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16. Abstract

This research study produced an optimization framework for determining the most efficient emission reduction strategies among vehicles and equipment in a large fleet. The Texas Department of Transportation's (TxDOT's) fleet data were utilized to identify the key factors as well as refine and demonstrate the developed framework. TxDOT owns and operates more than 11,000 vehicles, of which approximately 3,200 units are non-road diesel equipment. TxDOT is considering serious actions to reduce emissions from its fleet, especially in designated non-attainment (NA) and near non-attainment (NNA) areas. This project includes a comprehensive literature review, identifies the key parameters affecting the deployment of resources to reduce emissions, and develops a framework for producing an optimal emission reduction strategies deployment plan for a typical large fleet.

The capabilities of the proposed framework are demonstrated through a set of five case study scenarios. These scenarios cover a range of location preferences, budget limits, and analysis scales. TxDOT's fleet data were utilized in this effort. The mathematical formulation and optimization modeling is implemented using ILOG CPLEX and Visual C++ platforms.

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OPTIMIZED DEPLOYMENT OF EMISSION REDUCTION TECHNOLOGIES FOR LARGE FLEETS

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EXECUTIVE SUMMARY

This research study proposes an optimization framework for determining an optimal deployment plan of emission reduction technologies among vehicles in a large fleet. One of the main objectives for the research team was to structure the framework so it is able to handle a variety of vehicles and equipment as well as a wide range of emissions reduction strategies, location preferences, and pollutants. To achieve this objective, the framework was structured as a three-component system. Each component dealt with a specific task; i.e. an emissions estimation component, a data pre-processing module, an optimization component. The role of the components is to give flexibility to the users within each individual component while maintaining the consistency of the interactions between them. The resulting framework is flexible enough to include different combinations of location, vehicles, and other key factors in the analysis.

The emissions estimation encompasses methodologies for on-road and non-road mobile sources of emissions. This component was built based on the Environmental Protection Agency's (EPA's) MOVES model and EPA's guidelines for non-road equipment. The emissions estimation component provides an estimate of the total annual amount of desired pollutants for each individual vehicle or piece of equipment using the information recorded in a fleet inventory database.

The data pre-processing module performs two main tasks. First, it cleans up the list of vehicles and equipment through applying a set of user-defined conditions to filter out equipment that are not eligible for retrofitting. This includes, but is not limited to, conditions such as filtering out newer vehicles or low emission equipment. Second, it puts the information of the eligible equipment in the format compatible with the input requirements of the optimization component.

The optimization component consists of the mathematical formulation of the problem in the form of an objective function and a set of four constraints representing the selection criteria. The objective function represents the combined impact of pollutant emissions. The constraints were determined based on literature review and interview with TxDOT fleet manager. The resulted optimization component is an integer programming (PI) system and can be solved using standard optimization software packages.

To demonstrate the capabilities of the proposed framework, a set of five scenarios was developed and executed. These scenarios cover a range of location preferences, budget limits, and analysis scales. The case study analysis included five pollutants and nine strategies. TxDOT fleet data were utilized in this effort. The mathematical formulation and optimization modeling is implemented using ILOG CPLEX and

Visual C++ platforms. TxDOT fleet manager provided requirements regarding eligibility criteria for a piece of equipment to be retrofitted.

CHAPTER 1
INTRODUCTION

Air pollution is one of the major problems of modern cities and has serious negative effects on human health, the environment, and the economy. Air pollution has been associated with significant negative impacts on human health. For example, particulate matter pollution (PM) worsens heart diseases and causes premature deaths; carbon monoxide (CO) causes headaches, nausea, and chest pains; and nitrogen dioxide (NO_2) increases response to allergens [1].

Approximately 30 million adults and children in the United States have been identified with asthma. Some pollutants such as tiny airborne particles and ground-level ozone are known to trigger respiratory problems especially for people with asthma and the elderly. Furthermore, highly toxic chemicals, such as benzene and vinyl chloride, are released in the air by the vehicles and can cause cancer, birth defects, long-term injury to the lungs and brain, and even damage nerve system.

Air pollution has also significant negative impact on the environment. Mobile source emissions such as toxic air pollutants and chemicals contribute to environmental damages through forming acid rain and ground-level ozone, damaging crops, trees, wildlife, lakes, and other water bodies. These pollutants also cause damage to fish and other aquatic life. Finally, economic losses are also associated with air pollution in the form of lost work days and inhibiting agricultural crop and commercial forest yields with billions of dollars value each year [2].

EMISSIONS SOURCES

According to the U.S. Environmental Protection Agency (EPA) air pollution sources are categorized into stationary and mobile sources. Stationary sources are fixed in place. Common examples of stationary sources include power plants, manufacturing facilities and factories, and oil refineries. Mobile sources are non-fixed sources of air pollution and include vehicles, engines, and equipment that move from place to place.

Mobile sources are divided into two groups: on-road and non-road sources. On-road sources are those used on roads for movement. These include light and heavy duty trucks, light duty vehicles, passenger vehicles, motorcycles etc. Non-road sources include aircraft, engines, locomotives, and construction and agriculture equipment [3].

Mobile sources are usually the primary cause of air pollution in many urban areas. These sources emit pollutants such as carbon monoxide , volatile organic compounds (VOCs), nitrogen oxides (NOx), and particulate matter (PM) as well as hazardous air pollutants (air toxics) such as benzene, formaldehyde and acetaldehyde [4].

LARGE FLEET'S MOTIVATION TO REDUCE EMISSION

EPA regulates the Clean Air Act standards for air quality. Based on these standards 20 counties of Texas are categorized as non-attainment since these areas do not meet with the required air quality standards regarding one or more pollutants. According to Texas Department of Transportation (TxDOT), federal funding will be at risk if EPA's air quality standards are violated. Therefore, Texas Commission on Environmental Quality (TCEQ), TxDOT, and their partners focus on satisfying those requirements by trying to reduce the air pollution in Texas.

Large fleet operators such as TxDOT operate a large number of vehicles and equipments. Emissions coming from these fleets are responsible for large amounts of air pollution. Because of the semi-central nature of decision making and operation, fleet operators have the opportunity to use their resources to invest in lower emissions vehicles and emission reduction technologies. This study proposes a flexible optimization framework to assist fleet managers in selecting appropriate options for their fleet.

RESEARCH GOAL AND METHODOLOGY

This study developed a framework for optimal deployment of emission control strategies for large fleets. The goal is to reduce emissions from on-road vehicles and construction equipment fleet given budget and other relevant economic, operational, and technical constraints. The proposed framework enables fleet managers in utilizing their resources effectively to reduce the emissions from their vehicles and equipment in a cost-effective and optimal manner. The optimization framework focuses on choosing the best emission reduction strategies for selected vehicles and equipment.

The framework is demonstrated through utilizing TxDOT's on-road vehicles and construction equipment spread throughout all Texas counties. For demonstration purposes, several emission reduction technologies such as fuel additive (FA) and selective catalytic reduction (SCR) are included in the case study demonstration. However, the framework is not locked to these strategies; instead, it is designed to handle different types of emission reduction strategies. The target pollutants included in the framework are carbon dioxide (CO_2), CO, oxides of nitrogen (NOx), total hydrocarbons (THC), and PM finer than 2.5 nanometer (PM2.5).

The research team suggests the following problem statement:

> *For a fleet that contains both on-road vehicles and non-road equipment, find the optimal combination of emission reduction strategies that maximizes the emission reduction benefits in a cost-effective manner.*

This problem statement is translated to a mathematical format using an objective function and a series of constraints. The proposed objective function is composed of combined emission reduction benefits. The framework's structure is made flexible so that it can be applied to a broad range of emission reduction strategies for optimal deployment. The following steps are involved in achieving the goal of this study:

Task 1–Literature Review: This step helped researchers gain a better understanding of relevant issues such as how to estimate emissions for on-road and non-road vehicles, emission reduction strategies and their characteristics, and properties of large fleets vehicle and equipment databases. Material from EPA's website was extensively used to review the methodologies (MOVES and Non-Road Models) to estimate emissions. The research team identified and reviewed the issues of large vehicle fleets' air quality impacts and current practices relevant to reducing emissions from fleet activities.

Task 2–Characterize TxDOT's Fleet Operations and Emissions: TxDOT's fleet of vehicles and equipment are used in this study to build an understanding of large fleet operators' and owners' concerns about their air quality impacts. These included current and projected resources, limitations, and decision-making flow with regard to air quality performance as well as their current emission reduction practices, experience to date, and challenges. Key personnel at TxDOT were interviewed. Researchers also obtained the up-to-date TxDOT fleet database. The information and data obtained played a crucial role in developing the proposed framework.

Task 3–Identify and Characterize Emission Reduction Strategies: Potential emission reduction strategies, both technological options and operational practices, were identified and reviewed with an emphasis on CO, NOx and PM emissions. This task compiled an understanding of the potential emission reduction strategies, which contains information on characteristics of each option in terms of efficiency and applicability to large fleets' operations.

Task 4–Construct and Refine the Optimization Model: This task consisted of three major steps:

- Identifying the key factors that determine the deployment of emission reduction technologies among the target counties. These factors included specific information on vehicles such as horsepower and gross vehicle weight ratio (GVWR), cost of the reduction technologies, and emission reduction benefits that they provide.

- Constructing and formulating the objective function for determining the optimal assignment of emission reduction strategies.

- Identifying and formulating the constraints for such deployment analysis. The objective function and the constraints were developed in consultation with TxDOT staff.

Costs associated with deploying the strategies, location, operational hours, age of the equipment, and available budget are among the potential factors considered to be included in the framework. TxDOT staff was consulted on each step to ensure that the model captures the key components. Furthermore, a subset of fleet data obtained from TxDOT was used in a feedback loop process to refine the model.

Task 5–Model Demonstration Using TxDOT Fleet Data: The capabilities of the framework are demonstrated by applying a selection of emissions control strategies for vehicles and equipment in the TxDOT fleet. Researchers developed and executed a series of budget and deployment scenarios to showcase the flexibility of the framework. The most recent TxDOT fleet inventory was used for this purpose. The required information regarding the vehicles, TxDOT operation, emission reduction strategies' cost, and efficiencies were plugged into the framework, and the optimal distribution of strategies was determined.

Organization of This Report

The report has been divided into six chapters. Chapter 1 includes an introduction to the research and covers aspects such as statement of the problem, research goal and methodology, and organization of the report. Chapter 2 provides a literature review on emissions from fleet vehicles and applicable emission reduction strategies. Chapter 3 focuses on optimization framework development. Chapter 4 provides a summary of data utilized in this study. Chapter 5 discusses the framework demonstration through case studies. Chapter 6 contains the concluding remarks.

CHAPTER 2
LITERATURE REVIEW

This chapter provides an overview of the current literature regarding estimate emissions for on-road and non-road vehicles, and emission reduction strategies and their characteristics.

EMISSION ESTIMATION MODELS

The Clean Air Act defines the EPA's responsibilities for protecting public health and improving the nation's air quality [5]. The Act enables the EPA to set and enforce clean air standards that contribute to the improvement in human health. It also requires the EPA to develop and regularly update emissions factors and emissions estimation models for all emissions sources in the United States. As part of a broad array of strategies enacted to fulfill these mandates, the EPA has employed several emissions estimation methodologies that can be used to support emission reduction strategies. This section provides an overview of the current emissions models the EPA had developed.

MOBILE

MOBILE1 was the first model for highway vehicle emission factors that EPA had developed. Prior to this model, all emissions factors were tabulated in look-up tables. MOBILE1 was capable of modeling exhaust emission rates as functions of age and mileage.

The MOBILE model has undergone numerous revisions since its introduction and is now used for various activities beyond its original purpose, including developing emissions inventories and reductions for state pollution reduction plans, demonstrating conformity of transportation plans with air quality plans, and estimating the performance of certain air quality modeling functions. The MOBILE model received some criticisms, too. These included how the model represented (or failed to represent) emissions from speeds above 65 miles per hour; aggressive driving practices, such as rapid acceleration or deceleration; cold starts; air conditioner usage; road grade effects; use of lower polluting fuels; evaporative emissions (those due to things other than tailpipe fumes); high emitting vehicles; emissions system deterioration for vehicles with 50,000 miles or more; and the estimates and assumptions applicable to heavy duty vehicles.

MOBILE6.2 is the most recent version of the MOBILE family that provides estimates of current and future emissions from on-road motor vehicles. The model can provide estimate emissions of 21 pollutant types including hydrocarbons (HC), CO, NOx, and PM [6].

The model uses four roadway types including freeways, arterial/collectors, freeway ramps, and local roadways. Among those roadway types, the emissions from local roadways and freeway ramps are based on a single average speed (national average) whereas the emissions for freeways and arterials are based on the emissions testing according to the standard vehicle Federal Test Procedure (FTP) certification driving cycle, which is also known as LA4 cycle. MOBILE6 calculates emission factors for 28 individual vehicle types in low- and high-altitude regions of the United States. MOBILE6 emission factor estimates depend on various conditions, such as ambient temperatures, travel speeds, operating modes, fuel volatility, and mileage accrual rates. MOBILE6 will estimate emission factors for any calendar year between 1952 and 2050, inclusive [6].

All the vehicles of a certain class with a similar average speed are assumed to have the same driving pattern (drive cycle). A drive cycle is a series of data points representing the speed of a vehicle versus time. Total emission for each vehicle type is calculated using a standard drive cycle, then distance-based emissions rates (e.g., grams/mile) are calculated dividing the total emission by the total distance covered. However, since total distance is calculated according to a standard driving pattern, differences in driving patterns cannot be captured.

Emissions Estimation of Non-Road Equipment

EPA provides the methodology instructions for estimating pollutant emissions from construction equipment fleet [7]. The emissions estimation for non-road equipment in this study followed these guidelines.

Estimating emissions from the construction equipment fleet requires information regarding zero hour steady state emission factor (EF_{ss}), transient adjustment factor (TAF), and deterioration factor (DF). This information can be acquired from the EPA's guideline. The emissions tiers of different equipment are determined based on model year and horsepower. The steady-state emission factor (EF_{ss} in g/hp-hr) for each piece of equipment is determined based on engine horsepower and tier. The TAF is collected based on EPA's Source Category Code (SSC) and tier. The DF for each pollutant and tier type is calculated based on the data from the guideline, 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 = cumulative hours × load factor ÷ median life at full load in hours;

A = Relative Deterioration Factor depending on pollutant and tier; and

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

The final emission factors for HC, CO, and NOx (EF_{adj} in g/hp-hr) are then calculated as following:

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

PM emissions depend on the sulfur content of the fuel, so an adjustment factor (S_{PMadj}) is provided in the guideline to account the variation. 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 equipment can then be calculated using horse power, usage hours, and adjusted emission factor.

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

MOVES (Motor Vehicle Emission Simulator)

The previous EPA emissions model, MOBILE6, is an emissions factor model that generates pollutant emissions factors for various vehicles classes based on data collected from dynamometer tests of predefined driving schedules. Emissions factors generated through these tests are coupled with vehicle activity information in the form of vehicle miles travelled (VMT) and average speed to calculate emissions.

The EPA's newest emissions model, MOVES, utilizes a database-centered software framework and a disaggregate emissions estimation algorithm that includes many new features and provides much more flexibility for input and output options than the current MOBILE6.2 model [8]. This approach enables MOVES to perform estimation at different analysis levels such as at the national, state, and local levels. New input options and changes in the way MOVES handles existing information require the users to create local information for an accurate analysis. However, only the national average driving patterns are included in the default database of the model.

Users of the model specify vehicle types, time periods, geographical areas, pollutants, vehicle operating characteristics, and the road types being modeled. The MOVES model also incorporates estimates of energy consumption along with several coefficients including heating value, oxidization fraction, and carbon content. The model was designed to work with databases, allowing for new and updated data to be more easily incorporated into the model. The default database summarizes emissions information for the entire U.S. and is drawn from EPA research studies, Census Bureau vehicle surveys, Federal Highway Administration (FHWA) travel data, and other federal, state, local, industry, and academic sources.

The configuration of MOVES, which is based on a database-centered structure, gives more flexibility to users to control the local parameters. Most importantly, the driving patterns representing the different traffic conditions and average traffic speeds are not hard-coded into the model. Users can create and use local drive schedules (equivalent to drive cycles in MOBILE models) to perform an accurate analysis. This feature is specifically helpful for project-level conformity analyses that deal with changes in traffic patterns. In addition to project level analyses, the local drive cycles will enable modelers to accurately estimate the emissions impacts of traffic movement for other purposes such as state implementation plans (SIP) and attainment demonstration analyses.

The underlying methodology of the MOBILE family of models has been based on the estimation of mobile source emissions based on average operating characteristics over broad geographical areas. The most important shortcoming of this aggregate-level approach is that differences in driving patterns cannot be captured. For example, driving at 50 mph on a highway with a 50-mph speed limit is treated equally as driving at the same speed on a freeway with a 65-mph speed limit.

Unlike the aggregate approach used for the MOBILE model, MOVES utilizes a disaggregate measure called Vehicle Specific Power (VSP), which is a combined measure of instantaneous speed, acceleration, road grade, and road load [9]. The emissions associated with any given driving pattern are modeled based on distribution of time spent in operation modal bins that are defined based on VSP bins and speeds. In addition to exhaust emissions, MOVES also provides estimates of start, brake wear, tire wear, and extended idling emissions.

Drive schedules that represent typical operations at different average speeds for each vehicle type operating on a road are used to translate average speed information into VSP distributions. VSP is calculated on a second-by-second basis for a vehicle operating over these drive schedules based on equation 6.

$$VSP = \frac{A \times u + B \times u^2 + C \times u^3 + M \times u \times a}{M} \quad (6)$$

In this equation, u is the instantaneous speed of the vehicle, a is the instantaneous acceleration of the vehicle including the impact of the grade ($a = a + sin(atan(G/100))$); where G is the road grade in percent, A is a rolling resistance term, B is a rotating resistance term, C is a drag term, and M is the vehicle's mass).

In the MOVES model for each vehicle group, the running activities (i.e., non-start and non-idling) and associated emissions are organized into operating mode bins. The vehicle activity grouping is based on the instantaneous VSP and speed as shown in Table 1. The 23 operating modes represent ranges of vehicle speed and VSPs for running emissions estimations. The model uses 16 operating modes for running energy consumption estimation [9]. Energy consumption estimated by MOVES includes total energy consumption, fossil fuel energy consumption, and petroleum fuel energy consumption. MOVES-estimated mass emissions are THC, CO, NOx, sulfate PM, tire wear, and brake wear; PM2.5, methane (CH_4), nitrous oxide (N_2O), CO_2 on an atmospheric basis; and the "CO_2 (carbon dioxide)-equivalent" of CO_2 combined with N_2O and CH_4.

Corresponding emissions rates for each of these bins are then used to calculate emissions for any driving pattern based on the distribution of time spent in the bins. Figure 1 graphically demonstrates this process. This approach adds major flexibility to analysis because the emissions of any given drive schedule can be estimated.

Table 1. Operating Mode Bin Definitions for Running Emissions.

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

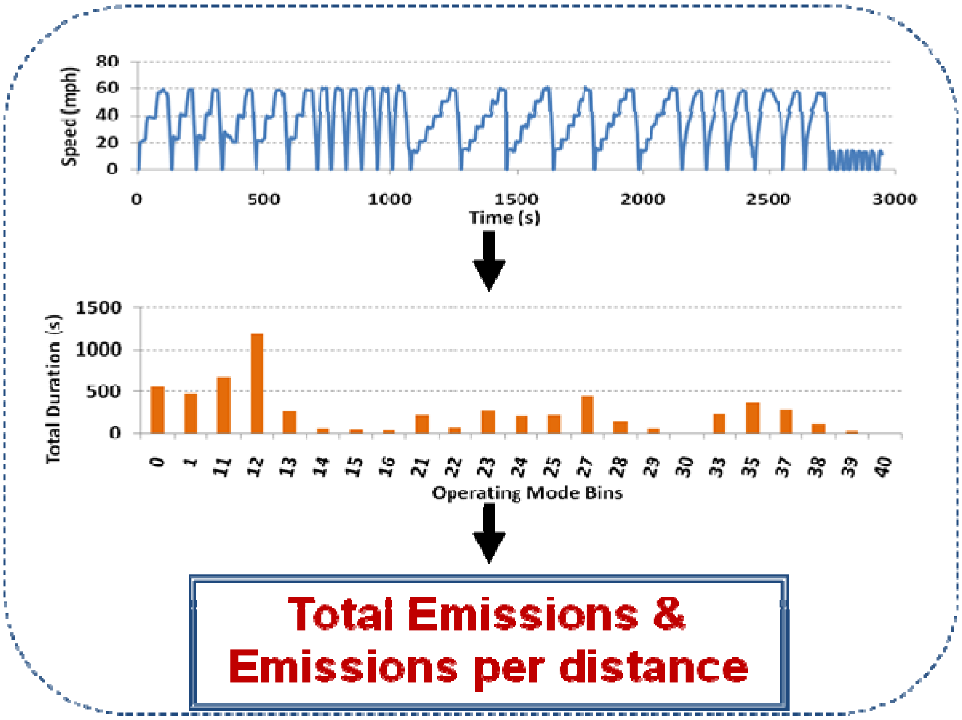

Figure 1. Emissions Estimation Process in MOVES.

In its macro-level analysis, MOVES utilizes "composite" driving schedules that are representative of driving patterns aggregated across different types of roadways, roadway characteristics, and driver behaviors. While these composite cycles are effective in large-scale emissions modeling, they are less effective in terms of micro-level analysis such as for specific roadways or specific vehicle classes. In its initial phases of development, MOVES was focused primarily on macro-scale applications such as would occur at the county or regional level. However, recent development on the model has focused on micro-scale applications at the roadway link level, project level, and other similar levels such as specific expressways and interchanges (the term "link" refers to a particular type and length and roadway for modeling purposes). This has required the development of link-specific and/or project-level driving cycles for use in the MOVES model.

The national default case uses 40 different drive schedules mapped to specific vehicle types and roadway types, but MOVES can accommodate any number of drive schedules. Each driving schedule's average speed is used to determine the weighting of that schedule for a given road type and source type, based on the average speed distribution. For each of the speed bins in the speed distribution, the model selects the two associated driving cycles with average speeds that bracket that bin's average speed. The VSP distributions for each driving schedule are then averaged together and weighted by the proximity of the speed bin average speed to the driving schedule average speeds.

MOVES uses a simplified road classification based on the Highway Performance Monitoring System (HPMS) functional classes as shown in Table 2 [9]. Functional classes are differentiated as rural and urban, and within each of these classifications six separate categories are used to distinguish the type of roadway based primarily on purpose or function within the regional roadway. An advantage of using HPMS-based functional class definitions is that these classifications include not only distinctions between interstate, collector, and local roadways, they also distinguish between rural and urban roadways. The primary vehicle classification in the MOVES model is called "Source Type" for on-road vehicles. The classifications roughly correspond to HPMS vehicle classes as shown in Table **3**.

Table 2. Summary of MOVES Road Types.

RoadTypeID	Description	HPMS functional Types
1	Off Network	Off Network
2	Rural Restricted Access	Rural Interstate
3	Rural Unrestricted Access	Rural Principal Arterial, Minor Arterial, Major Collector, Minor Collector & Local
4	Urban Restricted Access	Urban Interstate & Urban Freeway/Expressway
5	Urban Unrestricted Access	Urban Principal Arterial, Minor Arterial, Collector & Local

Table 3. MOVES Vehicular Source Types.

Vehicle Class	Source Type	Description
Light Duty	11	Motorcycle
	21	Passenger Car
	31	Passenger Truck: SUV, Pickup Truck, Minivans - Two-Axle/Four-Tire Single Unit
	32	Light Commercial Trucks - Two-Axle/Four-Tire Single Unit
Buses & Medium-Duty	41	Intercity Buses
	42	Transit Buses
	43	School Buses
	52	Single-Unit Short-Haul Trucks
	53	Single-Unit Long-Haul Trucks
	54	Single- Unit Motor Homes
Heavy Duty	51	Refuse Trucks
	61	Combination Short-Haul Trucks
	62	Combination Long-Haul Trucks

Vehicular classifications in the form of these source types must be used if emissions are to be accurately estimated in the MOVES model. Estimated populations for these classifications must be generated or collected if the estimates for each region are to be accurate. A primary source for this information is the FHWA's *Highway Statistics*. FHWA defines these various classifications as follows [10]:

- **Motorcycles**: Includes all two- or three-wheeled motorized vehicles that have saddle type seats and are steered by handlebars rather than a wheel. It includes motorcycles, motor scooters, mopeds, motor-powered bicycles, and three-wheeled motorcycles.
- **Passenger Cars**: Includes all sedans, coupes, and station wagons manufactured primarily for carrying passengers and also includes passenger vehicles pulling recreational or other light trailers. This category includes passenger vehicles that are pick-up trucks and vans.
- **Other Two-Axle, Four-Tire, Single-Unit Vehicles**: Includes all two-axle, four-tire vehicles, not classified as passenger cars. This classification includes pick-up trucks (not classified as passenger cars), panels, vans, and other vehicles such as campers, motor homes, ambulances, and hearses.
- **Buses**: Includes all vehicles manufactured as traditional passenger-carrying buses with two axles, six tires, and three or more axles. This classification includes only traditional buses (including school buses) functioning as passenger-carrying vehicles.
- **Single-Unit Trucks**: This category includes all trucks that operated on a single frame. These vehicles may have two, three, four or more axles.
- **Combination**: This category includes vehicles with multiple axles and consisting of multiple units, one of which is a tractor or straight truck power unit.

Three basic analysis scales are defined for MOVES [11]:

- Macro-scale: This level of analysis is appropriate for developing large-scale (e.g., national) inventories, for which the basic spatial unit would be the county.
- Meso-scale: This level is appropriate for generating local inventories at a finer level of spatial and temporal resolution, using as spatial units roadway links and traffic analysis zones or using vehicle trips consistent with output from standard travel demand models.
- Micro-scale: This level of analysis allows the estimation of emissions for specific corridors and/or intersections, which is appropriate for assessing the impact of transportation control measures and for performing project-level analyses.

For a given time, location, use type, and emission process, total emissions can be calculated using the following four steps:

1. Calculate the **Total Activity**, expressed in units of the activity basis for the given emission process.
2. Distribute the total activity into **Source and Operating Mode Bins**, which are defined as having unique emissions for that emission process.
3. Calculate an **Emission Rate**, which characterizes emissions for a given process, source bin, and operating mode bin and which accounts for additional effects such as fuel and meteorology.
4. Aggregate emission rates across these modes using the source bin and operating mode distribution from Step 1.

MOVES estimates two fundamentally different kinds of results: energy consumption and mass emissions. For convenience, all these quantities are considered emissions. Energy emissions estimated by MOVES are total energy consumption, fossil fuel energy consumption, and petroleum fuel energy consumption. The more familiar MOVES-estimated mass emissions are THC, CO, NOx, sulfate PM, tire wear PM2.5, brake wear PM2.5, CH_4, N_2O, CO_2 on an atmospheric basis, and the CO_2-equivalent of CO_2 combined with N_2O and CH_4 [12]. The current version of MOVES considers the following fuel types: Gasoline, Diesel Fuel, Compressed Natural Gas (CNG), Liquid Propane Gas (LPG), Ethanol (E85), Methanol (M85), Gaseous Hydrogen, Liquid Hydrogen, and Electricity [12].

To facilitate modeling the effects of alternative fuels on greenhouse gas emissions, MOVES further divides these top-level fuel types into fuel subtypes. In the default MOVES database, for example, the gasoline fuel type has three sub-types: conventional, reformulated, and gasohol (E10) [12]. This fuel classification scheme was expanded further to divide fuel sub-types into more specific fuel formulations. This additional breakdown is necessary because these fuel characteristics affect the emissions of pollutants added in MOVES and vary within a fuel subtype.

EMISSION REDUCTION STRATEGIES

Emission reduction strategies refer to any strategy that potentially reduces emissions from mobile sources. These strategies are either operational or non-operational strategies. Operational strategies are used to reduce trip volume or inefficiencies, thus reducing fuel consumption and emission. Eco-driving is an example of this family of strategies. EPA claims that eco-driving techniques, which include progressive shifting, speed moderation, and the avoidance of rapid accelerations and unnecessary stops, can result in truck fuel economy gains of 5 percent or more [13].

The majority of emission reduction strategies are non-operational. Non-operational emission reduction strategies for mobile sources are generally divided into four categories: replace, rebuilding, repowering, and retrofitting. *Retrofitting* refers to installing an emission control device on the vehicle; *Rebuilding* means rebuilding some core engine components of the equipment; *Repowering* refers to replacing the older diesel engines with a newer engine; and *Replacing* is the term used for replacing the entire older equipment or vehicle [14].

Replacing, repowering, and rebuilding are generally applicable to older vehicles and equipment. The majority of the emission reduction strategies fall under retrofit options. Some of these strategies are primarily developed to reduce the emission of certain pollutants while some of them provide emission reduction for multiple pollutants. The following section provides an overview of the existing emission reduction strategies that are applicable to fleet vehicles and equipment.

Fuel Strategies

This family of strategies includes alternative fuels and fuel enhancement strategies.

Fuel Additives

A fuel additive is a substance designed to be added to fuel or fuel systems or other engine-related systems such that it is present in-cylinder during combustion and can have one or a combination of the following effects: a) decreased emissions, b) improved fuel economy, c) increased performance of the vehicle or one of its components, or d) assists other emission control strategies in reducing emissions. In other words, fuel additives are compounds formulated to enhance the quality and efficiency of the fuels used in motor vehicles. In some cases, the supplier incorporates the additive into the fuel itself; at other times, the fuel additive is sold as a separate product.

Some of the fuel additive manufacturers claim that their products can reduce NOx and HC emissions up to 25 percent, PM emission up to 50 percent, and CO emission up to 30 percent [15]. Costs for fuel additives change $5 to $25 per gallon. EPA or California Air Resources Board (CARB) have not yet verified these fuel additives as a significant reducer of NOx emissions.

Biodiesel

Biodiesel is a renewable fuel produced from agricultural resources such as vegetable oils. Bio fuel is produced by reacting vegetable or animal fat with methanol or ethanol to produce a lower-viscosity fuel. Biodiesel can be blended into petroleum-based diesel fuel at any ratio; however, in the United States, it is most commonly blended at 20 percent, called B20. Pure biodiesel is called B100.

Typical emission benefits of B20 include a 10 percent decrease in CO, up to a 15 percent decrease in PM emissions, a 20 percent decrease in sulfate emissions, and a 10 percent decrease in HC emissions [16]. However, biodiesel may cause a decrease in fuel economy about 2–8 percent [17]. Under higher load operating conditions, biodiesel blends have been shown to slightly increase NOx emissions. In most cases biodiesel blends up to B20 can be used in combination with other exhaust control devices to achieve co-reductions of emissions.

In the case of large fleets, managers can transition to biodiesel without acquiring new spare parts inventories or rebuilding refueling stations. Generally, the use of biodiesel is not known to cause major maintenance issues. However, when used for the first time, biodiesel can loosen deposits accumulated on tank walls and pipes from previous diesel fuel, initially causing fuel filter clogs. As a result, vehicle owners should change the fuel filter after their first tank of biodiesel.

Exhaust Catalysts

Selective Catalytic Reduction

SCR systems use a metallic or ceramic wash-coated catalyzed substrate, or a homogeneously extruded catalyst and a chemical reductant; a reducing agent such as ammonia, to convert nitrogen oxides to molecular nitrogen, water, and small amounts of carbon dioxide. In mobile source applications, an aqueous urea solution or diesel exhaust fluid (DEF) is usually the preferred reductant source. The urea solution is injected into the exhaust stream upstream of the SCR. The heat from the exhaust and mixing hydrolyzes the urea to ammonia and CO_2. As exhaust and reductant pass over the SCR catalyst, chemical reactions occur that reduce NOx emissions to nitrogen and oxygen.

SCR is currently being used on on-road and non-road diesel engines and vehicles. There are now more than 500,000 SCR-equipped trucks operating in Europe. In OEM[1] applications, where the vehicle or engine manufacturers have control over engine calibrations, SCR systems have been reported to deliver a 5–7 percent fuel savings [16].

Open loop SCR systems can reduce NOx emissions from 70 to 90 percent. Closed loop systems on stationary engines can achieve NOx reductions of greater than 95 percent. SCR systems reduce HC emissions up to 80 percent and PM emissions 20 to 30 percent [16]. They also reduce the characteristic odor caused by hydrocarbons in the exhaust produced by a diesel engine and diesel smoke. Like all catalyst-based emission control technologies, SCR performance is enhanced by the use of low sulfur fuel.

[1] Original Equipment Manufacturer

SCR catalysts may also be combined with diesel oxidation catalysts (DOCs) or diesel particulate filters (DPFs) for additional reductions of PM, HC, and CO emissions.

Retrofit SCR costs are expected to range from about $18,000 with a DOC to $30,000 with a DPF per vehicle [16]. In addition to the initial cost, the reductant is needed to be filled when necessary. For light-duty vehicles, urea refill intervals will occur around the time of a recommended oil change, while urea replenishment for heavy-duty vehicles will vary depending on the vehicle specifics and application requirements. According to SCR Infrastructure Study [18], urea-to-fuel use ratio is 1 gallon of urea per 18 gallons of diesel consumed.

Diesel Oxidation Catalysts

A DOC uses a chemical process to break down pollutants in the exhaust stream into less harmful components. More specifically, it is a physical device with a porous ceramic honeycomb-like structure coated with a material that catalyzes a chemical reaction to reduce pollution. In the case of diesel exhaust, the catalyst oxidizes CO, HCs, and the liquid hydrocarbons adsorbed on carbon particles to CO_2 and water.

DOCs installed on a vehicle's exhaust system can reduce total PM by as much as 25 to over 50 percent, depending on the composition of the PM being emitted. DOCs can also reduce smoke emissions from older vehicles and virtually eliminate the obnoxious odors associated with diesel exhaust. Oxidation catalysts can reduce more than 90 percent of the CO and HC emissions and more than 70 percent of the toxic hydrocarbon emissions in diesel exhaust [16].

Because they are completely passive, flow-through devices, they can be retrofitted on a wide range of applications as long as the exhaust temperatures remain above approximately 150°C. Diesel oxidation catalysts are estimated to cost from $1,000 to $2,000 per catalyst depending on engine size, sales volume, and whether the installation is a muffler replacement or an in-line installation [16]. In most cases, installation of the device takes 1–3 hours. DOCs do not require any maintenance have a 100,000 to 150,000 mile warranty and can last 7 to 15 years. EPA verifies this technology.

Diesel Particulate Filters

A DPF collects the particulate matter in the exhaust stream. The high temperature of the exhaust heats the ceramic structure and allows the particles inside to break down (or oxidize) into less harmful components. DPFs have been widely used to retrofit on- and non-road diesel vehicles. DPFs can achieve up to and, in some cases, greater than 90 percent reductions in PM. Particulate filters can be combined with a DOC or directly catalyzed to control up to 90 percent or more of the toxic HCs emitted by a diesel engine. DPFs incorporating a catalyst function have been shown to decrease the levels of polyaromatic hydrocarbons, nitro-polyaromatic hydrocarbons, and the mutagenic activity of diesel PM.

DPFs cannot be used for any engine. They work best on engines built after 1995 [19]. Also, DPFs must be used with ultra-low sulfur diesel fuel. Use of regular diesel fuel could eventually clog the filter. DPF manufacturers recommend that these devices should be cleaned about every 100,000 miles. Generally this maintenance process takes about 3 hours. Most DPF units have a 100,000–150,000-mile warranty and they can last 7 to 15 years [19]. High-efficiency, passive filters for diesel retrofit applications are currently being sold for about $8,000 to $13,000 each [16]. Prices vary depending on the size of the engine being retrofit.

Flow-through Filters (FTF)

FTFs are a relatively new method for reducing diesel PM emissions. These filters can reduce PM by 30–75 percent, depending on the engine operating characteristics. Because of their open structure, these devices are less prone to plugging and may be more suited to older diesel engines with higher engine-out PM levels.

The surfaces of this type of filters can be catalyzed to facilitate regeneration of the soot, or an uncatalyzed filter can be combined with an upstream DOC to accomplish soot regeneration. The incorporation of a catalyst in either of these two ways offers co-benefits of 50–90 percent reduction of hydrocarbons and carbon monoxide in addition to the PM reductions.

Catalyzed, wire mesh FTF retrofit technologies have been verified by both CARB[2] and EPA for a range of on-road engine applications. Likewise, CARB has verified four partial filter designs as Level 2 PM reduction technologies. Flow-through, partial filters for diesel retrofit applications are currently being sold for about $5,000 to $7,000 each [16].

Lean NOx Catalysts (LNC or HC-SCR)

A lean NOx catalyst often includes a porous material made of zeolites (a micro-porous material with a highly ordered channel structure), along with either a precious metal or base metal catalyst. Zeolites provide microscopic sites that are fuel/hydrocarbon rich where reduction reactions can take place. Some lean NOx catalyst systems inject a small amount of diesel fuel or other reductant into the exhaust upstream of the catalyst. The fuel or other hydrocarbon reductant serves as a reducing agent for the catalytic conversion of NOx to N_2. Other systems operate passively without any added reductant at reduced NOx conversion rates. Without the added fuel and catalyst, reduction reactions that convert NOx

[2] California Air Resources Board

to N_2 would not take place because of excess oxygen present in the exhaust. Lean NOx catalysts are sometimes referred to as hydrocarbon SCR catalysts due to their characteristic selective reduction of NOx. Currently, peak NOx conversion efficiencies are typically around 25–40 percent (at reasonable levels of diesel fuel consumption) [16].

A retrofit system combined with a Level 3+ DPF has been verified by the CARB (25 percent NOx control) for a range of on-highway applications. The CARB-verified retrofit technology combines a lean NOx catalyst upstream of a DPF for a combined reduction of NOx and PM using controlled injection of diesel fuel upstream of the lean NOx catalyst. The cost of retrofitting a combined lean NOx catalyst + DPF system on a typical bus or truck engine is about $15,000 to $20,000, which includes the diesel particulate filter [16]. There is also an additional 5–10 percent cost for fuel as the reductant.

Lean NOx Traps

NOx adsorber catalysts, also referred to as lean NOx traps (LNT) or NOx storage catalysts, provide another catalytic pathway for reducing NOx in an oxygen-rich exhaust stream. The system works as follows. First, NO is catalytically oxidized to NO_2 over a precious metal catalyst. Then, NO_2 is stored on an adjacent alkaline earth oxide trapping site as a nitrate. The stored NOx is then periodically removed in a two-step regeneration process by temporarily inducing a rich exhaust condition followed by reduction to nitrogen using a process similar to the conventional three-way catalyst reaction. LNT systems on OEM applications have demonstrated NOx reduction up to 90 percent [16].

NOx adsorbers are particularly sensitive to sulfur and require low sulfur diesel fuel. The durability of LNTs is linked directly to sulfur removal by regeneration and is a major aspect of technology development. Sulfur must be removed from the trap by periodic high temperature excursions under reducing conditions, a procedure called “DeSOx.” The DeSOx regeneration temperatures are typically around 700°C and require about 15–20 minutes to be completed [16].

Exhaust Gas Recirculation (EGR)

EGR is a NOx emission reduction technique used mostly in diesel engines. EGR works by re-circulating a portion of engine’s exhaust gas back to the engine cylinders. The EGR valve re-circulates exhaust into the intake stream. Exhaust gases have already combusted, so they do not burn again when they are re circulated. These gases displace some of the normal intake charge. In turn, this displacement chemically slows and cools the combustion process by several hundred degrees, reducing NOx formation. Both low-pressure and high-pressure EGR systems exist. Low-pressure EGR is used mostly for retrofitting applications because it does not require engine modifications.

Diesel particulate filters are always used with a low-pressure EGR system to ensure that large amounts of PM are not re-circulated to the engine. EGR systems are capable of achieving NOx reductions of more than 40 percent. The cost of retrofitting a low pressure EGR system on a typical bus or truck engine is about $18,000 to $20,000, which includes the diesel particulate filter [16].

Liquefied Petroleum Gas

LPG, also known as propane, is a nonrenewable gaseous fossil fuel that turns into liquid under moderate pressure. It is a by-product of natural gas processing and oil refining. LPG can be used as transportation fuel. The type of LPG used as a motor vehicle fuel is a liquid mixture containing at least 90 percent propane, 2.5 percent butane, and higher hydrocarbons, and the balance is ethane and propylene.

LPG is currently the third most commonly used transportation fuel, behind gasoline and diesel. In the United States, LPG has been used mostly in fleets such as school buses, taxicabs, public service and police cars, and many other on-road fleet applications. Some non-road equipment such as industrial forklifts and farm vehicles also use LPG. Presently, major auto manufacturers and aftermarket converters offer on-road vehicles that can operate on both LPG and gasoline fuels. These vehicles are usually called bi-fuel or dual-fueled vehicles and can manually be switched between gasoline and LPG.

Closed Crankcase Ventilation (CCV) Systems

Unlike exhaust emissions, crankcase gases normally escape into the air through the crankcase vent tube. To control crankcase emissions, some diesel engine manufacturers make closed crankcase ventilation systems, which return the crankcase blow-by gases to engine for combustion. CCV systems prevent crankcase emissions from entering the atmosphere.

A retrofit CCV system has been introduced and verified for on-road applications by both the EPA and CARB in combination with a DOC. In the United States, this verified CCV/DOC system has been applied to such applications as school buses and non-road equipment used at marine ports. Crankcase emissions range from 10–25 percent of the total engine emissions, depending on the engine and the operating duty cycle. Crankcase emissions typically contribute to a higher percentage (up to 50 percent) of total engine emissions when the engine is idling. As noted above, the verified CCV technology is designed to virtually eliminate the crankcase emissions. According to the U.S. verification documents, the combined CCV/DOC system, controls PM emissions by up to 33 percent, CO emissions by up to 23 percent, and HC emissions by up to 66 percent [20].

The filter in the system must be replaced periodically. Recommended filter replacement intervals vary, based on the number of hours the vehicle/equipment is operated. For high mileage on-road engines, the maximum recommended interval between replacements is every 25,000 miles. For low-mileage vehicles, lower mileage intervals are recommended and replacement at least annually may be appropriate. The cost of the retrofit CCV emission control product is in the range of $450 and the costs of the verified CCV/DOC system ranges from about $1,200 to slightly over $2,000. The disposable filters are replaced at recommended intervals and the filter cost ranges from $30 to over $40 [20].

Idle Reduction Techniques

Idle reduction is typically used to describe technologies and practices that reduce the amount of time heavy-duty trucks idle their engines. However, light- and medium-duty vehicles and school buses can benefit from idle reduction strategies as well. Reducing idle time saves fuel, engine wear, and money while reducing emissions and noise.

Trucks idle their engines during rest periods to provide heating, cooling, and electrical power as well as to keep the engine warm and the battery charged. According to the U.S. Department of Energy, idling trucks use approximately 838 million gallons of fuel per year.

Portable Units

These are the devices that can be carried on the vehicle and can be used to provide some of the required services such as heating, cooling, and electricity to the carbine of the vehicle when the vehicle is stopped. Automatic engine start-stop control devices, auxiliary power units (APU), cab and block heaters, and thermal storage air conditioners are the most recognizable portable idle reduction technologies.

An automatic engine shutdown/startup system controls the engine start and stop based on a set time period or ambient temperature and other parameters (e.g., battery charge). Some of the engine manufacturers sell these devices for trucks from around $900–$1,200 [21].

Small diesel powered generators (5–10 horsepower) can be mounted on trucks to provide air conditioning, heat, and electrical power to run appliances. Estimated costs of these units are $6,000 to $8,000. A 10 percent fuel savings is estimated based on 2,400 hours idling per year [21].

Stationary Idle Reduction Systems

Stationary idle reduction refers to fixed units installed in truck stops to provide services such as air conditioning, heating, electricity, and internet. Since electricity is the preferred source of power for these units, they are also known as truck stop electrification (TSE) systems. Two categories of TSE technologies exist. The first category provides electricity to trucks via a power pedestal installed on each parking space. Trucks that are equipped with electric heating and air conditioning systems or an on-board cabin kit can plug in and power up these systems. In the second category of stationary idle reduction systems, a package of services including heating/air conditioning, electrical power, cable TV, and internet is provided to the cabin through a window-mounted unit.

CHAPTER 3
DEVELOPMENT OF OPTIMIZATION FRAMEWORK

This chapter presents the overall approach for formulating the optimization framework. A brief description of the problem and the methodology applied is presented as the starting point. What follows are the steps taken to construct the optimization framework including defining variables, objective function, and constraints as well as required pre-data processing of the inputs.

PROBLEM DESCRIPTION

Many large fleets are under pressure to reduce their air quality impact. Fleet owners and operators can reduce the emission created by their fleets by applying a range of emission reduction strategies. However, many different emission reduction technologies can be used to reduce different pollutants from different type of vehicles. The problem is to decide which vehicle or equipment in the fleet should use which emission reduction strategy to maximize the total emission reduction obtained in the entire fleet. Hence, the overall problem can be described as:

> *The main goal of this study is to develop an optimization framework that is capable to determine the optimal allocation of emission reduction strategies to vehicles and equipment in a large fleet in order to maximize the total emission reduction achieved.*

ANALYTICAL APPROACH

To solve the problem described above, an analytical approach was developed that consists of three major components: 1) total annual emission estimation, 2) data pre-processing, and 3) optimization. The emissions estimation component deals with calculating emissions for all the vehicles (both on-road and non-road) for all the included pollutants. Separate methodologies were developed to estimate emission for on-road vehicles and non-road equipment. These values are then subject to pre-processing. This step filters vehicle and puts them into different groups based on user's preference regarding location, strategies, and applicability of the selected emission reduction strategies. The resulting list of vehicles and equipment is then used as input to the optimization component along with the other necessary input values. The optimization component solves the problem according to the given input values while obeying certain set of constraints and outputs the results. Figure 2 shows the general outline of the framework and the components mentioned.

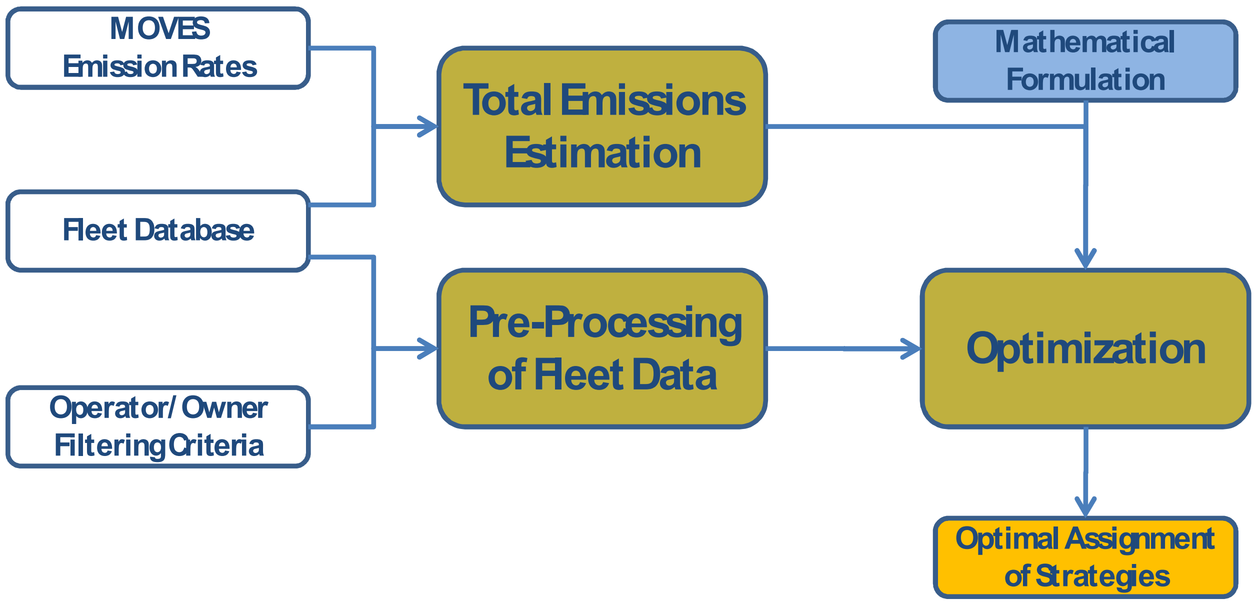

Figure 2. General Structure of the Proposed Optimization Framework.

Total Annual Emission Estimation (TAEE)

As described previously, mobile sources of emissions can be divided into two different categories: on road vehicles and non-road equipment. Emission estimations of these categories differ because of their operational characteristics. To calculate total annual emission estimations of non-road vehicles, the method presented in EPA's guidelines was used, described in Chapter 2. For on-road vehicles, the research team developed an emissions estimation methodology based on emission rates from the MOVES model. For each individual vehicle in the fleet, the total annual emission estimation for each pollutant (i.e., NOx, CO, CO_2, PM, and HC) was calculated.

TxDOT fleet data for fiscal year 2008 were used in the calculations for on-road and non-road vehicles. Several assumptions were made during the calculations. First, the retired vehicles in the fleet were not included into the emission estimation calculations since TxDOT no longer uses them. Second, few of the vehicles do not have the necessary information, and these data were discarded and not included in the calculations.

On-Road Vehicles' Emissions

To calculate the emissions for the on-road vehicles, EPA's MOVES model is used. The first step in this process is to map all the on-road vehicles in the fleet to appropriate source types specified in the MOVES model as shown in Table 4.

Table 4. Vehicle Types in MOVES Model.

MOVES use type	Description
21. Passenger Car	
31. Passenger Truck	Minivans, pickups, SUVs, and other 2-axle /4-tire trucks used primarily for personal transportation
32. Light Commercial Truck	Minivans, pickups, SUVs, and other 2-axle /4-tire trucks used primarily for commercial applications. Expected to differ from passenger trucks in terms of annual mileage, operation by time of day
51. Refuse Truck	Garbage and recycling trucks. Expected to differ from other single unit trucks in terms of drive schedule, roadway type distributions, operation by time of day
52. Single-Unit Short-Haul Truck	Single-unit trucks with majority of operation within 200 miles of home base
53. Single-Unit Long-Haul Truck	Single-unit trucks with majority of operation outside 200 miles of home base
54. Motor Home	
41. Intercity Bus	Buses that are not transit buses or school buses, e.g., those used primarily by commercial carriers for city-to-city transport
42. Transit Bus	Buses used for public transit
43. School Bus	School and church buses
61. Combination Short-Haul Truck	Combination trucks with majority of operation within 200 miles of home base
62. Combination Long-Haul Truck	Combination trucks with majority of operation outside 200 miles of home base
11. Motorcycle	

Note that the TxDOT fleet does not have motorcycles and buses. Also, all the small trucks are used for light commercial purposes. Therefore, all the small trucks in the fleet can be grouped into the "Light Commercial Truck" class defined above. Since other types of trucks are used for operations within 200 miles of home base, single unit trucks and combination trucks are grouped into the "Single-Unit Short-Haul" and "Combination Short-Haul" classes, respectively. Lastly, all cars are considered as "Passenger Cars." Hence, the whole TxDOT on-road fleet can be represented by the following four MOVES source types:

- 21: passenger car
- 32: light commercial truck
- 52: single unit short-haul truck
- 61: combination short-haul truck.

The TxDOT fleet database was examined to identify appropriate parameter(s) to classify vehicles into the abovementioned four source types (vehicle classes). Different parameters such as “Body Style,” “Engine Size,” “Engine Displacement,” “Wheel Base,” and “Tire Size” were examined; however, none could provide the information needed for this classification. Researchers then decided to build the classification based on MOBILE6 methodology, i.e., use GVWR as the basis for classification. GVWR is defined as the maximum weight of a vehicle when is loaded. The examination of the database also revealed that 4,300 lb is the optimal threshold for differentiating between TxDOT’s passenger cars and light trucks. Table 5 demonstrates these classifications.

Table 5. On-Road Vehicle Types Used in This Study.

GVWR (lb)	MOVES Source Type
0–4,300	21) Passenger Car
4,301–19,500	32) Light Commercial Truck
19,501–33,000	52) Single Unit Short Haul
33,001–60,000	61) Combination Short Haul

The MOVES model is used to determine corresponding emission rates for those vehicle classes in different counties. Since TxDOT’s vehicles are distributed in many Texas counties, to the researchers used a simplified set of emissions rates instead of generating rates for each individual county. The following six major counties of Texas in terms of traffic density were selected to represent their corresponding metropolitan area: Bexar County representing San Antonio, Dallas County representing Dallas, El Paso County representing El Paso, Harris County representing Houston, Tarrant County representing Fort Worth, and Travis County representing Austin. Using this setting, PM, CO_2, NOx, CO, and HC emission rates in grams per mile (g/mi) were obtained from MOVES’ national analysis level. The average of the emission rates of these six counties were taken as emission rates for all the other counties.

The fleet database contained the detailed data on vehicles activity, i.e., annual mileage. By multiplying the emission rates to the activity of corresponding vehicles (annual mileage), the researchers obtained the total annual estimated emission for on-road vehicles. Emission rates were estimated for all the vehicles, regardless of their eligibility to use emission reduction technologies.

Data Pre-Processing

In this step, the fleet database was pre-processed to generate appropriate input for the optimization component. For a vehicle to be considered to use with emission reduction technologies, it must satisfy a series of conditions. These conditions must be defined based on the criteria that the fleet owner or operator, in our case TxDOT, considers for their operating conditions. The vehicles that failed to meet the criteria set were removed from the input and the remaining was included into the optimization component.

The first condition considered in this step addresses expected remaining age and expected remaining use hours of vehicles and equipment. This condition is applied only to non-road equipment. A discussion with TxDOT fleet manager revealed that TxDOT requires a minimum remaining age and usage hours for a piece of non-road equipment to be considered for non-fuel retrofit strategies. The remaining usage hours and the expected usage hours at disposal of a piece of equipment are represented by $\mathrm{ru}_{\mathrm{c},\alpha,\mathrm{i}}$ and $\mathrm{U}_{\mathrm{c},\alpha,\mathrm{i}}$, respectively. Similarly, the remaining age and the expected age at disposal of a piece of equipment are represented by $\mathrm{ra}_{\mathrm{c},\alpha,\mathrm{i}}$ and $\mathrm{A}_{\mathrm{c},\alpha,\mathrm{i}}$ respectively. The fraction of remaining usage and remaining age for each type of vehicle and technology are represented by $L_{\alpha,t}$ and $R_{\alpha,t}$, respectively. Note that each vehicle type has a different remaining age and hour factor for each strategy. This condition can be shown mathematically as following:

$$\mathrm{ru}_{\mathrm{c},\alpha,\mathrm{i}} \geq L_{\alpha,t}\mathrm{U}_{\mathrm{c},\alpha,\mathrm{i}} \qquad \forall c,\ \forall \alpha,\ \forall t,\ i = 1 \ldots n_{c,\alpha} \tag{7}$$

$$\mathrm{ra}_{\mathrm{c},\alpha,\mathrm{i}} \geq R_{\alpha,t}\mathrm{A}_{\mathrm{c},\alpha,\mathrm{i}} \qquad \forall c,\ \forall \alpha,\ \forall t,\ i = 1 \ldots n_{c,\alpha} \tag{8}$$

A similar condition is used for on-road vehicles. For an on-road vehicle to be considered for retrofitting, it must have an age less than or equal to a certain year and it must also have a mileage less than or equal to a certain value. The age and the maximum age for retrofitting of a vehicle are represented by $\mathrm{ag}_{\mathrm{c},\alpha,\mathrm{i}}$ and $\mathrm{X}_{\mathrm{c},\alpha,\mathrm{i}}$, respectively. Similarly, the mileage and the maximum mileage for retrofitting of a vehicle are represented by $\mathrm{mi}_{\mathrm{c},\alpha,\mathrm{i}}$ and $\mathrm{M}_{\mathrm{c},\alpha,\mathrm{i}}$, respectively. The fraction of acceptable age and mileage for the combination of each type of vehicle and applicable strategy are represented by $G_{\alpha,t}$ and $N_{\alpha,t}$, respectively. This can be written mathematically as:

$$\mathrm{ag}_{\mathrm{c},\alpha,\mathrm{i}} \geq G_{\alpha,t}\mathrm{X}_{\mathrm{c},\alpha,\mathrm{i}} \qquad \forall c,\ \forall \alpha,\ \forall t,\ i = 1 \ldots n_{c,\alpha} \tag{9}$$

$$\mathrm{mi}_{\mathrm{c},\alpha,\mathrm{i}} \geq N_{\alpha,t}\mathrm{M}_{\mathrm{c},\alpha,\mathrm{i}} \qquad \forall c,\ \forall \alpha,\ \forall t,\ i = 1 \ldots n_{c,\alpha} \tag{10}$$

Notice that the representation used for vehicles differs from the representation in the optimization part. In the Data Pre-Processing part, each individual vehicle is represented by the parameters (c, α, i) where c

denotes the county in which the vehicle is located, α denotes the type of the vehicle, and i denotes the vehicle identification number. The reader should keep that in mind that vehicle type α in this part represents the actual type of the vehicle or equipment, e.g., grader, loader, passenger car.

Optimization

This component of the framework contains the mathematical formulation of the problem and constraints. Solving this mathematical formula with appropriate input values results in an optimal allocation of strategies to the vehicles that were found to be eligible by the previous step (pre-processing). As stated before, the objective is to maximize the expected overall emission reduction achieved. To do this, the researchers considered the combined emission reduction as the weighted sum of individual pollutants effects. The pollution weights can be also considered as important factors and can be assigned by the user. This gives the model the flexibility to be used in different areas and for different scenarios.

Since the methodology for estimating emissions of on-road and non-road vehicles is different, to the research team calculated these separately and differently in the total annual emission estimation component. However, once the emissions are estimated, they can be represented by an identical set of parameters, and the same optimization component is applied to all of them.

There are different ways of implementing the location factor in the formulation. The location of vehicles and equipment in TxDOT's fleet database is recorded by the county where these are stationed. Since the TxDOT fleet was used for a demonstration of the framework, the research team decided to use counties as the basic analysis unit to indicate vehicle's location. Depending on how the vehicle's location is recorded in a fleet inventory database, one can easily use the appropriate location indicator. Overall, county-based analysis was found satisfactory since counties provide a good resolution for a statewide analysis.

Each county (location parameter) is weighted according to its compliance with the national emissions standards status, i.e., attainment (A), early action compact area (EA), near non-attainment (NNA), and non-attainment (NA). This was done to reflect the air quality conditions in the analysis as emission reduction in a non-attainment area is usually considered of higher value to the public.

Three constraints were identified for the optimization component based on research and feedback from TxDOT. The first constraint is the budget constraint, which indicates that the total amount of money spent on the selected strategies cannot exceed a given budget value. The second constraint addresses strategies that are applied to a group of vehicles or equipment rather than individuals (group strategies), e.g., fuel strategies. It is assumed that since fuel is purchased in large quantities, if a fuel technology is considered for some equipment in a county, it is also used for all other applicable equipments in that county. If a user does not want this criterion, then he/she can easily formulate the desired fuel strategy in a way that this criterion is not applied to it. The third constraint enforces a user-defined maximum number of strategies for any given vehicle or equipment. Those numbers might change from county to county, but they are the same for all the vehicles located in the same county.

Figure 3 explains the problem in a graphical form. Note that in this figure N_c is the number of counties whereas N_t is the number of emission reduction strategies. Individual vehicles in each county are grouped according to equipment and vehicle type. The problem is how to allocate the emission reduction technologies to the vehicles optimally so that maximum total emission reduction is obtained.

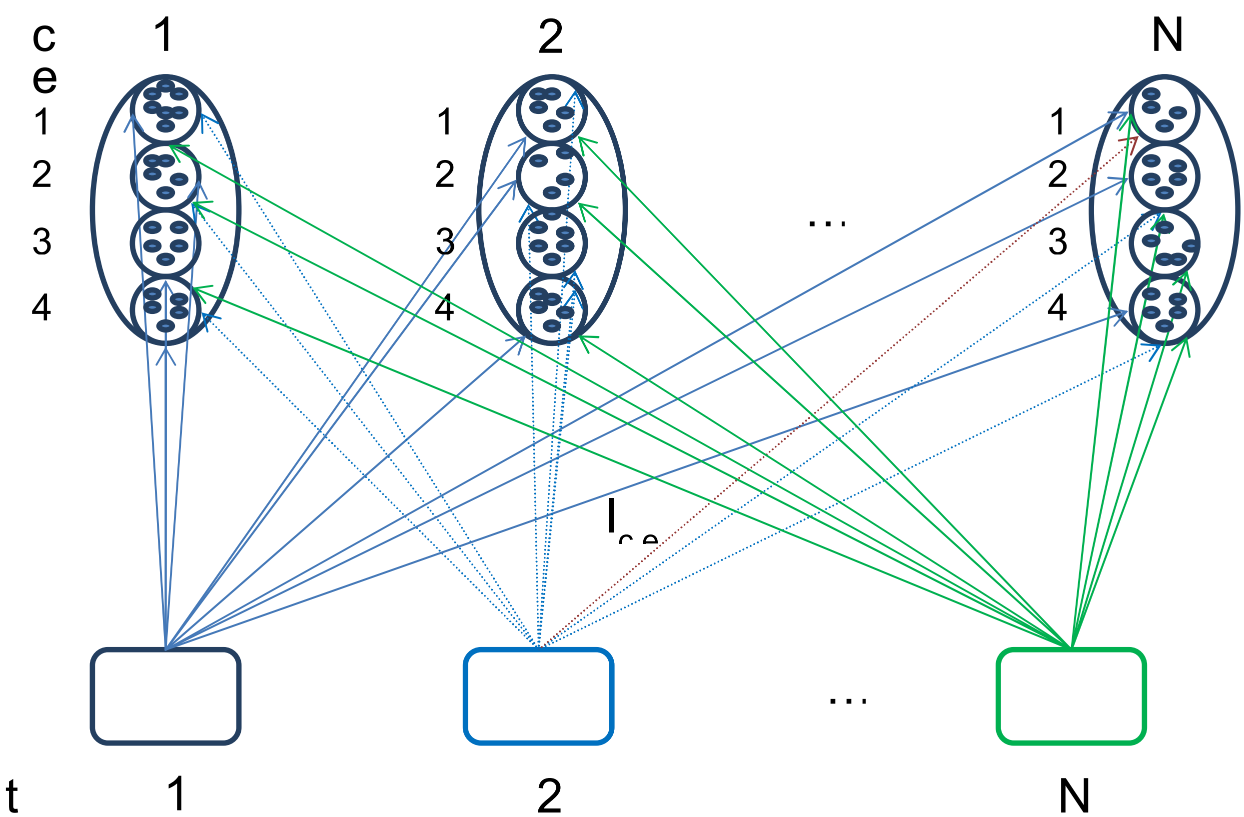

Figure 3. General Outline of the Optimization Problem.

The vehicle type definition (represented by e) in this component is different from the one used in pre-data processing (represented by α). The vehicle type definition used for optimization is a more general one. It covers two properties of the equipment and vehicles, i.e., a) fuel type that a vehicle uses (diesel or gasoline), and b) its use type (on-road or non-road). This gives four different equipment types, although in reality there are usually only three types because the majority of non-road equipment is powered by diesel engines. The main reason for defining vehicle types in this form is because the applicability of strategies to vehicles and equipment can generally determined based on these two properties. If more flexibility is desired, the users can add their own filtering criteria into the pre-processing component to limit the selection to a selected set of equipment or vehicles.

Mathematical Formulation

The problem is modeled as an integer programming (IP) system and formulated as below. This optimization component tries to maximize the emission reduction of a fleet using the available emission reduction strategies and by obeying the abovementioned set of constraints. The IP approach takes individual equipments as the decision variable.

List of Parameters

$\boldsymbol{E_{c,e,i,p}}$: Expected total annual emission of pollutant p emitted by i-th equipment of type e in county c

$\boldsymbol{M_p}$: Cost (Impact) of pollutant p

$\boldsymbol{C_{c,e,i,t}}$: Unit cost of applying emission reduction strategy t to i-th equipment of type e in county c

$\boldsymbol{R_{p,t}}$: Percentage of expected average reduction achieved in emission of pollutant p by applying strategy t

$\boldsymbol{n_{c,e}}$: Total number of equipments of type e in county c

$\boldsymbol{W_c}$: Weights of different counties depending on their attainment status (NA, NNA, EA, A)

$\boldsymbol{MaxTech_c}$: The maximum amount of technologies that can be applied for a single piece of equipment in county c

$\boldsymbol{Budget}$: Available budget that we have

Decision Variable

$\boldsymbol{I_{c,e,i,t}}$: A binary variable that takes 1 if strategy t is used for the i-th equipment of type e in county c

Data Sets

$\boldsymbol{C}$: Set of all counties

$\boldsymbol{E}$: Set of different equipment types (e = 1 for on-road + gasoline, e = 2 for on-road + diesel, e = 3 for non-road + diesel)

$\boldsymbol{V_{c,e}}$: Set of type e equipments located in county c

$\boldsymbol{P}$: Set of all pollutants

$\boldsymbol{T}$: Set of all strategies

$\boldsymbol{T_e}$: Set of strategies applicable to type e equipment. A subset of T

$\boldsymbol{T_G}$: Set of strategies applicable for groups of equipment, e.g., fuel strategies. A subset of T

Objective Function

The objective function of the framework tries to maximize the total emission reduction achieved by the entire fleet. The expression is summed over every county c, every vehicle type e, every vehicle i, every pollutant p, and every technology t as shown in equation 11.

$$max \sum_{c \epsilon C} \sum_{e \in E} \sum_{i=1}^{n_{c,e}} \sum_{p \epsilon P} \sum_{t \epsilon T_e} W_c E_{c,e,i,p} M_p R_{p,t} I_{c,e,i,t} \tag{11}$$

Constraints

The model maximizes the objective function while satisfying the following constraints:

1. Budget constraint: Total money spent on all emission reduction strategies cannot exceed the available budget.

$$\sum_{c \epsilon C} \sum_{e \in E} \sum_{i=1}^{n_{c,e}} \sum_{t \epsilon T_e} C_{c,e,i,t} I_{c,e,i,t} \leq Budget \tag{12}$$

2. Group strategies: Group strategies must be either applied to all equipment in a county or should not be applied at all in that county.

$$I_{c,e,1,t} = I_{c,e,2,t} = I_{c,e,3,t} = \cdots = I_{c,n_{c,e},e,t} \qquad \forall c,\ \forall e,\ \forall t \in T_G \tag{13}$$

3. Maximum number of strategies: At most, a certain number ($MaxTech_c$) of strategies can be applied to a piece of equipment or a vehicle in a county.

$$\sum_{t \in T_e} I_{c,e,i,t} \leq MaxTech_c \qquad \forall c, \qquad \forall e,\ \forall i\ \in V_{c,e} \tag{14}$$

4. Decision variable: Define binary decision variable; 1 if strategy t is used for the i-th equipment of type e in county c, 0 if it is not used for that equipment.

$$I_{c,e,i,t}\ \ binary \qquad \forall c,\ \forall e,\ \forall i \in V_{c,e},\ \forall t \tag{15}$$

The optimization component takes the following information as input:

1. Filtered fleet database, which has all the vehicles that are eligible to use emission reduction strategies.
2. County weights based on the attainment status.
3. Pollutant cost value or pollutant importance factor.
4. Reduction percentages of technologies for each pollutant.
5. Costs of strategies.
6. Budget.
7. Maximum number of strategies a vehicle or equipment can have.
8. Equipment type and strategy matrix (TTMATRIX) is a binary matrix representing which strategy can be applied to which type of equipment. Rows of the matrix represent equipment type (four types) and columns represent the strategies. If type e equipments can use strategy t, then the entry (e, t) takes the value 1; otherwise, the entry is 0. The information stored in that matrix is used in constraint 3 while summing strategies that are applicable to a particular type of equipment.

One of the main factors in designing the framework was to give the control to the users so they can achieve maximum flexibility in terms of applying the framework to different scenarios and equipment. That is the reason why all the parameters can be controlled as user-defined parameters or inputs. While using the program, users have the option to change the input values and some of the key parameters. The output is an emission reduction strategy assignment plan that maximizes the emission reduction benefit within the desired budget.

CHAPTER 4
CASE STUDY DATA

This chapter summarizes the data used in the case study demonstration. Finding the information involved extensive research on emission reduction technologies and their properties. The required vehicle information was based on TxDOT's on-road and non-road fleet database. The desired information was extracted and transformed into parameters that were compatible with the mathematical formulation of the framework.

TxDOT's On-Road and Non-Road Fleet Data

TxDOT operates one of the largest vehicle and construction equipment fleets in the United States. The fleet contains non-road equipment types such as graders, loaders, excavators, pavers, rollers, trenchers, cranes, and off-highway tractors as well as various on-road vehicles such as heavy-duty trucks, medium-duty trucks, and passenger vehicles. TxDOT has prepared a very well-organized database of its fleet containing different characteristics of equipment and vehicles such as horsepower, fuel consumption, model year, age, usage hours, location of the equipment, etc. This database served as the basis of the emissions estimation and data pre-processing components of the proposed framework.

Emission Reduction Strategies

To demonstrate the capabilities of the proposed framework, nine emission reduction strategies representing a broad range of emission reduction options were included in the case study analyses (see Table **6**). Chapter 2 has an overview of these strategies, some of which are applied to individual vehicles or pieces of equipment. On the other hand, some technologies (group strategies) are usually applied to a group of vehicles or equipment. Fuel strategies are the most commonly used type of group strategies.

Table 6. List of Emission Reduction Strategies Included in Case Study Analysis.

Diesel Oxidation Catalysts (DOC)	Diesel Particulate Filters (DPF)	Selective Catalytic Reduction (SCR)	Lean NOX Catalysts (LNC or HC-SCR)	Exhaust Gas Recirculation (EGR)
Closed Crankcase Ventilation (CCV)	Fuel Additives (FA)	Bio-Diesel (BD)	LPG	

Cost Structure

The expected annual cost for emission reduction strategy was calculated as following:

$$\text{Expected Annual Cost of a strategy} = \text{Purchasing Cost} + \text{Recurring Cost} \quad (16)$$

where

Purchasing Cost is the amount of money spend to buy the technology; and

Recurring Cost includes annual costs of maintenance and other miscellaneous costs due to specific properties of the strategy.

Since the amount of fuel used and the miles driven for each vehicle are also taken into consideration while calculating costs, technology costs needs to be calculated for each vehicle in the fleet. Therefore, rather than having a single cost for each technology, there are different costs for each combination of emission reduction strategy and vehicles.

Purchasing Cost and Expected Life Time

Table 7 shows purchasing cost of the selected strategies. Group technologies (i.e., fuel additives and biodiesel) are not assigned a purchasing cost. This is because the cost of these strategies is calculated as a recurring cost.

Table 7. Fixed Purchasing Cost of the Strategies Included in the Analysis.

	DOC	DPF	SCR	LNC or HC-SCR	EGR	CCV	Fuel Additives	Biodiesel	LPG
Purchasing Cost ($)	$2500	$10,000	15,000	$8,000	$9,000	$2,000	$0	$0	$2,500

Emission Reduction Values

The emission reduction percentages for each selected strategy were found from the research and review of literature as described in Chapter 2. These reduction values represent the range of the expected values from the corresponding family of strategies. Table 8 summarizes the reduction values used in this study. Negative values indicate an increase in the corresponding pollutant.

Table 8. Emission Reduction Percentages for the Strategies Included in the Analysis.

	DOC	DPF	SCR	LNC or HC-SCR	EGR	CCV	Fuel Additives	Biodiesel	LPG
NOx	0	0	80%	33%	40%	0	15%	−10%	20%
CO	70%	80%	0	0	0	23%	20%	10%	60%
CO_2	0	−5%	0	−5%	−5%	0	15%	0	0
HC	70%	80%	0	0	0	66%	15%	10%	0
PM	36%	80%	25%	0	−5%	33%	30%	15%	0

STRATEGY—VEHICLE-TYPE MATRIX

The strategy-vehicle type matrix shown in Table **9** demonstrates the compatibility of the selected strategies with the various equipment types. If a technology can be applied to a type of vehicle, the corresponding entry in the matrix is 1; otherwise, the entry is 0. Some strategies are applicable only to on-road vehicles or non-road equipment whereas some of them are applicable to all diesel equipment. This matrix is based on the compatibility information obtained from strategy screening performed as part of the literature review.

Table 9. Matrix of Equipment/Vehicle and Strategy Compatibilities.

	DOC	DPF	SCR	LNC or HC-SCR	EGR	CCV	Fuel Additives	Biodiesel	LPG
Gasoline, On-Road	0	0	0	0	0	0	1	0	1
Diesel, On-Road	1	1	1	1	1	1	1	1	1
Diesel, Non-Road	1	1	1	0	1	0	0	0	0

COUNTY WEIGHT

EPA uses counties as the base for determining the air quality attainment status of a region. This study follows this trend and uses the county as the basis of location factors. In this regard, emission reductions achieved in counties that have failed the national ambient air quality standards (i.e., non-attainment counties) should be worth more than the emission reduction achieved in counties with better ambient air quality. This phenomenon is represented in the framework by including a county weight parameter. Users of the framework can apply a value between 0 and 1 to each 4 attainment categories—1 reflecting the highest importance and 0 representing the lowest importance level. For the purpose of this study, the default case study is using the following county weights: NA = 1, NNA = 1, EA = 0.7, and A= 0.5. Table 10 lists the near non-attainment and non-attainment counties of Texas used in this study.

Table 10. List of Non-attainment and Near Non-attainment Counties of Texas.

County Name	Status	Metropolitan Area
Travis	Non-Attainment	Austin
Nueces	Near Non-Attainment	Corpus Christi
San Patricio	Near Non-Attainment	
Collin	Non-Attainment	Dallas–Fort Worth
Dallas	Non-Attainment	
Denton	Non-Attainment	
Ellis	Non-Attainment	
Hood	Non-Attainment	
Johnson	Non-Attainment	
Kaufman	Non-Attainment	
Parker	Non-Attainment	
Rockwall	Non-Attainment	
Tarrant	Non-Attainment	
El Paso	Non-Attainment	El Paso
Brazoria	Non-Attainment	Houston–Beaumont
Chambers	Non-Attainment	
Fort Bend	Non-Attainment	
Galveston	Non-Attainment	
Hardin	Non-Attainment	
Harris	Non-Attainment	
Jefferson	Non-Attainment	
Liberty	Non-Attainment	
Montgomery	Non-Attainment	
Orange	Non-Attainment	
Waller	Non-Attainment	
Bexar	Non-Attainment	San Antonio
Victoria	Near Non-Attainment	Victoria

Pollutant Cost

As with county weight, not every pollutant has the same level of importance for all regions. In fact, attainment status determination is based on different standards for different pollutants. In reality, a county is usually in attainment for all but one specific pollutant. On the other hand, some pollutants are considered more dangerous to people and the environment. To reflect this issue in the framework, a pollutant importance factor is included in the form of pollutant cost.

Use determines the appropriate pollutant cost for each region. Table 11 lists the pollutant costs used in this study for demonstration purposes. These costs are selected based on the review of the literature and are calculated according to the estimated negative impact of the corresponding pollutant on the environment or human population.

Table 11. Impact Cost of Pollutants.

Pollutants	$/ton	$/g
NOx	$3625	$0.00363
CO	$100	$0.00010
CO_2	$12	$0.00001
HC	$2750	$0.00275
PM2.5	$63339	$0.06334

CHAPTER 5
CASE STUDY RESULTS

Five scenarios were developed and executed to demonstrate the capabilities of the proposed framework. These scenarios cover a range of budget limits, location preferences, and analysis scales. The case study analysis includes five pollutants (NOx, CO, CO_2, HC, and PM2.5) and nine strategies (DOC, DPF, SCR, HC-SCR, EGR, CCV, LPG, FA, and BD[3]). The mathematical formulation and optimization modeling is implemented using ILOG CPLEX and Visual C++ platforms. This chapter provides an overview of this case study demonstration effort.

SCENARIO 1

This scenario represents a statewide analysis with all TxDOT vehicles and equipment included in the analysis. Furthermore, all pollutants and all strategies are also considered. All the counties, regardless of their air quality status, are assigned the same county weight of 1. Table 12 shows a summary of the characteristics of this scenario.

Table 12. Characteristics of Scenario 1.

Parameters & Dimensions					
Counties	**Vehicles**	**Pollutants**	**Technologies**	**County Weights**	**Max Number of Strategies on an Equipment**
All 254 counties of Texas	All vehicles and equipment - total of 11688 vehicles and equipment in 3 types	All 5 pollutants	All 9 strategies	1 for all counties	2 for all vehicles

Figure 4 depicts the value of the objective function, combined emission reduction benefit in U.S. Dollar, as a function of budget. The function in the figure has a concave shape, which indicates that the marginal emission reduction benefit decreases as the available budget increases. This is an expected behavior of the objective function for this type of problem. The reason is that high emission equipment pieces are expected to be retrofitted first. This in turn provides a large emission reduction benefit per unit of money spent on them. After the initial phase though, the lower emission equipment can be retrofitted, which does not provide as much reduction as the higher emissions equipment. Figure 5 shows the emission reductions resulted from a statewide analysis under a fixed budget of $1 million.

[3] Acronyms are defined in Table 6.

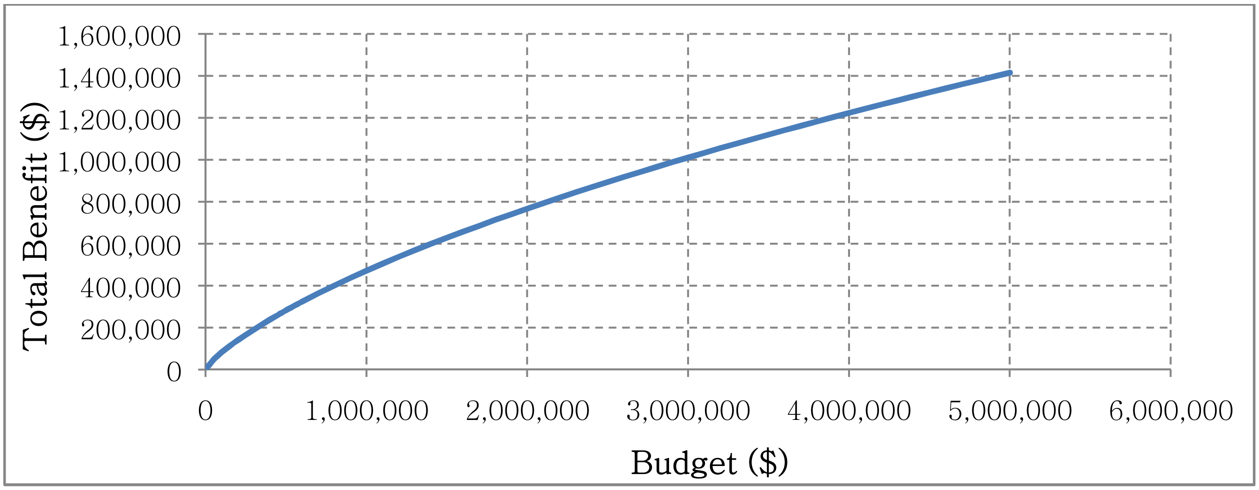

Figure 4. Value of Objective Function of Budget for Scenario 1.

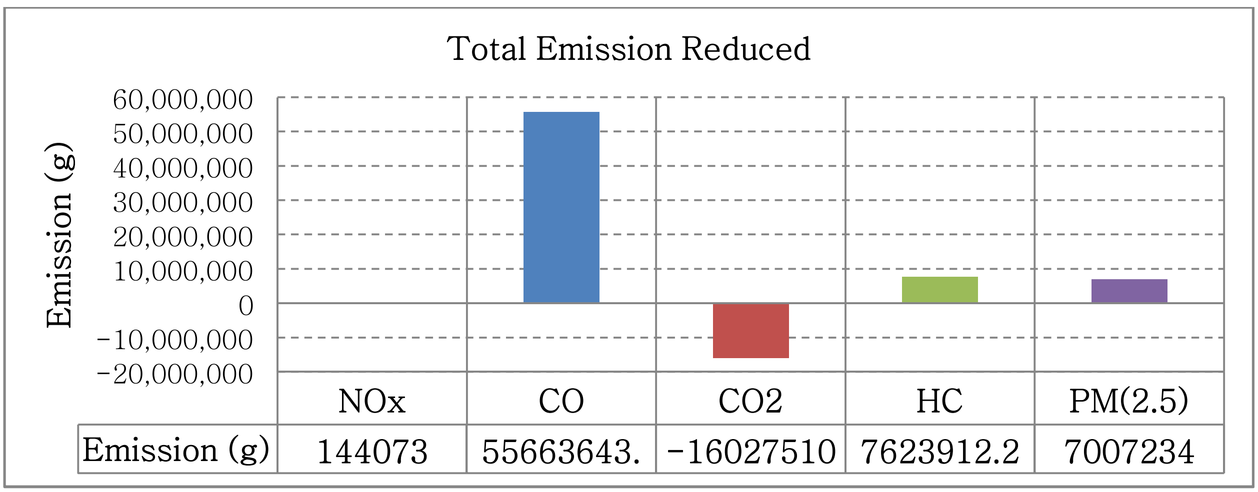

Figure 5. Summary of Expected Emission Reductions for the Selected Assignment Plan: Scenario 1.

The deployment plan results in emission reduction for CO, HC, and PM, and an increase in CO_2, which is also an indication of fuel consumption. This is because some of the technologies applied to the fleet increases the fuel consumption of vehicles and thus increases the CO_2 emission. Also, CO_2 has the least pollutant cost among all the other pollutants at $12/metric-ton. The emission reduction benefit for NOx is marginal. The main reason is that although NOx has a higher pollutant cost than CO, the CO reduction strategies are generally cheaper and provide a higher percentage of reductions, which results in high value of reducing CO.

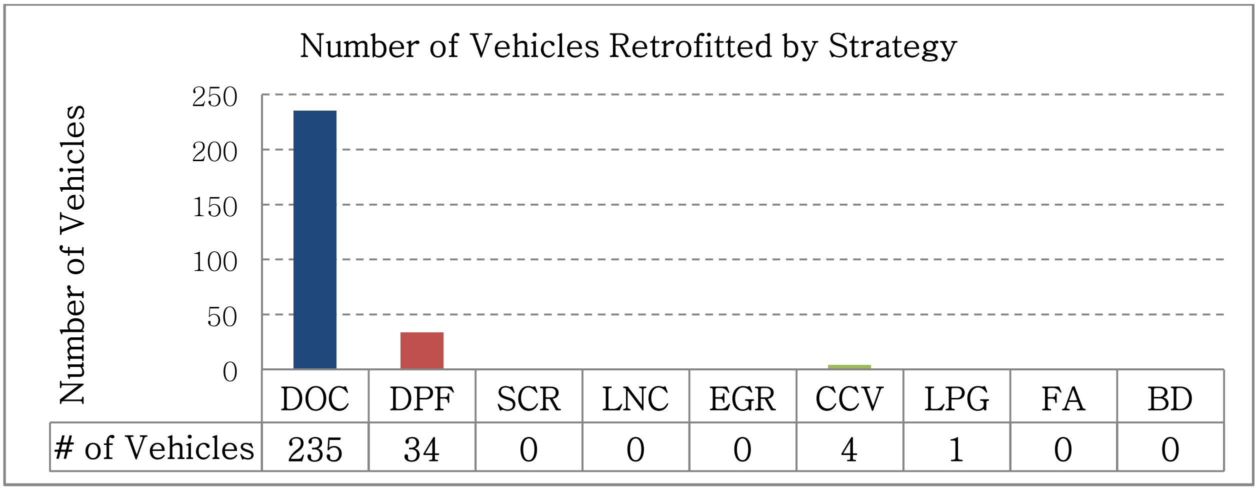

Figure 6. Distribution of Selected Strategies for Scenario 1.

Figure 6 shows the distribution of the strategies deployed. A total of 274 pieces of equipment in the fleet are selected to be retrofitted with emission reduction strategies. As the figure shows, most of the equipment pieces are selected to be retrofitted with DOC. This is mainly because DOC provides high reduction percentages for CO and HC and provides a decent reduction percentage for PM. Although DPF generally provides better emission reduction percentages than DOC, it has a higher cost for most pieces of equipment. Thus, it is more economical to choose DOC over DPF for most of the vehicles.

Besides DOC, DPF, CCV, and LPG, no other technology is selected. This is because the reduction percentages provided by those strategies are not as high as the selected ones. Another reason is that strategies such as DOC and DPF provide high emission reduction percentages for more than one pollutant, whereas the other strategies mainly focus on one primary pollutant. For example, although SCR provides a high reduction percentage for NOx emissions, it is not selected to be deployed on any equipment because it does not provide large reductions for other pollutants.

Figure 7 shows how selected strategies are distributed among different equipment types. The figure shows that almost all the selected strategies are assigned to non-road vehicles. This is because these pieces of equipment have usually higher emissions than on-road vehicles, which, in turn, translates into higher potential reduction of emissions.

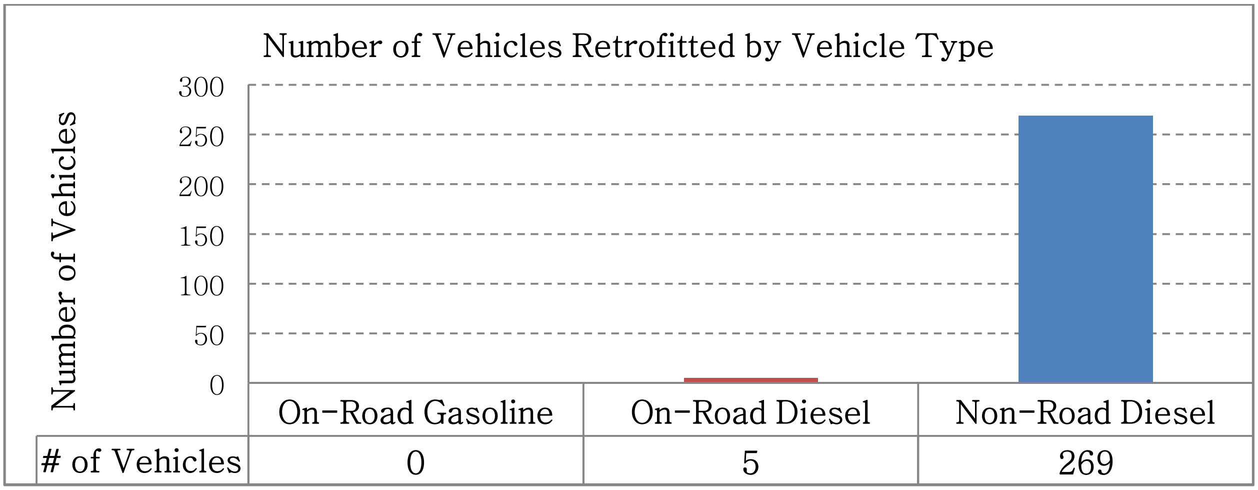

Figure 7. Distribution of Selected Equipment to be Retrofitted; Scenario 1.

SCENARIO 2

As in scenario 1, this scenario shows all the eligible vehicles are considered. The only difference is that the counties have different weights according to their air quality status. Table 13 lists the characteristics of this scenario.

Table 13. Characteristics of Scenario 2.

Parameters & Dimensions					
Counties	**Vehicles**	**Pollutants**	**Technologies**	**County Weights**	**Max. Number of Strategies on an Equipment**
All 254 counties of Texas	All vehicles and equipment—a total of 11688 vehicles and equipment in 3 types	All 5 pollutants	All 9 strategies	According to attainment status	2 for all vehicles

Figure 8 shows the changes in the expected benefit as a function of available budget. The graph has a concave shape similar to what was observed for scenario 1. The same explanation as scenario 1 also applies here. Figure 9 shows the resulted emission reduction benefits for a fixed budget of $1 million.

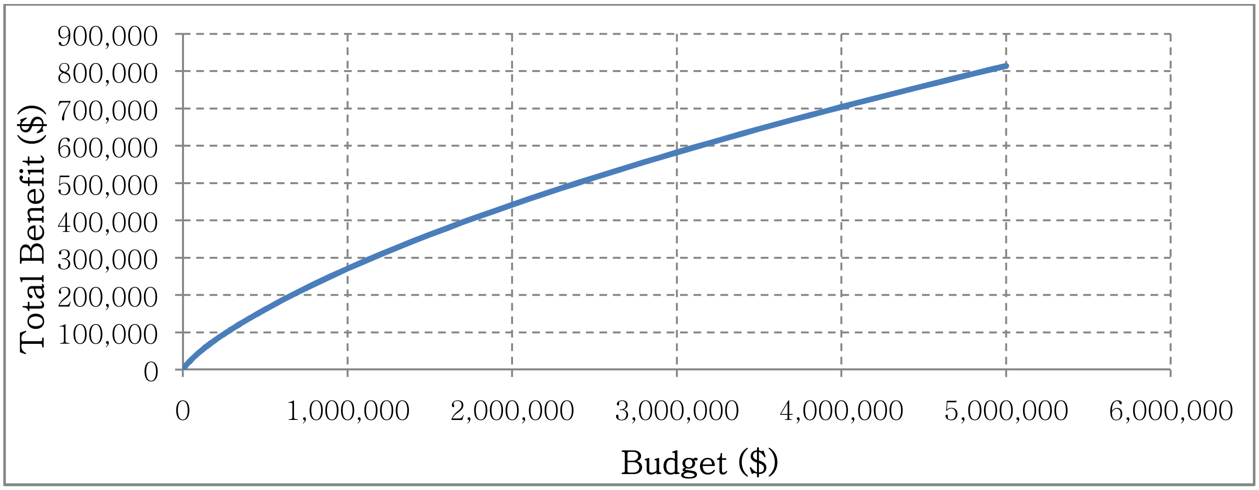

Figure 8. Value of Objective Function of Budget for Scenario 2.

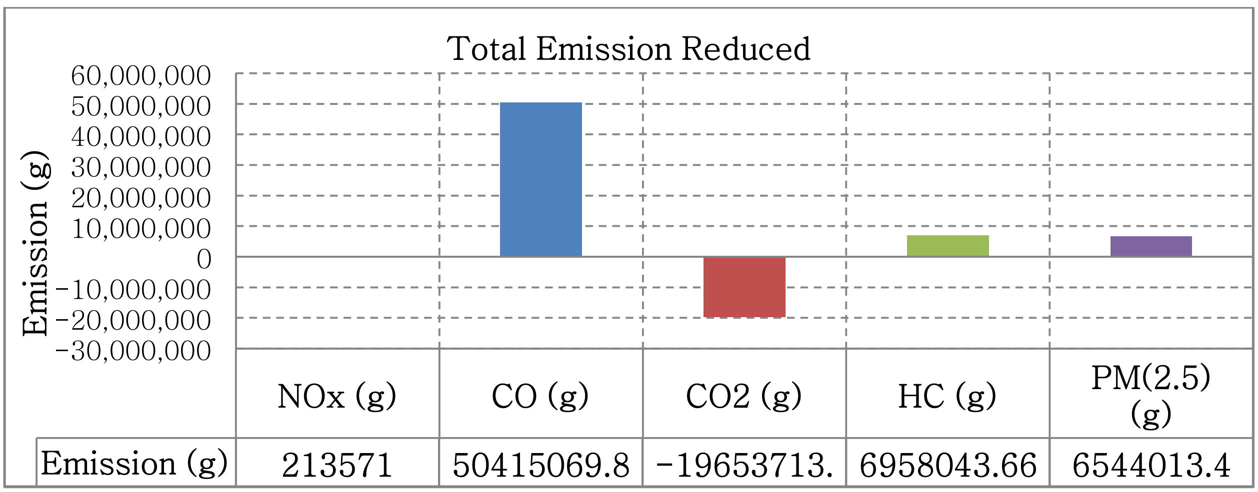

Figure 9. Summary of Expected Emission Reductions for the Selected Assignment Plan: Scenario 2.

Similar to scenario 1, CO is the pollutant that has the highest emission reduction among all the considered pollutants. CO_2 emission increases due to the fuel consumption penalty of some of the technologies. Similar discussions can be made as explained in scenario 1.

Figure 10 shows the distribution of the selected technologies. In this scenario, a total of 264 vehicles are retrofitted. Like in scenario 1, DOC is the most preferable technology. The reason is the same as mentioned in scenario 1. However, the number of equipments fitted with DOC is decreased compared to scenario 1; from 235 in scenario 1 to 218 in scenario 2. This is because in this scenario, equipment pieces in NA and NNA counties have assigned a larger priority and equipment selected from EA and A counties are in disadvantage. Again, non-road vehicles have the biggest portion of deployed strategies with 256 pieces of non-road equipment selected versus 8 on-road diesel vehicles. This again demonstrates the large emission contribution of non-road equipment.

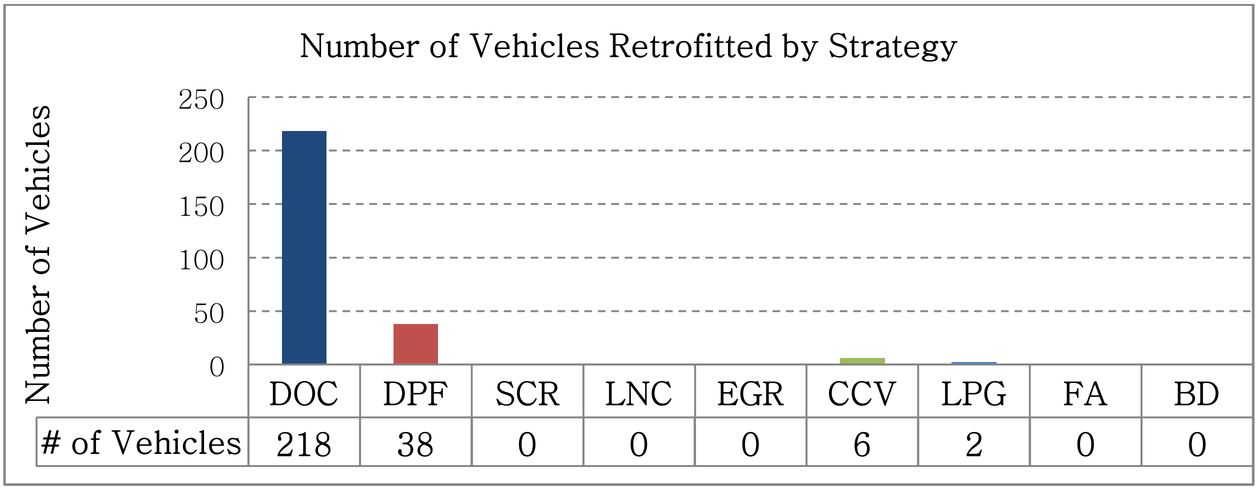

Figure 10. Distribution of Selected Strategies for Scenario 2.

SCENARIO 3

In this scenario, only counties that are considered to be non-attainment (NA) or near-non-attainment (NAA) are included. Again, all the pollutants and all the technologies are included. A summary of this scenario's characteristics is provided in Table 14. The shape of the expected benefit function is similar to scenarios 1 and 2, i.e., a concave curve.

Table 14. Characteristics of Scenario 3.

Parameters & Dimensions					
Counties	**Vehicles**	**Pollutants**	**Technologies**	**County Weights**	**Max Number of Strategies on an Equipment**
27 NNA and NA Counties	All equipment in this counties- total of 2821 vehicles and equipment in 3 types	All 5 pollutants	All 9 strategies	1 for all counties	2 for all vehicles

Figure 11 shows the results of the analysis for a budget of $400,000. Similar to the previous scenarios, CO is the pollutant with the highest amount of reduction. CO_2 emissions again increase due to an increase in fuel consumption. Relatively small emission reductions are achieved for HC and PM. NOx emissions neither decrease nor increase. The distribution of the selected strategies is shown in Figure 12. DOC is the most preferable technology for this scenario; 69 vehicles out of 96 vehicles and equipment are retrofitted with DOC. Besides DOC, DPF and also CCV is used for retrofitting some of these pieces of equipment. Similar to the previous cases, non-road vehicles have the priority of deployment.

Eighty-seven out of 96 retrofitted vehicles are non-road vehicles. None of the gasoline on-road vehicles are retrofitted. That is because emissions of gasoline on-road vehicles are small when they are compared to non-road vehicles. Moreover, the technologies for non-road vehicles considered in this study have higher reduction percentages than the technologies for on-road vehicles.

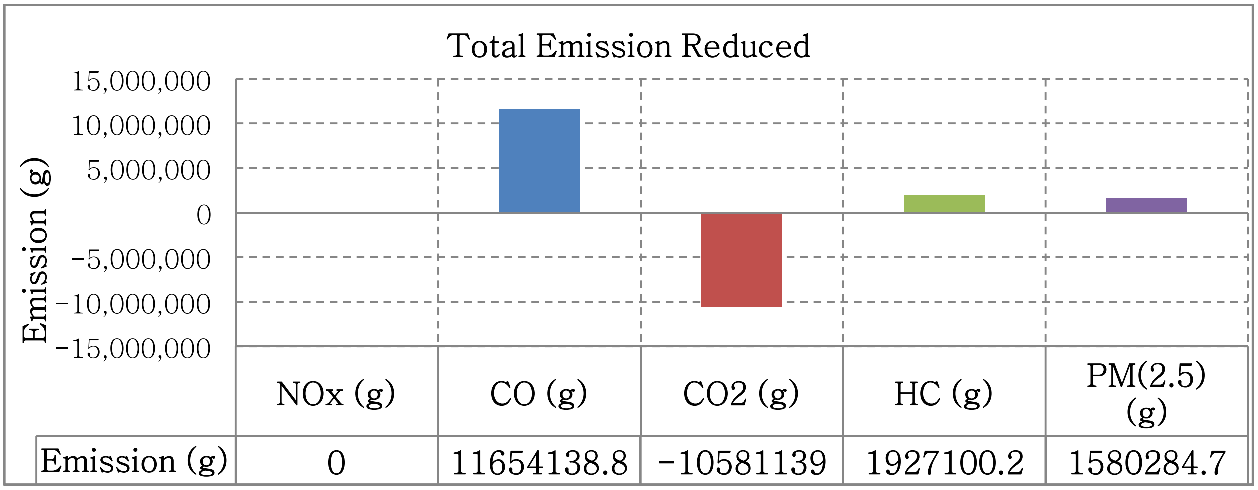

Figure 11. Summary of Expected Emission Reductions for the Selected Assignment Plan: Scenario 3.

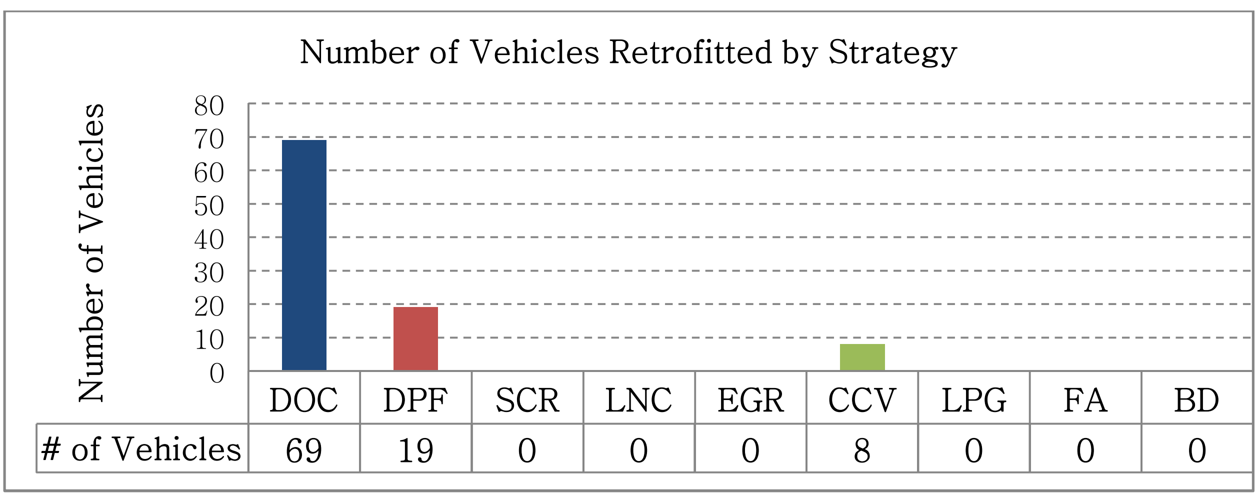

Figure 12. Distribution of Selected Strategies for Scenario 3.

SCENARIO 4

This scenario focuses on on-road diesel vehicles in non-attainment and near-non-attainment counties. All the pollutants and all the technologies are considered. Characteristics of scenario 4 are listed in Table 15. The benefit-budget function for this scenario is also a concave curve similar to previous scenarios.

Table 15. Characteristics of Scenario 4.

Parameters & Dimensions					
Counties	**Vehicles**	**Pollutants**	**Technologies**	**County Weights**	**Max Number of Strategies on an Equipment**
27 NNA and NA Counties	On-road diesel vehicles in this counties—a total of 987 vehicles in 1 type	All 5 pollutants	All 9 strategies	1 for all counties	2 for all vehicles

The results presented in Figure 13 belong to an analysis based on a fixed budget of $500,000. As in the previous scenarios, CO is the pollutant that has the highest emission reduction according to the resulted optimal strategy deployment. In addition, there are also HC, PM, and NOx reductions achieved. CO_2 differs from the previous scenarios in that it does not increase in this scenario. That is because the selected strategies for on-road diesel vehicles do not increase the fuel consumption, i.e., they do not have a fuel consumption penalty.

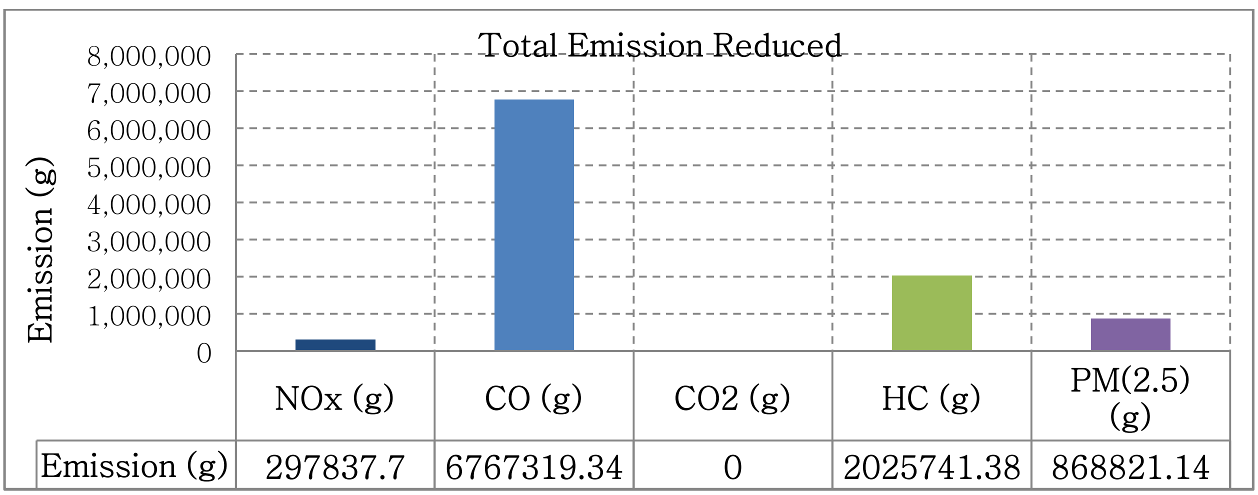

Figure 13. Summary of Expected Emission Reductions for the Selected Assignment Plan: Scenario 4.

As shown in Figure 14, 137 vehicles out of 217 are retrofitted with CCV. This shows that for on-road diesel vehicles, CCV seems to be the preferable choice. Moreover, 75 vehicles are also retrofitted with DOC. The remainder five vehicles are retrofitted with CNG/LPG.

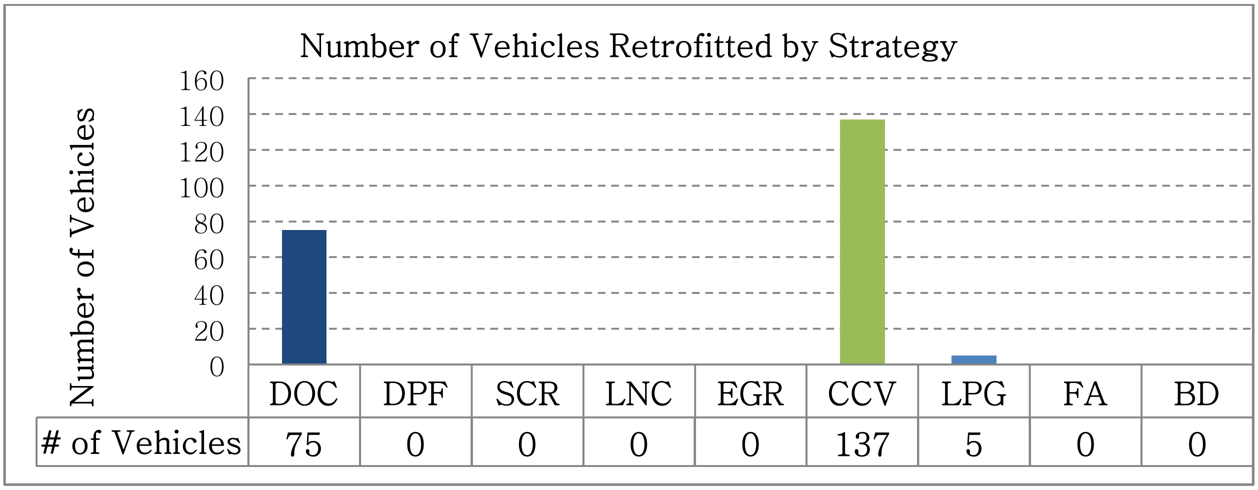

Figure 14. Distribution of Selected Strategies for Scenario 4.

SCENARIO 5

Scenario 5 puts emphasis on the on-road diesel vehicles in non-attainment and near-non-attainment counties located in the Houston' metropolitan area. Only one pollutant, NOx, and selected strategies are considered. Table 16 lists the characteristics of this scenario.

Figure 15 shows the changes in the objective function with respect to different budget values. The objective function still shows a concave trend; however, it does not change when the available budget value exceeds $1,500,000. Therefore, the maximum benefit we can obtain in this scenario is around $32,000 regardless of the budget value. First, scenario 5 focuses on a small number of counties and pieces of equipment in the Houston metropolitan area. Second, only one pollutant and a set of four strategies are included in this scenario. These limitations reduce the possibility of emission reduction and hence the total benefit.

Table 16. Characteristics of Scenario 5.

Parameters and Dimensions					
Counties	**Vehicles**	**Pollutants**	**Technologies**	**County Weights**	**Max Number of Strategies on an Equipment**
8 NNA and NA Counties in Houston Area	On-road diesel vehicles in this counties—a total of 333 vehicles in 1 type	Only NOx	SCR, DOC, FA, and DPF	1 for all counties	1 for all vehicles

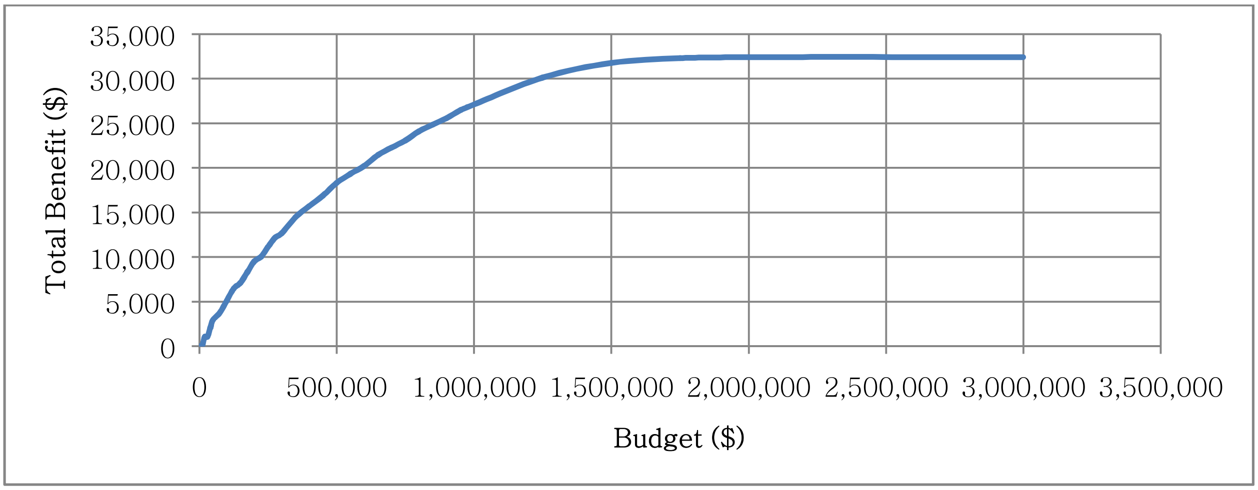

Figure 15. Value of Objective Function of Budget for Scenario 5.

Figure 16 show the results for scenario 5 based on a fixed budget of $400,000. Figure 16 indicates that over 4 tons of NOx can be reduced according to the resulted optimal deployment plan. As it can be seen in Figure 17, only SCR technology is selected for all the vehicles. According to the utilized percentage reduction values, SCR systems do not have any impact on the other pollutants and therefore emission reductions are zero for those pollutants. The main reason for having only SCR systems as the selected strategies is that NOx is the only pollutant included in the strategy and SCR provides the highest NOx reduction benefit.

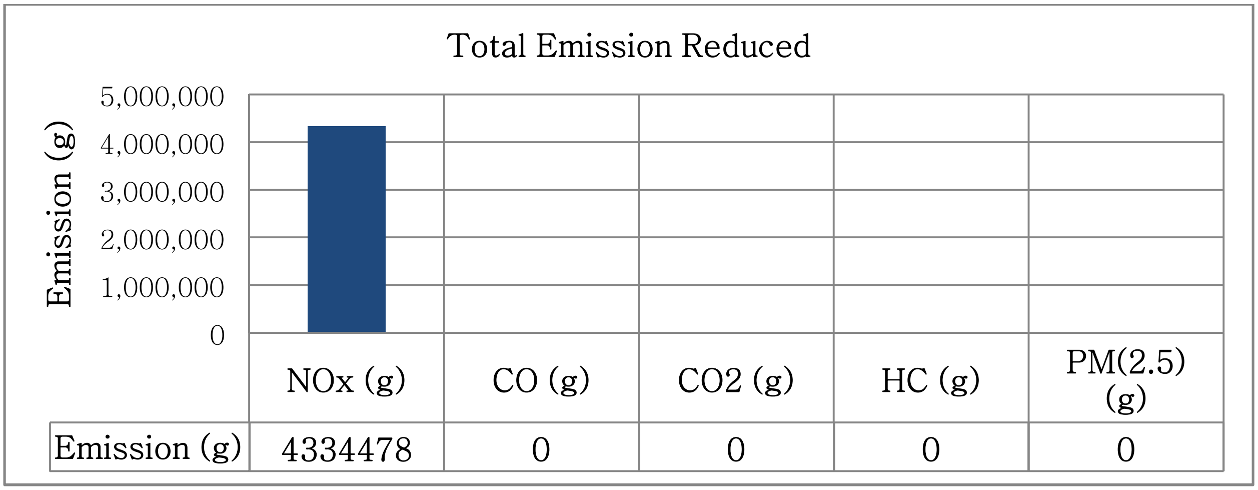

Figure 16. Summary of Expected Emission Reductions for the Selected Assignment Plan: Scenario 5.

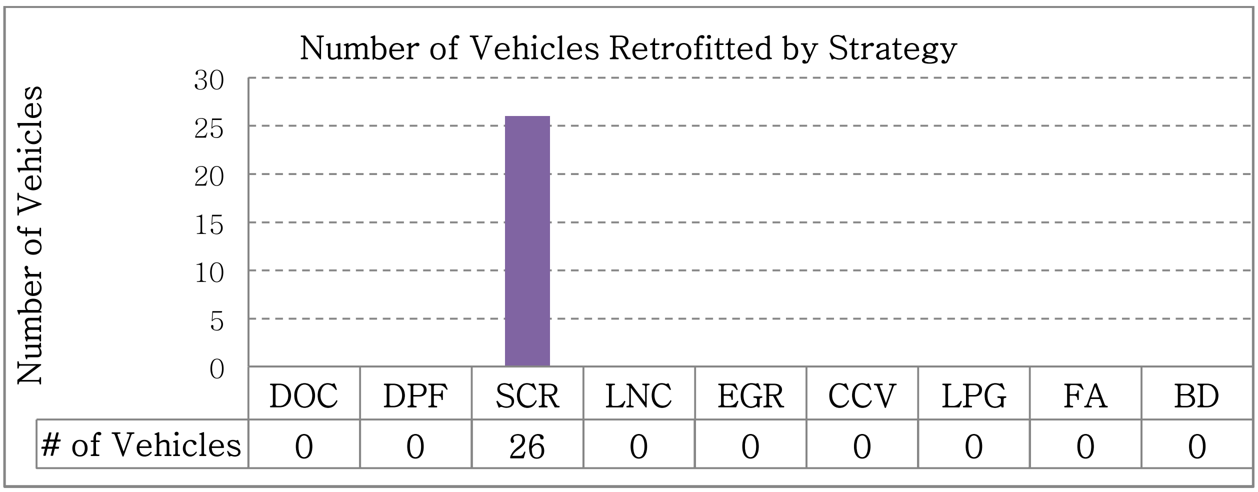

Figure 17. Distribution of Selected Strategies for Scenario 5.

DISCUSSIONS ON THE RESULTS

This chapter provided an overview of the application of the proposed optimization framework through a series of five case study analyses. The case studies were all based on TxDOT's database of its fleet vehicles and construction equipment. These case studies demonstrated the capability and flexibility of the proposed framework to handle different levels of analyses as well as different combinations of strategies and desired pollutions. The following summarizes observations for the presented case studies.

The first observation is that for all the scenarios, the objective function shows a concave behavior. This means that the marginal benefit obtained by increasing the budget amount decreases. As mentioned, this is an expected trend and in fact is a typical property of the benefit functions in general.

Second, non-road diesel vehicles have the priority of retrofitting over the other types of vehicles because the pollutants emitted by non-road diesel vehicles are generally higher than other types of equipment. Moreover, some of the technologies for non-road vehicles, like DOC and DPF, provide high emission reduction percentages for more than one pollutant. These factors make non-road vehicles more preferable for retrofitting than the other types of equipment.

Under the assumptions used in these case studies in most of the scenarios, CO has the highest emission reduction amount, whereas NOx reduction has the lowest. Although NOx has a higher pollutant cost and seems to be more significant than CO, strategies that provide considerable NOx reduction such as SCR are more expensive than CO reducing strategies and do not provide emission reduction for other pollutants. On the other hand, technologies such as DPF and DOC that are effective in CO reduction provide emission reduction of other pollutants as well. Therefore, it is preferable to use those technologies that aid with emission reduction of multiple pollutants than technologies that focus mainly on one pollutant.

It was also observed that CO_2 emissions increase in most of the scenarios. That is because some of the technologies deployed, such as DPF, increase the fuel consumption and hence CO_2 emissions. However, since CO_2 has a low pollutant cost compared to the other pollutants, an increase in CO_2 emissions does not affect the total benefit obtained and can be easily compensated by emission reductions in other pollutants.

Moreover, DOC is the most preferable technology, especially for non-road vehicles. The reason is DOC has a relatively low cost and provides high emission reduction percentages for multiple pollutants. Furthermore, CCV seems to be the most preferable technology for on-road diesel vehicles because it has relatively lower cost than other on-road diesel technologies and provides a decent emission reduction values.

Finally, fuel technologies were not found to be an economical choice according to the results obtained from these scenarios. Although FA provides emission reductions for all the pollutants, its reduction percentages are not as high as the other strategy. Moreover, FA cannot be deployed to individual vehicles—meaning, all the vehicles in the county have to use FA if it is deployed to one of the vehicles in that county. These reasons make FA uneconomical and therefore not preferable in the selection process.

CHAPTER 6
CONCLUSIONS

The goal of this research was to develop a framework for determining an optimal deployment plan of emission reduction technologies for large fleets of vehicles and construction equipment. The proposed optimization framework is a combination of three components: a) an emissions estimation component, b) a data pre-processing module, and c) an optimization component. Utilizing this structure, the framework is able to work with a variety of fleet equipment, location scenarios, pollutants, and different emission reduction strategies.

The emissions estimation component was built based on EPA's MOVES model and EPA's guidelines for non-road equipment. This component provides an estimate of the total annual amount of the desired pollutant for each individual vehicle or piece of equipment using the information recorded in a fleet inventory database. The data pre-processing module performs two tasks. First, it applies a set of user-defined conditions to filter out equipment that are not eligible for retrofitting, e.g., newer vehicles or low emissions equipment. Second, it puts the information of the eligible equipment in the format compatible with the input requirements of the optimization component. The optimization component consists of the mathematical formulation of the problem in the form of an objective function and a set of four constraints representing the selection criteria. The objective function represents the combined impact of five pollutant emissions. The constraints were determined based on literature review and interviews with TxDOT fleet manager. The resulted optimization component is an integer programming (PI) system and can be solved using standard optimization software packages.

A set of five scenarios were developed and executed to demonstrate the capabilities of the proposed framework. These scenarios cover a range of budget limits, location preferences, and analysis scales. The case study analysis included five pollutants and nine strategies. TxDOT's fleet data were utilized in this effort. The mathematical formulation and optimization modeling is implemented using ILOG CPLEX and Visual C++ platforms. TxDOT fleet manager provided requirements regarding eligibility criteria for a piece of equipment to be retrofitted.

The results of the case studies showed that the objective function had a concave behavior. This means that the marginal benefit obtained by increasing the budget amount decreases, which is a typical property of benefit functions in general. It was also observed that for the TxDOT fleet, non-road diesel vehicles have the priority of retrofitting over the other types of vehicles. That is because the pollutants emitted by non-road diesel vehicles are generally higher than other types of equipment; the emission reduction technologies for non-road vehicles, such as DOC and DPF, provide high emission reduction percentages for more than one pollutant. These factors make non-road vehicles more preferable for retrofitting than the other types of equipment.

The proposed framework can be used as a tool by fleet managers to deploy emission reduction technologies. The main challenge in developing the framework was incorporating the key factors in a way that gives the user the flexibility to choose a wide variety of scenarios. That was the reason a three component structure was selected. The role of the components is to give flexibility to the users within each individual component while maintaining the consistency of the interactions between them. The resulting framework is flexible enough to include different combinations of location, vehicles, and other key factors in the analysis. The framework can be used for two main purposes: a) determining the budget amount by performing a sensitivity analysis of the objective function versus different budget points, and b) determining the optimal assignment of the desired emissions.

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