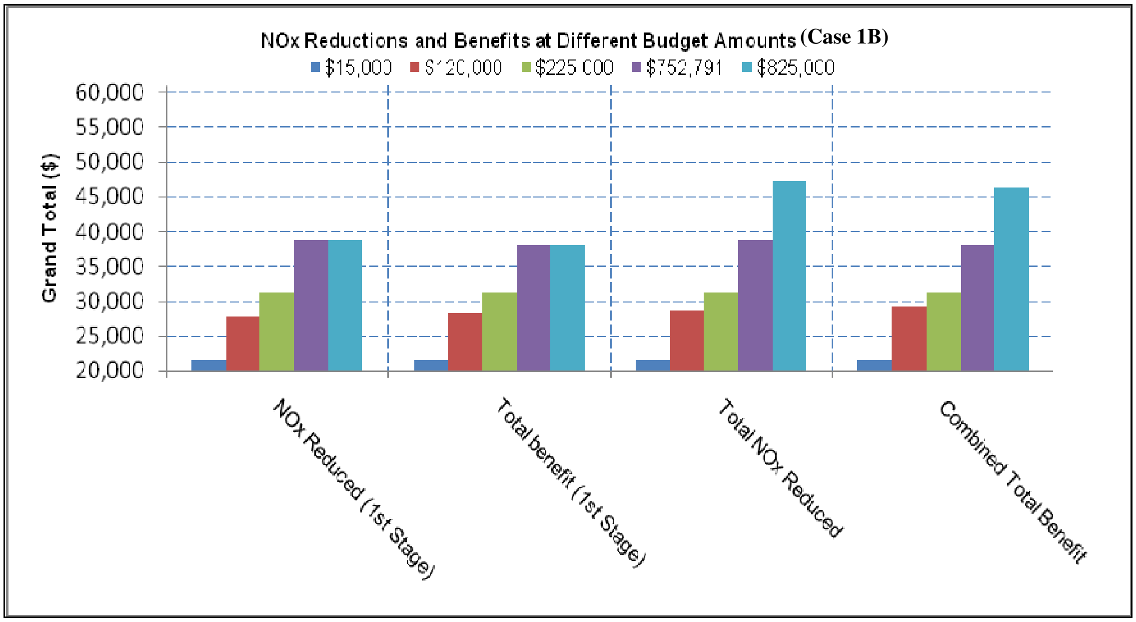

Figure 60. NOx Reductions and Benefits at Different Budget (Case 1B)

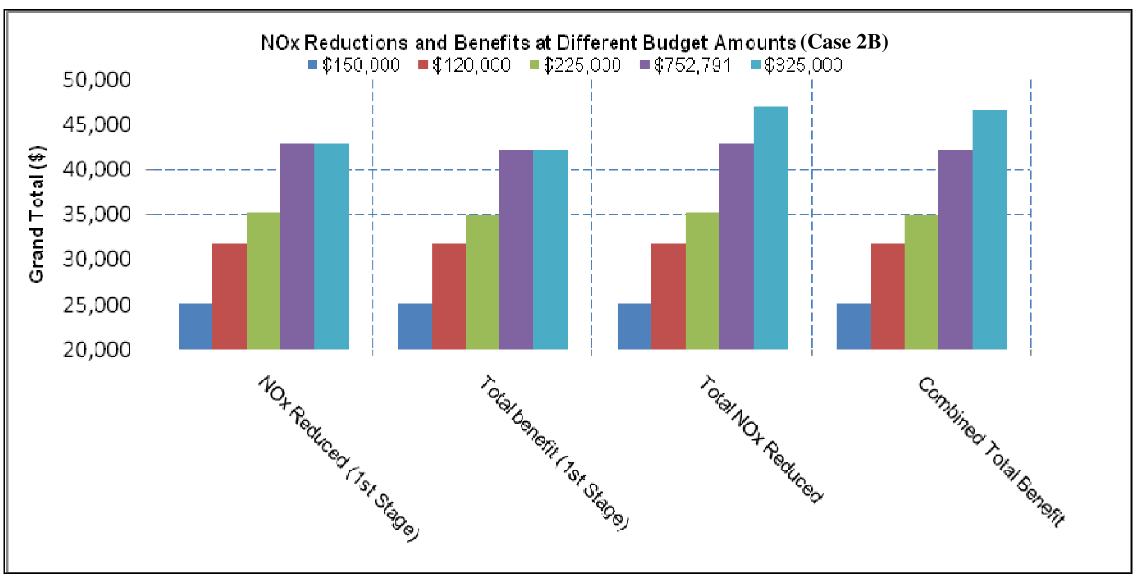

Figure 61. NOx Reductions and Benefits at Different Budget (Case 2B)

The FA coverage (both NA and NNA counties) for Case 2B, presented in Figure 62, is greater than that of Case 1B for budget $15,000. For both of the cases, sufficient money is not available to deploy SCR or HE units. Case 1B gives priority to NA counties over NNA counties. In Case 1B, Fort Worth district has very high budget allocation (about $6,125) compared to that of Case 2B (about $101) since in Case 2B considers also allocating budget in the NNA counties (Appendices D and F). Therefore, Fort Worth district has lesser share of budgets in Case 2B than Case 1B. For Case 1B, almost the entire budget is allocated in the NA counties and the remaining budget is not sufficient to deploy FA in the NNA counties. On the other hand, NNA counties have complete FA coverage in Case 2B. Therefore, both the total NOx reduction (first and second stage combined), and combined total benefit (first and second stage combined) are greater for Case 2B (Table 13) than that of Case 1B (Table 12).

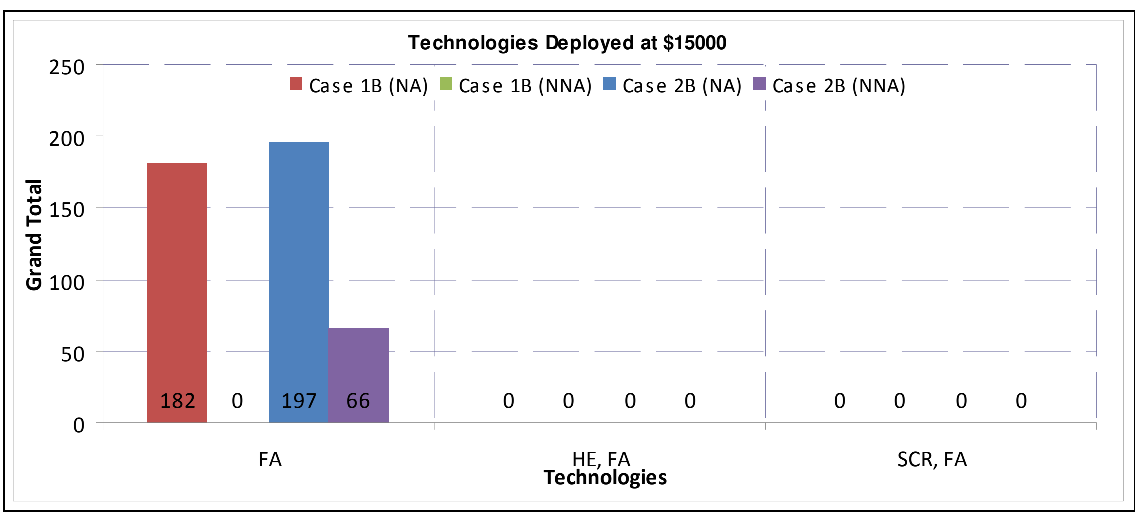

Figure 62. Technology Deployed at $15,000

Case 2B has higher FA coverage (both NA and NNA counties) and higher number of SCR units but lesser HE units than that of Case 1B at budget $120,000 and $225,000. As a result, the total NOx reduction (first and second stage combined) and the total combined benefit (first and second stage combined) is higher for Case 2B while the combined diesel benefit (first and second stage combined) is lower for Case 2B because of having less HE units. The deployment pattern for budget $120,000 and $225,000 are shown in Figures 63 and 64, respectively.

At budget $752,791, Case 1B has maximum possible units of SCR, HE and FA coverage in the NA counties and Case 1B allocates the entire budget in the NA counties only. Both the cases have equal units of SCR at this budget amount. However, Case 2B has higher FA coverage and less HE units than that of Case 1B.The technology deployment at this budget are presented in Figure 65. The total NOx reduction (first and second stage combined) and the total combined benefit (first and second stage combined) are greater for Case 2B than that of Case 1B. However, the combined diesel economy (first and second stage combined) for both cases is equal for each other.

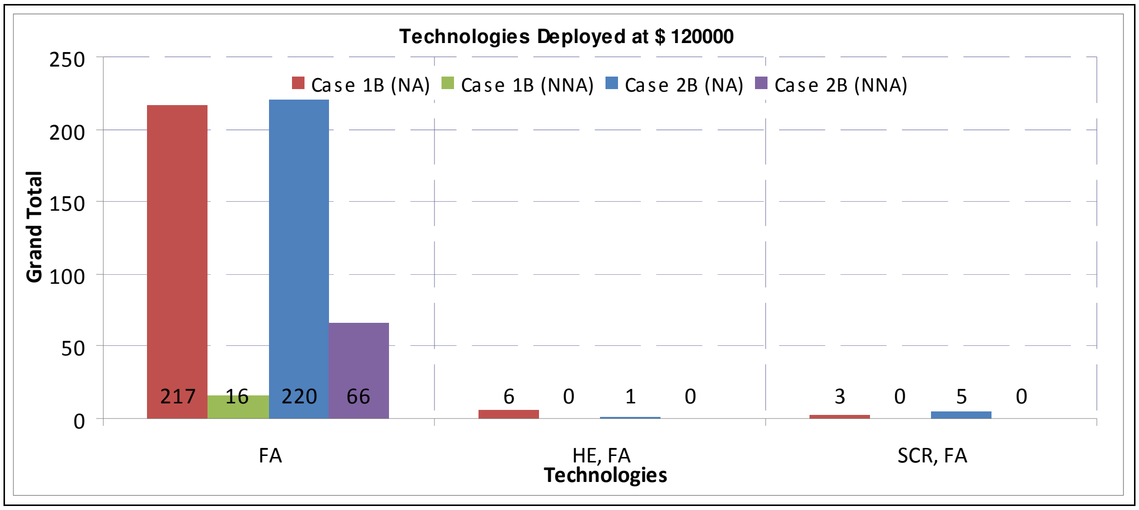

Figure 63. Technology Deployed at $120,000

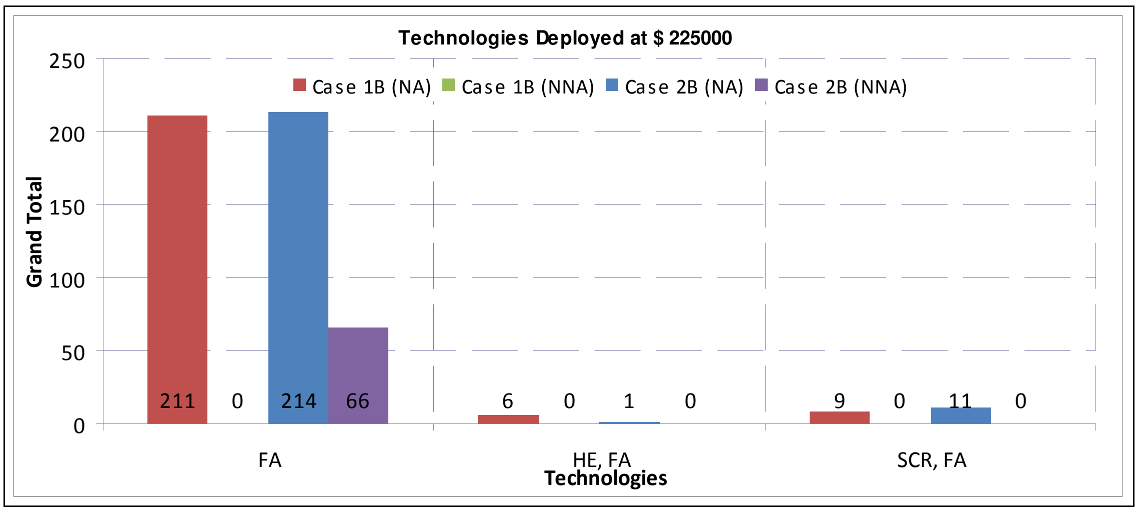

Figure 64. Technology Deployed at $225,000

At budget $825,000, the NA counties for both cases have the maximum possible units of HE, SCR and FA coverage (Figure 66). The differences in total NOx reduction (first and second stage combined) and combined total benefit (first and second stage combined) for both the cases are due to the differences among the technologies deployed for the respective cases. The NNA counties for Case 1B have higher FA coverage and SCR units while has lesser HE units than that of Case 2B. The total NOx reduction (first and second stage combined) is higher for Case 1B while the combined diesel economy (first and second stage combined) is lesser for Case 1B than that of Case 2B. Hence the combined total benefit (first and second stage combined) for Case 2B is higher than that of Case 1B.

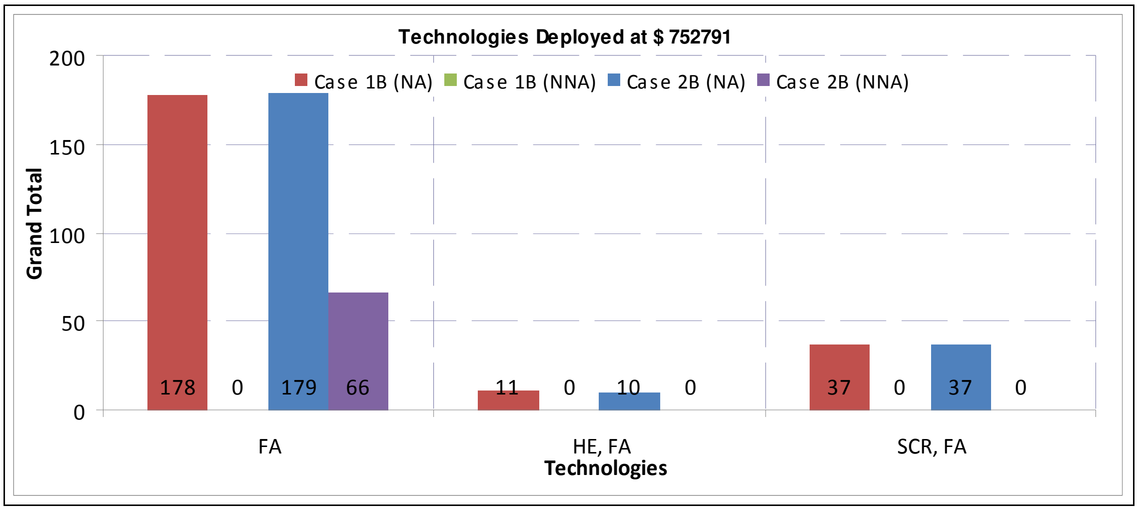

Figure 65. Technology Deployed at $752,791

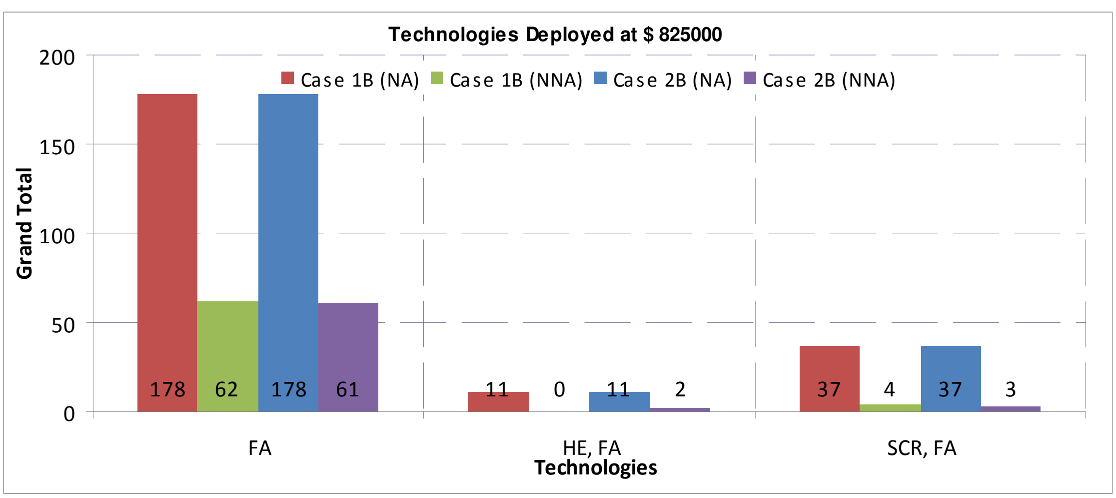

Figure 66. Technology Deployed at $825,000

Summary of Comparisons between Different Cases

Table 14 summarizes the comparisons between different cases considered in the study. The first split of a cell is for total NOx reduction (1st and 2nd Stage) and the second split is for total combined benefit (1st and 2nd Stage). They are presented below.

Table 14. Summary of Comparisons between Different Cases

	Case 1B	Case 2A	Case 2B
Case 1A	Case 1B>Case 1A (($775,000-$1,120,000) Δ_{max}= $608	Case 2A≥ Case 1A(up to $752,791) Δ_{max}= $4,207 Case 1A≥ Case 2A (from $850,000 onwards) Δ_{max}= $4,207 No difference for rest of the budget amounts.	
Case 1A	Case 1A>Case 1B ($200,000-$600,000) Δ_{max}= $4,440 Case 1A> Case 1B ($775,000-$1,120,000) Δ_{max}= $610	Case 1A≥ Case 2A ($500- $825,000) Δ_{max}= $4,207 Case 2A≥ Case 1A($850,000-$1,075,000) Δ_{max}= $90 No difference for rest of the budget amounts.	
Case 1B			Case 2B ≥Case 1B (up to $ 800,000) Δ_{max}= $4,207 Case 1B ≥Case 2B (For budget greater than $800,000) Δ_{max}= $61 No difference for rest of the budget amounts.
Case 1B			Case 2B ≥Case 1B (up to $1,130,000) Δ_{max}= $4,207 Case 1B >Case 2B (only at $1,135,000) No difference for rest of the budget amounts.
Case 2A			Case 2B > Case 2A ($45,000- $600,000; $775,000-$1,120,000) Δ_{max}= $867,$1,205 No difference for rest of the budget amounts
Case 2A			Case 2A> Case 2B ($45,000- $600,000; $775,000-$1,120,000) Δ_{max}= $732,$545 Case 2B> Case 2A ($975,000, exception) No difference for rest of the budget amounts.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The aim of this research was to develop a model for devising an optimal deployment plan of emission reduction technologies for TxDOT's construction equipment. Three different technologies were selected, namely HE, SCR and FA considering such factors as data availability, cost of technologies, emission reduction efficiencies. However, the model is quite general and will enable to include other technologies as and when necessary. Four categories of construction equipment such as, grader, loader, and excavator as well as other categories were selected. Grader, loader and excavator were selected for optimal deployment of HE, SCR and FA since those were the higher emitting equipment in Texas. The "other" category involved all the remaining equipment other than grader, loader and excavator and consideration of this category was required for estimating the FA requirement of a county.

Data regarding the three emission reduction technologies were obtained through communication with the respective vendors. Data involved cost of the technologies, emission reduction efficiencies, availability of the technologies, etc. TxDOT's preferences were also obtained regarding the deployment criteria and considered in developing the model and this was performed through consultation with TxDOT officials. TxDOT provided requirements regarding location preference for deploying the technologies and eligibility criteria for a piece of equipment to be retrofitted. All these criteria and data were considered while developing the model.

In this research two approaches: Method 1 and Method 2 were used for emission reduction employing a mix of technologies. In Method 1 three technologies, FA, HE and SCR were deployed in NA counties in the first stage and thereafter if there be any remaining budget, the same technologies were deployed in the NNA counties. With Method 1 two options were used: Method 1 with fuel economy constituting Case 1A and Method 1 without fuel economy as Case 1B.

In Method 2, FA, HE and SCR were deployed in NA counties together with FA in NNA counties in the first stage and in the second stage either SCR or HE was deployed on a given equipment subject to any left over budget after first stage deployment. Again, Method 2 with and without fuel economy options gave rise to Case 2A and Case 2B. These four cases/models were programmed as integer program using Visual C++ and ILOG CPLEX.

Method 1 was developed based on TxDOT's requirements. In Method 1, NA counties were given the first priority over NNA counties for deploying the emission reduction technologies (HE, SCR and FA), i.e. allocating the resources in the NA counties first and then, allocating the remaining resources in the NNA counties. But this pattern of deployment often caused the total NOx reduction and the total combined benefit to drop (e.g. see Figures 10 and Figure 11) with increasing budget amounts. Therefore, the concept of Method 2 was developed to overcome the situation faced in Method 1. In Method 2, FA deployment in the NNA counties was given equal priority as the deployment of technologies in NA counties, i.e. allocating the resources in the NA counties with FA deployment in NNA counties first and afterwards, allocating the remaining resources for SCR and HE deployment in the NNA counties. Comparing the graphs for Method 1 and Method 2 for total NOx reduction (first and second stage) and total combined benefit (first and second stage), it can be concluded that Method 2 prevents any drop in the graphs for these variables and the graphs for Method 2 progress upward without any drop with increasing the budget amounts.

Case 1A (Method 1 with fuel economy consideration), Case 1B (Method 1 without fuel economy consideration), Case 2A (Method 2 with fuel economy consideration), and Case 2B (Method 2 without fuel economy consideration) were the four alternatives considered in this research. It may be noted that Case 1A and Case 2A focused on maximizing the overall combined benefit (i.e. total NOx reduction and the combined diesel economy), while Case 1B and Case 2B focused on maximizing the total NOx reduction without considering fuel economy in the objective function.

The initial steep portion of the budget vs total benefit graphs for total NOx reduction and total combined benefit for all the four Cases indicate that the NOx reduction and benefit increases very sharply for slight increase in the investment at lower budget amounts. This conceivable as FA is inexpensive and at lower investment or budget levels, more expensive technologies like SCR or HE is not affordable, FA usage becomes beneficial by covering more counties thereby making both total NOx reduction benefit and total combined benefit higher. Thus, at lower investment, deploying FA is the most beneficial option. Also, it can be seen that the benefit cost ratio is poor except for lower budget amounts.

There were differences in the total NOx reduction and the total combined benefit among the cases described above. Often the difference was small or there is no difference at all. The difference ranges for overall NOx reduction and overall benefit were $7 to $ 4,207 and $1 to $ 4,440, respectively. The differences were primarily dependent upon the available budget, emissions, horsepower, usage hours, fuel consumption, location-wise distribution of the equipment, and the total number of NA and NNA counties.

The graphs for Case 1A (Method 1 with fuel economy consideration) and Case 1B (Method 1 without fuel economy consideration) for variables such as, NOx reduction (first stage) and total benefit (first stage) revealed that both of them progress in the same direction, i.e. both the graphs pointed in the same direction. Similarly, the graphs for Case 2A (Method 2 with fuel economy consideration) and Case 2B (Method 2 without fuel economy consideration) for variables such as NOx reduction (first stage), total benefit (first stage), overall NOx reduction and overall benefit traveled in the same direction. Thus, it can be concluded that both the objectives such as maximizing NOx reduction and maximizing fuel economy benefit are almost parallel. This fact causes the concerned graphs for Case 1A and Case 1B, and Case 2A and Case 2B to follow almost the similar path and direction.

This research developed the base for the models described herein. The models can be used as a tool by the decision maker to decide about the deployment preference of technologies. The models developed were demonstrated with three emission reduction technologies. However, the models are flexible enough to include other sets of technologies. For a given budget, the decision maker can run this model and obtain the results for total NOx reduction, combined diesel economy and total combined benefit. This will enable the decision maker to devise the required deployment plan given a choice of emission reduction technologies in the NA and NNA counties. The sensitivity analysis for total NOx reduction and total combined benefit can easily be performed by varying the budget amounts. By observing the pattern of the budget vs total benefit graphs, the decision maker can decide how much investment would be beneficial for him.

Future Research

There are some scopes for further research. These are briefly discussed below.

- Some constraints can be added in the model, such as, a minimum requirement of NOx level to be achieved while deploying the emission reduction technologies.
- The model can be expanded to include additional emission reduction technologies and other different categories of construction equipment.
- Some other options like engine repower, idle reduction can also be incorporated in the model as emission reduction strategy along with the emission reduction technologies.

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APPENDIX A

SAMPLE TxDOT's CONSTRUCTION EQUIPMENT DATABASE

Table A.1. Sample TxDOT's Construction Equipment Database with Emission Estimation

Equip. No	Class-Code	Equipment Type	Model-Year	Horsepower	Tier Classification	Relative Deterioration Factor	Load Factor Activity.dat	Activity hrs/yr Activity.dat
01108A	90030	Grader	1998	144	Tier 1	0.024	0.59	962
01078A	90030	Grader	1998	144	Tier 1	0.024	0.59	962
01036G	90020	Grader	2000	140	Tier 1	0.024	0.59	962
01041G	90030	Grader	2000	140	Tier 1	0.024	0.59	962
01135A	90030	Grader	1999	144	Tier 1	0.024	0.59	962
01039G	90030	Grader	2000	140	Tier 1	0.024	0.59	962

Table A.2. Sample TxDOT's Construction Equipment Database with Emission Estimation

Equip. No	Life Hrs Us.pop	DF_NOx	EFssNOx g/hp-hr	TAF(NOx)	EFadj_NOx (g/hp-hr)	Usage Hour	Emission NOx (gm)	County	Status
01108A	4667	1.09340	5.6523	0.95	5.87121777	248	209672.9289	Brazoria	NA
01078A	4667	1.09340	5.6523	0.95	5.87121777	281	237572.9557	Collin	NA
01036G	4667	1.09340	5.6523	0.95	5.87121777	81	66579.60948	Collin	NA
01041G	4667	1.09340	5.6523	0.95	5.87121777	156	128227.396	Collin	NA
01135A	4667	1.09340	5.6523	0.95	5.87121777	152	128509.2145	Dallas	NA
01039G	4667	1.09340	5.6523	0.95	5.87121777	44	36166.70145	Dallas	NA

APPENDIX B

QUESTIONNAIRE SURVEY

Sample Cover Letter and Questionnaire to TxDOT and Technology Vendors

Letter to TxDOT: Information Regarding Insight about Emission Reduction Needs

<Date>

<Title> <First Name> <Last Name>
<Company name>
<Company Address>

Dear Mr. /Ms. <Last Name>,

I am M. Ehsanul Bari, a graduate student in the Department of Civil Engineering at Texas A&M University (TAMU). I work as a Graduate Assistant Research (GAR) at the Center for Air Quality Studies under the supervision of Dr. Joe Zietsman. Currently, I am working in Texas Transportation Institute on the project for Texas Department of Transportation (TxDOT) titled "Characterization of In-Use Emissions from Non-Road Equipment (RMC 0-5955)".

I am working on a thesis which is related to the project (RMC 0-5955). My thesis topic is "Optimal Deployment Plan of Emission Reduction Technologies for TxDOT Construction Equipment". Dr. Zietsman is also a member of my thesis committee. He advised me to communicate with you in order to gain some insight about TxDOT's needs with regards to emissions reduction and some related topics. The aim of my thesis work is to develop an optimization model that will help to deploy emission reduction technologies optimally for TxDOT's construction equipment. Therefore, I need to understand TxDOT's view of emissions from their construction equipment fleet.

I have prepared a short questionnaire and attached it with this email. It would be highly appreciated if you could have a look at the questions and provide answers to them. Please let me know when would be a good time for me to phone you to discuss these questions.

Sincerely

M. Ehsanul Bari
Graduate Student and Graduate Assistant Research (GAR)
Center for Air Quality Studies, Texas Transportation Institute
Texas A&M University

Questionnaire to TxDOT: Information Regarding Insight about Emission Reduction Needs

1. Four districts of Texas have 20 nonattainement counties and 3 near nonattainment counties. The districts with the nonattainment and near nonattainment counties are as follows.

   <u>Nonattainment District (counties)</u>
   Houston District (Brazoria, Fort Bend, Galveston, Harris, Montgomery, Waller)
   Dallas District (Collin, Dallas, Denton, Ellis, Kaufman, Rockwall)
   Fort Worth District (Johnson, Parker, Tarrant)
   Beaumont District (Chambers, Hardin, Jefferson, Liberty, Orange)
   <u>Near nonattainment District (counties)</u>
   Corpus Christi District (Nueces, San Patricio)
   Youkum District (Victoria)

   a) Is there any location (District) preference where TxDOT wants to spend more money for reducing emissions such as Houston vs. Dallas District? Please mention what the preferences are.
   b) What are the reasons for these preferences?

2. Does TxDOT have a fixed budget for deploying emissions reduction equipment? If so, how much?

3. Is there any specific target for reducing emissions?

4. Does TxDOT have a value per ton of emissions reduced? If so, how much for each one (NOx, PM, $PM_{2.5}$, CO_2, CO, HC)?

5. What motivates TxDOT to reduce emissions?

Letter to TxDOT: Information Regarding Construction Equipment Fleet

<Date>

<Title> <First Name> <Last Name>
<Company name>
<Company Address>

Dear Mr. /Ms. <Last Name>,

I am M. Ehsanul Bari, a graduate student in the Department of Civil Engineering at Texas A&M University. I work as a Graduate Assistant Research at the Center for Air Quality Studies under the supervision of Dr. Joe Zietsman. Currently, I am working in Texas Transportation Institute on the project for Texas Department of Transportation (TxDOT) titled "Characterization of In-Use Emissions from Non-Road Equipment (RMC 0-5955)".

I am working on a thesis which is related to the project (RMC 0-5955). My thesis topic is "Optimal Deployment Plan of Emission Reduction Technologies for TxDOT Construction Equipment". Dr. Zietsman is also a member of my thesis committee. He advised me to communicate with you in order to gain some insight about TxDOT's construction equipment fleet and their needs with regards to emissions reduction and some related topics. The aim of my thesis work is to develop an optimization model that will help to deploy emission reduction technologies optimally for TxDOT's construction equipment. Therefore, I need to know some information regarding the construction equipment fleet.

I have prepared a short questionnaire and attached it with this email. It would be highly appreciated if you could have a look at the questions and provide answers to them. Please let me know when would be a good time for me to phone you to discuss these questions.

Sincerely

M. Ehsanul Bari
Graduate Student and Graduate Assistant Research (GAR)
Center for Air Quality Studies
Texas Transportation Institute
Texas A&M University

Questionnaire to TxDOT: Information Regarding Construction Equipment Fleet

1. What is the average life of a grader, loader and excavator?

2. What are the criteria TxDOT uses for retiring their equipment?

3. Is TxDOT interested in improving fuel efficiency? If so, how does this importance rank versus pollutant emissions?

4. Is there any age requirement/restriction for equipment to be eligible for retrofitting, such as it must have at least 5 years of remaining useful life to be retrofitted?

5. Is there any target for TxDOT in terms of reducing emissions in their non-road fleet e.g. x% NOx reduction per year, y% $PM_{2.5}$ reduction per year?

6. What categories of equipment are typically targeted first for emissions reductions?

7. Please, provide us with any additional information that might be helpful for formulating the optimization model.

Letter to Technology Vendor: Information Regarding the Emission Reduction Technology

<Date>

<Title> <First Name> <Last Name>
<Company name>
<Company Address>

Dear Mr. /Ms. <Last Name>,

I am M. Ehsanul Bari, a graduate student in the Department of Civil Engineering at Texas A&M University. I am working as a Graduate Assistant Research at the Center for Air Quality Studies, Texas Transportation Institute (TTI) under the supervision of Dr. Josias Zietsman, Center Director. Currently, I am working in the project for Texas Department of Transportation (TxDOT) titled "Characterization of In-Use Emissions from Non-Road Equipment (RMC 0-5955)".

I am working on my thesis which is related to the project (RMC 0-5955). My thesis topic is "Optimal Deployment Plan of Emission Reduction Technologies for TxDOT Construction Equipment". As a part of my work at TTI, one of my tasks is to propose a deployment plan of emission reduction technologies for the construction equipment of TxDOT. Therefore, I need to know some information regarding the emission reduction technology provided by your company.

I have prepared a questionnaire and I am attaching it with this email. It would be highly appreciated if you could have a look at the questions and provide answers to them.

I look forward to hearing from you at your earliest convenience. Thank you very much.

With kindest regards

M. Ehsanul Bari
Graduate Student and Graduate Assistant Research (GAR)
Center for Air Quality Studies
Texas Transportation Institute
Texas A&M University

Questionnaire for Hydrogen Enrichment (HE) System

1. What are the different categories of operation and maintenance costs of the Hydrogen enrichment (HE) system?
2. Are there any requirements for using HE on the equipment (e.g. providing extra battery to power the HE unit)? Please mention, if any.
3. What method was followed for estimating the emission reduction efficiency of HE? Was any test performed for it? If not, what is the source of this information?
4. Does HE increase/decrease the fuel efficiency? If so, by how much?
5. Is it possible to remove the entire HE unit from a piece of equipment and install it to another piece of equipment? If possible, what will be the cost for that?
6. Suppose a fuel additive has 5.8% NOx reduction efficiency and the fuel additive is used on an equipment/vehicle and Hydrogen Enrichment System is installed on that equipment/vehicle. Will there be any additional NOx reduction benefit? If so, how much will be the combined NOx reduction efficiency?

Table B.1. Information Regarding HE System

Horsepower	Tier	Is it Available	Purchasing Cost ($)	Installation Cost ($)	Operation Cost($/hr)	Maintenance Cost ($/hr)	Other Cost ($/hr)	Life (years)	Emission Reduction Efficiency (%)				
									NOx	PM	$PM_{2.5}$	CO	HC
<=100	All												
	Base												
	Tier 0												
	Tier 1												
	Tier 2												
	Tier 3												
101~200	All												
	Base												
	Tier 0												
	Tier 1												
	Tier 2												
	Tier 3												
So on	All												
	Base												
	Tier 0												
	Tier 3												

Questionnaire for Selective Catalytic Reduction (SCR) System

1. What are the different categories of operation and maintenance costs?
2. What is the cost associated with urea tank and urea usage?
3. Are there any requirements of using a SCR unit on a piece of equipment (e.g. installing a new kit for the SCR or using extra battery to run the unit, etc)? Please mention, if any.
4. What method was followed for estimating the emission reduction efficiency of SCR? Was any test performed for it? If not, what is the source of this information?
5. Does SCR increase/decrease the fuel efficiency? If so, by how much?
6. Does the SCR unit have ammonia slippage? If so, how is it dealt with?
7. Is it possible to remove the entire SCR unit from a piece of equipment and install it to another piece of equipment? If possible, what will be the cost for that?

Table B.2. Information Regarding SCR System

Horsepower	Tier	Is it Available	Purchasing Cost ($)	Installation Cost ($)	Operation Cost($/hr)	Maintenance Cost ($/hr)	Other Cost ($/hr)	Life (years)	Emission Reduction Efficiency (%)				
									NOx	PM	$PM_{2.5}$	CO	HC
<=100	All												
	Base												
	Tier 0												
	Tier 1												
	Tier 2												
	Tier 3												
101~200	All												
	Base												
	Tier 0												
	Tier 1												
	Tier 2												
	Tier 3												
So on	All												
	Base												
	Tier 0												
	Tier 3												

Questionnaire for Fuel Additive (FA)

1. What is the mixing ratio of the Fuel Additive (FA) with diesel fuel?
    - Are the dosage rates different with respect to different categories of equipment (grader, rubber tire loader and excavator)?
    - Are the dosage rates different with respect to different ranges of horse power of the equipment?
2. What method was followed for estimating the emission reduction efficiency of FA? Was any test performed for it? If not, what is the source of this information?
3. Does FA increase/decrease the fuel efficiency? If so, by how much?

Table B.3. Information Regarding FA

Horsepower	Tier	Is it Available	Purchasing Cost ($)	Emission Reduction Efficiency (%)				
				NOx	PM	$PM_{2.5}$	CO	HC
<=100	All							
	Base							
	Tier 0							
	Tier 1							
	Tier 2							
	Tier 3							
101~200	All							
	Base							
	Tier 0							
	Tier 1							
	Tier 2							
	Tier 3							
So on	All							
	Base							
	Tier 0							
	Tier 3							

APPENDIX C

DETAILED INFORMATION REGARDING DEPLOYMENT OF TECHNOLOGIES (CASE 1A)

Case 1A: Method 1 with Consideration of Fuel Economy

Table C.1. Budget Allocation and Technology Deployment at Budget $110,000

Budget($)	Remaining($)				
110,000	14.38				
Districts	Cost Allocation	FA	HE-FA	SCR-FA	
Houston	43,885.5	31	3	1	
Dallas	16,393.5	64	1	0	
F. Worth	23,202.2	37	2	0	
Beaumont	25,847.9	30	3	0	
Austin	656.6	54	0	0	
C. Christi	0	0	0	0	
Yoakum	0	0	0	0	
San Antonio	0	0	0	0	
	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	0	59	4	0
Loader	109	0	105	4	0
Excavator	29	0	27	1	1
Others	25	0	25	0	0
	NA	NNA			
HE	0	0			
SCR	0	0			
FA	216	0			
HE-FA	9	0			
SCR-FA	1	0			

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
7.48068	7.48068	126.965	5.8919	5.8919	963.071	0

Table C.2. Budget Allocation and Technology Deployment at Budget $170,000

Budget($)	Remaining($)
170,000	0.38

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	61,399.50	30	3	2
Dallas	33,393.50	62	3	0
F. Worth	48,702.20	34	5	0
Beaumont	25,847.90	30	3	0
Austin	656.55	54	0	0
C. Christi	0	0	0	0
Yoakum	0	0	0	0
San Antonio	0	0	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	0	57	5	1
Loader	109	0	103	6	0
Excavator	29	0	25	3	1
Others	25	0	25	0	0

	NA	NNA
FA	210	0
HE-FA	14	0
SCR-FA	2	0

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
7.92686	7.92686	126.965	6.24332	6.24332	1,104.74	0

Table C.3. Budget Allocation and Technology Deployment at Budget $250,000

Budget($)	Remaining($)
250,000	1.38

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	61,399.50	30	3	2
Dallas	77,289.50	60	2	3
F. Worth	66,531.20	34	3	2
Beaumont	44,121.90	30	1	2
Austin	656.55	54	0	0
C. Christi	0	0	0	0
Yoakum	0	0	0	0
San Antonio	0	0	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	0	57	3	3
Loader	109	0	102	4	3
Excavator	29	0	24	2	3
Others	25	0	25	0	0

	NA	NNA
FA	208	0
HE-FA	9	0
SCR-FA	9	0

NOx Reduced (1^{st} Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1^{st} Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
8.67434	8.67434	126.965	6.83205	6.83205	386.37	0

Table C.4. Budget Allocation and Technology Deployment at Budget $400,000

Budget($)	Remaining($)
400,000	24.82

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	105,326	28	2	5
Dallas	103,521	59	1	5
F. Worth	101,980	33	1	5
Beaumont	70,461.90	29	0	4
Austin	18,009.60	53	0	1
C. Christi	0	0	0	0
Yoakum	155.83	7	0	0
San Antonio	520.73	28	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	12	67	3	5
Loader	109	17	116	0	10
Excavator	29	3	26	1	5
Others	25	3	28	0	0

	NA	NNA
FA	202	35
HE-FA	4	0
SCR-FA	20	0

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
9.70	10.38	126.97	7.64	8.18	-233.66	0

Table C.5. Budget Allocation and Technology Deployment at Budget $752,791

Budget($)	Remaining($)
752,791	0.38

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	192,128	23	2	10
Dallas	267,020	48	4	13
F. Worth	128,103	32	0	7
Beaumont	130,231	23	5	5
Austin	35,308.6	52	0	2
C. Christi	0	0	0	0
Yoakum	0	0	0	0
San Antonio	0	0	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	0	49	0	14
Loader	109	0	82	10	17
Excavator	29	0	22	1	6
Others	25	0	25	0	0

	NA	NNA
FA	178	0
HE-FA	11	0
SCR-FA	37	0

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
10.6846	10.6846	126.965	8.41534	8.41534	-638.68	0

Table C.6 Budget Allocation and Technology Deployment at Budget $925,000

Budget($)	Remaining($)
925,000	6,719.86

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	192,128	23	2	10
Dallas	267,020	48	4	13
F. Worth	128,103	32	0	7
Beaumont	130,231	23	5	5
Austin	35,308.6	52	0	2
C. Christi	60,654.6	13	5	1
Yoakum	26,298.8	5	1	1
San Antonio	78,536.1	33	5	2

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	63	6	15
Loader	109	32	110	13	18
Excavator	29	6	24	3	8
Others	25	7	32	0	0

	NA	NNA
FA	178	51
HE-FA	11	11
SCR-FA	37	4

NOx Reduced (1^{st} Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1^{st} Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
10.6846	13.9017	126.965	8.41534	10.9492	-638.68	643.68

Table C.7. Budget Allocation and Technology Deployment at Budget $1,150,000

Budget($)	Remaining($)					
1,150,000	2,262.86					
Districts	Cost Allocation	FA	HE-FA	SCR-FA		
Houston	192,128	23	2	10		
Dallas	267,020	48	4	13		
F. Worth	128,103	32	0	7		
Beaumont	130,231	23	5	5		
Austin	35,308.6	52	0	2		
C. Christi	12,3030	12	0	7		
Yoakum	70,267.8	3	0	4		
San Antonio	201,649	28	1	11		
	NA	NNA	FA	HE-FA	SCR-FA	
Grader	63	21	59	0	25	
Loader	109	32	106	11	24	
Excavator	29	6	24	1	10	
Others	25	7	32	0	0	
	NA	NNA				
HE	0	0				
SCR	0	0				
FA	178	43				
HE-FA	11	1				
SCR-FA	37	22				
NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
10.6846	15.589	126.965	8.41534	12.2781	-638.68	-442.71

APPENDIX D

DETAILED INFORMATION REGARDING DEPLOYMENT OF TECHNOLOGIES (CASE 1B)

Case 1B: Method 1 without Consideration of Fuel Economy

Table D.1. Budget Allocation and Technology Deployment at Budget $15,000

Budget($)	Remaining($)
15,000	5.96

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	249.68	24	0	0
Dallas	7,697.17	44	0	0
F. Worth	6,124.80	32	0	0
Beaumont	265.83	28	0	0
Austin	656.55	54	0	0
C. Christi	0	0	0	0
Yoakum	0	0	0	0
San Antonio	0	0	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	50	0	50	0	0
Loader	89	0	89	0	0
Excavator	25	0	25	0	0
Others	18	0	18	0	0

	NA	NNA
FA	182	0
HE-FA	0	0
SCR-FA	0	0

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
5.9219	5.9219	126.965	4.66418	4.66418	0	0

Table D.2 Budget Allocation and Technology Deployment at Budget $110,000

Budget($)	Remaining($)
110,000	4,801.86

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	35,899.5	33	0	2
Dallas	25,593.5	64	0	1
F. Worth	6,202.2	39	0	0
Beaumont	35,621.9	31	0	2
Austin	656.55	54	0	0
C. Christi	362.56	19	0	0
Yoakum	155.83	7	0	0
San Antonio	706.14	40	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	82	0	2
Loader	109	32	139	0	2
Excavator	29	6	34	0	1
Others	25	7	32	0	0

	NA	NNA
FA	221	66
HE-FA	0	0
SCR-FA	5	0

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
7.54455	8.70807	126.965	5.94221	6.85861	-166.82	0

Table D.3. Budget Allocation and Technology Deployment at Budget $120,000

Budget($)	Remaining($)
120,000	0.20

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	35,385.5	32	2	1
Dallas	25,593.5	64	0	1
F. Worth	23,202.2	37	2	0
Beaumont	34,930.9	30	2	1
Austin	656.55	54	0	0
C. Christi	74.67	6	0	0
Yoakum	0	0	0	0
San Antonio	156.52	10	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	6	65	3	1
Loader	109	6	111	3	1
Excavator	29	1	29	0	1
Others	25	3	28	0	0

	NA	NNA
FA	217	16
HE-FA	6	0
SCR-FA	3	0

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
7.65381	7.89218	126.965	6.02826	6.216	493.322	0

Table D.4. Budget Allocation and Technology Deployment at Budget $170,000

Budget($)	Remaining($)
170,000	3,605.86

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	53,440.5	32	0	3
Dallas	25,593.5	64	0	1
F. Worth	41,357.2	37	0	2
Beaumont	44,121.9	30	1	2
Austin	656.55	54	0	0
C. Christi	362.56	19	0	0
Yoakum	155.83	7	0	0
San Antonio	706.14	40	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	80	1	3
Loader	109	32	137	0	4
Excavator	29	6	34	0	1
Others	25	7	32	0	0

	NA	NNA
FA	217	66
HE-FA	1	0
SCR-FA	8	0

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
8.156	9.31952	126.965	6.42379	7.3402	-171.94	0

Table D.5. Budget Allocation and Technology Deployment at Budget $225,000

Budget($)	Remaining($)					
225,000	53.38					
Districts	Cost Allocation	FA	HE-FA	SCR-FA		
Houston	70,440.5	30	2	3		
Dallas	34,093.5	63	1	1		
F. Worth	75,634.2	34	2	3		
Beaumont	44,121.9	30	1	2		
Austin	656.55	54	0	0		
C. Christi	0	0	0	0		
Yoakum	0	0	0	0		
San Antonio	0	0	0	0		
	NA	NNA	FA	HE-FA	SCR-FA	
Grader	63	0	58	2	3	
Loader	109	0	103	2	4	
Excavator	29	0	25	2	2	
Others	25	0	25	0	0	
	NA	NNA				
FA	211	0				
HE-FA	6	0				
SCR-FA	9	0				
NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
8.58586	8.58586	126.965	6.76236	6.76236	53.71	0

Table D.6. Budget Allocation and Technology Deployment at Budget $400,000

Budget($)	Remaining($)
400,000	10.15

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	114,304	28	1	6
Dallas	103,521	59	1	5
F. Worth	93,480.2	34	0	5
Beaumont	70,461.9	29	0	4
Austin	18,009.6	53	0	1
C. Christi	0	0	0	0
Yoakum	155.83	7	0	0
San Antonio	57.41	5	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	5	61	2	5
Loader	109	4	103	0	10
Excavator	29	1	24	0	6
Others	25	2	27	0	0

	NA	NNA
FA	203	12
HE-FA	2	0
SCR-FA	21	0

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
9.73	9.97	126.97	7.66	7.85	-368.49	0.00

Table D.7. Budget Allocation and Technology Deployment at Budget $752,791

Budget($)	Remaining($)				
752,791	0.38				
Districts	Cost Allocation	FA	HE-FA	SCR-FA	
Houston	192,128	23	2	10	
Dallas	267,020	48	4	13	
F. Worth	128,103	32	0	7	
Beaumont	130,231	23	5	5	
Austin	35,308.6	52	0	2	
C. Christi	0	0	0	0	
Yoakum	0	0	0	0	
San Antonio	0	0	0	0	
	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	0	49	0	14
Loader	109	0	82	10	17
Excavator	29	0	22	1	6
Others	25	0	25	0	0
	NA	NNA			
FA	178	0			
HE-FA	11	0			
SCR-FA	37	0			

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
10.6846	10.6846	126.965	8.41534	8.41534	-638.68	0

Table D.8. Budget Allocation and Technology Deployment at Budget $825,000

Budget($)	Remaining($)
825,000	219.86

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	192,128	23	2	10
Dallas	267,020	48	4	13
F. Worth	128,103	32	0	7
Beaumont	130,231	23	5	5
Austin	35,308.6	52	0	2
C. Christi	18,154.6	18	0	1
Yoakum	17,798.8	6	0	1
San Antonio	36,036.1	38	0	2

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	69	0	15
Loader	109	32	113	10	18
Excavator	29	6	26	1	8
Others	25	7	32	0	0

	NA	NNA
FA	178	62
HE-FA	11	0
SCR-FA	37	4

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
10.6846	13.0061	126.965	8.41534	10.2438	-638.68	-128.24

Table D.9. Budget Allocation and Technology Deployment at Budget $1,150,000

Budget($)	Remaining($)
1,150,000	2,262.86

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	192,128	23	2	10
Dallas	267,020	48	4	13
F. Worth	128,103	32	0	7
Beaumont	130,231	23	5	5
Austin	35,308.6	52	0	2
C. Christi	123,030	12	0	7
Yoakum	70,267.8	3	0	4
San Antonio	201,649	28	1	11

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	59	0	25
Loader	109	32	106	11	24
Excavator	29	6	24	1	10
Others	25	7	32	0	0

	NA	NNA
FA	178	43
HE-FA	11	1
SCR-FA	37	22

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
10.6846	15.589	126.965	8.41534	12.2781	-638.68	-442.71

APPENDIX E

DETAILED INFORMATION REGARDING DEPLOYMENT OF TECHNOLOGIES (CASE 2A)

Case 2A: Method 2 with Consideration of Fuel Economy

Table E.1. Budget Allocation and Technology Deployment at Budget $130,000

Budget($)	Remaining($)
130,000	1,206.86

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	52,385.5	30	4	1
Dallas	16,393.5	64	1	0
F. Worth	23,202.2	37	2	0
Beaumont	34,930.9	30	2	1
Austin	656.55	54	0	0
C. Christi	362.56	19	0	0
Yoakum	155.83	7	0	0
San Antonio	706.14	40	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	80	3	1
Loader	109	32	137	4	0
Excavator	29	6	32	2	1
Others	25	7	32	0	0

	NA	NNA
FA	215	66
HE-FA	9	0
SCR-FA	2	0

NOx Reduced (1^{st} Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1^{st} Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
8.82745	8.82745	126.965	6.95264	6.95264	861.90	0

Table E.2. Budget Allocation and Technology Deployment at Budget $170,000

Budget($)	Remaining($)				
170,000	6,001.86				
Districts	Cost Allocation	FA	HE-FA	SCR-FA	
Houston	61,399.5	30	3	2	
Dallas	24,893.5	63	2	0	
F. Worth	31,702.2	36	3	0	
Beaumont	44,121.9	30	1	2	
Austin	656.55	54	0	0	
C. Christi	362.56	19	0	0	
Yoakum	155.83	7	0	0	
San Antonio	706.14	40	0	0	
	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	78	4	2
Loader	109	32	137	3	1
Excavator	29	6	32	2	1
Others	25	7	32	0	0
	NA	NNA			
HE	0	0			
SCR	0	0			
FA	213	66			
HE-FA	9	0			
SCR-FA	4	0			

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
9.1549	9.1549	126.965	7.21054	7.21054	697.00	0

Table E.3. Budget Allocation and Technology Deployment at Budget $250,000

Budget($)	Remaining($)
250,000	28.8602

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	69,899.5	29	4	2
Dallas	68,089.5	60	3	2
F. Worth	57,479.2	34	4	1
Beaumont	44,121.9	30	1	2
Austin	9,156.55	53	1	0
C. Christi	362.56	19	0	0
Yoakum	155.83	7	0	0
San Antonio	706.14	40	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	78	4	2
Loader	109	32	132	7	2
Excavator	29	6	30	2	3
Others	25	7	32	0	0

	NA	NNA
FA	206	66
HE-FA	13	0
SCR-FA	7	0

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
9.72981	9.72981	126.965	7.66335	7.66335	707.26	0

Table E.4. Budget Allocation and Technology Deployment at Budget $400,000

Budget($)	Remaining($)					
400,000	0.86					
Districts	Cost Allocation	FA	HE-FA	SCR-FA		
Houston	104,802	27	4	4		
Dallas	103,521	59	1	5		
F. Worth	101,980	33	1	5		
Beaumont	70,461.9	29	0	4		
Austin	18,009.6	53	0	1		
C. Christi	362.56	19	0	0		
Yoakum	155.83	7	0	0		
San Antonio	706.14	40	0	0		
	NA	NNA	FA	HE-FA	SCR-FA	
Grader	63	21	75	4	5	
Loader	109	32	131	0	10	
Excavator	29	6	29	2	4	
Others	25	7	32	0	0	
	NA	NNA				
FA	201	66				
HE-FA	6	0				
SCR-FA	19	0				
NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
10.8301	10.8301	126.965	8.52993	8.52993	-122.16	0

Table E.5. Budget Allocation and Technology Deployment at Budget $600,000

Budget($)	Remaining($)
600,000	247.86

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	175,128	25	0	10
Dallas	181,254	54	2	9
F. Worth	119,375	32	1	6
Beaumont	87,461.9	27	2	4
Austin	35,308.6	52	0	2
C. Christi	362.56	19	0	0
Yoakum	155.83	7	0	0
San Antonio	706.14	40	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	71	1	12
Loader	109	32	125	3	13
Excavator	29	6	28	1	6
Others	25	7	32	0	0

	NA	NNA
FA	190	66
HE-FA	5	0
SCR-FA	31	0

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
11.6332	11.6332	126.965	9.16246	9.16246	-596.82	0

Table E.6. Budget Allocation and Technology Deployment at Budget $752,791

Budget($)	Remaining($)
752,791	7275.86

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	183,628	24	1	10
Dallas	267,020	48	4	13
F. Worth	128,103	32	0	7
Beaumont	130,231	23	5	5
Austin	35,308.6	52	0	2
C. Christi	362.56	19	0	0
Yoakum	155.83	7	0	0
San Antonio	706.14	40	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	70	0	14
Loader	109	32	115	9	17
Excavator	29	6	28	1	6
Others	25	7	32	0	0

	NA	NNA
FA	179	66
HE-FA	10	0
SCR-FA	37	0

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
11.8452	11.8452	126.965	9.32949	9.32949	-638.68	0

Table E.7. Budget Allocation and Technology Deployment at Budget $925,000

Budget($)	Remaining($)				
925,000	192.86				
Districts	Cost Allocation	FA	HE-FA	SCR-FA	
Houston	192,128	23	2	10	
Dallas	267,020	48	4	13	
F. Worth	128,103	32	0	7	
Beaumont	130,231	23	5	5	
Austin	35,308.6	52	0	2	
C. Christi	60,654.6	13	5	1	
Yoakum	25,655.8	4	3	0	
San Antonio	85,706.1	30	10	0	
	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	61	8	15
Loader	109	32	108	16	17
Excavator	29	6	24	5	6
Others	25	7	32	0	0
	NA	NNA			
HE	0	0			
SCR	0	0			
FA	178	47			
HE-FA	11	18			
SCR-FA	37	1			

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
11.8481	13.708	126.965	9.33175	10.7966	-638.68	1,256.25

Table E.8. Budget Allocation and Technology Deployment at Budget $1,050,000

Budget($)	Remaining($)
1,050,000	22.86

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	192,128	23	2	10
Dallas	267,020	48	4	13
F. Worth	128,103	32	0	7
Beaumont	130,231	23	5	5
Austin	35,308.6	52	0	2
C. Christi	87,685.6	13	2	4
Yoakum	43,298.8	3	3	1
San Antonio	166,202	28	5	7

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	59	7	18
Loader	109	32	107	13	21
Excavator	29	6	24	1	10
Others	25	7	32	0	0

	NA	NNA
FA	178	44
HE-FA	11	10
SCR-FA	37	12

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
11.85	14.97	126.97	9.33	11.79	-638.68	47.65

Table E.9. Budget Allocation and Technology Deployment at Budget $1,182,020

Budget($)	Remaining($)			
1,182,020	4.86			
Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	192,128	23	2	10
Dallas	267,020	48	4	13
F. Worth	128,103	32	0	7
Beaumont	130,231	23	5	5
Austin	35,308.6	52	0	2
C. Christi	157,308	9	2	8
Yoakum	70,267.8	3	0	4
San Antonio	201,649	28	1	11

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	59	0	25
Loader	109	32	103	13	25
Excavator	29	6	24	1	10
Others	25	7	32	0	0

	NA	NNA
FA	178	40
HE-FA	11	3
SCR-FA	37	23

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
11.8481	15.6606	126.965	9.33175	12.3345	-638.68	-447.65

APPENDIX F

DETAILED INFORMATION REGARDING DEPLOYMENT OF TECHNOLOGIES (CASE 2B)

Case 2B: Method 2 without Consideration of Fuel Economy

Table F.1. Budget Allocation and Technology Deployment at Budget $15,000

Budget($)	Remaining($)
15,000	4,417.69

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	358.48	35	0	0
Dallas	7,893.53	65	0	0
F. Worth	101.37	10	0	0
Beaumont	347.86	33	0	0
Austin	656.55	54	0	0
C. Christi	362.56	19	0	0
Yoakum	155.83	7	0	0
San Antonio	706.14	40	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	56	21	77	0	0
Loader	94	32	126	0	0
Excavator	23	6	29	0	0
Others	24	7	31	0	0

	NA	NNA
FA	197	66
HE FA	0	0
SCR FA	0	0

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
6.95835	6.95835	126.965	5.4805	5.4805	0	0

Table F.2. Budget Allocation and Technology Deployment at Budget $120,000

Budget($)	Remaining($)
120,000	6,301.86

Districts	Cost Allocation	FA	HE FA	SCR FA
Houston	35,899.5	33	0	2
Dallas	25,593.5	64	0	1
F. Worth	14,702.2	38	1	0
Beaumont	35,621.9	31	0	2
Austin	656.55	54	0	0
C. Christi	362.56	19	0	0
Yoakum	155.83	7	0	0
San Antonio	706.14	40	0	0

	NA	NNA	FA	HE FA	SCR FA
Grader	63	21	82	0	2
Loader	109	32	138	1	2
Excavator	29	6	34	0	1
others	25	7	32	0	0

	NA	NNA
HE	0	0
SCR	0	0
FA	220	66
HE FA	1	0
SCR FA	5	0

NOx Reduced (1^{st} Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1^{st} Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
8.80291	8.80291	126.965	6.93331	6.93331	-31.21	0

Table F.3. Budget Allocation and Technology Deployment at Budget $130,000

Budget($)	Remaining($)				
130,000	1.86				
Districts	Cost Allocation	FA	HE-FA	SCR-FA	
Houston	44,399.5	32	1	2	
Dallas	16,393.5	64	1	0	
F. Worth	23,202.2	37	2	0	
Beaumont	44,121.9	30	1	2	
Austin	656.55	54	0	0	
C. Christi	362.56	19	0	0	
Yoakum	155.83	7	0	0	
San Antonio	706.14	40	0	0	
	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	80	2	2
Loader	109	32	137	3	1
Excavator	29	6	34	0	1
Others	25	7	32	0	0
	NA	NNA			
HE	0	0			
SCR	0	0			
FA	217	66			
HE-FA	5	0			
SCR-FA	4	0			

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
8.9205	8.9205	126.965	7.02592	7.02592	410.03	0

Table F.4. Budget Allocation and Technology Deployment at Budget $170,000

Budget($)	Remaining($)
170,000	3,605.86

Districts	Cost Allocation	FA	HE FA	SCR FA
Houston	53,440.5	32	0	3
Dallas	25,593.5	64	0	1
F. Worth	41,357.2	37	0	2
Beaumont	44,121.9	30	1	2
Austin	656.55	54	0	0
C. Christi	362.56	19	0	0
Yoakum	155.83	7	0	0
San Antonio	706.14	40	0	0

	NA	NNA	FA	HE FA	SCR FA
Grader	63	21	80	1	3
Loader	109	32	137	0	4
Excavator	29	6	34	0	1
others	25	7	32	0	0

	NA	NNA
HE	0	0
SCR	0	0
FA	217	66
HE FA	1	0
SCR FA	8	0

NOx Reduced (1^{st} Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1^{st} Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
9.31952	9.31952	126.965	7.3402	7.3402	-171.94	0

Table F.5. Budget Allocation and Technology Deployment at Budget $225,000

Budget($)	Remaining($)				
225,000	6,062.86				
Districts	Cost Allocation	FA	HE-FA	SCR-FA	
Houston	88,442.5	30	0	5	
Dallas	25,593.5	64	0	1	
F. Worth	49,857.2	36	1	2	
Beaumont	53,162.9	30	0	3	
Austin	656.55	54	0	0	
C. Christi	362.56	19	0	0	
Yoakum	155.83	7	0	0	
San Antonio	706.14	40	0	0	
	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	80	0	4
Loader	109	32	137	0	4
Excavator	29	6	31	1	3
others	25	7	32	0	0
	NA	NNA			
FA	214	66			
HE-FA	1	0			
SCR-FA	11	0			

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
9.73574	9.73574	126.965	7.66802	7.66802	-313.96	0

Table F.6. Budget Allocation and Technology Deployment at Budget $250,000

Budget($)	Remaining($)					
250,000	4,865.86					
Districts	Cost Allocation	FA	HE-FA	SCR-FA		
Houston	88,442.5	30	0	5		
Dallas	43,013.5	63	0	2		
F. Worth	58,634.2	36	0	3		
Beaumont	53,162.9	30	0	3		
Austin	656.55	54	0	0		
C. Christi	362.56	19	0	0		
Yoakum	155.83	7	0	0		
San Antonio	706.14	40	0	0		
	NA	NNA	FA	HE-FA	SCR-FA	
Grader	63	21	80	0	4	
Loader	109	32	136	0	5	
Excavator	29	6	31	0	4	
Others	25	7	32	0	0	
	NA	NNA				
FA	213	66				
HE-FA	0	0				
SCR-FA	13	0				
NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
9.92393	9.92393	126.965	7.81624	7.81624	-354.25	0

Table F.7. Budget Allocation and Technology Deployment at Budget $600,000

Budget($)	Remaining($)
600,000	19.86

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	175,128	25	0	10
Dallas	172,754	55	1	9
F. Worth	128,103	32	0	7
Beaumont	87,461.9	27	2	4
Austin	35,308.6	52	0	2
C. Christi	362.56	19	0	0
Yoakum	155.83	7	0	0
San Antonio	706.14	40	0	0

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	71	1	12
Loader	109	32	126	1	14
Excavator	29	6	28	1	6
Others	25	7	32	0	0

	NA	NNA
FA	191	66
HE-FA	3	0
SCR-FA	32	0

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
11.6348	11.6348	126.965	9.16375	9.16375	-603.84	0

Table F.8. Budget Allocation and Technology Deployment at Budget $752,791

Budget($)	Remaining($)
752,791	7275.86

Districts	Cost Allocation	FA	HE FA	SCR FA
Houston	183,628	24	1	10
Dallas	267,020	48	4	13
F. Worth	128,103	32	0	7
Beaumont	130,231	23	5	5
Austin	35,308.6	52	0	2
C. Christi	362.56	19	0	0
Yoakum	155.83	7	0	0
San Antonio	706.14	40	0	0

	NA	NNA	FA	HE FA	SCR FA
Grader	63	21	70	0	14
Loader	109	32	115	9	17
Excavator	29	6	28	1	6
others	25	7	32	0	0

	NA	NNA
FA	179	66
HE FA	10	0
SCR FA	37	0

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
11.8452	11.8452	126.965	9.32949	9.32949	-638.68	0

Table F.9. Budget Allocation and Technology Deployment at Budget $825,000

Budget($)	Remaining($)
825,000	927.86

Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	192,128	23	2	10
Dallas	267,020	48	4	13
F. Worth	128,103	32	0	7
Beaumont	130,231	23	5	5
Austin	35,308.6	52	0	2
C. Christi	26,654.6	17	1	1
Yoakum	17,798.8	6	0	1
San Antonio	26,828.1	38	1	1

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	69	0	15
Loader	109	32	113	11	17
Excavator	29	6	25	2	8
Others	25	7	32	0	0

	NA	NNA
HE	0	0
SCR	0	0
FA	178	61
HE-FA	11	2
SCR-FA	37	3

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
11.8481	12.9892	126.965	9.33175	10.2305	-638.68	119.26

Table F.10. Budget Allocation and Technology Deployment at Budget $925,000

Budget($)	Remaining($)				
925,000	3860.86				
Districts	Cost Allocation	FA	HE-FA	SCR-FA	
Houston	192,128	23	2	10	
Dallas	267,020	48	4	13	
F. Worth	128,103	32	0	7	
Beaumont	130,231	23	5	5	
Austin	35,308.6	52	0	2	
C. Christi	53,178.6	16	0	3	
Yoakum	35,471.8	5	0	2	
San Antonio	79,698.1	35	1	4	
	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	66	0	18
Loader	109	32	112	11	18
Excavator	29	6	24	1	10
Others	25	7	32	0	0
	NA	NNA			
FA	178	56			
HE-FA	11	1			
SCR-FA	37	9			

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
11.8481	14.0405	126.965	9.33175	11.0585	-638.68	-202.01

Table F.11. Budget Allocation and Technology Deployment at Budget $1,050,000

Budget($)	Remaining($)
1,050,000	6,436.86

Districts	Cost Allocation	FA	HE FA	SCR FA
Houston	192,128	23	2	10
Dallas	267,020	48	4	13
F. Worth	128,103	32	0	7
Beaumont	130,231	23	5	5
Austin	35,308.6	52	0	2
C. Christi	105,706	13	0	6
Yoakum	35,471.8	5	0	2
San Antonio	149,595	31	1	8

	NA	NNA	FA	HE FA	SCR FA
Grader	63	21	62	0	22
Loader	109	32	109	11	21
Excavator	29	6	24	1	10
Others	25	7	32	0	0

	NA	NNA
FA	178	49
HE FA	11	1
SCR FA	37	16

NOx Reduced (1^{st} Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1^{st} Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
11.85	15.06	126.97	9.33	11.86	-638.68	-344.61

Table F.12. Budget Allocation and Technology Deployment at Budget $1,182,020

Budget($)	Remaining($)			
1,182,020	4.86			
Districts	Cost Allocation	FA	HE-FA	SCR-FA
Houston	192,128	23	2	10
Dallas	267,020	48	4	13
F. Worth	128,103	32	0	7
Beaumont	130,231	23	5	5
Austin	35,308.6	52	0	2
C. Christi	157,308	9	2	8
Yoakum	70,267.8	3	0	4
San Antonio	201,649	28	1	11

	NA	NNA	FA	HE-FA	SCR-FA
Grader	63	21	59	0	25
Loader	109	32	103	13	25
Excavator	29	6	24	1	10
others	25	7	32	0	0

	NA	NNA
FA	178	40
HE-FA	11	3
SCR-FA	37	23

NOx Reduced (1st Stage) (ton)	Total NOx Reduced (ton)	Total NOx (ton)	%NOx Reduced (1st Stage)	Total %NOx Reduced	Diesel Econ. (1st Stage) ($)	Diesel Econ. (2nd Stage) ($)
11.8481	15.6606	126.965	9.33175	12.3345	-638.68	-447.65

APPENDIX G

SAMPLE DEPLOYMENT PLAN

Total Budget: 250,000

NONATTAINMENT AREAS

Equip NO0	Grader	FA	Austin	NAs	CoID 11
Equip NO1	Grader	FA	Austin	NAs	CoID 11
Equip NO2	Loader	FA	Austin	NAs	CoID 11
Equip NO3	Loader	FA	Austin	NAs	CoID 11
Equip NO4	Others	FA	Austin	NAs	CoID 11
Equip NO5	Excvtr	SCR, FA	Houston	NAs	CoID 20
Equip NO6	Excvtr	FA	Houston	NAs	CoID 20
Equip NO7	Grader	FA	Houston	NAs	CoID 20
Equip NO8	Loader	FA	Houston	NAs	CoID 20
Equip NO9	Loader	FA	Houston	NAs	CoID 20
Equip NO10	Others	FA	Houston	NAs	CoID 20
Equip NO11	Grader	FA	Austin	NAs	CoID 28
Equip NO12	Grader	FA	Austin	NAs	CoID 28
Equip NO13	Loader	FA	Austin	NAs	CoID 28
Equip NO14	Loader	FA	Austin	NAs	CoID 28
Equip NO15	Others	FA	Austin	NAs	CoID 28
Equip NO16	Excvtr	FA	Beaumont	NAs	CoID 36
Equip NO17	Grader	SCR, FA	Beaumont	NAs	CoID 36
Equip NO18	Grader	FA	Beaumont	NAs	CoID 36
Equip NO19	Loader	FA	Beaumont	NAs	CoID 36
Equip NO20	Loader	FA	Beaumont	NAs	CoID 36
Equip NO21	Others	FA	Beaumont	NAs	CoID 36
Equip NO22	Excvtr	FA	Dallas	NAs	CoID 43

Equip NO23	Grader FA	Dallas	NAs	CoID 43
Equip NO24	Grader FA	Dallas	NAs	CoID 43
Equip NO25	Grader FA	Dallas	NAs	CoID 43
Equip NO26	Loader FA	Dallas	NAs	CoID 43
Equip NO27	Loader FA	Dallas	NAs	CoID 43
Equip NO28	Loader FA	Dallas	NAs	CoID 43
Equip NO29	Loader FA	Dallas	NAs	CoID 43
Equip NO30	Others FA	Dallas	NAs	CoID 43
Equip NO31	Excvtr FA	Dallas	NAs	CoID 57
Equip NO32	Excvtr FA	Dallas	NAs	CoID 57
Equip NO33	Excvtr FA	Dallas	NAs	CoID 57
Equip NO34	Excvtr FA	Dallas	NAs	CoID 57
Equip NO35	Excvtr FA	Dallas	NAs	CoID 57
Equip NO36	Grader FA	Dallas	NAs	CoID 57
Equip NO37	Grader FA	Dallas	NAs	CoID 57
Equip NO38	Grader FA	Dallas	NAs	CoID 57
Equip NO39	Grader FA	Dallas	NAs	CoID 57
Equip NO40	Loader FA	Dallas	NAs	CoID 57
Equip NO41	Loader FA	Dallas	NAs	CoID 57
Equip NO42	Loader FA	Dallas	NAs	CoID 57
Equip NO43	Loader SCR, FA	Dallas	NAs	CoID 57
Equip NO44	Loader FA	Dallas	NAs	CoID 57
Equip NO45	Loader FA	Dallas	NAs	CoID 57
Equip NO46	Loader FA	Dallas	NAs	CoID 57
Equip NO47	Loader FA	Dallas	NAs	CoID 57
Equip NO48	Loader FA	Dallas	NAs	CoID 57
Equip NO49	Loader FA	Dallas	NAs	CoID 57
Equip NO50	Loader FA	Dallas	NAs	CoID 57
Equip NO51	Loader FA	Dallas	NAs	CoID 57

Equip NO52	Loader	FA	Dallas	NAs	CoID 57
Equip NO53	Loader	FA	Dallas	NAs	CoID 57
Equip NO54	Loader	SCR, FA	Dallas	NAs	CoID 57
Equip NO55	Loader	FA	Dallas	NAs	CoID 57
Equip NO56	Loader	FA	Dallas	NAs	CoID 57
Equip NO57	Others	FA	Dallas	NAs	CoID 57
Equip NO58	Excvtr	FA	Dallas	NAs	CoID 61
Equip NO59	Grader	FA	Dallas	NAs	CoID 61
Equip NO60	Grader	FA	Dallas	NAs	CoID 61
Equip NO61	Loader	FA	Dallas	NAs	CoID 61
Equip NO62	Loader	FA	Dallas	NAs	CoID 61
Equip NO63	Loader	FA	Dallas	NAs	CoID 61
Equip NO64	Loader	FA	Dallas	NAs	CoID 61
Equip NO65	Loader	FA	Dallas	NAs	CoID 61
Equip NO66	Others	FA	Dallas	NAs	CoID 61
Equip NO67	Grader	FA	Dallas	NAs	CoID 70
Equip NO68	Grader	FA	Dallas	NAs	CoID 70
Equip NO69	Loader	FA	Dallas	NAs	CoID 70
Equip NO70	Loader	FA	Dallas	NAs	CoID 70
Equip NO71	Loader	FA	Dallas	NAs	CoID 70
Equip NO72	Loader	FA	Dallas	NAs	CoID 70
Equip NO73	Others	FA	Dallas	NAs	CoID 70
Equip NO74	Grader	SCR, FA	Houston	NAs	CoID 79
Equip NO75	Loader	FA	Houston	NAs	CoID 79
Equip NO76	Loader	FA	Houston	NAs	CoID 79
Equip NO77	Loader	FA	Houston	NAs	CoID 79
Equip NO78	Others	FA	Houston	NAs	CoID 79
Equip NO79	Grader	FA	Houston	NAs	CoID 84
Equip NO80	Grader	FA	Houston	NAs	CoID 84

Equip NO81	Loader	FA	Houston	NAs	CoID 84
Equip NO82	Loader	FA	Houston	NAs	CoID 84
Equip NO83	Loader	SCR, FA	Houston	NAs	CoID 84
Equip NO84	Others	FA	Houston	NAs	CoID 84
Equip NO85	Grader	SCR, FA	Beaumont	NAs	CoID 100
Equip NO86	Loader	FA	Beaumont	NAs	CoID 100
Equip NO87	Loader	FA	Beaumont	NAs	CoID 100
Equip NO88	Loader	SCR, FA	Beaumont	NAs	CoID 100
Equip NO89	Others	FA	Beaumont	NAs	CoID 100
Equip NO90	Excvtr	SCR, FA	Houston	NAs	CoID 101
Equip NO91	Grader	FA	Houston	NAs	CoID 101
Equip NO92	Loader	FA	Houston	NAs	CoID 101
Equip NO93	Loader	FA	Houston	NAs	CoID 101
Equip NO94	Others	FA	Houston	NAs	CoID 101
Equip NO95	Grader	FA	Austin	NAs	CoID 105
Equip NO96	Grader	FA	Austin	NAs	CoID 105
Equip NO97	Loader	FA	Austin	NAs	CoID 105
Equip NO98	Loader	FA	Austin	NAs	CoID 105
Equip NO99	Loader	FA	Austin	NAs	CoID 105
Equip NO100	Others	FA	Austin	NAs	CoID 105
Equip NO101	Grader	FA	Beaumont	NAs	CoID 123
Equip NO102	Grader	FA	Beaumont	NAs	CoID 123
Equip NO103	Loader	FA	Beaumont	NAs	CoID 123
Equip NO104	Loader	FA	Beaumont	NAs	CoID 123
Equip NO105	Others	FA	Beaumont	NAs	CoID 123
Equip NO106	Grader	FA	Fort Worth	NAs	CoID 126
Equip NO107	Loader	FA	Fort Worth	NAs	CoID 126
Equip NO108	Others	FA	Fort Worth	NAs	CoID 126
Equip NO109	Grader	FA	Dallas	NAs	CoID 129

Equip NO110	Grader	FA	Dallas	NAs	CoID 129
Equip NO111	Loader	FA	Dallas	NAs	CoID 129
Equip NO112	Loader	FA	Dallas	NAs	CoID 129
Equip NO113	Others	FA	Dallas	NAs	CoID 129
Equip NO114	Excvtr	FA	Beaumont	NAs	CoID 146
Equip NO115	Excvtr	FA	Beaumont	NAs	CoID 146
Equip NO116	Grader	FA	Beaumont	NAs	CoID 146
Equip NO117	Grader	FA	Beaumont	NAs	CoID 146
Equip NO118	Grader	FA	Beaumont	NAs	CoID 146
Equip NO119	Grader	FA	Beaumont	NAs	CoID 146
Equip NO120	Loader	FA	Beaumont	NAs	CoID 146
Equip NO121	Loader	FA	Beaumont	NAs	CoID 146
Equip NO122	Loader	FA	Beaumont	NAs	CoID 146
Equip NO123	Loader	FA	Beaumont	NAs	CoID 146
Equip NO124	Others	FA	Beaumont	NAs	CoID 146
Equip NO125	Excvtr	SCR, FA	Houston	NAs	CoID 170
Equip NO126	Grader	FA	Houston	NAs	CoID 170
Equip NO127	Grader	FA	Houston	NAs	CoID 170
Equip NO128	Loader	FA	Houston	NAs	CoID 170
Equip NO129	Loader	FA	Houston	NAs	CoID 170
Equip NO130	Others	FA	Houston	NAs	CoID 170
Equip NO131	Excvtr	FA	Beaumont	NAs	CoID 181
Equip NO132	Grader	FA	Beaumont	NAs	CoID 181
Equip NO133	Grader	FA	Beaumont	NAs	CoID 181
Equip NO134	Loader	FA	Beaumont	NAs	CoID 181
Equip NO135	Loader	FA	Beaumont	NAs	CoID 181
Equip NO136	Others	FA	Beaumont	NAs	CoID 181
Equip NO137	Excvtr	FA	Fort Worth	NAs	CoID 184
Equip NO138	Grader	FA	Fort Worth	NAs	CoID 184

Equip NO139	Grader	FA	Fort Worth	NAs	CoID 184
Equip NO140	Loader	FA	Fort Worth	NAs	CoID 184
Equip NO141	Loader	FA	Fort Worth	NAs	CoID 184
Equip NO142	Loader	FA	Fort Worth	NAs	CoID 184
Equip NO143	Others	FA	Fort Worth	NAs	CoID 184
Equip NO144	Excvtr	FA	Dallas	NAs	CoID 199
Equip NO145	Grader	FA	Dallas	NAs	CoID 199
Equip NO146	Grader	FA	Dallas	NAs	CoID 199
Equip NO147	Loader	FA	Dallas	NAs	CoID 199
Equip NO148	Loader	FA	Dallas	NAs	CoID 199
Equip NO149	Loader	FA	Dallas	NAs	CoID 199
Equip NO150	Loader	FA	Dallas	NAs	CoID 199
Equip NO151	Others	FA	Dallas	NAs	CoID 199
Equip NO152	Excvtr	SCR, FA	Fort Worth	NAs	CoID 220
Equip NO153	Excvtr	FA	Fort Worth	NAs	CoID 220
Equip NO154	Excvtr	FA	Fort Worth	NAs	CoID 220
Equip NO155	Excvtr	FA	Fort Worth	NAs	CoID 220
Equip NO156	Excvtr	FA	Fort Worth	NAs	CoID 220
Equip NO157	Excvtr	FA	Fort Worth	NAs	CoID 220
Equip NO158	Grader	SCR, FA	Fort Worth	NAs	CoID 220
Equip NO159	Grader	FA	Fort Worth	NAs	CoID 220
Equip NO160	Grader	FA	Fort Worth	NAs	CoID 220
Equip NO161	Grader	FA	Fort Worth	NAs	CoID 220
Equip NO162	Grader	FA	Fort Worth	NAs	CoID 220
Equip NO163	Grader	FA	Fort Worth	NAs	CoID 220
Equip NO164	Grader	FA	Fort Worth	NAs	CoID 220
Equip NO165	Loader	FA	Fort Worth	NAs	CoID 220
Equip NO166	Loader	FA	Fort Worth	NAs	CoID 220
Equip NO167	Loader	FA	Fort Worth	NAs	CoID 220

Equip NO168	Loader	FA	Fort Worth	NAs	CoID 220
Equip NO169	Loader	FA	Fort Worth	NAs	CoID 220
Equip NO170	Loader	FA	Fort Worth	NAs	CoID 220
Equip NO171	Loader	FA	Fort Worth	NAs	CoID 220
Equip NO172	Loader	FA	Fort Worth	NAs	CoID 220
Equip NO173	Loader	FA	Fort Worth	NAs	CoID 220
Equip NO174	Loader	FA	Fort Worth	NAs	CoID 220
Equip NO175	Loader	FA	Fort Worth	NAs	CoID 220
Equip NO176	Loader	FA	Fort Worth	NAs	CoID 220
Equip NO177	Loader	FA	Fort Worth	NAs	CoID 220
Equip NO178	Loader	SCR, FA	Fort Worth	NAs	CoID 220
Equip NO179	Loader	FA	Fort Worth	NAs	CoID 220
Equip NO180	Others	FA	Fort Worth	NAs	CoID 220
Equip NO181	Excvtr	FA	Austin	NAs	CoID 227
Equip NO182	Excvtr	FA	Austin	NAs	CoID 227
Equip NO183	Excvtr	FA	Austin	NAs	CoID 227
Equip NO184	Excvtr	FA	Austin	NAs	CoID 227
Equip NO185	Excvtr	FA	Austin	NAs	CoID 227
Equip NO186	Grader	FA	Austin	NAs	CoID 227
Equip NO187	Grader	FA	Austin	NAs	CoID 227
Equip NO188	Grader	FA	Austin	NAs	CoID 227
Equip NO189	Grader	FA	Austin	NAs	CoID 227
Equip NO190	Grader	FA	Austin	NAs	CoID 227
Equip NO191	Grader	FA	Austin	NAs	CoID 227
Equip NO192	Loader	FA	Austin	NAs	CoID 227
Equip NO193	Loader	FA	Austin	NAs	CoID 227
Equip NO194	Loader	FA	Austin	NAs	CoID 227
Equip NO195	Loader	FA	Austin	NAs	CoID 227
Equip NO196	Loader	FA	Austin	NAs	CoID 227

Equip NO197	Loader	FA	Austin	NAs	CoID 227
Equip NO198	Loader	FA	Austin	NAs	CoID 227
Equip NO199	Loader	FA	Austin	NAs	CoID 227
Equip NO200	Loader	FA	Austin	NAs	CoID 227
Equip NO201	Loader	FA	Austin	NAs	CoID 227
Equip NO202	Loader	FA	Austin	NAs	CoID 227
Equip NO203	Loader	FA	Austin	NAs	CoID 227
Equip NO204	Loader	FA	Austin	NAs	CoID 227
Equip NO205	Loader	FA	Austin	NAs	CoID 227
Equip NO206	Loader	FA	Austin	NAs	CoID 227
Equip NO207	Others	FA	Austin	NAs	CoID 227
Equip NO208	Excvtr	FA	Houston	NAs	CoID 237
Equip NO209	Grader	FA	Houston	NAs	CoID 237
Equip NO210	Grader	FA	Houston	NAs	CoID 237
Equip NO211	Loader	FA	Houston	NAs	CoID 237
Equip NO212	Loader	FA	Houston	NAs	CoID 237
Equip NO213	Loader	FA	Houston	NAs	CoID 237
Equip NO214	Others	FA	Houston	NAs	CoID 237
Equip NO215	Grader	FA	Austin	NAs	CoID 246
Equip NO216	Grader	FA	Austin	NAs	CoID 246
Equip NO217	Grader	FA	Austin	NAs	CoID 246
Equip NO218	Grader	FA	Austin	NAs	CoID 246
Equip NO219	Grader	FA	Austin	NAs	CoID 246
Equip NO220	Grader	FA	Austin	NAs	CoID 246
Equip NO221	Loader	FA	Austin	NAs	CoID 246
Equip NO222	Loader	FA	Austin	NAs	CoID 246
Equip NO223	Loader	FA	Austin	NAs	CoID 246
Equip NO224	Loader	FA	Austin	NAs	CoID 246
Equip NO225	Others	FA	Austin	NAs	CoID 246

NONATTAINMENT AREAS ONLY

Total Budget ($):250,000

Total Cost ($):243,909.616

Remaining Budget ($):6,090.38393

Total NOx Reduced: 8.76040303 Ton(s)

Houston	:	#HE: 0	#SCR 0	#FA 30	#HE, FA 0	#SCR, FA 5
Dallas	:	#HE: 0	#SCR 0	#FA 63	#HE, FA 0	#SCR, FA 2
F. Worth	:	#HE: 0	#SCR 0	#FA 36	#HE, FA 0	#SCR, FA 3
Beaumont	:	#HE: 0	#SCR 0	#FA 30	#HE, FA 0	#SCR, FA 3
Austin	:	#HE: 0	#SCR 0	#FA 54	#HE, FA 0	#SCR, FA 0
Corpus Christi	:	#HE: 0	#SCR 0	#FA 0	#HE, FA 0	#SCR, FA 0
Yoakum	:	#HE: 0	#SCR 0	#FA 0	#HE, FA 0	#SCR, FA 0
San Antonio	:	#HE: 0	#SCR 0	#FA 0	#HE, FA 0	#SCR, FA 0

NEAR NANATTAINMENT AREAS

Equip NO0	Excvtr	FA	San Antonio	NNAs	CoID 15
Equip NO1	Grader	FA	San Antonio	NNAs	CoID 15
Equip NO2	Grader	FA	San Antonio	NNAs	CoID 15
Equip NO3	Grader	FA	San Antonio	NNAs	CoID 15
Equip NO4	Grader	FA	San Antonio	NNAs	CoID 15
Equip NO5	Grader	FA	San Antonio	NNAs	CoID 15
Equip NO6	Grader	FA	San Antonio	NNAs	CoID 15
Equip NO7	Grader	FA	San Antonio	NNAs	CoID 15
Equip NO8	Loader	FA	San Antonio	NNAs	CoID 15
Equip NO9	Loader	FA	San Antonio	NNAs	CoID 15
Equip NO10	Loader	FA	San Antonio	NNAs	CoID 15
Equip NO11	Loader	FA	San Antonio	NNAs	CoID 15
Equip NO12	Loader	FA	San Antonio	NNAs	CoID 15
Equip NO13	Loader	FA	San Antonio	NNAs	CoID 15
Equip NO14	Loader	FA	San Antonio	NNAs	CoID 15

Equip NO15	Loader	FA	San Antonio	NNAs	CoID 15
Equip NO16	Loader	FA	San Antonio	NNAs	CoID 15
Equip NO17	Loader	FA	San Antonio	NNAs	CoID 15
Equip NO18	Loader	FA	San Antonio	NNAs	CoID 15
Equip NO19	Loader	FA	San Antonio	NNAs	CoID 15
Equip NO20	Loader	FA	San Antonio	NNAs	CoID 15
Equip NO21	Loader	FA	San Antonio	NNAs	CoID 15
Equip NO22	Others	FA	San Antonio	NNAs	CoID 15
Equip NO23	Grader	FA	San Antonio	NNAs	CoID 46
Equip NO24	Grader	FA	San Antonio	NNAs	CoID 46
Equip NO25	Loader	FA	San Antonio	NNAs	CoID 46
Equip NO26	Loader	FA	San Antonio	NNAs	CoID 46
Equip NO27	Others	FA	San Antonio	NNAs	CoID 46
Equip NO28	Excvtr	FA	San Antonio	NNAs	CoID 94
Equip NO29	Grader	FA	San Antonio	NNAs	CoID 94
Equip NO30	Grader	FA	San Antonio	NNAs	CoID 94
Equip NO31	Loader	FA	San Antonio	NNAs	CoID 94
Equip NO32	Loader	FA	San Antonio	NNAs	CoID 94
Equip NO33	Loader	FA	San Antonio	NNAs	CoID 94
Equip NO34	Others	FA	San Antonio	NNAs	CoID 94
Equip NO35	Excvtr	FA	Corpus Christi	NNAs	CoID 178
Equip NO36	Excvtr	FA	Corpus Christi	NNAs	CoID 178
Equip NO37	Grader	FA	Corpus Christi	NNAs	CoID 178
Equip NO38	Grader	FA	Corpus Christi	NNAs	CoID 178
Equip NO39	Grader	FA	Corpus Christi	NNAs	CoID 178
Equip NO40	Loader	FA	Corpus Christi	NNAs	CoID 178
Equip NO41	Loader	FA	Corpus Christi	NNAs	CoID 178
Equip NO42	Loader	FA	Corpus Christi	NNAs	CoID 178
Equip NO43	Loader	FA	Corpus Christi	NNAs	CoID 178
Equip NO44	Loader	FA	Corpus Christi	NNAs	CoID 178
Equip NO45	Loader	FA	Corpus Christi	NNAs	CoID 178
Equip NO46	Loader	FA	Corpus Christi	NNAs	CoID 178

Equip NO47	Others	FA	Corpus Christi	NNAs	CoID 178
Equip NO48	Grader	FA	Corpus Christi	NNAs	CoID 205
Equip NO49	Grader	FA	Corpus Christi	NNAs	CoID 205
Equip NO50	Loader	FA	Corpus Christi	NNAs	CoID 205
Equip NO51	Loader	FA	Corpus Christi	NNAs	CoID 205
Equip NO52	Loader	FA	Corpus Christi	NNAs	CoID 205
Equip NO53	Others	FA	Corpus Christi	NNAs	CoID 205
Equip NO54	Excvtr	FA	Yoakum	NNAs	CoID 235
Equip NO55	Grader	FA	Yoakum	NNAs	CoID 235
Equip NO56	Grader	FA	Yoakum	NNAs	CoID 235
Equip NO57	Grader	FA	Yoakum	NNAs	CoID 235
Equip NO58	Loader	FA	Yoakum	NNAs	CoID 235
Equip NO59	Loader	FA	Yoakum	NNAs	CoID 235
Equip NO60	Others	FA	Yoakum	NNAs	CoID 235
Equip NO61	Excvtr	FA	San Antonio	NNAs	CoID 247
Equip NO62	Grader	FA	San Antonio	NNAs	CoID 247
Equip NO63	Grader	FA	San Antonio	NNAs	CoID 247
Equip NO64	Loader	FA	San Antonio	NNAs	CoID 247
Equip NO65	Others	FA	San Antonio	NNAs	CoID 247

NEAR-NONATTAINMENT AREAS ONLY

Total Budget ($):250,000

Total Budget NNA ($):6,090.38393

Total Cost ($):1,224.52369

Remaining Budget ($):4,865.86024

Total NOx Reduced: 9.92392603 Ton(s)

Houston :	#HE: 0	#SCR 0	#FA 30	#HE, FA 0	#SCR, FA 5
Dallas :	#HE: 0	#SCR 0	#FA 63	#HE, FA 0	#SCR, FA 2
F. Worth :	#HE: 0	#SCR 0	#FA 36	#HE, FA 0	#SCR, FA 3
Beaumont :	#HE: 0	#SCR 0	#FA 30	#HE, FA 0	#SCR, FA 3
Austin :	#HE: 0	#SCR 0	#FA 54	#HE, FA 0	#SCR, FA 0

Corpus Christi:	#HE: 0	#SCR 0	#FA 19	#HE, FA 0	#SCR, FA 0
Yoakum :	#HE: 0	#SCR 0	#FA 7	#HE, FA 0	#SCR, FA 0
San Antonio :	#HE: 0	#SCR 0	#FA 40	#HE, FA 0	#SCR, FA 0

VITA

Muhammad Ehsanul Bari was born in Morgantown, West Virginia, USA. After graduating from high school, he entered Bangladesh University of Engineering and Technology (BUET) to pursue a Bachelor's Degree in Civil Engineering. He graduated in 2006 and secured a position within top 5% in his graduating class of about 200 students, with academic distinction. After graduating from BUET, he worked as a Junior Research Fellow in the Accident Research Institute. Then he pursued a Master of Science degree in Civil Engineering with specialization in Transportation Engineering at Texas A&M University (TAMU) in 2007. While pursuing his masters at TAMU, he worked as a Graduate Assistant Researcher in the Center for Air Quality Studies at the Texas Transportation Institute. Mr. Bari received his Master of Science Degree in Civil Engineering in August 2009. His research interest includes transportation planning, traffic operations, operations research and mathematical programming, and environmental concerns.

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