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Optimal Deployment of Emissions Reduction Technologies for Construction Equipment

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ABSTRACT

The objective of this research was to develop a multiobjective optimization model to deploy emissions reduction technologies for nonroad construction equipment to reduce emissions in a cost-effective and optimal manner. Given a fleet of construction equipment emitting different pollutants in the nonattainment (NA) and near -nonattainment (NNA) counties of a state and a set of emissions reduction technologies available for installation on equipment to control pollution/emissions, the model assists in determining the mix of technologies to be deployed so that maximum emissions reduction and fuel savings are achieved within a given budget. Three technologies considered for emissions reduction were designated as X, Y, and Z to keep the model formulation general so that it can be applied for any other set of technologies. Two alternative methods of deploying these technologies on a fleet of equipment were investigated with the methods differing in the technology deployment preference in the NA and NNA counties. The model having a weighted objective function containing emissions reduction benefits and fuel-saving benefits was programmed with C++ and ILOG-CPLEX. For demonstration purposes, the model was applied for a selected construction equipment fleet owned by the Texas Department of Transportation, located in NA and NNA counties of Texas, assuming the three emissions reduction technologies X, Y, and Z to represent, respectively, hydrogen enrichment, selective catalytic reduction, and fuel additive technologies. Model solutions were obtained for varying budget amounts to test the sensitivity of emissions reductions and fuel-savings benefits with increasing the budget. Different mixes of technologies producing maximum oxides of nitrogen (NO_x) reductions and total combined benefits (emissions reductions plus fuel savings) were indicated at different budget ranges. The initial steep portion of the plots for NO_x reductions and total combined benefits against budgets for different combinations of emissions reduction technologies indicated a high benefit-cost ratio at lower budget amounts. The rate of NO_x reductions and the increase of combined benefits decreased with increasing the budget, and with the budget exceeding certain limits neither further NO_x reductions nor increased combined benefits were observed. Finally, the Pareto front obtained would enable the decision-maker to achieve a noninferior optimal combination of total NO_x reductions and fuel-savings benefits for a given budget.

IMPLICATIONS

This paper describes a model that was developed to help decision-makers/fleet managers deploy emissions reduction technologies to maximize the benefit of emissions reductions and fuel savings from their construction equipment fleet. The model is based on a cost-effectiveness analysis. The model was demonstrated with three different emissions reduction technologies having different operational and performance characteristics. The model structure is quite flexible and thus can be adapted and applied to any type of emissions reduction technologies and can be implemented on on-road and nonroad sources.

INTRODUCTION

Pollutant emissions are a serious concern for human health and for the environment[1] because they can cause a range of problems to the human body (including death) and damage to trees, crops, plants, lakes, and animals. The U.S. Environmental Protection Agency (EPA) categorized air pollution sources as stationary and mobile. Stationary sources include facilities such as oil refineries, chemical processing facilities, power plants, and other manufacturing facilities. There are federal and state air pollution control requirements for most stationary sources.[2] Mobile sources are divided into two groups: on-road and nonroad. According to EPA, on-road sources are vehicles used on roads for movement of passengers or freight. They include light-duty vehicles, light-duty trucks, heavy-duty vehicles, medium-duty passenger vehicles, and motorcycles. Nonroad sources consist of engines, aircraft, marine vessels, locomotives, and equipment used for construction, agriculture, transportation, and recreational purposes.[3]

On-road and nonroad diesel engines are responsible for emitting harmful pollutants, such as nitrogen oxides (NO_x) and particulate matter (PM). On the basis of EPA's 1999 report regarding national NO_x emissions, on-road and nonroad sources contributed 34 and 22% of the nation's total NO_x emissions, respectively. Among the nonroad sources, diesel equipment emitted 49% of NO_x. Fine particulate matter ($PM_{2.5}$) emissions for on-road and nonroad sources were 10 and 18% of the nation's total $PM_{2.5}$ emissions, respectively, and among the nonroad sources, diesel equipment contributed 57% of $PM_{2.5}$.[3] These facts indicate that NO_x and $PM_{2.5}$ emissions from the nonroad sector, especially diesel equipment, are very significant, causing air pollution and health-related problems.[4]

Diesel exhaust is considered a probable human carcinogen. According to EPA, emissions from nonroad sources will continue to increase and contribute large amounts of PM and NO_x. EPA's data from 2005 indicated that nonroad engines contributed approximately 66% of the nation's $PM_{2.5}$ from all mobile sources. These nonroad engine emissions affected approximately 88 million Americans living in areas violating $PM_{2.5}$ air quality standards. Similarly, NO_x and volatile organic compound (VOC) emissions from nonroad engines were approximately 36 and 37%, respectively, from all mobile sources. These two pollutants affected approximately 159 million Americans living in areas exceeding EPA's 8-hr ozone standard.[5]

EPA's 2008 National Emissions Inventory (NEI) data show that the total national NO_x emissions from on-road and nonroad sources were 4,675,896 and 1,884,943 t, respectively. The same NEI data also indicate that the nonroad sources emitted approximately 29% of the total NO_x emissions from the mobile sources. The share of diesel equipment was approximately 74% of NO_x among the nonroad sources. Similarly, the total $PM_{2.5}$ emissions from the on-road and nonroad sources were 269,454 and 116,752 t, respectively. The nonroad sources contributed approximately 66% of the total $PM_{2.5}$ emissions from the mobile sources, and among the nonroad sources diesel equipment contributed approximately 66% of $PM_{2.5}$ emissions.[6]

Construction equipment is a sector of nonroad sources. The construction industry uses more than 2 million pieces of nonroad diesel construction equipment. Most of the equipment has a long operational life—more than 25–30 yr. A report from the Clean Air Act Advisory Committee indicates that construction equipment contributed 32% of all mobile-source NO_x emissions and 37% of PM emissions. Nonroad equipment, having less stringent emissions standards, emits more pollution than heavy-duty highway vehicles.[7] Although stringent emissions standards were established for new nonroad equipment in 2008, most of the nonroad diesel equipment in use before 2008 will operate for many more years before retirement. EPA realized the issue with the construction equipment fleet and considered the emissions reductions from the construction equipment fleet as an important component of an emissions control strategy.[8]

Various emissions reduction technologies are used to control emissions from on-road and off-road equipment in the United States. Reduced emissions is a benefit to society through improved health and to public agencies through reaching conformity, compliance, and attainment. However, purchasing these emissions reduction technologies is a cost to the concerned agency. Thus, it is essential for an agency to utilize their budget to install the emissions reduction technologies in a cost-effective and optimal manner, and no model has yet been developed for this purpose.

Therefore, the purpose of this study was to develop a multiobjective optimization model for optimal deployment of emissions control technologies to maximize the benefit from emissions reductions and fuel savings from nonroad construction equipment located in nonattainment (NA) and near-nonattainment (NNA) counties. NA counties are those that failed to meet federal standards for ambient air quality, and the NNA counties are those that are at risk of violating standards although these areas currently meet federal standards.[9] The model will aid the decision-maker or fleet manager to quickly decide how to choose the most appropriate emission reduction technology to be deployed and maximize the overall benefit.

LITERATURE REVIEW

In this section, emissions estimation methodologies based on EPA's guidelines and procedures will be discussed. Different emissions reduction strategies such as aftertreatment devices, engine technologies, and fuel technologies will be briefly presented. At the end of this section, several studies incorporating optimal allocation and configuration will be discussed.

Emissions Estimation Methodology

EPA developed the NONROAD model for estimating pollutant emissions such as carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbon, NO_x, and PM from compression-ignition engines. For calculating emissions from construction equipment fleets, information on the zero-hour steady-state emissions factors (EF_{ss}), transient adjustment factors (TAF), and deterioration factors (DF) are required. After obtaining the values for EF_{ss}, TAF, and DF, the final emissions factor (EF_{adj} in g/hp-hr) for each pollutant can be calculated. The construction equipment emissions are then calculated from the adjusted emissions factor with the information on horsepower and usage hours using eq 1.[10]

$$\textit{Emissions } E(\mathrm{g}) = EF_{adj} \times \textit{horsepower} \times \textit{usage hours} \quad (1)$$

Abolhasani et al.[11] compared the average emissions rates estimated from portable emissions measurement system (PEMS) data to estimates inferred from the NONROAD model. They developed and demonstrated a study design for deployment of a PEMS unit for excavators. They found that the PEMS-based emissions factors were similar in magnitude and were approximately comparable to those from the NONROAD model. They demonstrated the importance of considering intercycle variability in real-world in-use emissions to develop more accurate emissions inventories. It is possible to improve nonroad emissions factors and inventory models by considering such factors as intervehicle and intercycle variability.

Emissions Reduction Options

Retrofit, rebuild, replace, and repower are some strategies to reduce emissions from mobile sources. "Retrofit" means installing an emissions 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.[12] The Manufacturers of Emissions Controls Association (MECA),[13] Hansen,[14] EPA,[15] the California Air Resources Board,[16] Genesis Engineering, Inc., and Levelton Engineering, Ltd.,[17] and Lee et al.[18] provide descriptions of some emissions reduction options that are briefly presented in Table 1. The emissions reduction options are divided into three categories: (1) exhaust gas aftertreatment technologies, (2) engine technologies, and (3) fuel technologies according to Hansen[14] and Genesis Engineering, Inc., and Levelton Engineering, Ltd.[17]

To formulate effective and cost-efficient emissions control strategies, it is essential to have a better understanding of the overall effect of emissions control strategies on chemically interrelated important atmospheric pollutants. Luecken and Cimorelli[19] used an air quality model to observe the potential effect of three emissions reductions on concentrations of ozone, $PM_{2.5}$, and four important hazardous air pollutants (e.g., formaldehyde, acetaldehyde, acrolein, and benzene). Their simulations indicated the difficulty in assessing the response of toxic air pollutants to emissions reductions aimed at decreasing criteria pollutants such as ozone and $PM_{2.5}$. This type of research can help air quality managers avoid strategies that may improve one pollutant but degrade air quality by increasing other pollutants.

Studies Involving Optimal Allocation and Configuration

The studies described in this section involved multiobjective, mixed-integer programming, linear programming, integer programming (IP), and mixed-integer nonlinear programming. Chang and Wang[20] developed and applied a multiobjective mixed-integer programming model for resolving the potential conflict between environmental

Table 1. A brief description of several emissions reduction options.

Category	Example	Description
Exhaust gas aftertreatment technologies	DOC	Can reduce PM emissions, but the total NO_x emissions remain unchanged for DOC.
	Diesel particulate filter	Physically traps diesel particulates and prevents their release into the atmosphere and can reduce PM emissions.
	Selective catalytic reduction	Capable of reducing NO_x, PM, and HC emissions.
	Lean NO_x catalysts	Capable of reducing NO_x emissions.
Engine technologies	Engine repower and rebuild	Provides NO_x and PM reduction benefits.
	Exhaust gas recirculation	Involves recirculation of a portion an engines' exhaust gas into its combustion chambers. Reduces NO_x emissions, but increases PM, HC, and CO emissions and causes a fuel economy penalty.
	Crankcase emissions control	Capable of reducing PM emissions.
Fuel technologies	Natural gas	Reduces emissions and provides a potential operating cost savings.
	Biodiesel	Derived from renewable sources such as vegetable oil, animal fat, and cooking oil. Emits more NO_x emissions than off-road diesel engines. Compatible for use with high-efficiency catalytic emissions–reduction technology.
	Hydrogen	Has low energy density in the gaseous form. Hence, if less expensive and liquefied hydrogen become readily available, then it becomes practical for use in the nonroad equipment sector.
	Fuel additive	Can reduce engine emissions and/or improve fuel economy. Some manufacturers claim that their products can reduce NO_x, HC, PM, and/or CO emissions and can decrease fuel consumption. Some of the products might increase one or more pollutant emissions while reducing other pollutant emissions and increasing fuel efficiency.
	Hydrogen enrichment	HE systems create a better flame front in the engine that helps reduce emissions. Can reduce NO_x and CO emissions and decrease fuel consumption.

Notes: DOC = diesel oxidation catalysts.

and economic goals and for evaluating sustainable strategies for waste management in a metropolitan region. They considered four objectives: economics, noise control, air pollution control, and traffic congestion limitations. The constraint set consisted of mass balance, capacity limitations, operation, site availability, traffic congestion, financial, and related environmental quality constraints. They performed a case study in the city of Kaohsiung in Taiwan.

Nema and Gupta[21] formulated a multiobjective IP model to obtain the optimal configuration of a hazardous waste management system for transportation, treatment, and disposal of hazardous waste at a minimum cost and imposing minimum risk to the environment. The objectives addressed were minimization of cost, minimization of risk, and minimization of a composite objective function consisting of cost and risk. The constraints consisted of mass balance of waste, allowable capacities for treatment and disposal technologies, and constraints related to waste-waste and waste-technology compatibility. An illustrative case example was performed to demonstrate the model's usefulness.

Eshwar and Kumar[22] used linear programming with fuzzy coefficients for optimal deployment of construction equipment. The objective was to identify the exact amount of equipment to be bought or rented to complete the project in the targeted period. The required minimum number of each type of equipment, the cost and the rent of equipment, the amount of equipment that could be hired, and the duration of service were considered as constraints. The model was able to optimally deploy equipment and was capable of successfully handling the uncertainty.

Swersey and Thakur[23] developed an IP model for locating vehicle emissions testing stations. The constraints used were maximum travel distance from each town to its nearest station, average waiting time at the station, maximum hours of operations, and maximum number of lanes at each station. The station configuration that was in use had more stations than IP solutions. The IP model was able to reduce the estimated cost of the objective function by at least $3 million.

Mastsukura et al.[24] proposed a mixed-integer model to minimize CO_2 emissions through determining the optimal set of ship routes and fleet of ships. Ship capacity and maximum transportation time were considered as constraints in the model. A case study was performed at the Kobe port of Japan.

Sirikitputtisak et al.[25] developed a mixed-integer nonlinear programming model for a multiperiod optimal energy planning program. The objective function included the minimization of overall electricity costs and meeting the projected electricity demand over a span of 14 yr. Construction time, fluctuation of fuel prices, and CO_2 emissions reduction target were included in the constraints set. The program that was developed can be extended to other states, provinces, or even countries.

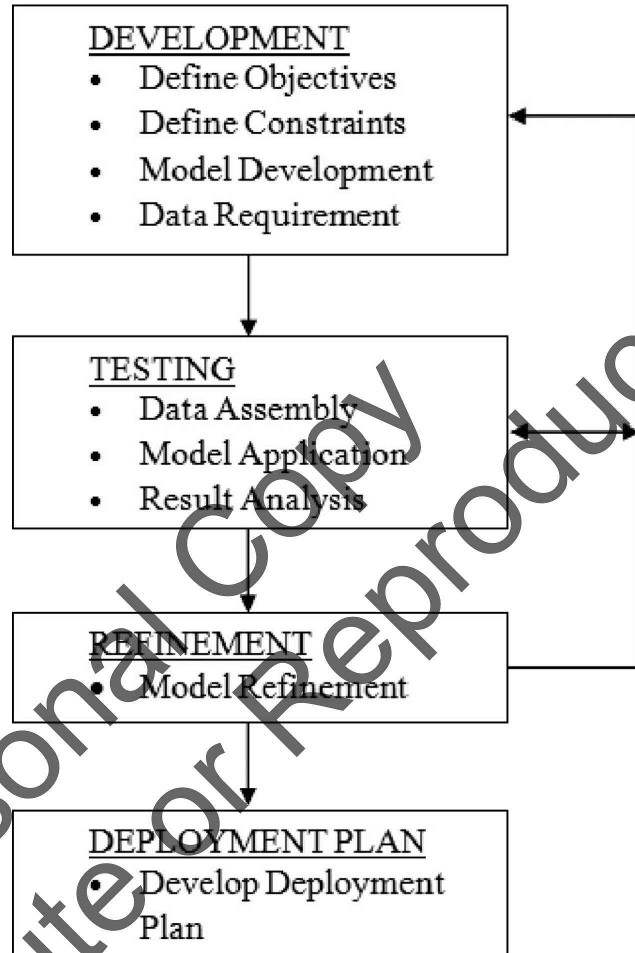

Figure 1. Flowchart of the overall approach.

MODEL FORMULATION

Figure 1 shows a flowchart of the overall approach that involves several steps ranging from development of the model to proposing a deployment plan of emissions control technologies. This model, which incorporates net present worth of benefits and costs, is an improved version of the model formulated by Bari.[26] The process begins with conceptualizing the model through incorporating the objectives, constrains, and required data. The subsequent steps are testing and refinement of the model. The final step is the output of the model that will provide a deployment plan prescribing a mix of emissions reduction technologies for deployment.

The objective of this optimization model is to maximize the emissions reduction and fuel savings for a given nonroad construction equipment fleet. The constraint set consists of relevant economic, operational, and technical constraints. Table 2 summarizes the definition of the major variables used in the model. The set C is defined as the set containing the NA and NNA counties, indexed by c. The set n_c is the total number of counties in consideration. The set E is the set of different categories of construction equipment indexed by e, and the set n_e is the total categories of construction equipment for consideration. The set n_{ce} is the total number of equipment of category e located 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 denotes the total number of pollutants to consider.

Set T represents the set of emissions reduction technologies indexed by t, and n_t is the total number of emissions control technologies to consider. Em denotes

Table 2. Nomenclature of the variables used in the model.

Variable	Definition
C	Set of NA and NNA counties
n_c	Total number of counties
E	Set of different categories of construction equipment
n_e	Total categories of construction equipment
$n_{c,e}$	Total number of equipment of category *e* in county *c*
P	Set of different pollutants
n_p	Total number of pollutants
T	Set of emissions reduction technologies
n_t	Total number of emissions reduction technologies
Em	Emissions from a piece of equipment
C_p	Cost of pollutant *p*
$R_{p,t}$	Emissions reduction efficiency of technology *t* for pollutant *p*
I	Binary variable
AP	Set of analysis periods for each piece of equipment
$F_{c,e,i.}$	Fuel consumption of a piece of equipment
C_F	Cost of fuel per gallon
FE_t	Fuel efficiency of technology *t*
C_t	Cost associated with technology *t*
$Com_{c,e,i,t}$	Operation and maintenance costs of technology *t* for each piece of equipment
$ru_{c,e,i}$	Remaining usage hours of a piece of equipment
$U_{e,i}$	Expected usage hours of a piece of equipment
$ra_{c,e,i}$	Remaining age of a piece of equipment
$A_{e,i}$	Expected age of a piece of equipment

the emissions from a particular piece of equipment. C_p represents the cost of the pollutant *p*, and R_{pt} is the emissions reduction efficiency of technology *t* for pollutant *p*. The variable *I* represents a binary variable having a value of 0 or 1. If a particular technology is selected for a piece of equipment, then the value of *I* will be 1; otherwise it will be zero.

The set *AP* is the analysis period for each piece of equipment during which retrofit costs could be incurred or benefits received, and *AP* is indexed by α. For an equipment of category *e* located in county *c*, the corresponding analysis period would be $\alpha_{c,e,i}$. For the net present worth analysis, the interest rate *r* was considered to be 3%.[27] For simplicity, it was assumed that the usage hour and fuel consumption for each piece of equipment as well as operation and maintenance costs for each technology will remain constant for each year within the analysis period.

Similarly, the benefits obtained from emissions reduction and fuel savings for each piece of equipment will remain constant for each year within the analysis period. The cost of emissions per pollutant *p* from the *i*th equipment of category *e* located in county *c* is $Em_{c,e,i,p}C_p$. If technology *t* is applied on that particular piece of equipment, the emissions reduction benefit will then be $Em_{c,e,i,p}C_pR_{p,t}I_{c,e,i,t}$. The final expression of the present worth value of total emissions reductions over a period of $\alpha_{c,e,i}$ for each piece of equipment is

$$\sum_{\alpha \in AP}\sum_{c \in C}\sum_{e=1}^{n_e}\sum_{i=1}^{n_{c,e}}\sum_{p=1}^{n_p}\sum_{t=1}^{n_t}(Em_{c,e,i,p}C_pR_{p,t}I_{c,e,i,t}) \times \left\{\frac{(1+r)^{\alpha_{c,e,i}-1}}{r(1+r)^{\alpha_{c,e,i}}}\right\} \quad (2)$$

Henceforth, the second factor of the above expression is denoted by $\beta_{c,e,i}$ so that

$$\beta_{c,e,i} = \left\{\frac{(1+r)^{\alpha_{c,e,i}-1}}{r(1+r)^{\alpha_{c,e,i}}}\right\} \quad (3)$$

The fuel consumption of a piece of equipment is denoted by $F_{c,e,i}$, the fuel efficiency of technology *t* is FE_t, and the cost of fuel per gallon is C_F. If the technology selected causes a fuel penalty, then the value of FE_t will be negative. Therefore, the expression for fuel savings is $F_{c,e,i}C_FFE_tI_{c,e,i,t}$. The final expression of the present worth value of the total fuel savings over a period of $\alpha_{c,e,i}$ for each piece of equipment is

$$\sum_{\alpha \in AP}\sum_{c \in C}\sum_{e=1}^{n_e}\sum_{i=1}^{n_{c,e}}\sum_{t=1}^{n_t}(\beta_{c,e,i}F_{c,e,i}C_FFE_tI_{c,e,i,t}) \quad (4)$$

Objective Function

Two objectives were considered: (1) maximization of emissions reduction and (2) maximization of fuel savings. The final expression of the weighted objective function consisting of emissions reduction benefits and fuel savings is shown in eq 5.

$$\text{Maximize } Z = W1\sum_{\alpha \in AP}\sum_{c \in C}\sum_{e=1}^{n_e}\sum_{i=1}^{n_{c,e}}\sum_{p=1}^{n_p}\sum_{t=1}^{n_t}(\beta_{c,e,i}Em_{c,e,i,p}C_pR_{p,t}I_{c,e,i,t}) + W2\sum_{\alpha \in AP}\sum_{c \in C}\sum_{e=1}^{n_e}\sum_{i=1}^{n_{c,e}}\sum_{t=1}^{n_t}(\beta_{c,e,i}F_{c,e,i}C_FFE_tI_{c,e,i,t}) \quad (5)$$

In eq 5, *W1* and *W2* are the weights associated with the emissions reduction benefits and the benefit from fuel savings, respectively, such that *W1* + *W2* = 1. Note that *W1* and *W2* can be assigned any values between 0 and 1 to represent the contribution of emissions reduction and fuel saving benefits, respectively.

Model Constraints

For formulation of constraints, information about the type of emissions reduction technologies (e.g., retrofit, fuel additive, etc.) is necessary. For the model presented here, it is assumed that three technologies (labeled as X, Y, and Z) are available for use. Further, assume that X and Y correspond to some retrofit type of technology and Z represents a fuel additive that is injected into the fuel system. The purchase and installation cost of emissions reduction technology *t* is denoted by C_t and the operation and maintenance cost are represented by $Com_{c,e,i,t}$. The purchase and installation costs associated with emissions reduction technology *t* is then $C_tI_{c,e,i,t}$, and the operation and maintenance costs are $Com_{c,e,i,t}I_{c,e,i,t}$. The expression for the budget constraint is presented in eq 6, in which the first and second terms represent the purchase and installation costs and the operation and maintenance costs, respectively, incurred for retrofit technologies and the third term is the cost associated with the fuel additive.

$$\sum_{c \in C} \sum_{e=1}^{n_e} \sum_{i=1}^{n_{c,e}} \sum_{t=1}^{(n_t-1)} C_t I_{c,e,i,t} + \sum_{\alpha \in AP} \sum_{c \in C} \sum_{e=1}^{n_e} \sum_{i=1}^{n_{c,e}} \sum_{t=1}^{(n_t-1)} (\beta_{c,e,i} Com_{c,e,i,t} I_{c,e,i,t}) + \sum_{\alpha \in AP} \sum_{c \in C} \sum_{e=1}^{n_e} \sum_{i=1}^{n_{c,e}} (\beta_{c,e,i} C_3 I_{c,e,i,t}) \leq \text{Budget (\$)} \quad (6)$$

To understand the criteria of selecting a piece of equipment eligible for being retrofitted, Texas Department of Transportation (TxDOT) officials were consulted. Through consultation with TxDOT, which is known to own the largest construction equipment fleet in the United States, it was found that a piece of equipment should have a remaining age and remaining usage hours of at least half of its expected age and expected usage hours before disposal for retrofitting. The remaining usage hours and the expected usage hours at disposal of a piece of equipment are represented by $ru_{c,e,i}$ and $U_{e,i}$, respectively. Similarly the remaining age and the expected age at disposal of a piece of equipment are represented by $ra_{c,e,i}$ and $A_{e,i}$, respectively. The constraints for remaining usage hours and remaining age are presented in eqs 7 and 8. Note that the coefficient of 0.5 used in eqs 7 and 8 can be changed to suit the policy of a given equipment fleet manager.

$$ru_{c,e,i} \geq 0.5U_{e,i} \quad (7)$$

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

$$ra_{c,e,i} \geq 0.5A_{e,i} \quad (8)$$

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

The combination of technologies, such as X ($t = 1$) with Z ($t = 3$) and Y ($t = 2$) with Z ($t = 3$), is possible (as indicated by experts' guidelines) whereas researchers considered that X and Y technologies are mutually exclusive and not deployed together. These constraints are shown in eqs 9 and 10.

$$\textstyle\sum_{t=1}^{n_t} I_{c,e,i,t} \leq 2 \quad (9)$$

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

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

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

Another requirement was that the fuel additive, such as Z ($t = 3$), must be deployed for all or none of the equipment within a county because fuel is generally supplied for all equipment within a county from a common fuel depot. Thus the fuel additive constraint is shown in eq 11.

$$I_{c,e,i=1,t=3} = I_{c,e,i=2,t=3} = \ \cdots\ = I_{c,e,i,t=3}\ \forall\, c,e \quad (11)$$

Therefore, the final optimization model is an IP model. The objective function is expressed by eq 5, which is subjected to the constraints expressed in eqs 6–11. The model result will be a deployment plan of emissions control technologies with a view to maximize the emissions reduction and fuel-savings benefits depending on the values of *W1* and *W2*. Most IP problems, such as the one presented here, are combinatorial and NP-hard and therefore not easily solvable. The model was programmed and solved with Visual C++ and ILOG CPLEX. The model formulation is quite general and can be upgraded and expanded to include emissions reduction options other than NO_x and the other set of emissions reduction technologies and can be applied to on-road and nonroad sources in excess of nonroad construction equipment fleet.

CASE STUDY

For demonstration purposes, the model was solved considering three main categories of construction equipment (e.g., graders, loaders, and excavators) from TxDOT's construction equipment fleet assuming that the three emissions reduction technologies labeled previously as X, Y, and Z, represent, respectively, hydrogen enrichment (HE), selective catalytic reduction (SCR), and fuel additive (FA) technologies. The selected technologies HE, SCR, and FA have different operational and performance characteristics. FA is very inexpensive with low emissions reduction efficiency and providing no fuel economy. HE is moderately expensive with moderate emissions reduction efficiency and leading to better fuel economy. SCR is the most expensive technology with the highest emissions reduction efficiency, but it is coupled with a fuel penalty. These three emissions reduction technologies were selected because their different operational characteristics would enable testing the adaptability of the model and data for these technologies were readily available.

Texas has 254 counties, of which 20 counties are designated as NA and 3 counties are designated as NNA counties by EPA. Figure 2 presents the Texas districts in the 8-hr ozone NA and NNA counties.[9] Federal funding will be at risk if Texas violates the air quality standards established by the Federal Clean Air Act and regulated by EPA. For this reason, the Texas Commission on Environmental Quality, TxDOT, and their local partners have focused most of their emissions reduction programs on these NA areas.[28]

TxDOT has one of the largest construction equipment fleets in the United States and they own and operate approximately 3200 pieces of nonroad diesel equipment.[18] Their construction equipment fleet consists of graders, loaders, excavators, pavers, rollers, trenchers, cranes, and off-highway tractors. They have prepared a well-organized database of their nonroad fleet containing different characteristics of equipment such as horsepower, fuel consumption, model year, age, usage hours, and location of the equipment, etc. This database was helpful in estimating the emissions from the construction equipment fleet using EPA's procedure as previously mentioned.

According to EPA's 2008 NEI data, the total NO_x emissions from on-road and nonroad sources were 354,370 and 131,566 t, respectively, in Texas; nonroad sources accounted for 27% of the total NO_x emissions

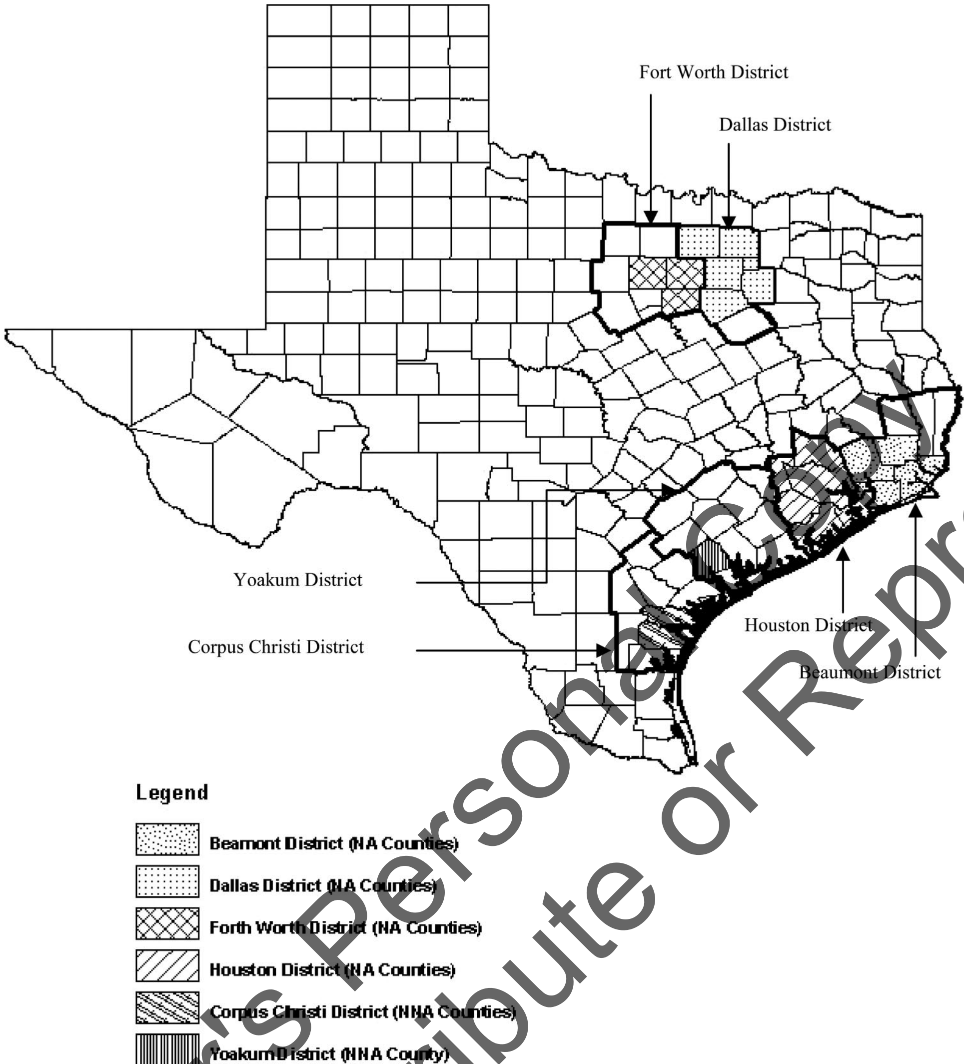

Figure 2. NA and NNA counties in Texas.

from the mobile sources in Texas.[6] The Texas Transportation Institute (TTI) estimated the total NO_x emissions from TxDOT's diesel construction equipment fleet to be 461 t over fiscal years 2005–2007 for a total of 3170 pieces of diesel construction equipment in Texas.[18] NO_x is a precursor of ozone, which is responsible for adverse health effects such as respiratory problems. Therefore, a priority for TxDOT is to reduce NO_x emissions from their large diesel construction equipment fleet, especially equipment located in NA and NNA counties.

The three main categories of diesel construction equipment—graders, loaders, and excavators—were selected for the study because these were the highest NO_x-emitting pieces of equipment of TxDOT's equipment fleet. The average NO_x emissions from graders, loaders, and excavators over fiscal years 2005–2007 were 146.1, 116.6, and 56.3 t, respectively, resulting in a total of 319 t of NO_x from these three categories of equipment.[18] NO_x emissions from graders, loaders, and excavators constituted approximately 69% of the total 461 t of NO_x emissions mentioned above. The remaining categories of equipment other than these three were considered as "other" categories in the analysis for estimating the amount of technology Z required for deployment in a county. According to TxDOT, all pieces of equipment in a county were fueled from a common diesel tank located in that county. Therefore, technology Z had to be deployed for all of the pieces of equipment located in a particular county (i.e., either the entire county receives Z or it does not receive it at all). The total amount of Z required for a county was estimated based on the amount of diesel required for the remaining or other categories of equipment in addition to graders, loaders, and excavators.

Data Requirement and Collection

Emissions Reduction Technologies. Data regarding the three different emissions reduction technologies were collected through communications with different technology vendors, questionnaire surveys, telephone interviews, and e-mails. The main purpose of the questionnaire survey was to acquire information regarding the characteristics and properties of the technologies, their availability, the different costs associated with them, requirements, fuel economy, and emissions reduction efficiencies. Because no reliable data were available regarding the effectiveness of the emissions control technologies, the data provided by the vendors had to be used. However, the model is general enough to be upgraded easily after better emissions reduction efficiency data are available.

The combinations of X with Z and Y with Z were considered in the model. The combined NO_x reduction efficiencies were estimated based on consultation with the vendors of X and Y. The vendor of X mentioned that the combination of X and Z systems will have an additive effect in NO_x reduction efficiency, with the combined NO_x reduction efficiency being 41.8%. Consultation with the vendor of Y revealed that the NO_x reduction efficiency due to the combination of Y and Z systems will not be additive, but it will have a combined effect with a combined efficiency of 81.16%. The vendor of Y mentioned that Y was not applicable for equipment having a horsepower of less than 100. The cost of technology Y and size of the components made the system impractical to retrofit on such a small mobile engine.

According to the vendors, technology X has a warranty up to 4545 hr of operation and technology Y has a life of 5 yr. Using the 4545 operation hours for every piece of equipment in the NA and NNA counties, researchers found that the technology life of X calculates out to be greater than 5 yr for every piece of construction equipment in the study. The lifetime of technology Y is the limiting factor. Therefore, the maximum value that $\alpha_{c,e,i}$ can have is 5 yr in this study. Some of the equipment had a remaining age of less than 5 yr before disposal, and some of the equipment had already reached or exceeded the age for disposal. Under the circumstances, the following conditions were considered to determine the value of $\alpha_{c,e,i}$ for each piece of equipment:

(1) If the remaining age is $\geq$ 5 yr, then $\alpha_{c,e,i}$ = 5 yr.
(2) If 0 < the remaining age is < 5 yr, then $\alpha_{c,e,i}$ = the remaining age.
(3) If the remaining age is $\leq$ 0 yr, then $\alpha_{c,e,i}$ = 1 yr.

The second and third conditions mentioned above are valid only for Z deployment because the remaining age requirement for X or Y deployment is greater than 5 yr for all of the pieces of equipment being considered in the fleet.

The cost of diesel per gallon was incorporated into the model to consider the fuel savings or fuel penalty resulting from the installation of emissions reduction technology on a piece of equipment. The cost of diesel used in this study was $2.216/gal on the basis of a May 2009 diesel price.[29] Table 3 summarizes the data regarding the selected emissions reduction technologies used in this research.

Table 3. Data regarding selected emissions reduction technologies.

Technology	X	Y	Z
Purchase and installation cost ($)	8400	17100[c]	18[e]
Operation cost ($)	–	0.25[d]	–
Maintenance cost ($)	100[a]	0.75[d]	–
Dosage rate (mL)	–	–	4.25[f]
Fuel efficiency (%)	8[b]	−1	–
NO_x reduction efficiency (%)	36	80	5.8
NO_x combined reduction efficiency (%)	41.8	81.16[g]	–

Notes: [a]Per year; [b]After 240 hr of operation; [c]Within 101–300 hp; [d]Per hour; [e]Per gallon of Z; [f]Per gallon of diesel; [g]On the basis of consultation with the vendor for Y.

Table 4. Cost of NO_x obtained from different studies.

Pollutant	HERS Model[30] ($/t)	Delucchi[33] Low ($/t)	Delucchi[33] High ($/t)	Small and Kazimi[34] and Levinson[36] ($/t)[a]
NO_x	3,625	1,445 (1.59)	21,180 (23.34)	1,210 (1.33)

Notes: Values in parentheses are in $/kg as obtained from the studies. [a]Values obtained by Small and Kazimi as modified by Levinson.

Air Pollution Damage Cost. The damage cost of NO_x was obtained from the Highway Economic Requirements System (HERS) model[30] developed for the Federal Highway Administration. It was designed to simulate improvement selection decisions on the basis of the relative benefit-cost merits of alternative improvement options. The HERS model uses damage costs for different pollutants. The pollutants are CO, VOCs, NO_x, sulfur dioxide, $PM_{2.5}$, and road dust. The estimates were derived from the study performed by McCubbin and Delucchi.[31] The damage cost of NO_x used in the HERS model was $3,625/t, which was calculated from the total annual costs from health and property damages.

First, the total amount of each pollutant emitted annually by highway vehicles was calculated. The damage cost of each pollutant in dollars per ton was then derived by dividing the total annual cost from health and property damages by the respective pollutant emitted annually. These values are assumed to provide acceptable estimates of damage costs for each pollutant.[30] The damage cost for NO_x (i.e., $3,625) was used in this research for calculating NO_x reduction benefits.

Burris and Sullivan[32] identified a potential methodology for obtaining the incremental societal costs and benefits from a variable pricing project. They applied the methodology to the QuickRide high occupancy/toll lanes in Houston, TX. They considered vehicular pollutant emissions to estimate the benefits and costs of the project. They obtained the monetary values of emissions from research conducted by Delucchi[33] and Small and Kazimi.[34] These two works based the cost of emissions on the cost of healthcare for treatment of diseases related to motor vehicle emissions. Table 4 shows the NO_x costs obtained from different studies.

Analysis Scheme

For a given budget, TxDOT's preference is to allocate the available budget first in the NA counties for deploying the emissions control technologies, and then spend the remaining budget in the NNA counties. The construction fleet database revealed that approximately 77% of the fleet was in the NA counties, with the remaining 23% in the NNA counties. As previously mentioned, TxDOT suggested that the criteria regarding the remaining age and remaining usage hours should be at least equal to 50% of its expected age and expected usage hours, respectively, before considering a piece of equipment to be retrofitted. The data regarding the usage hours and the age at disposal

Table 5. Value of *W1* and *W2* for different cases.

Cases	Weights Associated with Benefits for	
	NO_x Reduction, *W1*	Fuel Savings, *W2*
1A and 2A	1	0
1B and 2B	0.7	0.3
1C and 2C	0.5	0.5 (base case)
1D and 2D	0.3	0.7
1E and 2E	0	1

of a piece of equipment were obtained from TxDOT. Approximately 25% of TxDOT's equipment had sufficient remaining age and remaining usage hours to satisfy the requirement.

Two different approaches were followed in obtaining the model solution. The first approach will be called "method 1," in which all of the technologies (i.e., X, Y, and Z) are optimally deployed only in the NA counties at the first stage. 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 of the technologies (i.e., X, Y, and Z) are optimally deployed in the NA counties along with the deployment of technology Z only in the NNA counties at the first stage. Then X and Y are deployed in the NNA counties in the second stage. Method 1 strictly follows the guidelines provided by TxDOT. Method 2 has been proposed as an alternative and was found to be a better option for deployment of emissions reduction technologies.

For both methods, the objective function consisted of two weighted-objectives: (1) maximizing NO_x reduction and (2) maximizing fuel savings subject to the constraints expressed in eqs 6–11. Technology X results in fuel savings whereas technology Y causes a fuel penalty. For the weighted objective function expressed by eq 5, five pairs of values for *W1* and *W2* were selected for each method (1 and 2) chosen for deployment of emissions reduction technologies. This produced five cases designated as A, B, C, D, and E for each method. Table 5 shows the values used for *W1* and *W2* used in this study for five different cases for each method (1 and 2). Table 6 summarizes the analysis scheme, and Figure 3 presents the flowcharts for methods 1 and 2.

RESULTS AND DISCUSSION

This section presents the model application results prescribing a mix of technologies to be deployed for emissions reduction on construction equipment. Two alternative approaches or methods have been tested, each having five options (A, B, C, D, and E) producing 10 cases. In the analyses, cases 1C and 2C, having weights of $W1 = 0.5$ and $W2 = 0.5$, respectively, for NO_x reduction and fuel-savings benefits in the weighted objective function were considered as the base cases. Comparison between the base case (i.e., cases 1C and 2C) and the other cases (i.e., A, B, D, and E) of the respective methods for total NO_x reduction and total combined benefits are analyzed and discussed. Next, comparisons between method 1 and method 2 for the respective cases are shown, followed by an analysis of the benefit-cost (B-C) ratio for both methods.

In the following discussion, total NO_x reduction means reduction of NO_x emissions from the equipment fleet located in NA and NNA counties. Combined fuel savings is defined as the fuel saved from the equipment fleet located in NA and NNA counties using the emissions reduction technologies. The total combined benefits include the NO_x reduction benefits and the fuel savings in the NA and NNA counties from installing emissions control technologies.

Table 7, a and b, present a summary of the intra- and intermethod comparison of the different cases, representing the deployment options of emissions reduction technologies in terms of total NO_x reductions and the total combined benefits. The first and the second part of Table 7a show the comparison of various cases for NO_x reductions with that of the respective base cases under method 1 and method 2, respectively. The third part of Table 7a presents the comparison between corresponding cases in methods 1 and 2. Table 7b contains a similar comparison of cases from the two methods in terms of the total combined benefits. Table 7, a and b, clearly show which case performs better in the different budget ranges together with the corresponding ranges of NO_x reductions and combined benefits. The intra- and intermethod comparisons of various cases are discussed in the following paragraphs.

Figure 4 shows the variation of the total combined benefits for methods 1 and 2 with increasing the budget.

Table 6. Analysis scheme.

Approach	Options	Cases
Method 1 (In the first stage deploy X, Y, and Z in NA counties; in second stage, deploy same technologies in NNA counties with remaining budget, if any)	Different combinations of two weighted objectives (i.e., NO_x reduction and fuel savings; see Table 5)	1A, 1B, 1C, 1D, and 1E
Method 2 (In the first stage, deploy X, Y, and Z in NA counties and Z in NNA counties; in second stage, deploy X or Y on any given equipment in the NNA counties with remaining budget, if any)		2A, 2B, 2C, 2D, and 2E

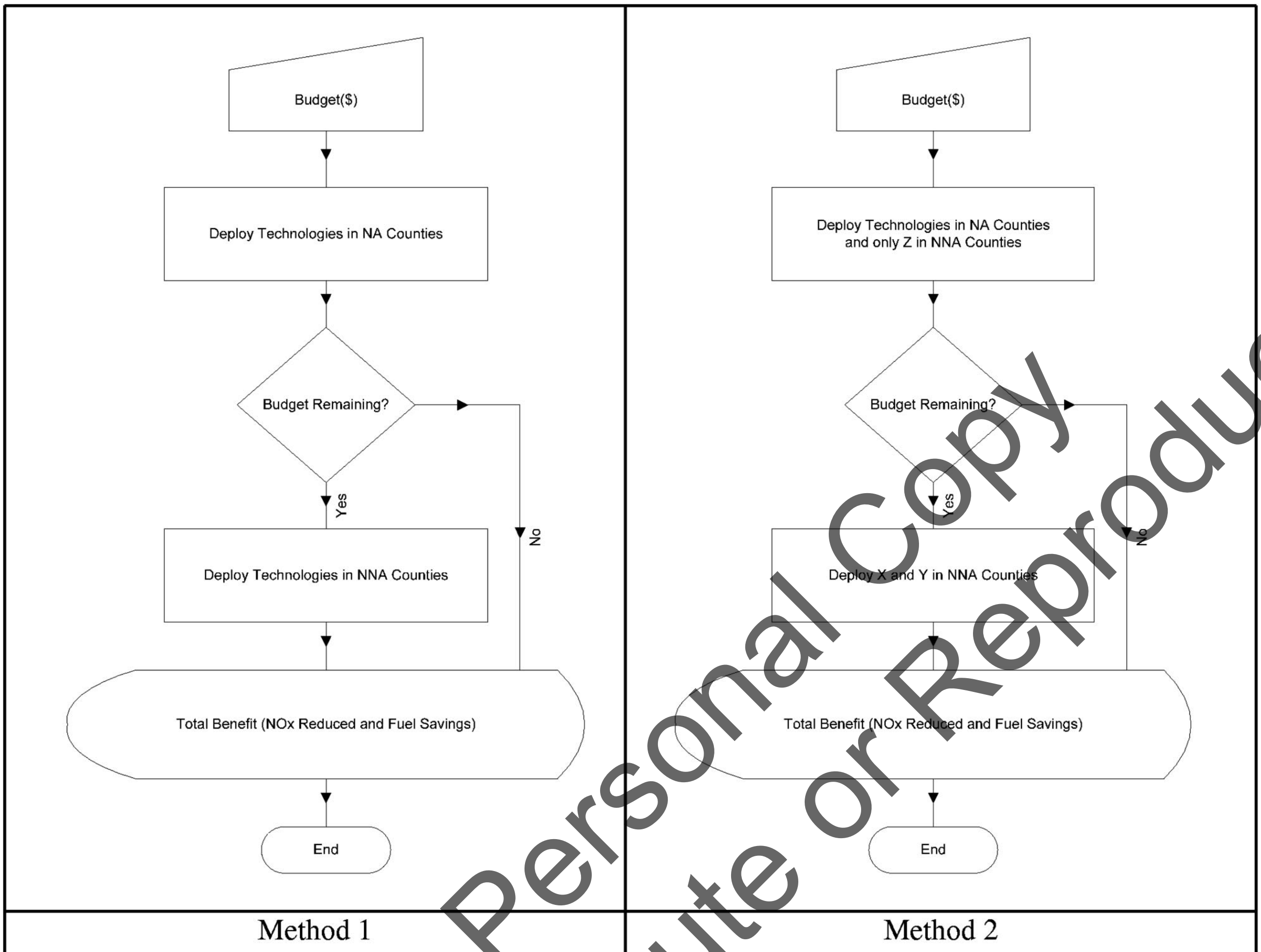

Figure 3. Flowcharts of methods 1 and 2.

These combined benefits result in the first year of deploying the emissions reduction technologies. The total combined benefit is composed of the benefits from the total NO_x reductions and total fuel savings. As expected, the total benefit generally increases with an increasing budget. However, method 1 shows that there are some drops in the total benefit as the budget increases. For example, B1 has a larger budget than B2, but the figure shows that the overall benefit for budget B1 is less than budget B2. This is the result of the deployment pattern chosen by TxDOT (i.e., giving priority to NA counties over NNA counties). The NA counties receive expensive technology such as X or Y in budget B1; therefore, less money is available for the NNA counties. Thus, the benefits for the NA counties rise but the benefits for NNA counties decrease, and as a result, the overall benefits decrease. However, in budget B2, the NA counties do not receive similar amounts of the expensive technology (such as X or Y) because the budget is insufficient and hence a larger budget amount is available for the NNA counties. This causes the overall benefit for B2 to be greater than B1. Therefore, method 2 was proposed to improve the deployment pattern and prevent the benefit decreases observed in method 1. In method 2, benefits are obtained even with a small increase in investment through deploying Z in the NNA counties at the first stage. Note that unlike method 1, method 2 does not depend on large investment amounts to realize benefits.

To present the sensitivity of the NO_x reductions and combined benefits with budgets, graphs of total NO_x reductions and total combined benefits are plotted for budgets ranging from approximately $500 to $1,500,000. The model solutions were developed for budgets up to $1,500,000 because NA and NNA counties receive the maximum possible units of X, Y, and Z coverage up to this budget amount; thereafter, NO_x reductions and the total combined benefits remain constant with further investment increases.

Comparison of Cases with the Base Case under Method 1

Figure 5, a and b, present the total NO_x reductions and total combined benefits, respectively, for all five cases in method 1. Comparisons of the cases in method 1 with the base case 1C are presented in the following paragraphs with reference to Table 7, a and b, and Figure 5, a and b.

Case 1A versus Case 1C. A comparison between case 1A and case 1C for the total NO_x reductions indicated that case 1C had greater NO_x reductions than case 1A for budgets ranging from $90,000 to $120,000, $180,000 to

Table 7a. Comparison of cases for total NO_x reductions.

Comparison Type	Cases Compared	Budget Range ($)	Outcome	Range of Total NO_x Reduction (t)
Comparison of cases with the base case under method 1	1A vs. 1C	90–120,000; 180,000–300,000; 900,000–1,200,000	1C>1A	0.0038–3.12
		Remaining budgets	1A≥1C	0–2.47
	1B vs. 1C	500–100,000	1B≥1C	0–1.72
		180,000–300,000		0.67–2.35
		600,000–1,500,000		0–0.78
		150,000–170,000	1C>1B	1.3–1.6
		400,000–500,000		0.51–2.48
	1C vs. 1D	500–50,000	1C≥1D	0–3.12
		80,000–110,000		0–3.70
		150,000–180,000		0.2–2.65
		300,000–1,500,000		0.28–5.74
		Remaining budgets	1D>1C	0.12–1.96
	1C vs. 1E	Entire budget range	1C>1E	0.57–51.51
Comparison of cases with the base case under method 2	2A vs. 2C	60,000–70,000	2A>2C	0.01–0.15
		90,000–700,000		0.04–0.98
		900,000–1,200,000		0.08–0.80
	2B vs. 2C	Entire budget range	2B≥2C	0–0.86
	2C vs. 2D	90,000–1,150,000	2C>2D	0.39–18.30
	2C vs. 2E	Entire budget range	2C>2E	0.60–51.51
Comparison of corresponding cases under methods 1 and 2	1A vs. 2A	500–500,000	2A>1A	0.03–2.73
		800,000–1,150,000	1A≥2A	0–0.084
	1B vs. 2B	500–500,000	2B>1B	0.03–3.05
		800,000–1,500,000	1B≥2B	0–0.11
	1C vs. 2C	500–200,000	2C>1C	0.03–3.50
		400,000–1,500,000	1C>2C	0–0.30
	1D vs. 2D	500–600,000	2D>1D	0.03–3.75
		800,000–1,150,000	1D≥2D	0–0.66

Table 7b. Comparison of cases for total combined benefits.

Comparison Type	Cases Compared	Budget Range ($)	Outcome	Range of Total Combined Benefit
Comparison of cases with the base case under method 1	1A vs. 1C	130,000–200,000; 400,000–1,200,000	1C≥1A	$0–11,100
		Remaining budgets	1A≥1C	$0–6,800
	1B vs. 1C	110,000–190,000	1C>1B	$320–8,865
		400,000–1,500,000		$30–9,855
		Remaining budgets	1B≥1C	$0–3,740
	1C vs. 1D	500–50,000	1C≥1D	$0–9,770
		80,000–110,000		$0–9,950
		150,000–180,000		$3,260–6,620
		300,000–600,000		$2,750–13,570
		1,100,000–1,500,000		$1,005–3,660
		Remaining budgets	1D>1C	$125–7,910
	1C vs. 1E	Entire budget range	1C>1E	$1,950–152,470
Comparison of cases with the base case under method 2	2A vs. 2C	500–1,000,000	2C≥2A	$0–3,970
		1,140,000–1,500,000		$0–100
		1,100,000–1,130,000	2A>2C	$10–40
	2B vs. 2C	500–1,000,000	2C≥2B	$0–1,480
		1,160,000–1,500,000		$0–100
		1,100,000–1,150,000	2B>2C	$10–170
	2C vs. 2D	90,000–1,150,000	2C>2D	$1,605–55,970
	2C vs. 2E	Entire budget range	2C>2E	$2,040–152,470
Comparison of corresponding cases under methods 1 and 2	1A vs. 2A	500–900,000	2A>1A	$90–8,675
	1B vs. 2B	500–1,000,000	2B>1B	$90–9,110
		1,140,000–1,190,000		$15–110
	1C vs. 2C	500–200,000	2C>1C	$90–9,485
		400,000–1,500,000	1C≥2C	$0–170
	1D vs. 2D	500–900,000	2D>1D	$90–11,330
		1,000,000–1,500,000	1D≥2D	$0–1,300

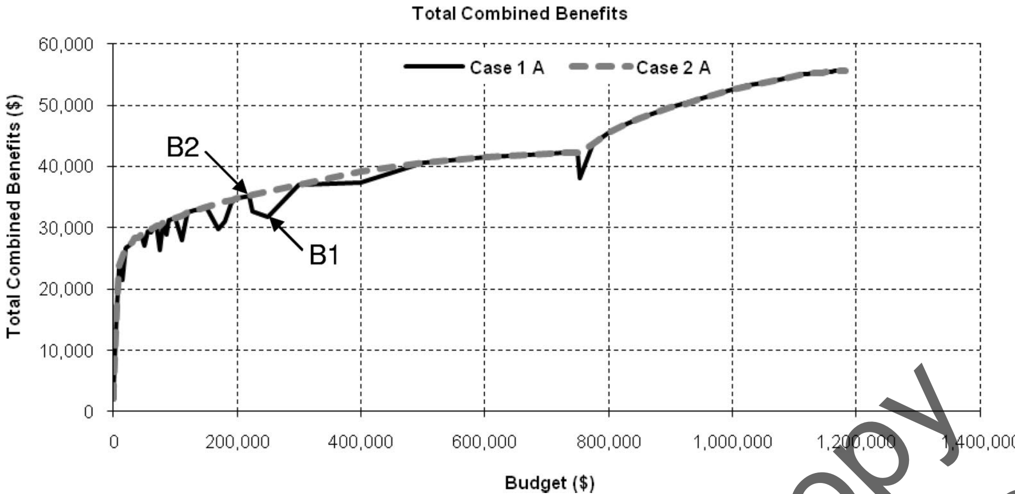

Figure 4. Total benefits for different budgets in methods 1 and 2 in the first year of deployment.

$300,000, and $900,000 to$1,200,000, respectively. The minimum and maximum differences in NO_x reductions within these budget ranges were 0.0038 and 3.12 t, respectively. Case 1A had either equal or greater NO_x reductions than case 1C for the remaining budget amounts. The maximum difference in NO_x reductions came to approximately 2.47 t within the remaining budget amounts.

Comparing the total combined benefits of cases 1A and 1C shows that case 1C had equal or higher benefits than that of case 1A for budgets ranging from $130,000 to $200,000 and $400,000 to $1,200,000. The maximum difference of total benefits in these budget ranges was approximately $11,100. For the remaining budget amounts, case 1A had either equal or greater total combined benefits than case 1C, with a maximum difference of approximately $6,800.

Case 1B versus Case 1C. Comparisons between case 1B and case 1C for total NO_x reductions indicated that the total NO_x reductions for case 1B were equal to or greater than those of case 1C for budgets ranging from $500 to $100,000, $180,000 to $300,000, and $600,000 to $1,500,000. The difference in NO_x reductions ranged from approximately 0 to 1.72 t, 0.67 to 2.35 t, and 0 to 0.78 t, respectively. Case 1C exceeded case 1B in terms of total NO_x reductions for budgets ranging from $150,000 to $170,000 and $400,000 to $500,000, with the corresponding NO_x reductions varying from approximately 1.3 to 1.6 t and 0.51 to 2.48 t, respectively.

Case 1C exceeded case 1B for total combined benefits for budgets ranging from $110,000 to $190,000 and $400,000 to $1,500,000, with the difference in the total combined benefits varying from approximately $320 to $8,865 and $30 to $9,855, respectively. For the remaining budget amounts, case 1B was either equal to or greater than case 1C in terms of total combined benefits, having a maximum difference of approximately $3,740 of total benefits.

Case 1C versus Case 1D. Case 1C was compared with case 1D and the results indicated that case 1C was equal to or greater than Case 1D for total NO_x reductions for budgets ranging from $500 to $50,000, $80,000 to $110,000, $150,000 to $180,000, and $300,000 to $1,500,000. The difference in total NO_x reductions ranged from approximately 0 to 3.12 t, 0 to 3.70 t, 0.2 to 2.65 t, and 0.28 to 5.74 t, respectively. For the remaining budget amounts, case 1D exceeded case 1C for total NO_x reductions, with the corresponding differences in NO_x reductions varying from approximately 0.12 to 1.96 t.

For the total combined benefits, case 1C was equal to or greater than case 1D for budgets ranging from $500 to $50,000, $80,000 to $110,000, $150,000 to $180,000, $300,000 to $600,000, and $1,100,000 to $1,500,000. The differences in total benefits within these budget ranges varied from approximately $0 to $9,770, $0 to $9,950, $3,260 to $6,620, $2,750 to $13,570, and $1,005 to $3,660, respectively. For the remaining budget amounts, case 1D exceeded case 1C for total combined benefits, with the differences in total benefit varying from approximately $125 to $7,910.

Case 1C versus Case 1E. Case 1C had greater total NO_x reductions than case 1E for the entire budget range of $500–1,500,000, with the difference in NO_x reductions varying from approximately 0.57 to 51.51 t. Similarly, for total combined benefits, case 1C exceeded case 1E for the entire budget range, with the difference in total combined benefits ranging from approximately $1,950 to $152,470.

Comparison of Cases with the Base Case under Method 2

Figure 6, a and b, show the total NO_x reductions and total combined benefits for method 2. On the basis of these figures and Table 7, a and b, comparisons of different cases under method 2 with base case 2C are presented in the following paragraphs.

Case 2A versus Case 2C. A comparison of total NO_x reductions between case 2A and case 2C revealed that case 2A exceeded case 2C in terms of NO_x reductions for budgets ranging from $60,000 to $70,000, $90,000 to $700,000, and $900,000 to $1,200,000. The differences in total NO_x

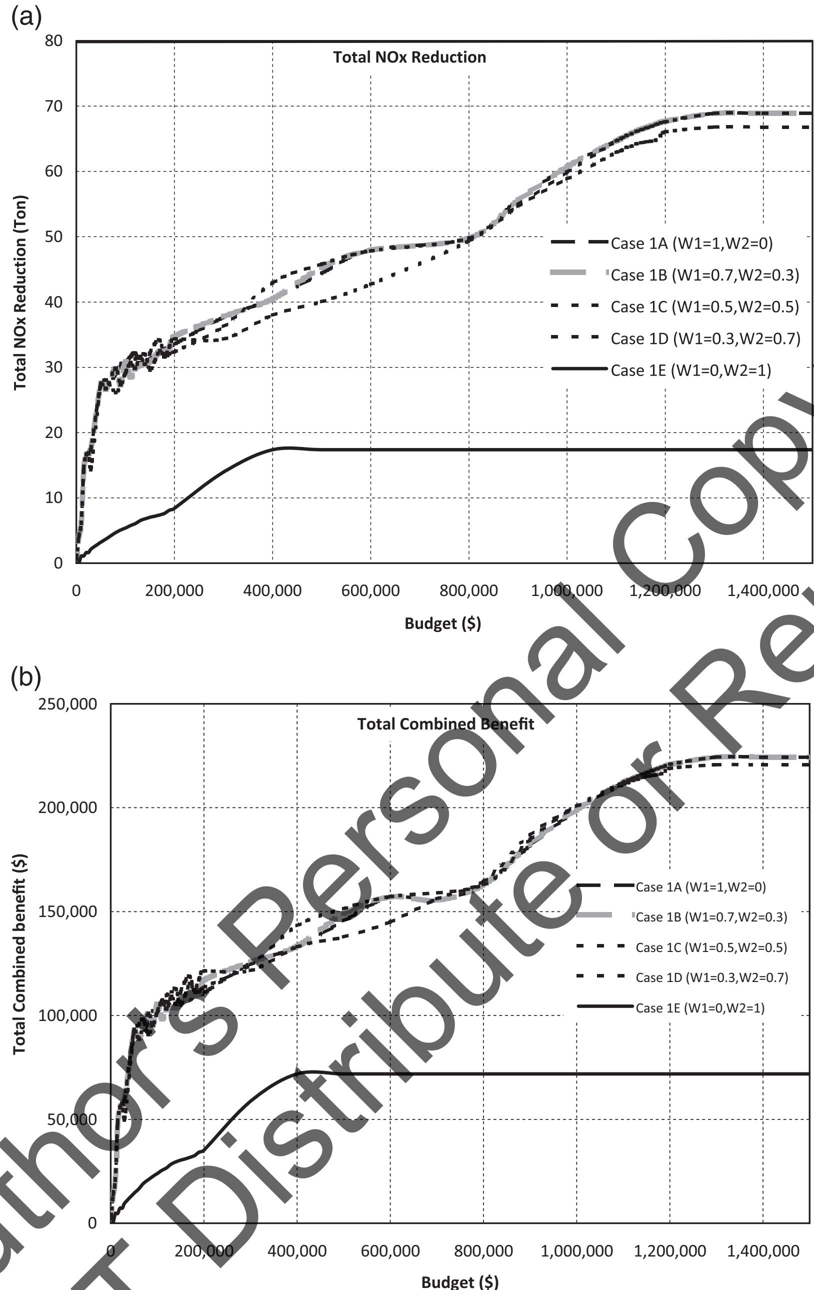

Figure 5. NO_x reductions and benefits obtained by method 1: (a) total NO_x reductions, and (b) total combined benefits.

reductions in these budget ranges varied from approximately 0.01 to 0.15 t, 0.04 to 0.98 t, and 0.08 to 0.80 t, respectively. For the remaining budget amounts, there was no difference between the two cases.

Case 2C was equal to or better than case 2A for total combined benefits for budgets ranging from \$500 to \$1,000,000 and \$1,140,000 to \$1,500,000. The differences in the total combined benefits in these budget ranges varied from \$0 to \$3,970 and \$0 to \$100, respectively. Case 2A showed greater combined benefits than case 2C, with the difference in the total combined benefits ranging from \$10 to \$40 for the budget ranging from \$1,100,000 to \$1,130,000.

Case 2B versus Case 2C. Case 2B had equal or greater total NO_x reductions than case 2C for the entire budget range of \$500–1,500,000. The difference in total NO_x reductions varied from approximately 0 to 0.86 t within that budget range.

Case 2C had equal or greater total combined benefits than case 2B for the budget ranges of \$500–1,000,000 and \$1,160,000–1,500,000. The differences in total combined benefits in these budget ranges were approximately \$0–1,480 and \$0–100, respectively. However, case 2B had greater total combined benefits than case 2C for budgets ranging from \$1,100,000 to \$1,150,000, with the difference in the total combined benefits in the range of approximately \$10–170.

Case 2C versus Case 2D. The total NO_x reductions and the total combined benefits for case 2C were greater than those

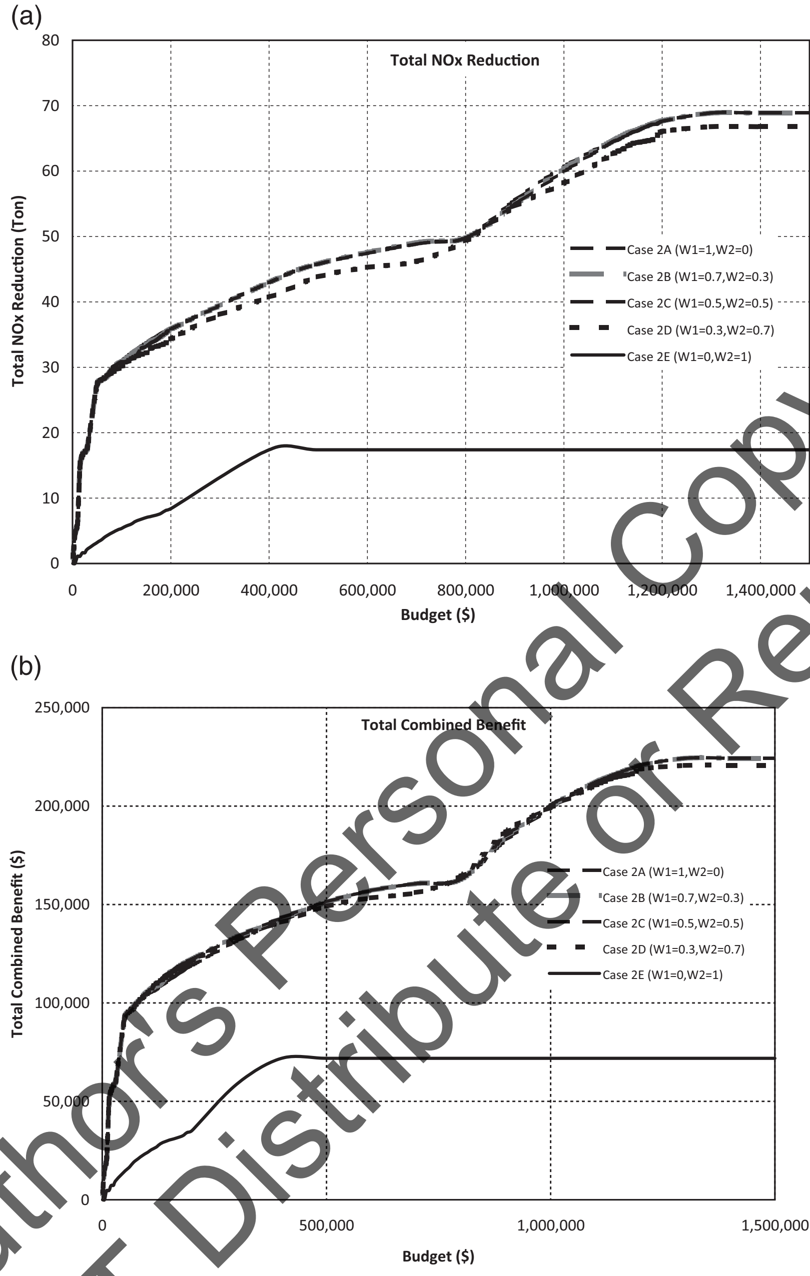

Figure 6. NO_x reductions and benefits obtained by method 2: (a) total NO_x reductions, and (b) total combined benefits.

for case 2D for the budget ranging from \$90,000 to \$1,150,000. The corresponding differences in total NO_x reductions and total combined benefits varied from approximately 0.39 to 18.30 t and approximately \$1,605 to \$55,970, respectively. For the remainder of the budget amounts, total NO_x reductions and total combined benefits were equal for both of the cases.

Case 2C versus Case 2E. In terms of total NO_x reductions and total combined benefits, case 2C was better than case 2E for the entire budget range of \$500–1,500,000, with the corresponding differences ranging from approximately 0.60 to 51.51 t and approximately \$2,040 to \$152,470, respectively.

Comparison between Corresponding Cases of Methods 1 and 2

This section presents a comparison between method 1 and 2 for the respective cases. Figures 7a–7h show the graphical comparison of the corresponding cases of the two methods in terms of total NO_x reductions and total combined benefits for both methods. Table 7, a and b, show summaries of the comparisons for total NO_x reductions and total combined benefits, respectively.

Case 1A versus Case 2A. Figure 7a and Table 7a show that case 2A performs better than case 1A at certain budget ranges. Case 2A exceeded case 1A in terms of total NO_x reductions for budgets ranging from \$500 to \$500,000 and the difference in total NO_x reductions varied from approximately 0.03 to 2.73 t in that budget range. For the remaining budget amounts, case 1A had equal or greater NO_x reduction benefits than case 2A for a budget ranging from $800,000 to $1,150,000, with NO_x reduction differences in the range of approximately 0–0.084 t.

Similarly, Figure 7b and Table 7b show that case 2A had greater total combined benefits than case 1A for the budget ranging from $500 to $900,000 with the difference in total combined benefits ranging from approximately $90 to $8,675. For the remainder of the budget amounts, the differences between the two cases were negligible.

Case 1B versus Case 2B. Referring to Figure 7c and Table 7a for total NO_x reductions and Figure 7d and Table 7b for total combined benefits, cases 1B and 2B show a similar pattern as described previously for cases 1A and 2A. Case 2B exceeded case 1B for total NO_x reductions for the budget ranging from $500 to $500,000, and the differences in total NO_x reductions varied from approximately 0.03 to 3.05 t in that budget range. For the remaining budget amounts, case 1B had equal or greater NO_x reductions than case 2B, with the difference in NO_x reductions ranging from approximately 0 to 0.11 t for the budget range of $800,000–1,500,000.

Figure 7d and Table 7b show that case 2B had greater total combined benefits than case 1B for budgets ranging from $500 to $1,000,000 and $1,140,000 to $1,190,000, with the total combined benefits difference ranging from approximately $90 to $9,110 and $15 to $110, respectively. For the remaining budget amounts, the differences between both of the cases were very negligible.

Case 1C versus Case 2C. Figure 7e and Table 7a show that case 2C had greater NO_x reductions than case 1C for budgets ranging from $500 to $200,000, with the corresponding difference in NO_x reductions varying from approximately 0.03 to 3.50 t. For the remaining budget amounts, case 1C had greater NO_x reductions than case 2C for budgets ranging from $400,000 to $1,500,000, with the difference in NO_x reductions ranging from 0 to 0.30 t.

Figure 7f and Table 7b indicate that case 2C had greater total combined benefits than case 1C for budgets varying from $500 to $200,000, with the difference in total combined benefits ranging from approximately $90 to $9,485. Case 1C had equal or greater total combined benefits than case 2C for budgets ranging from $400,000 to $1,500,000, with the difference in total combined benefits varying from approximately $0 to $170.

Case 1D versus Case 2D. Figure 7g and Table 7a show that case 2D exceeded case 1D in terms of total NO_x reductions for the budget ranging from $500 to $600,000, with the difference in total NO_x reductions varying from approximately 0.03 to 3.75 t. For the budget ranging from $800,000 to $1,150,000, case 1D had equal or greater NO_x reduction benefits than case 2D and the corresponding difference in NO_x reductions ranged from approximately 0 to 0.66 t.

For total combined benefit, Figure 7h and Table 7b show that case 2D had greater combined benefits than case 1D for the budget ranging from $500 to $900,000, with the difference in total combined benefits varying from approximately $90 to $11,330. Case 1D was equal to or greater than case 2D for the remaining budget amounts ($1,000,000–1,500,000), with the differences in the total combined benefits ranging from approximately $0 to $1,300.

Case 1E versus Case 2E. Cases 1E and 2E were the same in terms of deploying emissions reduction technologies. Both cases focus on maximizing fuel savings ($W1 = 0$ and $W2 = 1$) only. The cases do not focus in maximizing NO_x reductions because $W1 = 0$. Thus, with $W1 = 0$ and $W2 = 1$, both methods produced the same deployment pattern. Therefore, there was no difference between the cases. Figure 7i shows the total NO_x reductions and total combined benefits for cases 1E and 2E.

The discussion of the intra- and intermethod comparison of different cases shows that there were differences in total combined benefits among the cases. Often the difference in benefits was negligible or small, ranging from approximately $1 to $330. At times, the difference in the total combined benefits was high, ranging from approximately $1,000 to $152,500. The differences in the range of overall benefits between any two cases, for the intra- and intermethod comparison, varied from $1 to $152,500. The differences were primarily dependent on the available budget, emissions, horsepower, usage hours, fuel consumption, distribution of the equipment, and the total number of NA and NNA counties.

The graphs of combined benefits for cases 2A–2D appeared to be parallel, showing a similar increasing trend. Thus, both of the objectives, NO_x reductions and fuel savings, were equally beneficial and made the showed graphs for cases 2A–2D follow almost similar paths and directions (Figure 6b).

Figures 7a–7h show that the method 2 cases have higher NO_x reductions and higher total combined benefits than the method 1 cases for certain budget ranges, clearly showing that the method 2 graphs lie above the method 1 graphs. Method 2 cases prevented the benefit drops, which occurred in the method 1 cases for total NO_x reductions and total combined benefits. The method 2 graphs for total NO_x reductions and total combined benefits increased upward without any drop in NO_x reductions or benefits with the increased budget amounts.

In method 1, NA counties consume most of the available budget, leaving less available for NNA counties and thus sometimes lowering the overall benefits. However, in the same situation, the overall benefit could be increased by also spending a portion of the investment in the NNA counties. In method 1, after all of the equipment in the NA counties are supplied with Z, because Z is least expensive, depending on the available budget, X or Y can then be deployed on the equipment. If the available funding is not sufficient for deploying X, Y, or both in the NA counties, the remaining budget is assigned to the NNA counties and leads to increased overall benefits.

By increasing the budget (in the same situation), after the available funding is just sufficient to deploy X, Y, or both in the NA counties, all of the funding is assigned in

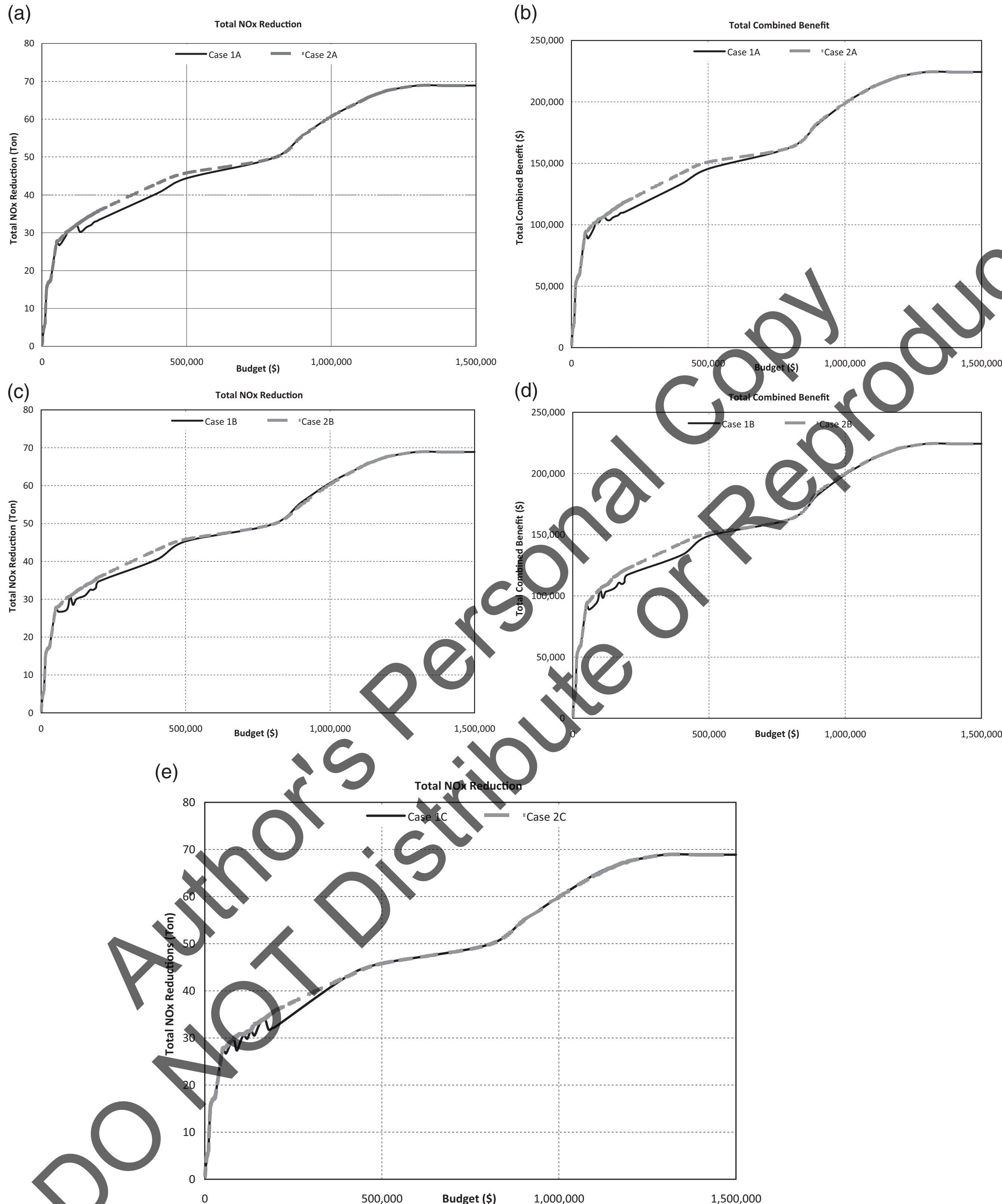

Figure 7. Comparison between cases: (a) total NO_x reductions (case 1A vs. case 2A), (b) total combined benefits (case 1A vs. case 2A), (c) total NO_x reductions (case 1B vs. case 2B), (d) total combined benefits (case 1B vs. case 2B), (e) total NO_x reductions (case 1C vs. case 2C).

the NA counties and the NNA counties may receive less, or nothing, compared with the previous situation. This causes the NO_x reductions and the overall benefits to drop compared with the previous situation.

The method 2 concept was developed to overcome the situation observed in method 1. In method 2, NO_x reductions and benefits are realized even with a small investment increase by deploying Z in the NNA counties

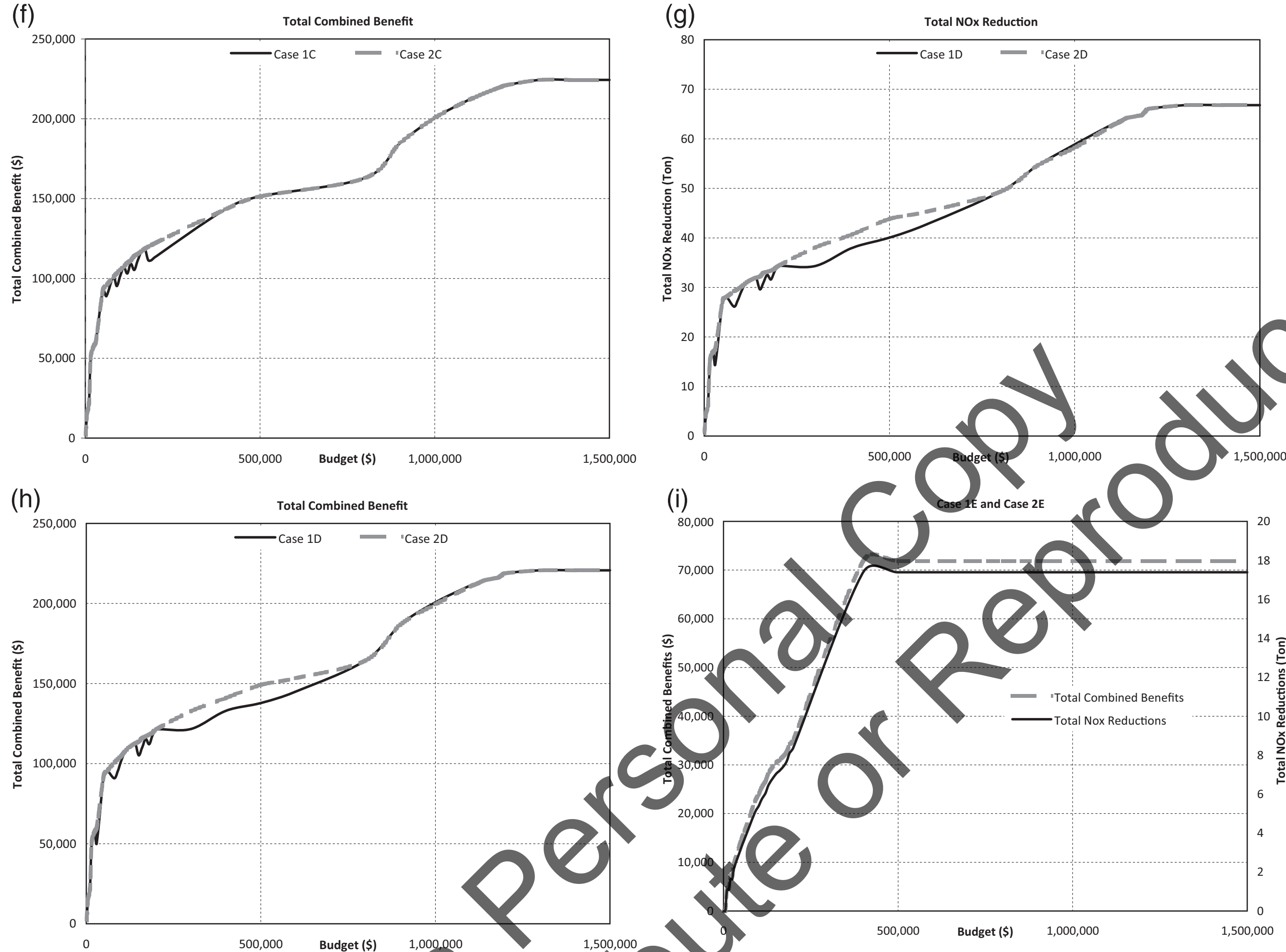

Figure 7. (cont.) (f) total combined benefits (case 1C vs. case 2C), (g) total NO_x reductions (case 1D vs. case 2D), (h) total combined benefits (case 1D vs. case 2D), and (i) total NO_x reductions and total combined benefits for case 1E and case 2E.

in the first stage. Deploying Z in the NNA counties in the first stage prevents the drop in NO_x reductions and combined benefits, which were observed in method 1 with increasing the budget.

Comparison of B-C Ratio of Methods 1 and 2

Figures 5b and 6b show that total combined benefits increase with increasing the investment under methods 1 and 2. The initial steep portion of the graphs (up to investment of approximately $100,000) indicates a higher B-C ratio for all cases except cases 1E and 2E. The B-C ratio is greater than 1 for investments up to $100,000 for both methods. In method 1, the B-C ratio varied from approximately 3.97 to 1 with investments up to $100,000. For budgets exceeding $100,000, the B-C ratio shows a decreasing trend, with the B-C ratio dropping from approximately 1 to 0.18. These B-C ratio values hold true on the average for all method 1 cases except case 1E. However, method 2 showed a higher B-C ratio, which ranged from approximately 4.15 to 1 for investments up to $100,000. Thereafter, the B-C ratio dropped from a value of approximately 1 to 0.18 for investments greater than $100,000. This is generally true for all method 2 cases except case 2E. For cases 1E and 2E, benefits started to accrue around a budget of $10,000 and the B-C ratio varied from 0.54 to 0.19 for budgets exceeding $10,000.

Identification of the Pareto Front

The rationale for this analysis is that providing decision-makers with the Pareto front/Pareto optimal solutions will assist them in determining the tradeoffs needed when selecting one candidate optimal solution versus others. Winston and Venkataramanan[35] defined Pareto optimal solutions as follows: "a solution (call it A) to a multiple-objective problem is Pareto optimal if no other feasible solution is at least as good as A with respect to every objective and strictly better than A with respect to at least one objective." A related definition is "a feasible solution B dominates a feasible solution A to a multiple-objective problem if B is at least as good as A with respect to every objective and is strictly better than A with respect to at least one objective." The set of all noninferior (not dominated) solutions is called the Pareto front.

Figure 8a shows the feasible solution sets for all cases in both methods. From these solution sets, the dominated/inferior points were identified and removed. The remaining solution set is the collection of noninferior solutions. Figure 8b presents the noninferior solution sets for all cases in methods 1 and 2. Table

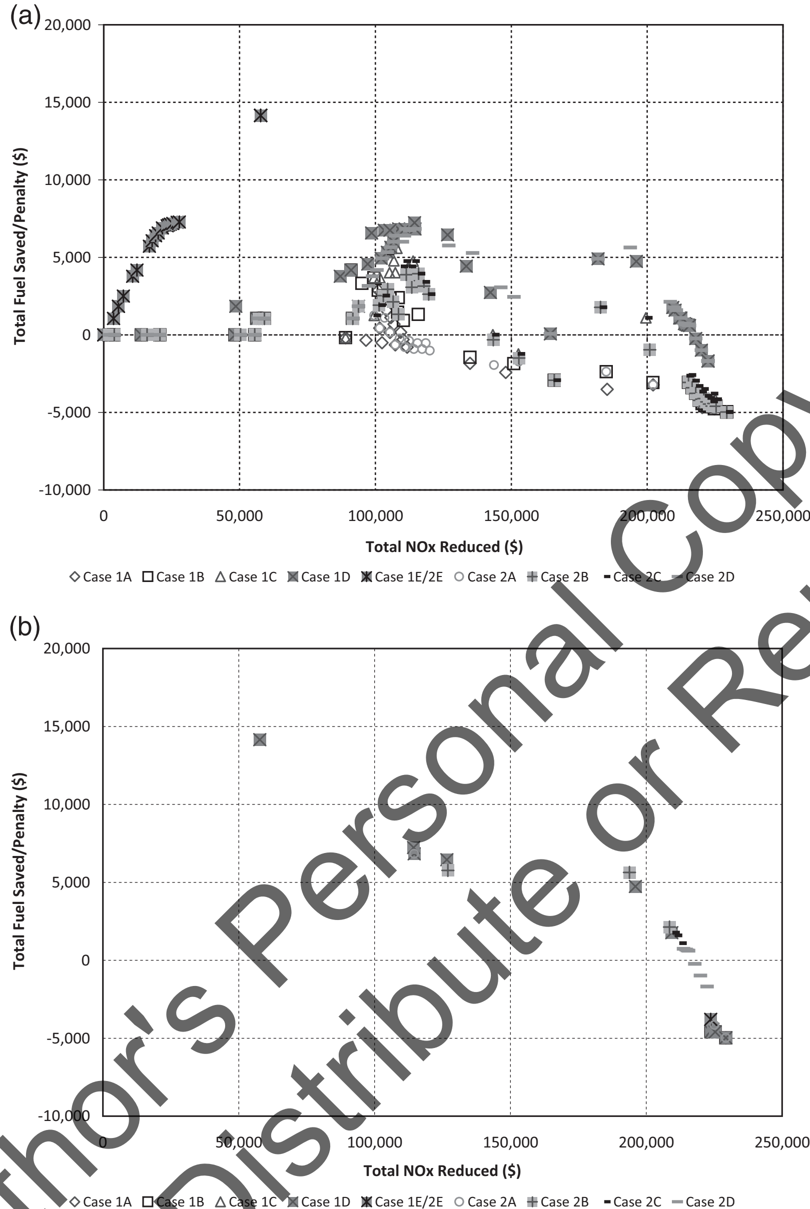

Figure 8. Identification of Pareto front for methods 1 and 2 (all cases): (a) feasible solution sets and (b) Pareto front.

8 presents a summary of the Pareto front for all of the cases in both methods. All of the points shown in Figure 8b or values in Table 8 are the noninferior solution for that particular budget amount. The decision-maker can achieve an optimal combination of NO_x reductions and fuel-savings benefits for a particular budget by choosing the appropriate weights *W1* and *W2* for NO_x reduction benefits and fuel-savings benefits, respectively.

This type of analysis will help the decision-maker achieve the noninferior solution set desired and will aid the decision-maker in determining which tradeoff to select from the multiple objectives available. Most of the cases (e.g., cases 1A, 1B, 1C, 2A, 2B, and 2C) had noninferior solutions in the budget range of approximately $1,180,000–1,300,000. Cases 1D and 2D had noninferior solutions in a wide budget range of approximately $200,000–1,300,000. Cases 1E or 2E had only one noninferior solution at a budget of $400,000.

Examining the values of total NO_x reductions and total fuel savings from Table 8 shows that the NO_x reduction objective is more dominant than the fuel-savings objective. Observing Figures 5b and 6b of cases 1A and 1E and cases 2A and 2E for the total combined benefits lead to the same conclusion because the graphs for cases 1A and 2A lie high above the graphs for cases 1E and 2E, respectively.

CONCLUSIONS

A multiobjective optimization model was developed in this study to provide an optimal emissions reduction technology deployment plan for nonroad construction equipment located in the NA and NNA counties. The model

Table 8. Summary of Pareto front for methods 1 and 2.

Budget ($)	Case	Total NO_x Reduced (t)	Total NO_x Reduced ($)	Total Fuel Savings ($)[a]
1,180,000	1A	67.24	223,824	−4,592
1,200,000	1A	67.71	225,385	−4,595
1,300,000	1A	68.90	229,324	−4,975
1,180,000	1B	67.24	223,824	−4,592
1,200,000	1B	67.71	225,385	−4,595
1,300,000	1B	68.90	229,324	−4,975
1,200,000	1C	67.60	225,037	−4,151
1,300,000	1C	68.90	229,324	−4,975
200,000	1D	34.34	114,576	6,830
300,000	1D	34.33	114,372	7,231
400,000	1D	37.99	126,572	6,451
1,000,000	1D	58.86	196,005	4,736
1,100,000	1D	62.90	209,402	1,768
400,000	1E or 2E	17.39	57,730	14,153
1,180,000	2A	67.24	223,824	−4,592
1,200,000	2A	67.71	225,385	−4,595
1,300,000	2A	68.90	229,324	−4,975
1,190,000	2B	67.44	224,488	−4,422
1,200,000	2B	67.71	225,385	−4,595
1,300,000	2B	68.90	229,324	−4,975
1,190,000	2C	67.21	223,729	−3,788
1,200,000	2C	67.60	225,037	−4,151
1,300,000	2C	68.90	229,324	−4,975
200,000	2D	34.34	114,576	6,830
300,000	2D	38.07	126,990	5,765
1,000,000	2D	58.20	193,801	5,637
1,100,000	2D	62.63	208,534	2,131
1,110,000	2D	63.04	209,874	1,768
1,120,000	2D	63.31	210,771	1,595
1,130,000	2D	63.80	212,422	1,092
1,140,000	2D	64.20	213,730	729
1,160,000	2D	64.47	214,647	683
1,170,000	2D	64.63	215,161	630
1,180,000	2D	64.75	215,570	607
1,190,000	2D	65.45	217,880	−231
1,200,000	2D	66.07	219,931	−985
1,300,000	2D	66.80	222,378	−1,686

Notes: [a]Negative value in this column indicates a fuel penalty.

focused on maximizing the benefits from emissions reductions and fuel savings for construction equipment satisfying operational, technical, and economic constraints. Application of the model was demonstrated using selected categories of TxDOT's construction equipment and a set of emissions reduction technologies having different operational and performance characteristics. The model formulation is quite general and can be upgraded and expanded to include emissions reduction options other than NO_x or other sets of emissions reduction technologies. The model can also be applied to other on-road and nonroad sources in addition to the nonroad construction equipment fleet examined in this study. The following are the main conclusions of this study:

- Model solutions suggested using different mixes of technologies to produce maximum NO_x reductions and total combined benefits (emissions reduction plus fuel savings) at different budget ranges.
- The initial steep portion of the plots for NO_x reductions and total combined benefits against the budget for different combinations of emissions reduction technologies indicated a high B-C ratio at lower budget amounts. The incremental benefits in terms of NO_x reductions and total benefits, as well as the B-C ratio, showed decreasing trends with increasing budgets, and with the budget exceeding certain limits, no further NO_x reductions or increases in total benefits were obtained.
- A Pareto front derived for various combinations of emissions reduction technologies would assist the decision-maker in determining the tradeoffs to make between the NO_x reductions and fuel-savings benefits.
- The study was limited because of the lack of reliable data regarding the effectiveness of the emissions control technologies. However, the model is general and can be upgraded easily after better emissions reduction costs and efficiency data become available.

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