MODELING TRANSPORTATION IN ABU DHABI: A 25-YEAR PROJECTION OF EMISSIONS UNDER ALTERNATIVE SCENARIOS OF THE PASSENGER VEHICLE FLEET

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ABSTRACT

Leslie E. Chinery: Modeling Transportation in Abu Dhabi: A 25-Year Projection of Emissions Under Alternative Scenarios of the Passenger Vehicle Fleet
(Under the direction of Dr. Jacqueline MacDonald Gibson)

The transportation sector is a rapidly increasing source of greenhouse gas (GHG) and criteria air pollutant emissions worldwide. These emissions contribute to global climate change and declining local air quality, with implications for human health. This study develops a model of the passenger vehicle fleet of Abu Dhabi, United Arab Emirates, from 2005 to 2030 to evaluate the emissions of GHGs and air pollutants under alternative vehicle fleet composition scenarios. A baseline scenario is compared with two alternative scenarios to evaluate the impact of compressed natural gas (CNG) vehicles and fuel economy improvements on fuel consumption, emissions, and costs. While both CNG vehicles and fuel economy improvements reduce fuel consumption and emissions below baseline levels, the CNG scenario costs US$867- US$994 million more than the fuel economy scenario in 2030. Therefore, fuel economy improvements are expected to be a much more cost-effective mitigation strategy for passenger transport in Abu Dhabi.

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AFV	Alternative fuel vehicle
CH_4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
gge	Gasoline gallon equivalents
GHG	Greenhouse gas
GWP	Global warming potential
HCFC	Hydrochlorofluorocarbon
ICE	Internal combustion engine
LDV	Light duty vehicle
$MtCO_2eq$	Metric tons carbon dioxide equivalent
NMHC	Non-methane hydrocarbon
NMOG	Non-methane organic gas
N_2O	Nitrous oxide
NO_x	Nitrogen oxides
PM	Particulate matter
SO_2	Sulfur dioxide
STMP	Surface Transport Master Plan
VKT	Vehicle kilometers traveled
VMT	Vehicle miles traveled
VO	Vehicle ownership

INTRODUCTION

One of today's greatest environmental challenges is the overconsumption of energy. As is well known, combustion of fossil fuels to produce energy contributes to the degradation of local air quality and to global climate change. Transportation was the fastest growing energy end-use sector between 1990 and 2002 and will continue to expand as demand for personal transportation grows with rising standards of living (Kahn Ribiero, 2007). In the coming decades, the transportation sector will likely undergo dramatic changes as nations around the world address rising greenhouse gas and air pollutant emissions. As over 80 percent of the energy consumed in the global transportation sector is used by road vehicles, the passenger vehicle fleet will become an important target for strategies to reduce fuel consumption and its associated emissions (de la Rue du Can & Price, 2008).

This study provides a quantitative analysis of the future passenger vehicle fleet of Abu Dhabi, United Arab Emirates (UAE), under baseline trends as well as two potential alternative technology scenarios. Specifically, the study assesses the energy use, emissions, and costs associated with increasing the percent of compressed natural gas (CNG) vehicles in the passenger fleet to 10 percent by 2030. Next, the study evaluates the energy use, emissions and costs associated with increasing the fuel economy of gasoline vehicles 10 percent above present values by 2030. Finally, it compares the emissions reductions achieved from these two scenarios with baseline emissions trends to determine whether improving fuel economy can achieve similar emissions reductions as the incorporation of CNG vehicles at the same or lower cost.

This analysis is important because it will evaluate three potential scenarios of vehicle fleet composition in Abu Dhabi from 2005 to 2030, and will use these projections to estimate selected GHG and air pollutant emissions in order to determine the impact of alternative mitigation strategies. Additionally, comparing the two non-baseline scenarios in terms of cost-effectiveness at reducing emissions will provide a useful metric for comparing the diverse technologies on emissions performance. The model developed in this study is an exercise in demonstrating the impact of potential pathways for personal transportation in Abu Dhabi, but is by no means a completely accurate representation of Abu Dhabi's vehicle fleet. While the simplifying assumptions made in this study may sacrifice some accuracy, the simplified model enables a relatively straightforward calculation of emissions that clearly demonstrates the potential impact of alternative strategies in Abu Dhabi's personal transportation sector.

Overview of Transportation in Abu Dhabi

Transportation accounted for 29% of energy-related GHG emissions in the UAE in 1994, with an estimated 17,683 metric kilotons of CO_2 emissions (UAE Ministry of Energy 2006). The transportation sector in the UAE is steadily expanding and is likely to be an even larger source of both GHG and air pollutant emissions in the future. Major factors contributing to the increase in the UAE's transportation emissions are the increased level of vehicle ownership, increasing percentage of light trucks in the passenger fleet, and growth in annual vehicle miles traveled (Kazim, 2003; ADDOT, 2009).

Currently, surface transportation in the UAE is dominated by the private car with minimal infrastructure in place for alternative forms of transport (ADDOT, 2009).

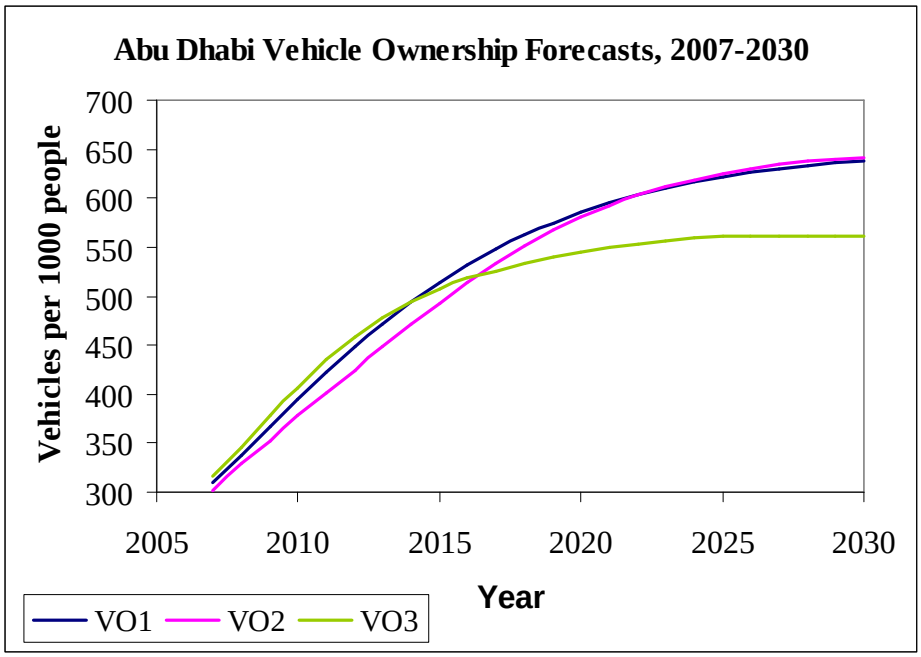
According to Kazim (2003), annual growth in personal vehicle demand across the UAE is about 6 percent, based on data from 1980 through 2003. Between 1997 and 2001, the number of "saloons" (passenger cars) registered in Abu Dhabi increased by about 16%, whereas the number of registered light trucks increased by 56% (ADDOT Appendix A, p. 62). During this same period, the total number of all types of licensed vehicles in Abu Dhabi increased by about 26%, demonstrating an increasing market share of light trucks among new vehicles sold (ADDOT Appendix A, p. 62). A more recent breakdown of registered vehicles by vehicle type is not available.

In July 2009, the Emirate of Abu Dhabi developed a Surface Transport Master Plan (STMP) that details an ambitious sustainable framework for reducing the impacts of transportation in Abu Dhabi. In this study, the Department of Transport developed a comprehensive model called the "Enhanced Transport Model" to evaluate four alternate scenarios of transportation policy through 2030 for their fulfillment of the economic, cultural, and environmental goals of the plan: a Highway scenario, a Public Transport scenario, a Demand-Management scenario, and a Low-Carbon scenario. Developing a low carbon economy by 2030 and reducing local air quality impacts are two of the major environmental goals outlined by the STMP. The model developed in the STMP is applied to all of surface transportation in Abu Dhabi, including freight, buses, and heavy duty vehicles.

In the Surface Transport Master Plan, there are three scenarios of future vehicle demand for Abu Dhabi. These scenarios, called "vehicle ownership" (VO) forecasts, measure vehicle demand as vehicles per 1000 people from 2007 through 2030 under alternative sets of assumptions. The vehicle ownership scenarios are time trend logistic curves based on S-curve models of vehicle ownership, using data from 2000 through 2006 on

population, number of vehicles, and non-oil GDP per capita to determine future trends (ADDOT, 2009). All three VO forecasts demonstrate a rapid increase in vehicle ownership per thousand people through the 2020s, when vehicle demand reaches a saturation level in the population of between 560 and 650 vehicles per thousand people by 2030. For comparison, the 2007 vehicle saturation levels in Western Europe and the United States were 587 and 844, respectively (CTA&ORNL, 2009). The vehicle ownership forecast curves are shown in Figure 1 (see Table 19 in Appendix B for figure data).

Figure 1. Vehicle Ownership Forecasts in Abu Dhabi, 2007-2030



Source: ADDOT Appendix B, p. 203

While historical trends in vehicle kilometers traveled (VKT) are unavailable for the UAE, a 2000 travel behavior survey indicated that the average passenger vehicle trip in Abu Dhabi is about 9 km, and that approximately 2.25 trips are taken per person per day (ADDOT Appendix A, p. 53). It can be assumed that, like most developed countries, the UAE is experiencing continued growth in annual distance traveled. In the US, for example, vehicle

miles traveled (VMT) increased at an average annual rate of 1.7 percent between 1997 and 2007 (CTA & ORNL, 2009).

Climate Change and Air Quality Impacts of Transportation

Over the past several decades the scientific community has come to a consensus that human activities are driving the current trend of climatic change, primarily due to emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2) from the combustion of fossil fuels. Whereas the UAE is responsible for less than one half of one percent of the world's total GHG emissions, it has the second highest per capita emissions rate in the world (WRI, 2009) andwill likely be disproportionately affected by the future consequences of climate change due to its coastal geography and hot, arid climate (Harder et al., in press).

In 2004, GHG emissions from the global transportation sector consumed 22 percent of primary energy worldwide and were responsible for approximately 27 percent of global GHG emissions (de la Rue du Can, 2008). Transportation GHG emissions in the UAE are consistent with the worldwide percentage as 29 percent of total domestic GHG emissions originated from the transportation sector in 1994, the most recent year for which an official inventory is available (Ministry of Energy, 2006).

The primary GHG from vehicles is carbon dioxide (CO_2), although methane (CH_4), nitrous oxide (N_2O) and hydrochlorofluorocarbons (HCFCs) from refrigerants are also emitted in smaller quantities. GHG emissions from conventional personal vehicles are dependent upon the amount of fuel consumed as well as the carbon intensity of the fuel. Every gallon of gasoline emits approximately 8.8 kg of CO_2, whereas a gallon of diesel emits approximately 10.1 kg of CO_2 (US EPA, 2005).

Transportation is also a significant source of several criteria air pollutants that contribute to declining air quality in the UAE. The major air pollutants associated with conventional internal combustion engine (ICE) vehicles are: particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HCs), volatile organic compounds (VOCs), and sulfur dioxide (SO_2). According to Cohen (2003), the majority of vehicular PM emissions are fine particulates of 2.5 micrometers or less, which have the most severe health impacts. In addition, transportation emissions tend to contribute to the development of smog in urban areas, which also contributes to respiratory and other diseases associated with poor air quality (Yeh, 2007). Abu Dhabi's Surface Transport Master Plan states that "traffic alone is responsible for breaching air quality standards in Abu Dhabi City and Al Ain" (ADDOT, 2009, p. 117).

Several variables influence emissions from personal vehicles, including the number of vehicles on the road, composition of the vehicle fleet by weight class, average fuel economy, vehicle fuel type, and the distance traveled by vehicles each year. Transportation poses a unique challenge for mitigation efforts due to its highly diffuse nature, slow rate of vehicle turnover, high sunk costs in infrastructure and diverse underlying trends (Rajan, 2006). There are two broad approaches to reducing emissions from the vehicle fleet: (1) the technological approach, focused on making more fuel-efficient vehicles from less polluting energy sources and (2) the demand-side approach, which aims to reduce the total number of vehicles on the road, encourage consumers to purchase more fuel-efficient vehicles, and minimize or reverse growth in annual distance traveled (Yang et al., 2009; Rajan, 2006). Despite many challenges, numerous existing technologies can have a considerable impact on

mobile emissions if implemented in the personal transportation sector, especially when coupled with demand-side management.

Compressed Natural Gas Vehicles

One strategy for curbing local air pollution and GHG emissions from transport is the use of compressed natural gas (CNG) as an alternative to gasoline in automotive fuel chains. The majority of CNG vehicles currently on the road have been incorporated into government vehicle fleets and public transportation buses via procurement policies in an attempt to curb urban air pollution (Yeh, 2007; Reynolds et al., 2008). However, CNG is gaining momentum as a potential alternative to gasoline in the passenger vehicle fleet as well. CNG passenger vehicles can be manufactured as dedicated CNG vehicles or converted from conventional vehicles (Yeh, 2007).

CNG offers several environmental benefits over petroleum that make it an attractive alternative fuel, although estimates of its net impact on air quality are not consistent across the literature. According to Yeh (2007), vehicles that use CNG emit less PM, non-methane organic gases (NMOG), carbon monoxide (CO), and air toxics (substances that may exhibit carcinogenicity) (Tamura & Eisinger, 2003). A study conducted by Cohen, Hammit and Levy (2003) found that CNG buses decrease PM, NOx, downstream SO_2, and ozone. A study by Dondero and Goldemberg (2005) found that converted CNG vehicles reduced CO by 53%, non-methane hydrocarbons (NMHCs) by 55%, and CO_2 emissions by 20% compared with gasoline vehicles. However, the same study indicated an increase in hydrocarbons of 162% and of NO_x emissions by 171% (cited in Yeh, 2007). According to Hekkert et al. (2005), CNG vehicles emit between 120 and 198 grams of CO_2 per kilometer or 6.5 kg per gasoline gallon equivalent (gge), where gge is a conversion factor equal to the

amount of CNG with the same energy content as a gallon of gasoline (approximately 127 cubic feet). A gallon of gasoline emits between 165 and 260 grams of CO_2 per km traveled, or 8.8 kg of CO_2 per gallon. In addition, many consider natural gas vehicles to be a potential stepping stone towards future vehicles with even lower emissions, such as fuel cell vehicles, because they are a transitional technology that can be implemented in the near term as an alternative to gasoline without requiring radical changes to fuel distribution infrastructure and vehicle technology (Hekkert et al., 2005).

For the UAE, many aspects of CNG make it an appealing alternative to gasoline as a transportation fuel. For one thing, natural gas supplies the majority of domestically produced electricity in the UAE and therefore already has an extensive distribution infrastructure (Kazim, 2007). The use of CNG for passenger transportation would allow the UAE to utilize its existing natural gas infrastructure, requiring only an increase in the number of consumer distribution stations. Secondly, CNG is already being considered as a feasible alternative vehicle fuel, eliminating the need to garner political support. In fact, the STMP describes the encouragement of CNG vehicles through government procurement policies and potential "feebates" for consumers (ADDOT, 2009). Feebate programs combine rebates given to consumers of fuel-efficient vehicles and fees charged for purchasers of less efficient vehicles in order to bolster consumer demand for fuel economy (Peters et al., 2008). Thirdly, air pollution negatively impacts the state of environmental health in Abu Dhabi, and therefore reducing criteria air pollutant emissions through a transportation fuel with lower pollutant content may have significant benefits for the health of the population. In addition, CNG fuel is generally less expensive for consumers than gasoline.

Despite its environmental benefits, several drawbacks arise from the use of CNG as a vehicle fuel, including safety concerns. For example, CNG must be kept highly pressurized at several thousand pounds per square inch (psi) and may spontaneously combust if not handled properly (Cohen et al., 2003). The United States Transportation Research Board reported the potential for spontaneous ignition of CNG if it reaches a critical concentration of 5 to 15 percent in the air (cited by Cohen et al., 2003). Another disadvantage to CNG is the relative scarcity of refueling stations. According to a news article, the Abu Dhabi is planning to install 16 natural gas fueling stations across the emirate that will be available to the public, including 9 in the city of Abu Dhabi (Ameinfo, 2006). However, stations that distribute CNG are still much less prevalent than petroleum refueling stations. CNG vehicles are less efficient than internal combustion engines due to a lower compression rate and conversion of heat energy to kinetic energy, high "pumping losses" to the engine during idling, and increased vehicle weight due to heavier fuel tanks (Cohen, 2003). Public transportation buses using CNG have a 20 to 40 percent lower engine efficiency than conventional diesel buses (Cohen, 2003). Finally, CNG vehicles have a much higher retail cost than conventional gasoline or diesel vehicles.

In order for CNG vehicles to have a measurable impact on transportation emissions, they must be incorporated into the passenger vehicle fleet, which will take time. According to Schafer et al., "the impact of improved-technology vehicles on automobile fleet energy use and emissions depends on the time required to achieve i. market competitiveness, ii. significant market shares of new vehicle sales, and iii. a significant penetration into the existing vehicle fleet (Schäfer et al., 2006).

A more prevalent distribution infrastructure for CNG must be established to increase the availability of refueling stations and appeal to consumers. Another requirement will be raising consumer awareness and demand for CNG vehicles. There is a delicate balance between vehicle demand and fuel station availability. This can be demonstrated by the case of New Zealand in the 1980s, where favorable government loan programs rapidly increased consumer demand for CNG vehicles; this demand was deflated once these loan programs were discontinued in 1985. In this case, the collapse of demand led to refueling station closures, which lowered demand for CNG vehicles due to inadequate refueling infrastructure. Finally, public perception of quality is very important for the adoption of new vehicle technologies, and increasing the number of CNG vehicles on the roads too rapidly before learning and economies of scale are realized may impair quality to some extent by not allowing for adequate technological evolution (Yeh, 2007).

Fuel Economy Improvements

The use of CNG as a mitigation strategy for vehicle emissions will require a somewhat drastic shift in vehicle technology from the internal combustion engine, and must overcome several obstacles as discussed above. An alternative strategy for reducing mobile emissions is to reduce the amount of gasoline consumed by increasing the fuel economy of conventional internal combustion engine (ICE) passenger vehicles. The advantage to this strategy is that it utilizes existing vehicle technology and eliminates, or at least postpones, the need for an entirely new refueling infrastructure. Fuel economy improvements can achieve significant fuel savings at a reasonably low cost while maintaining vehicle size and performance.

Several components contribute to the fuel economy of a vehicle, including engine efficiency, which is the efficiency at which fuel energy is converted to useful kinetic energy, and vehicle fuel consumption, a measure of how much fuel is required to travel a given distance (typically measured in L/100km). Fuel consumption depends upon vehicle characteristics such as size, power and weight as well as driving behavior (Bandivadekar et al., 2008b). The total fuel economy of a vehicle is therefore a function of engine efficiency and fuel consumption, as well as the distance traveled.

Over the past decades, the efficiency of the internal combustion engine has improved considerably; rather than raising the fuel economy and lowering vehicle emissions, however, these improvements have mainly been channeled to counteract the trends of increasing vehicle power and weight. According to a National Research Council report (2002), between 1985 and 2001 US vehicles grew 20 percent heavier and their "0 to 60" acceleration time, a common metric of performance, decreased by 25 percent; during this time, however, there was only a slight decline in fuel economy, indicating that engine efficiency improvements were occurring. If these engine efficiency improvements had been used to increase fuel economy rather than vehicle performance and weight, there would likely have been a noticeable improvement in fuel economy and therefore a reduction in emissions per vehicle during this period.

One challenge to measuring the impact of fuel economy improvements on vehicle fuel consumption is that in practice, these improvements often result in fewer realized emissions reductions than are technologically feasible. The "rebound" effect describes the phenomenon that when consumers use more fuel efficient vehicles, they tend to drive more because of the lower cost of driving. Attempts to quantify the rebound effect vary widely

across a range of studies. For example, a study by Portney et al. (2003) estimated the rebound effect to be approximately 10-20 percent of the total potential fuel savings through tighter fuel economy standards. On the other hand, a study by Small and Van Dender (2007) calculated the short-run rebound effect as 4.5 percent based on US data from 1966 to 2001; the long-term rebound effect estimated by this study was 22.2 percent. The Small and Van Dender study also found that the magnitude of the rebound effect declines with increasing income and is dependent upon the price elasticity of fuel demand and real costs of fuel. Over time, the rebound effect tends to decline because of rising incomes and lower real fuel costs. This is the trend observed in the latter part of the twentieth century, and is expected to continue into the future (Small & Van Dender, 2007).

One potential unintended consequence of more fuel efficient vehicles, especially if mandated by fuel economy standards, is the size of vehicles and therefore potentially their safety. To increase fuel economy, auto manufacturers tend to reduce the weight of their vehicles because this is quick and inexpensive way to reduce fuel consumption. Some argue that reducing the size and weight of vehicles negatively impacts the safety of the vehicle fleet by increasing the mortality rate of accidents (NRC, 2002). However, this argument may be misleading as there are counteracting safety impacts depending on which types of vehicles undergo a reduction in weight. If the majority of downsized vehicles are passenger cars, then there is an increased risk of fatality in multicar collisions; however, if the majority of downsizing occurs for light trucks, then the risk of fatality in a multicar accident is actually decreased as the disparity between the weight of the involved vehicles is reduced (Portney et al., 2003). Therefore, the cumulative effect of increased fuel economy on safety is ambiguous and difficult to determine.

A drawback to fuel economy improvements is that they may raise the retail price of a vehicle. This may encourage people to wait longer before purchasing a new vehicle or to purchase less efficient vehicles, thus proliferating the existing aging and less fuel efficient vehicle fleet. On the other hand, the total costs of vehicle ownership are likely to decrease as consumers spend less on fuel, despite the rebound effect. According to a survey conducted in the US, households spend an average of 7.1 percent of their income on vehicle purchases, 4.6 percent of income on gasoline and motor oil, and 4.9 percent of income on other vehicle expenditures (CTA & ORNL, 2009). While this implies that higher initial costs of vehicle purchase could potentially have a larger impact on households, the act of purchasing a vehicle is not frequent and therefore lower fuel costs may dominate vehicle purchase decisions. However, there is considerable difficulty in determining consumers' willingness to pay for improvements in fuel economy (Turrentine et al., 2007). Some studies have indicated that consumers require a payback period of three years or less in order to purchase vehicles with higher fuel economy, implying a high discount rate and irrational consumer behavior when it comes to fuel economy improvements (Yeh, 2007, Greene et al., 2005).

Despite these challenges, improving the fuel economy of the vehicle fleet is still a beneficial and cost-effective mitigation strategy for transportation emissions and will therefore be considered as an alternative to increasing the number of CNG vehicles in Abu Dhabi's passenger vehicle fleet.

Previous Studies

Several studies have assessed the impact of changes in the composition of the vehicle fleet on GHG emissions and air quality in various regions, including Madrid, Great Britain,

California, and the United States, among others (Lumbreras et al., 2008; Bristow et al., 2008; Yang, 2009; Bandivadekar et al., 2008a). Other studies have compared the performance and emissions impact of alternative vehicles and fuels such as battery electric, hybrid electric, biofuel, natural gas, and fuel cell vehicles (Van Mierlo et al., 2006; Hekkert et al., 2005; Hackney et al., 2001). In addition, some studies have been conducted to evaluate the impact of switching vehicles, mainly public transportation buses, to CNG as an alternative to diesel (Reynolds & Kandlikar, 2008; Cohen et al., 2003; Cohen, 2005; Goyal & Sidhartha, 2003). Separate studies by Yeh (2007), Greene (2005), and Janssen et al. (2006), among others, have evaluated the market penetration of CNG vehicles in international markets. Only a few studies have been conducted in the Middle Eastern region evaluating energy use in transportation, including ones in Saudi Arabia, Jordan, Iran, and Kuwait (Dincer et al., 2004; Jaber et al., 2008; Sadeghi & Hosseini, 2008; Jafari & Baratimalayeri, 2008; Koushki, P.A., 2007).

Various existing models evaluate both criteria air pollutant and GHG emissions from transportation. One such model is the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Graphical User Interface (GREETgui) model Version 1.8, developed by Argonne National Laboratory, which uses fuel and alternative technology market share input data to estimate full life-cycle emissions of vehicles in the U.S. through 2020 (Wang et al., 2007; Bandevadekar et al., 2008b). Life-cycle analyses of transportation, commonly called “well-to-wheel” analyses, include emissions from vehicle operation (“tank-to-wheel” emissions) as well as the extraction, refinement, and distribution of fuel (“well-to-tank” emissions). Argonne National Laboratory also developed the VISION model, which estimates fuel consumption and GHG emissions from highway vehicles through 2050 using

baseline projections from the U.S. Energy Information Administration (EIA) (Singh et al., 2003). Yet another comprehensive study of emissions from road transport in the U.S. was conducted by the Laboratory for Energy and the Environment at the Massachusetts Institute of Technology; this study, entitled "On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions," (Bandevadekar et al., 2008a) uses another version of GREET (version 2.7) to estimate emissions from changes in vehicle technology.

Two of the major European transportation models are the **CO**mputer **P**rogramme to Calculate **E**missions from **R**oad **T**ransport (COPERT 4) and TREMOVE. The COPERT 4 was developed by the Laboratory of Applied Thermodynamics at Aristotle University Thessaloniki in collaboration with the European Environment Agency. COPERT uses data on the number of vehicles in each technology category and annual distances traveled to estimate fuel consumption of regulated (CO, NO_x, VOC, PM) and unregulated (N_2O, NH_3, SO_2, NMVOC) air pollutant emissions from European road transport (Lumbreras et al., 2008; Gkatzoflias et al., 2007). TREMOVE incorporates a cost analysis of transportation policy options in addition to modeling emissions (De Ceuster et al., 2007).

This study builds on this previous body of research to provide a simplified model comparing CNG vehicles and fuel economy improvements for their mitigation potential for GHG and air emissions in Abu Dhabi. Whereas the Surface Transport Master Plan is multi-modal and includes changes in highway infrastructure, public transportation, travel demand, and alternative vehicles in each of its scenarios, this study focuses solely on light-duty passenger vehicles without the changes in infrastructure or increased provision of public transportation. In doing so, this study enables comparison between specific vehicle fleet mitigation strategies, holding infrastructure variables as constant. CNG vehicles are chosen

because they are being considered as a mitigation strategy in the STMP. The model developed in this study builds on methods from previous studies and provides the first direct comparison of CNG vehicles and fuel economy improvements in Abu Dhabi and demonstrates which technology will potentially have a greater emissions impact at the lowest cost.

METHODS

The GREET, VISION, COPERT, and TREMOVE models described above represent only a few of the numerous transportation models available. However, many of the models require input data that are not available for the UAE and are more complex than what is necessary to accomplish the objective of this study. Therefore, rather than using an existing model to estimate future transportation emissions in Abu Dhabi this study creates a new model building on several of the methods from previous studies. The model is encoded in the software Analytica, by Lumina Decision Systems, Inc., which uses influence diagrams to visually demonstrate relationships among variables and facilitates calculations across multiple dimensions, called arrays. The program uses Monte Carlo simulation to address uncertainty among variables. The model uses estimates of emission factors and cost data, national fleet data, and equations and relationships among variables derived from previous studies on fleet impact assessments and transportation projections (for example, Bandevadekar et al., 2008b; Kazim, 2003; Hackney & de Neufville, 2001). The model is designed to be a simplified and straightforward representation of the passenger vehicle fleet in Abu Dhabi.

This analysis includes three main scenarios: (1) baseline, (2) CNG, and (3) fuel economy. In the baseline scenario, current trends in the passenger fleet are assumed to continue into the future. The baseline scenario is designed to provide a metric against which the alternative scenarios can be measured for their fleet impact. The CNG scenario differs from the baseline scenario only in that 10 percent of the 2030 vehicle fleet is comprised of

CNG vehicles. This requires a larger annual percent increase in the annual growth rate of CNG vehicles than in the baseline scenario. The fuel economy scenario uses the same composition of the vehicle fleet as the baseline scenario, but the average fuel economy of gasoline ICE vehicles is increased by a certain percent above the baseline each year, so that in 2030 the average fuel economy of the gasoline vehicles is 10 percent above the baseline level.

Description of Model

Before assessing the impact of alternative vehicle technologies, the number of vehicles, composition of the vehicle fleet, and other variables that influence emissions must be projected. The first step in this analysis is therefore to develop a model of future vehicle growth and fleet composition by fuel type and weight class, as well as fuel economy of the vehicle fleet. This is then used to calculate potential emissions of GHG and air pollutants for a "baseline" scenario assuming current trends continue. Once a basic model structure of the vehicle fleet is complete, the model can be applied to two alternative scenarios in order to demonstrate the impacts of CNG and fuel economy improvements on fleet fuel consumption and emissions. Finally, the alternative scenarios are compared for their cost-effectiveness in reducing emissions below the baseline level. The comparison of emissions reductions per increase in vehicle cost is a useful metric for comparing the mitigation potential of these two vehicle technology paths.

First and foremost, an appropriate time span for this analysis is essential. Too short of a time span does not allow adequate opportunity for fleet turnover to occur. A minimum of at least 10 to 15 years is required for emerging vehicle technologies to be incorporated into

the vehicle fleet on the scale necessary to impact transportation emissions (Schafer et al, 2006). However, beyond 30 years, there is significant uncertainty regarding both future technologies and potential policy paths. Therefore, between 15 and 30 years is an appropriate window in which to measure the impact of vehicle technologies. This assessment covers a period of 25 years, from 2005 through 2030. The base year was chosen to be 2005 because UAE data on the number of vehicles are available for this year, and 2030 was chosen as the end year because the STMP modeled future vehicle ownership through this year.

The model inputs used in this analysis were gathered from the models listed above or from previous studies of vehicle fleet impact assessments. Many of the required data inputs are based on US or other nations' vehicle fleets as more detailed UAE transportation data are unavailable. Because the literature reports a range of possible values for several of the variables, the model represents these variables with probability distributions across the range of values encountered in the literature. Wherever possible, data from Middle Eastern studies were used to approximate the UAE vehicle fleet.

Modeling the vehicle fleet is a very complex process due to the diffuse nature of the fleet, interactions among variables, and diverse underlying trends. This complexity is apparent in the sheer number of inputs and calculations involved in the models discussed above. Because this analysis is intended to be a simplified representation of the vehicle fleet, the model relies on a number of assumptions, which are described below. The model is relatively easy to expand and therefore any of the assumptions listed below can be altered to incorporate more complex relationships into the vehicle fleet model if desired.

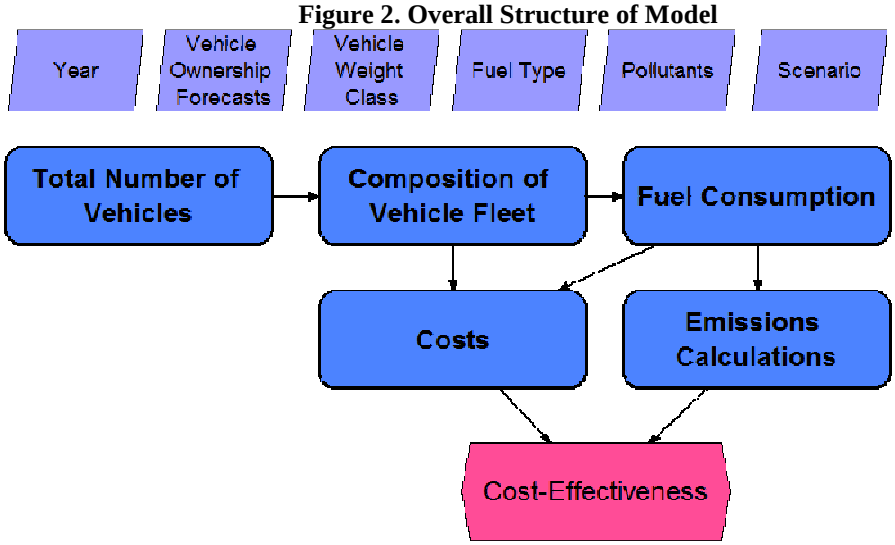
1. **Annual change in total number of vehicles is the net growth of the vehicle fleet.** This model does not separately calculate new vehicles sales each year or the scrappage (retirement) rates of existing vehicles, but rather uses the net change in vehicles, which is the quantity of new vehicles sold minus the number of vehicles retired.
2. **Vehicle fuel types.** The vehicle fuel types included in this analysis are conventional gasoline internal combustion engine (ICE), conventional diesel ICE, and CNG vehicles. It is likely that there are other alternative fuel vehicles such as biofuel, hydrogen, and hybrid gasoline-electric, among others, in the vehicle fleet. However, these are excluded for the sake of simplicity in the model, due to a lack of a reasonable approximation of their prevalence and based on the assumption that these vehicles likely make up only a small fraction of the vehicle fleet. This is true in the United States, where alternative vehicles make up less than 1 percent collectively of the entire vehicle fleet (CTA & ORNL, 2009).
3. **Constant market share of diesel vehicles.** It is assumed that diesel vehicles are not gaining market share due to their emissions of local air pollutants of concern in the UAE.
4. **Vehicle weight classes.** In this analysis, light-duty trucks are assumed to be of the "Class 1" weight class of below 2722 kg (6000 pounds) or the "Class 2a" weight class, between 2722 and 3855 kg (6000 to 8500 pounds) of gross vehicle weight (GVW). There are likely also heavier Class 2b trucks in the passenger fleet with weights above 3855 kg (8500 pounds), but these are classified as medium-duty vehicles and are therefore not part of the light-duty vehicle fleet.

5. **Breakdown of fleet by weight class.** The percent of LDTs in the fleet is assumed to remain relatively constant over time. This is based on a fleet breakdown of registered vehicles in Abu Dhabi between 1997 and 2001 which shows that this percentage hovered around 30 percent (ADDOT, 2009). A more recent breakdown of the Abu Dhabi fleet by weight class does not exist, nor do historical data to establish a trend in LDT prevalence over time.
6. **Air pollutants.** Only particulate matter (PM) and NOx are included in this analysis. Vehicles are also mobile sources of hydrocarbons, SO_2, CO, VOCs, and air toxics. However, this is only a partial analysis of emissions and therefore PM and NOx are chosen to represent air pollutant emissions because they are two of the largest classes of vehicular emissions, and are expected to improve with CNG vehicles.
7. **Greenhouse gases.** CO_2 and CH_4 are included in this analysis. CO_2 accounts for about 96 percent of GHG emissions from transportation and is relatively easy to calculate because they only depend on the total fuel consumption for each type of fuel (Davies et al., 2007). CH_4,is included because CNG vehicles increase methane emissions above conventional vehicles. N_2O and HCFCs are also emitted from transportation but represent only a minute fraction of GHG emissions and vary widely based on specific vehicle technology.
8. **Linear growth of fuel economy.** Fuel economy is assumed to increase linearly by year such that in 2030, the fuel economy of gasoline vehicles is 10 percent above the baseline fuel economy.

9. **Exponential growth of CNG vehicles.** CNG vehicles are assumed to increase exponentially in the vehicle fleet, consistent with a study of fuel cell vehicles in the UAE by Kazim (2003).

The overall structure of the model is shown in Figure 2. The model is comprised of separate sub-models, called modules, for each of the major variables. The following text first explains the index variables used in all of the modules and then describes each module in detail. A summary of all inputs to the model is provided in Appendix A.

Figure 2. Overall Structure of Model



Index Nodes

In this model, several of the variables are indexed by common categories. These categories are defined in index nodes as lists of labels so that the categories can be applied to multiple variables without being individually listed in each variable. For example, most variables are indexed by year, so the "Year" index variable is a list of years from 2005 through 2030. Table 1 summarizes the index nodes used in the model.

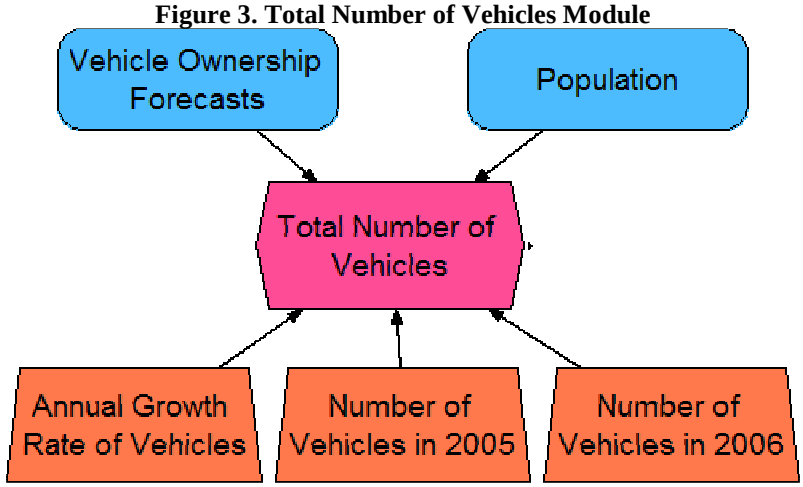
Table 1. Summary of Index Nodes Used in the Model

Index	Description	Representation in Model
Year (t)	Timeline of the analysis, starting with base year 2005 and ending in 2030.	Sequence: 2005-2030
Vehicle Fuel Type	Three vehicle fuel types included in analysis: gasoline, diesel, and CNG.	Gasoline Diesel CNG
Vehicle Weight Class	Passenger cars (Car) and light duty trucks (LDT). LDTs include sport utility vehicles, vans, and pickup trucks below 8500 lbs GVW.	Car LDT
Pollutants	Air pollutants: Nitrogen oxide (NOx) and exhaust particulate matter (PM). GHGs: carbon dioxide and methane.	NOx PM CO_2 CH_4
Vehicle Ownership Forecasts	Labels used in the STMP for their vehicle ownership (VO) projections (VO1, VO2, VO3) as well as Kazim projection.	VO1 VO2 VO3 Kazim
Scenario	The three scenarios of this analysis: baseline, CNG, and fuel economy.	Baseline CNG FE

Total Number of Vehicles

The module of total number of vehicles in the passenger fleet is shown in Figure 3. The outcome of this module is a range of projections of the total number of vehicles in the future vehicle fleet, calculated using four potential scenarios of vehicle demand growth. The total number of vehicles between 2005 and 2030 is based on car ownership forecasts from Abu Dhabi's Surface Transport Master Plan (ADDOT, 2009) as well as an exponential growth equation from Kazim (2003), described below.

Figure 3. Total Number of Vehicles Module



Of the three car ownership forecasts mentioned previously, the STMP adopted the forecast with the lowest saturation level of vehicles in the population in 2030, as this is congruent with the sustainable development goals outlined in the Plan Abu Dhabi 2030 (ADDOT, 2009; Abu Dhabi Urban Planning Council, 2009). However, all three scenarios are included in this analysis to show a range of possible vehicle fleet projections. A projection of future population is also provided in the STMP Appendix B (p. 201). The total number of vehicles can thus be determined by multiplying vehicles per thousand people times the projected population of Abu Dhabi:

$$N_{total} = \frac{VO}{1000\,people} \times Pop \qquad (1)$$

For comparison, the model also projects the number of future vehicles using a method described by Kazim (2003). Kazim used an exponential growth function of time with the annual vehicle demand growth rate for the UAE to project future vehicle numbers:

$$N = N_0 \times e^{\alpha(t-t_0)}, t_0 \le t \le t_1 \qquad (2)$$

where

N is the number of vehicles in year **t**

$\mathbf{N_0}$ is the initial number of vehicles in the base year, $\mathbf{t_o}$

α is the annual growth rate of vehicles, determined to be 6% for the UAE

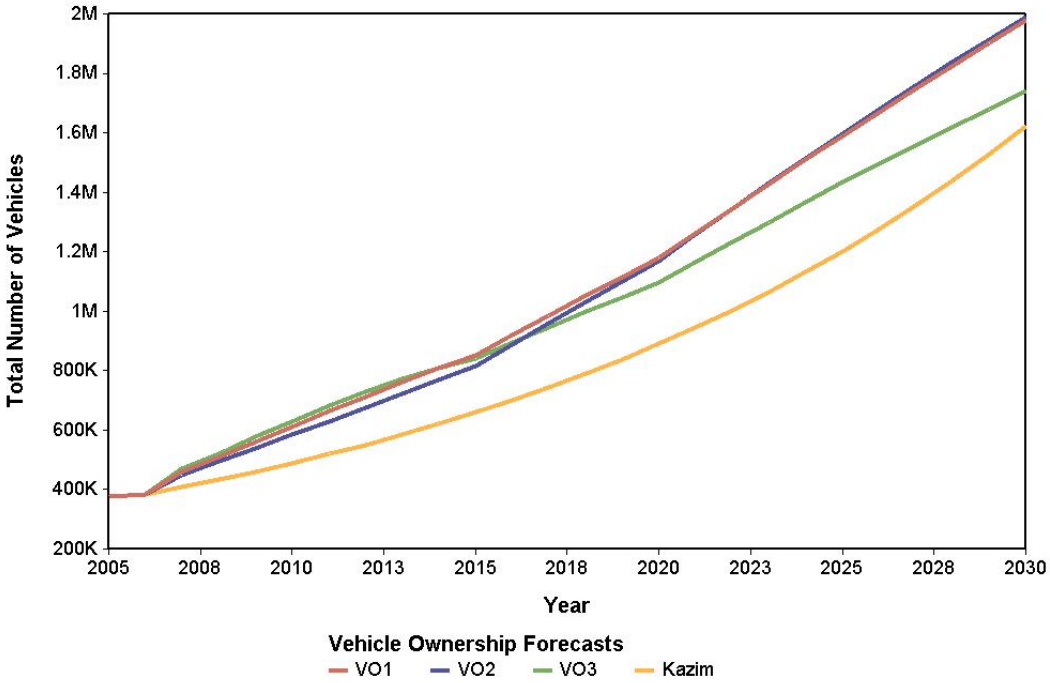
$\mathbf{t_1}$ is the end year

Although Kazim's analysis is for the entire UAE for 2000 to 2025, the equation is adapted for the purposes of this analysis using the 2006 data point from the STMP as the number of vehicles in the base year (N_0), as this is the most recent year of data. The equation used to calculate the total number of vehicles in the Abu Dhabi vehicle fleet is:

$$N = 384{,}272 \times e^{0.06(t-2006)}, 2006 \le t \le 2030 \qquad (3)$$

Both methods of vehicle fleet estimations are shown graphically in Figure 4. While the Kazim method estimates a lower number of vehicles than those in the STMP, its shape is consistent with the STMP vehicle ownership (VO) forecast curves, which will prove useful when estimating the composition of the future vehicle fleet.

Figure 4. Total Number of Vehicles in Abu Dhabi Passenger Fleet, 2005-2030

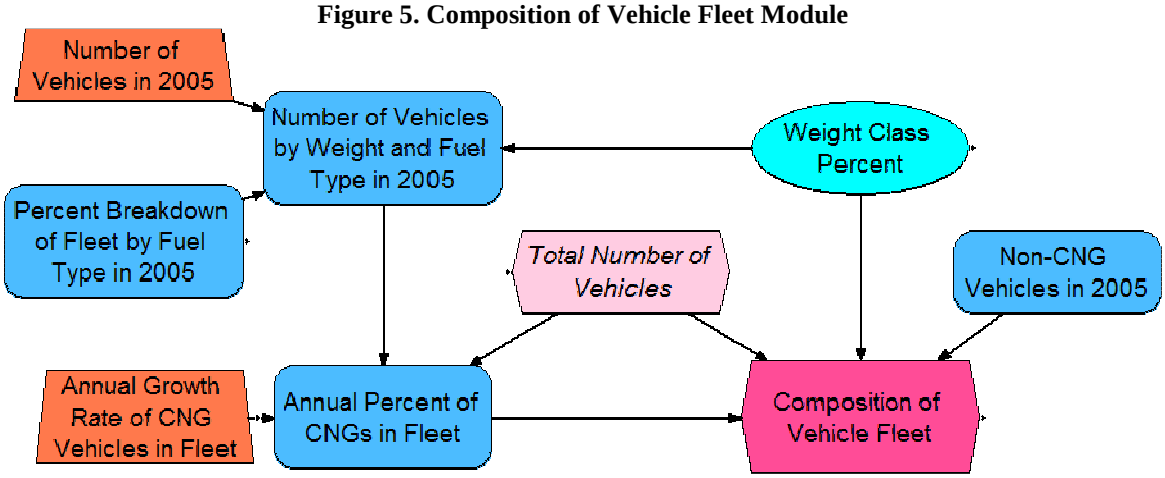


Composition of the Vehicle Fleet

Once the projection of the total number of vehicles is complete, the composition of the current and future vehicle fleets must be modeled. This includes a breakdown based on passenger cars versus light duty trucks, as well as gasoline, diesel, and CNG. As very little data is published on the Abu Dhabi vehicle fleet, this model uses literature from other nations to define the base year (2005) breakdown of the vehicle fleet by fuel type and weight class.

The composition of the vehicle fleet was projected by first determining the breakdown of vehicles in 2005 using UAE vehicle weight class data and US data on vehicle fuel types. The number of CNG vehicles in the base year, which is based on actual data and therefore constant across the four scenarios, was then used in an exponential growth equation to determine the number of CNG vehicles under the exponential growth (Kazim) vehicle projection. The percent of CNG vehicles under the Kazim scenario was applied to the three car ownership-based projections to obtain the number of CNG vehicles under all four scenarios of future vehicle growth. The remaining non-CNG vehicles were then multiplied by the original base year ratio of diesel and gasoline vehicles to determine the annual number of each vehicle fuel type in the fleet under the four total vehicle scenarios. The module demonstrating this process is shown in Figure 5.

Figure 5. Composition of Vehicle Fleet Module



The STMP Appendices (2009) include the number of registered vehicles in Abu Dhabi broken down by class from 1997 through 2001. The data for passenger cars (saloons) and light trucks are shown in Table 2. Unfortunately, a similar breakdown of registered vehicles is not available past 2001. Because more recent data for the UAE were not included in the STMP, it is difficult to determine whether the percentage of registered light duty trucks has continued to increase in Abu Dhabi. To represent this uncertainty, the model expresses the percent of light duty trucks in the fleet as a triangular distribution using the minimum, maximum, and mean values from 1997 to 2001.

Table 2. Breakdown of Registered Cars and Light Trucks in Abu Dhabi

Year	Number of Passenger Cars (Saloons)	Passenger Car Percent of Total Fleet	Number of Light Trucks	Light Truck Percent of Total Fleet	Total Saloons and Light Trucks
1997	121,209	76	37,705	24	158,914
1998	123,510	69	55,715	31	179,225
1999	125,562	69	56,870	31	182,432
2000	132,907	70	57,504	30	190,411
2001	140,713	71	59,006	29	199,719
Mean		*71%*		*29%*	

Source: ADDOT, 2009 Appendix A p. 62.

The U.S. Transportation Energy Data Book (CTA & ORNL, 2009) provides a detailed breakdown of the vehicle fleet by fuel type for the United States. Because this data is unavailable for the UAE, the model assumes the US data can serve as a reasonable proxy to determine baseline levels of gasoline, diesel, and CNG vehicles in Abu Dhabi's vehicle fleet. Table 3 shows percentages of gasoline, diesel and CNG vehicles in the US in 2005.

Table 3. Breakdown of 2005 U.S. Vehicle Fleet by Fuel Type

Year	Gasoline	Diesel	CNG	Other AFVs
2005	96.57	3.0	0.0862	0.347

Source: CTA & ORNL, 2009; Bandevadekar et al., 2008a

The number of CNG vehicles in the future passenger fleet is determined using the exponential growth equation from Kazim's 2003 study adapted to the context of this study:

$$N_{CNG_0} \times e^{\beta(t-t_0)}, t_0 \leq t \leq 2030 \qquad (4)$$

where

$\mathbf{N_{CNG0}}$ = (proportion of CNG vehicles in baseline year) * $\mathbf{N_{CNG0}}$, the total number of CNG vehicles in the base year

β is the annual growth rate of CNG vehicles in the fleet

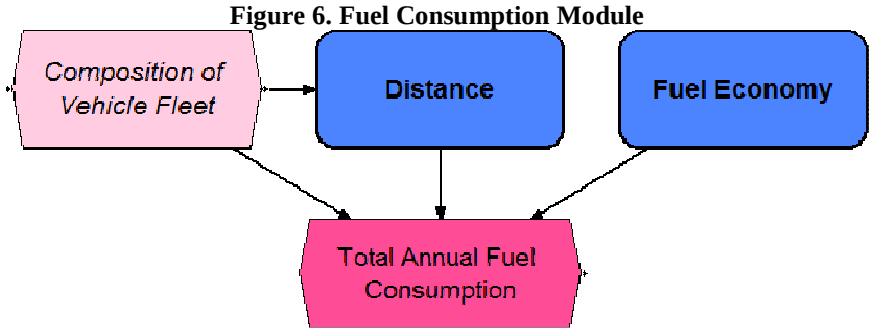
The annual number of CNG vehicles in the fleet is then divided by the total number of vehicles in the Kazim projection to obtain an annual percent of CNG vehicles. This percent is multiplied by the three VO projections to obtain the total number of CNG vehicles under each growth scenario (see equation 5). The annual growth rate of CNG vehicles in the fleet (**β**) is assumed to be 7.1 percent, which is the average growth rate of CNG vehicles in the US between 1990 and 2007. Both the initial number of CNG vehicles in the fleet and the baseline annual growth rate of CNG vehicles in the fleet may overestimate the prevalence of CNG vehicles in the UAE fleet as the U.S. CNG market is more established and therefore likely larger than that of the UAE.

$$\frac{N_{CNG}}{N_{Total,Kazim}} \times N_{Total,VO_i}, i = 1,2,3 \qquad (5)$$

Fuel Consumption

The fuel consumption of the vehicle fleet is projected by multiplying the fuel economy of the vehicle fleet by the distance traveled each year. Both the distance traveled and fuel economy were determined by compiling values from the literature, as this data was unavailable for the UAE. A schematic of the fuel consumption module is shown in Figure 6. This module calculates the total annual consumption of gasoline, diesel, and CNG by the passenger vehicle fleet. The data inputs and calculations for fuel economy and distance traveled are detailed below.

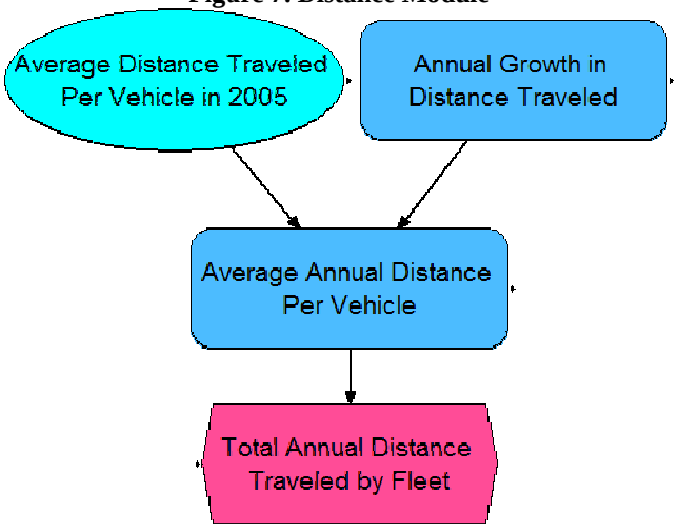
Figure 6. Fuel Consumption Module



Annual Distance Traveled

Figure 7 shows the model representation of the annual distance traveled by the fleet. Average annual per vehicle distance is calculated by first multiplying the average distance traveled per vehicle by the annual growth rate in distance traveled. The average per vehicle distance is taken from a Kuwait study of the driving habits of 1570 households, and is represented in the model by a lognormal distribution using a mean of 23,360 km (14,515 miles) and standard deviation of 19,345 km (12,020 miles). The annual per vehicle distance is then multiplied by the number of each type of vehicle (by weight class, fuel type) to obtain the total annual distance traveled by all vehicles in the fleet from 2005 to 2030.

Figure 7. Distance Module



Fuel Economy

Because this model is a representation of the overall fleet and does not model the individual vehicles within the fleet, it uses predetermined values of average fuel economy encountered in the U.S. literature. The on-road fuel economy estimates used in this study are determined by measuring the fuel consumption of each vehicle type in a laboratory under both highway and urban driving cycles, which is then adjusted to reflect more realistic driving conditions. The fleet-wide fuel economy average is calculated based on the number of each type of vehicle on the road. The exact methods for performing this calculation and modeling individual and fleet fuel economy rely on different assumptions, the discussion of which is beyond the scope of this study. The U.S. has one of the lowest levels of average fuel economy in the world, so using U.S. fuel economy values may overestimate fuel consumption. On the other hand, however, the U.S. fuel economy values may underestimate fuel consumption in that transportation fuel is heavily subsidized in the UAE and therefore drivers may prefer vehicles with lower average fuel economy.

Several sources cite the average new vehicle fuel economy by fuel type and weight class, but do not provide an average fuel economy of existing vehicles on the road by fuel type. Therefore, the model adjusts average fleet fuel economy levels by the fuel economy ratio of each technology to gasoline vehicles. For example, the VISION model lists the average fuel economy of existing vehicles in the 2005 U.S. fleet as approximately 22.9 mpg for cars and 18 mpg for light trucks (Singh et al., 2003). Since the majority of vehicles are fuelled by gasoline, this fuel economy estimate is used as the baseline fuel economy of existing gasoline vehicles. This was then multiplied by the fuel economy ratio of CNG cars, CNG light trucks, diesel cars, and diesel trucks to obtain the baseline fuel economy for CNG and diesel vehicles. Table 4 lists the inputs used in calculating the average base year fuel economy for each vehicle type.

Table 4. Calculation of Average Fuel Economy in 2005 by Vehicle Type

Vehicle Fuel Type	Weight Class	Fuel Economy Ratio to Gasoline ICE	Average On-Road Fleet Fuel Economy (miles per gallon gasoline equivalent)
Gasoline ICE	Passenger Car	1	22.92
	Light Truck	1	17.96
Diesel ICE	Passenger Car	1.45	33.23
	Light Truck	1.209	21.71
CNG	Passenger Car	1.076	24.66
	Light Truck	0.916	16.45

(Singh et al., 2003)

Modeling the future fuel economy of passenger vehicles in the UAE presents another challenge. One possibility is to assume that the current fuel economy will remain constant from 2005 through 2030. This is assumed to represent an absolute minimum level of potential fuel economy as it is unlikely that the fuel economy of vehicles will decrease over time, although it is possible that overall fleet fuel economy could be lowered due to the

societal preference for larger vehicles. A second option is to assume that in the "business-as-usual" scenario the fuel economy will increase by a certain percent due to the natural progression of technological improvements, including substitution of lighter materials, decreases in aerodynamic drag, and increases in engine efficiency. Under this assumption, the fuel economy of the entire fleet is slowly increased as newer, more fuel-efficient vehicles are incorporated into the fleet, replacing less efficient existing vehicles.

While the second option may provide a more realistic estimate, no data are available on which to base a projection of how the fuel economy in the vehicle fleet may change in the baseline scenario. Also, assuming constant fuel economy enables an easier comparison of the relative impact of CNG versus fuel economy technology. Therefore, the model assumes that fuel economy levels of the entire vehicle fleet remain constant through 2030 in the baseline and CNG scenarios, implying a growth rate of 0. For the fuel economy scenario, the annual growth rate is 0.4 percent for gasoline vehicles so that in 2030 the average fuel economy of gasoline vehicles is 10 percent higher than 2005 levels.

The fuel economy of diesel and CNG vehicles is not projected to increase in any of the scenarios in order to ease comparison between improvements in gasoline fuel economy and CNG vehicles. The annual fuel economy of the vehicle fleet is therefore projected with the following equation:

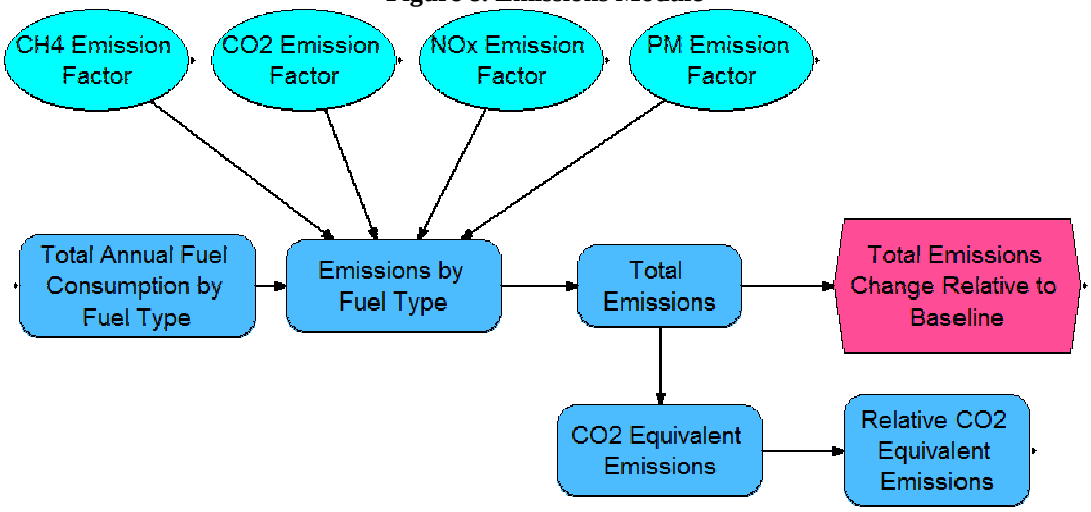
$$FE_{2005} \times (1 + FE_{growth})^{t-2005} \qquad (6)$$

Emissions

The model representation of GHG and air pollutant emissions is shown in Figure 8. The model uses estimates of emission factors from previously published studies on fleet

impacts to calculate emissions. The emissions factors for each fuel type are then multiplied by the total annual fuel consumption by each vehicle type to project the total emissions of CO_2, PM, and NO_x. Tables 5 through 8 list the emissions factors used in this model. Approximately 96 percent of transportation emissions of GHGs are in the form of CO_2, but this model also includes CH_4 as CNG vehicles have much higher CH_4 emissions than conventional gasoline and diesel vehicles (Davies et al., 2007; Wang et al., 2007). In addition, methane and nitrogen oxide emissions are dependent on several factors including emissions control technology, whereas a gallon of fuel emits the same amount of CO_2 regardless of technology.

Figure 8. Emissions Module



Numerous factors impact the emissions of various pollutants from transportation fuels. Many studies and models exist to determine emissions factors based on ambient temperatures, time of year, distance traveled, and many variables associated with vehicle operation (OTAQ, 1998). As there are a range of emission factors estimates in the literature, the model includes this uncertainty by using a probability distribution to represent potential values of emission factors. Because a volume of fuel emits a known amount of CO_2 which depends on the carbon content of the fuel, CO_2 emission factors are shown as a constant

(EPA, 2005; GHG Protocol, 2010). For PM and NOx, the model uses triangular distributions based on the minimum, mean, and maximum values found in a literature review.

Table 5. CO_2 Emission Factors (kg/gasoline gallon equivalent)

Fuel Type	Value
Gasoline	8.81
Diesel	10.15
CNG	6.84

Source: EPA, 2005; GHG Protocol, 2010

Table 6. NOx Emission Factors (g/gasoline gallon equivalent)

Fuel Type	Minimum	Maximum
Gasoline	3.299	9.453
Diesel	3.959	19.65
CNG	3.134	8.654

(Mohamadabadi, 2009); (Wang et al., 2007)

Table 7. PM Emission Factors (g/gasoline gallon equivalent)

Fuel Type	Minimum	Maximum
Gasoline	0.365	0.535
Diesel	0.487	1.06
CNG	0.208	0.381

(Mohamadabadi, 2009); (Wang et al., 2007).

Table 8. CH_4 Emission Factors (g/gasoline gallon equivalent)

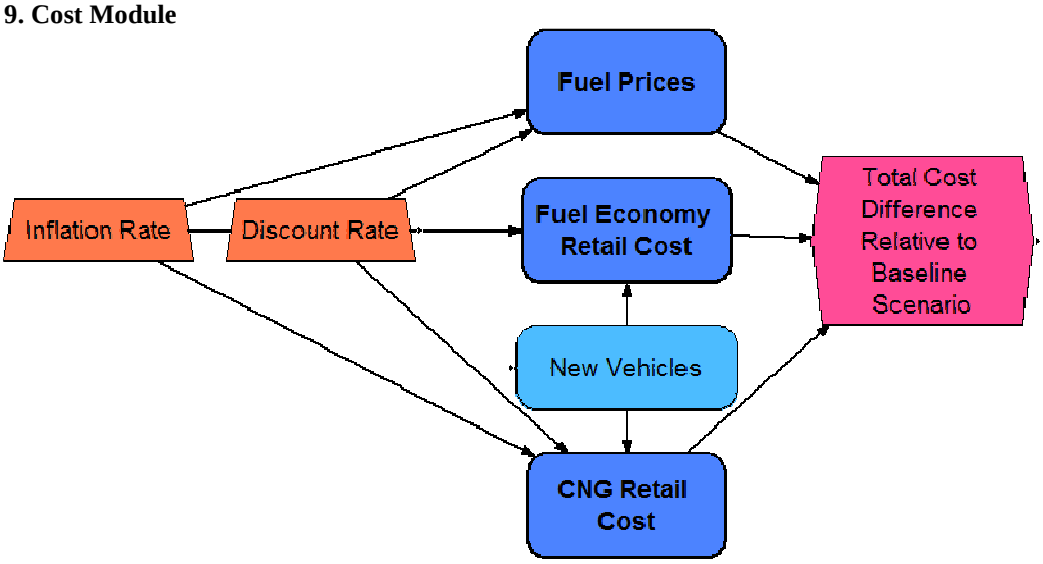
Fuel Type	Minimum	Maximum
Gasoline	0.2768	0.34164
Diesel	0.06228	0.073008
CNG	2.6296	3.24558

(Wang et al., 2007)

Cost Analysis

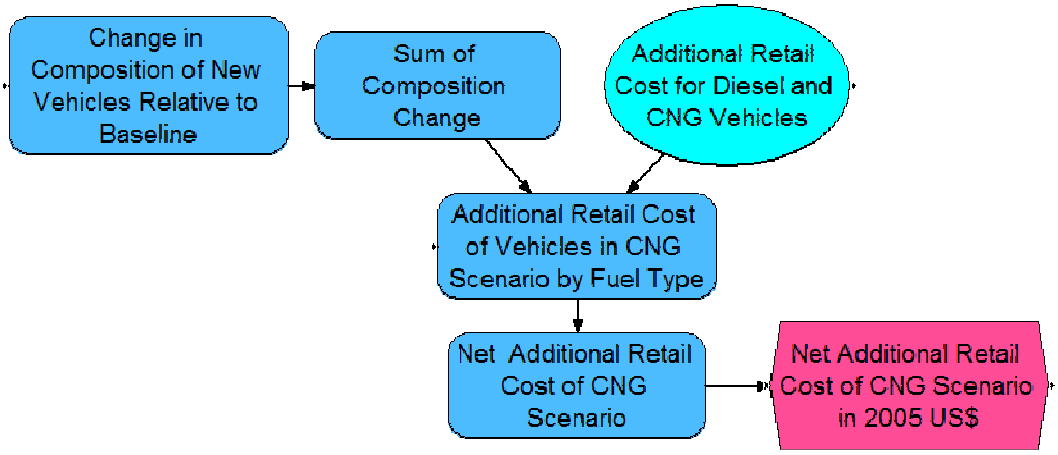
The cost of the CNG and Fuel Economy scenarios above the baseline was determined by summing the additional retail costs with the difference in fuel costs of each scenario above the baseline. Figure 9 shows the model representation of cost calculations. A real discount rate of 2.5 percent was used to discount future values to 2005 US$.

Figure 9. Cost Module



In order to estimate the additional retail costs of the alternative scenarios, the model determines the additional retail cost of CNG and diesel vehicles using estimates provided by the VISION model and a study by Mohamadabadi (Singh et al., 2003; Mohamadabadi et al., 2009) represented as a uniform distribution across the range of additional cost estimates. Because the fuel economy of the gasoline vehicles is increasing at such a slow rate in the fuel economy scenario (0.4 percent per year), the model assumes that there is no additional retail cost for more fuel efficient vehicles above the baseline. This is a reasonable assumption because engine efficiency improvements have occurred over the past several decades, but have been used to offset increased fuel consumption of vehicle attributes such as performance and size. Therefore, the model assumes that a small percent of these engine efficiency improvements will be geared towards reducing vehicle fuel consumption over the next 25 years without increasing vehicle cost. Additionally, some of the fleet fuel economy improvement may be achieved by consumers purchasing smaller vehicles, which would not increase retail costs. The retail cost module for the CNG scenario is shown in Figure 10.

Figure 10. CNG Scenario Retail Cost Module



The change in fuel costs between scenarios was determined by multiplying the difference in fuel consumption between the baseline, fuel economy, and CNG scenarios by a projection of future fuel prices. There is significant uncertainty in projecting future fuel prices, but the UAE subsidizes fuel in the UAE so that its retail price for consumers is relatively constant and not as volatile as world fuel prices. Therefore, the model base year fuel prices adjusted for inflation are a reasonable approximation for future fuel prices. Again, this is not intended to be a completely accurate projection of fuel prices but rather a representation of the potential costs of the CNG and fuel economy scenario paths. The parameters used in the retail and fuel price projections are shown in Table 9. The module for fuel cost calculation is shown in Figure 11.

Figure 11. Fuel Cost Module

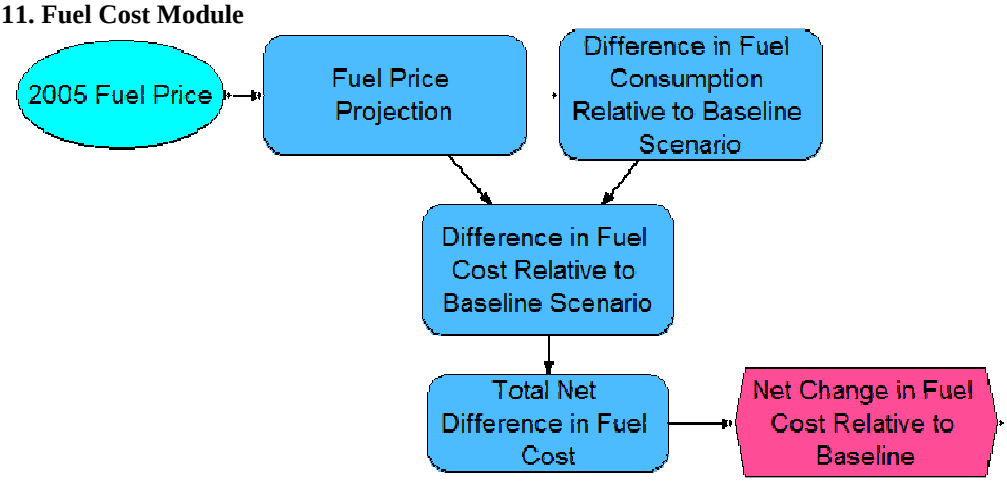


Table 9. Parameters Used in Cost Analysis

Variable	Distribution	Unit	Minimum	Maximum	References
Additional Retail Cost of Diesel Vehicles	Uniform	2005 US$	1820	2543	Singh et al., 2003; Mohamadabadi et al., 2009
Additional Retail Cost of CNG Vehicles	Uniform	2005 US$	6830	8934	Singh et al., 2003; Mohamadabadi et al., 2009
2005 Gasoline Price	Uniform	2005 US$/gallon	1.06	1.70	Chung, 2009; Carlisle, 2010; Daya, 2010; Sathish, 2010
2005 Diesel Price	Uniform	2005 US$/gallon	1.06	2.16	Metschies, 2005; Sathish, 2010
2005 CNG Price	Uniform	2005 US$/gasoline gallon equivalent (gge)	0.70	1.12	Chung, 2009; NGV communications group, 2010

Cost-Effectiveness Analysis

While there are many options for evaluating the costs and benefits of transportation policy, cost-effectiveness can be a useful tool for comparing diverse policy options for reducing emissions. Cost-effectiveness analysis has been used in several transportation studies for evaluating both emissions reductions and health benefits of vehicle fleet changes, including Cohen et al. (2003) and Yeh et al. (2009), among others. The equation for determining cost-effectiveness is:

$$CE_{alt} = \frac{Cost_{alternative} - Cost_{conventional}}{Emissions_{conventional} - Emissions_{alternative}} \qquad (7)$$

A smaller cost-effectiveness ratio implies a more favorable technology if the objective is to minimize the cost of a unit of emissions reduction.

RESULTS

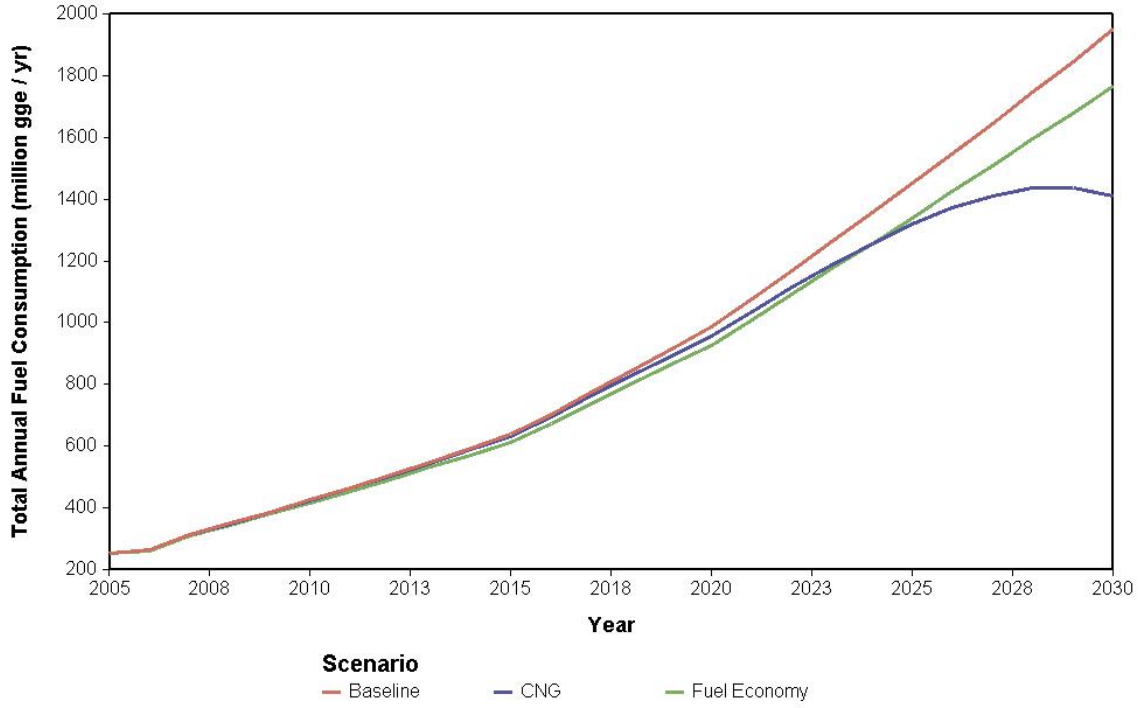
In 2030, the passenger vehicle fleet of Abu Dhabi is projected to contain between 1.62 and 1.99 million vehicles. Under baseline conditions, the 2030 vehicle fleet will contain between 1652 and 2027 CNG vehicles. While it is possible that the percent of CNG vehicles will not increase under baseline conditions, that is an unlikely scenario as the UAE is already considering CNG vehicles as a mitigation strategy in their STMP. In the CNG scenario, the number of CNG vehicles in the 2030 fleet is projected to be between 288,000 and 354,000 about 300 times larger than under baseline conditions.

Table 10 lists the total consumption of each fuel type in the baseline, fuel economy, and CNG scenarios under all four projections of vehicle fleet growth. In the baseline scenario, the Abu Dhabi passenger fleet will consume approximately 1588 to 1948 million gallons of gasoline in 2030. The CNG scenario will decrease 2030 gasoline consumption by 27.7 percent under all four vehicle ownership forecasts, which is almost three times the reduction of the fuel economy scenario. However, CNG consumption increases drastically from baseline levels in the CNG scenario. The projected gasoline consumption of each scenario is also shown graphically in Figure 12 for the VO2 vehicle forecast. Unless otherwise noted, all figures and tables in this section present results for the VO2 vehicle forecast as it is the highest projection of vehicle growth and therefore represents an upper estimate of fuel consumption and emissions. The other VO forecasts and Kazim projection yield similar results as the VO2 forecast, only lower.

Table 10. Mean Fuel Consumption Under Each Scenario and VO Forecast in 2030

Fuel	Scenario	VO1	VO2	VO3	Kazim
Gasoline (million gallons) *(95%CI)*					
	Baseline	1937 *(362-6166)*	1948 *(364-6205)*	1703 *(318-5422)*	1588 *(297-5057)*
	CNG	1400 *(260-4472)*	1409 *(261-4500)*	1231 *(228-3932)*	1148 *(213-3667)*
	Fuel Economy	1753 *(327-5581)*	1764 *(329-5616)*	1541 *(288-4907)*	1438 *(268-4576)*
Diesel (million gallons) *(95%CI)*					
	Baseline and Fuel Economy	17.4 *(3.2-55.8)*	17.5 *(3.3-56.2)*	15.3 *(2.9-49.1)*	14.2 *(2.7-45.8)*
	CNG	10.2 *(1.9-33.1)*	10.2 *(1.9-33.3)*	8.9 *(1.6-29.1)*	8.3 *(1.5-27.2)*
CNG (billion cubic feet) *(95%CI)*					
	Baseline and Fuel Economy	0.39 *(0.07-1.24)*	0.39 *(0.07-1.25)*	0.34 *(0.06-1.09)*	0.32 *(0.06-1.02)*
	CNG	68.5 *(12.8-216.5)*	68.9 *(12.9-217.8)*	60.2 *(11.2-190.3)*	56.1 *(10.5-177.5)*

Figure 12. Gasoline Consumption under Baseline, CNG and FE Scenarios, 2005-2030



Emissions

Total emissions of PM, NOx, and CO_2equialent (CO_2, and CH_4) for each scenario are shown in Figures 13, 14, and 15, respectively. For NOx and CO_2, the fuel economy scenario results in fewer emissions throughout the entire time span of the analysis. For PM, however, the CNG scenario approaches the emissions reductions of the fuel economy scenario towards the end of the timeline. The results for the second vehicle ownership forecast (VO2) are shown in the remaining graphs in this section unless noted otherwise. Total emissions data for 2030 are also shown in Table 11.

Table 11. Total Emissions for Each Scenario in 2030

Scenario Mean (95%CI)	PM Emissions (metric tons)	NOx Emissions (metric tons)	CO_2 Emissions (million metric tons)	CH_4 Emissions (metric tons)	CO_2eq. Emissions ($MMtCO_2e$)
Baseline	880 *(162-2794)*	12,051 *(2155-39,330)*	17.2 *(3.3,54.2)*	614 *(113-1915)*	17.22 *(3.3,54.3)*
CNG	800 *(146-2489)*	11,865 *(2145-37,470)*	16.3 *(3.1-51.3)*	2101 *(395-6565)*	16.34 *(3.1,51.5)*
Fuel Economy	798 *(147-2532)*	10,927 *(1955-35,650)*	15.6 *(2.9-49.1)*	557 *(103-1737)*	15.58 *(3.0,49.1)*

Figure 13. Mean PM Emissions for Each Scenario under VO2 Growth, 2005-2030

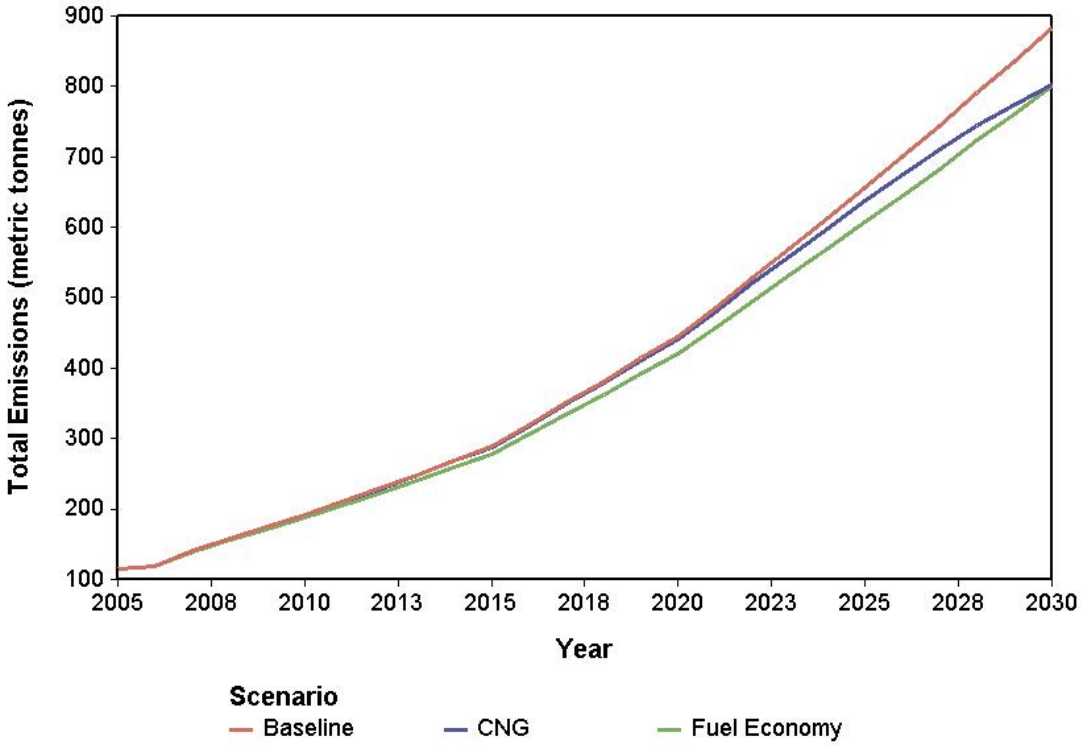


Figure 14. Mean NOx Emissions for Each Scenario under VO2 Growth, 2005-2030

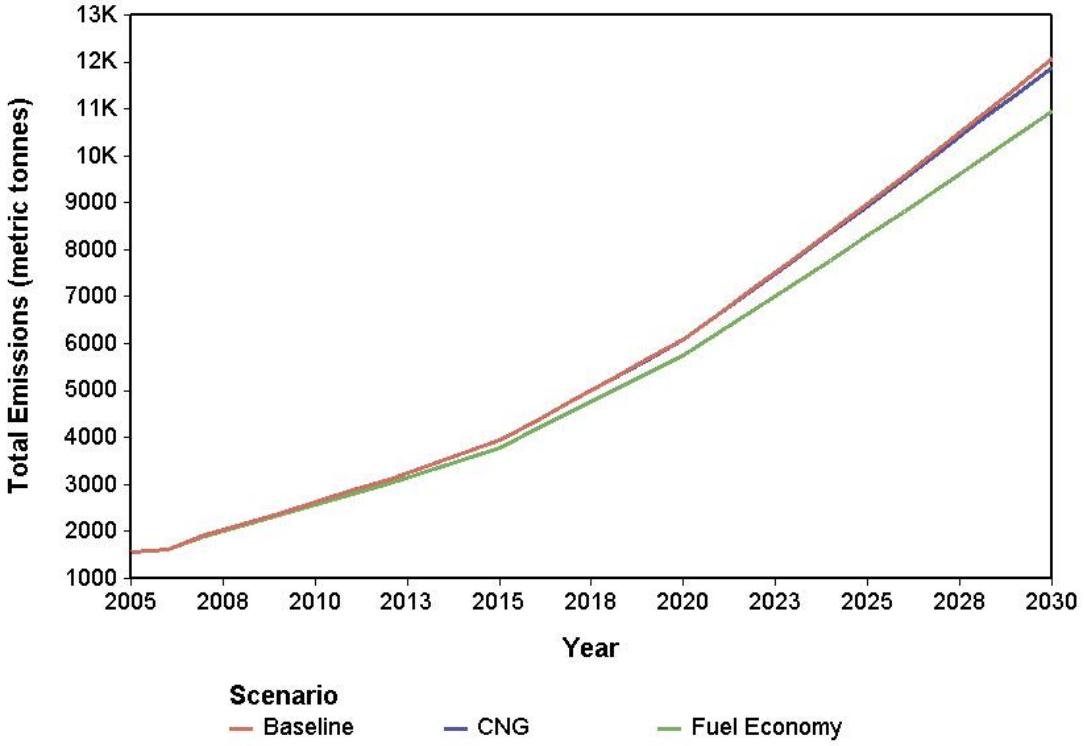
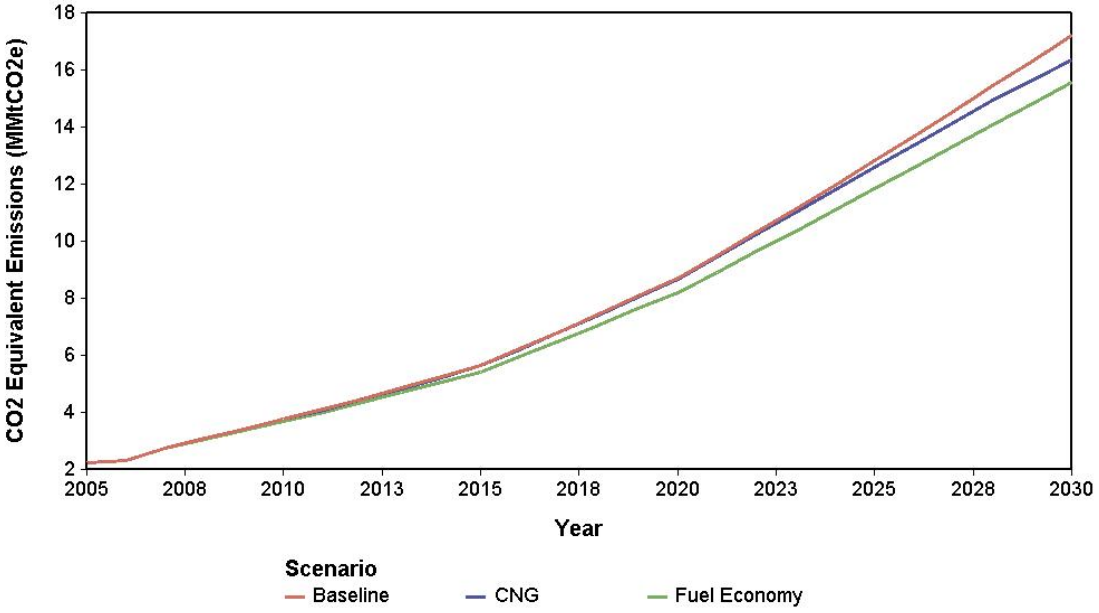


Figure 15. Mean CO_2e Emissions for Each Scenario under VO2 Growth, 2005-2030



In addition to modeling total emissions, it is important to look at the change in emissions between the fuel economy and CNG scenarios and the baseline scenarios in order

to determine the impact of compressed natural gas vehicles and fuel economy improvements on total emissions. The change in emissions for PM, NOx, and CO_2e between the baseline, fuel economy, and CNG scenarios (under VO2 growth) as well as the percent change from the baseline are listed in Table 12, and shown graphically in Figures 16, 17, and 18, respectively. For both the CNG and fuel economy scenarios, the percent reduction from baseline emissions increases over time as the alternative technology becomes more prevalent in the on-road vehicle fleet. Fuel economy improvements seem to have a relatively consistent percent reduction of pollutants from the baseline scenario, while CNG has diverse effects on PM, NOx, CO_2, and CH_4.

Table 12. Difference in Emissions from Baseline Scenario in 2020 and 2030

Scenario	Year	PM (metric tons/year)	NOx (metric tons/year)	CO_2 (metric tons/year)	CH_4 (metric tons/year)	$MMtCO_2e$
Fuel Economy	2020 *(95%CI)*	-26 *(-81,-4.7)*	-348 *(-1138,-62)*	-504K *(-1.6M,-95K)*	-18 *(-55, -3)*	-0.504 *(-1.59, -0.095)*
	2030 *(95%CI)*	-83 *(-261,-15)*	-1125 *(-3681,-201)*	-1.63M *(-5.1M, -309)*	-57 *(-179, -11)*	-1.63 *(-5.14, -0.308)*
CNG	2020 *(95%CI)*	-4 *(-15,-0.61)*	-10 *(-151,+115)*	-50K *(-159K, -9522)*	+81 *(+15, +253)*	-0.0481 *(-0. 153, -0.009)*
	2030 *(95%CI)*	-81 *(-266,-11)*	-175 *(-2778,+2133)*	-913K *(-2.9M, -309K)*	+1489 *(+278, +4673)*	-0.876 *(-2.79, -0.166)*

Figure 16. Mean Difference in PM Emissions from Baseline Scenario

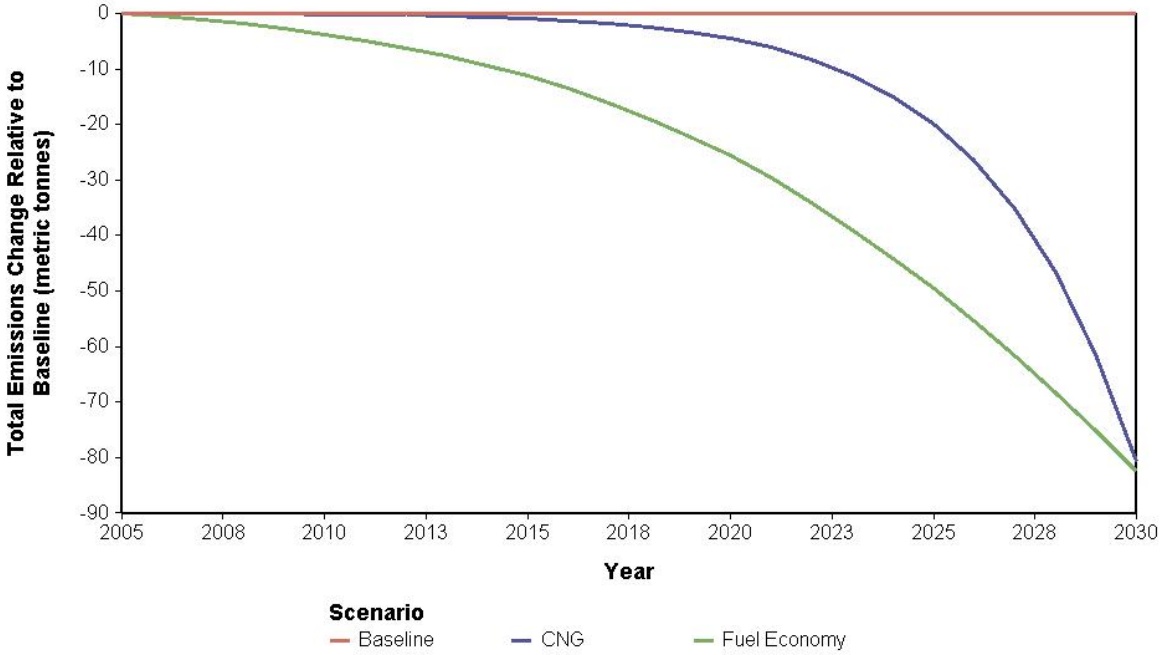


Figure 17. Mean Difference in NOx Emissions from Baseline Scenario

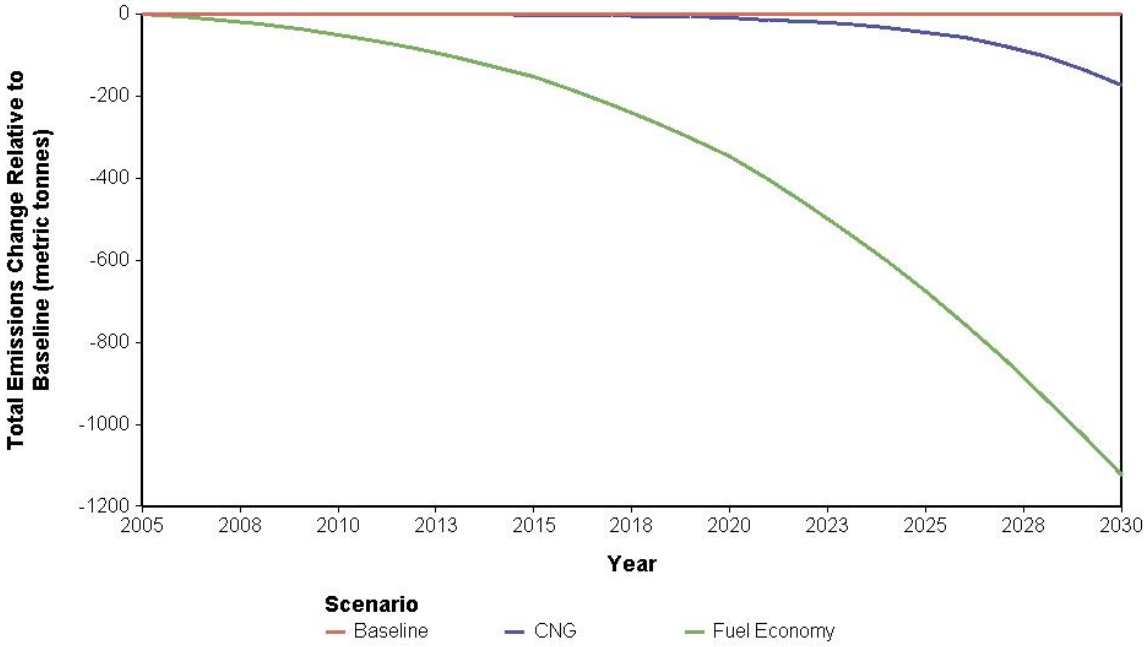
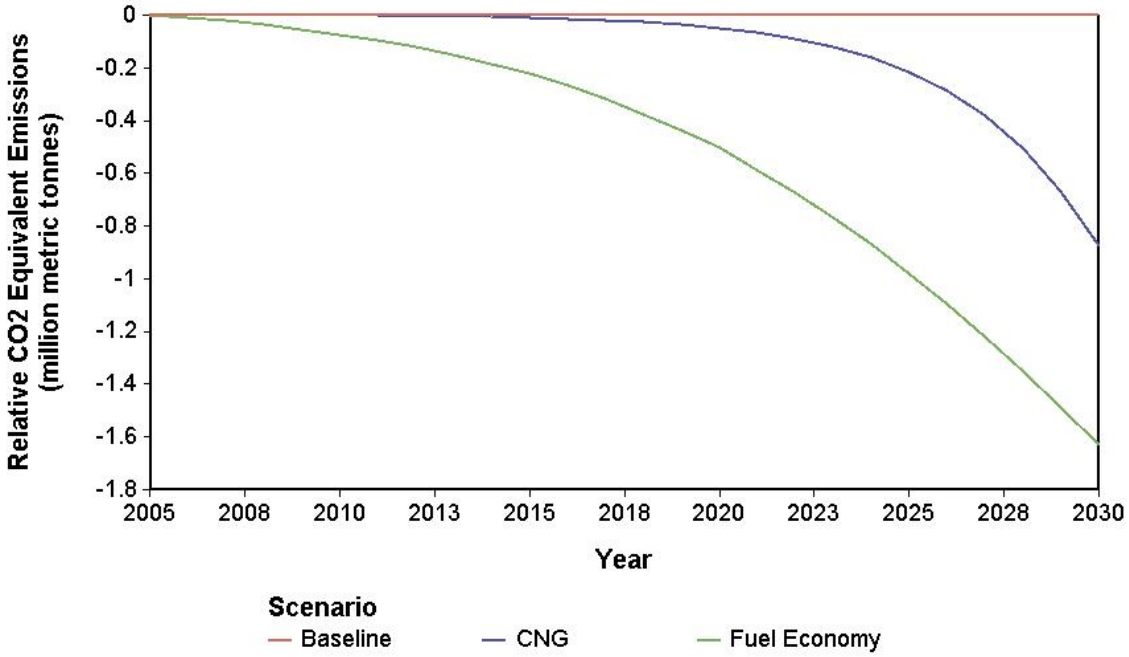


Figure 18.Mean Difference in CO_2e Emissions from Baseline Scenario



Costs

Now that the change in emissions between the baseline, fuel economy, and CNG scenarios has been determined, it is important to estimate the net change in costs of each scenario in order to calculate the cost-effectiveness of each option. Table 13 lists the change in total costs of the fuel economy and CNG scenarios from the baseline scenario. In all years, the CNG scenario costs money above the baseline due to the retail premium of CNG vehicles above gasoline vehicles. However, some of this additional cost is offset by the savings in fuel as the cost of CNG at the pump is lower than the cost of gasoline or diesel.

Table 13. Mean Change in Costs from Baseline Scenario for Selected Years
(Million 2005 US$)

	Scenario	2015	2020	2025	2030
RETAIL COST	CNG	$23.0 *(20,26)*	$88.5 *(77,101)*	$315.7 *(273,361)*	$989.6 *(857,1132)*
	Fuel Economy	$0	$0	$0	$0
FUEL COST	CNG	-$2.1 *(-7.7, -0.11)*	-$9.3 *(-34,-0.46)*	-$37.2 *(-138,-1.8)*	-$133.5 *(-490,-6.4)*
	Fuel Economy	-$27.0 *(-87, -4.9)*	-$54.9 *(-177,-9.9)*	-$94.7 *(-306,-17)*	-$139.5 *(-450,-25)*
TOTAL COST	CNG	$20.9 *(15,25)*	$79.3 *(51,97)*	$278.5 *(169,346)*	$856.2 *(470,1080)*
	Fuel Economy	-$27.0 *(-87,-4.9)*	-$54.9 *(-177,-9.9)*	-$94.7 *(-306,-17)*	-$139.5 *(-451,-25)*

Furthermore, the assumption that increasing the fuel economy of the vehicle fleet at such a slow rate does not increase the retail cost of vehicles may result in an overestimation of cost savings in the fuel economy scenario. While increasing the retail cost of new gasoline vehicles would increase the cost of the fuel economy scenario, it would take a significantly large retail cost premium that increased exponentially over time for the fuel economy scenario to become more expensive than the CNG scenario. The annual growth in the difference in costs for each of the scenarios between 2005 and 2030 is shown in Figure 19. Finally, the range of total difference in costs across all four vehicle ownership projections is shown in Figure 20 for the CNG scenario and Figure 21 for the fuel economy scenario.

Figure 19. Annual Difference in Costs Relative to Baseline Scenario

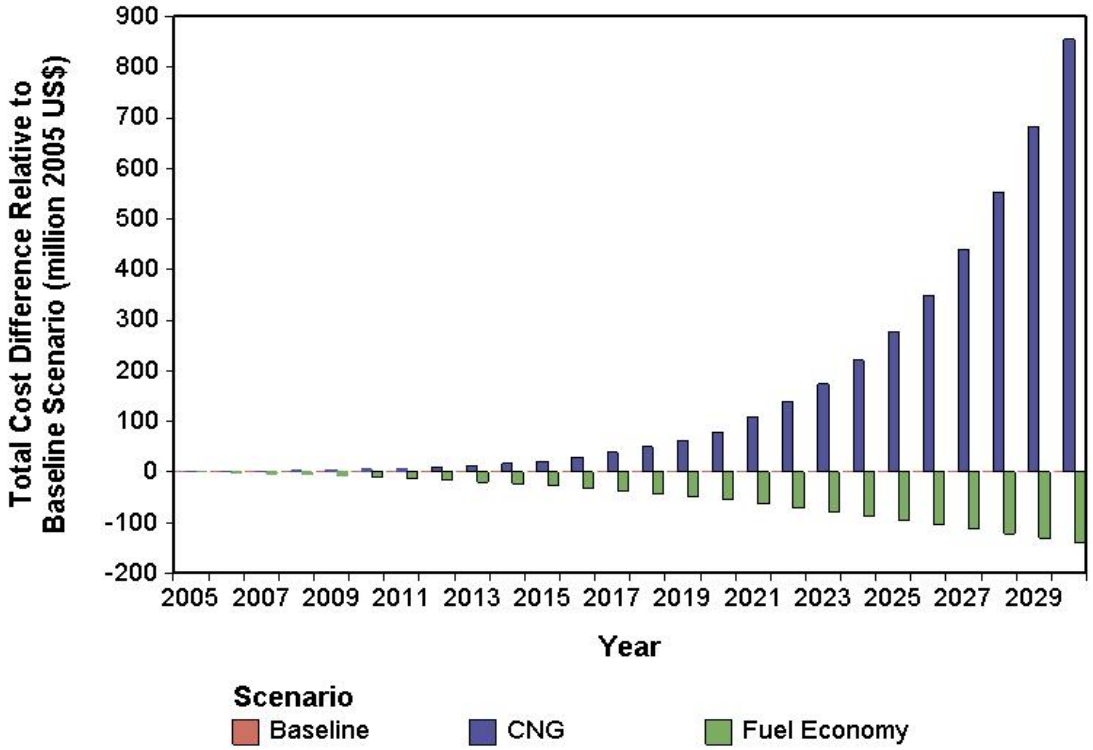


Figure 20. Range of Cost Difference between Baseline and CNG Scenarios

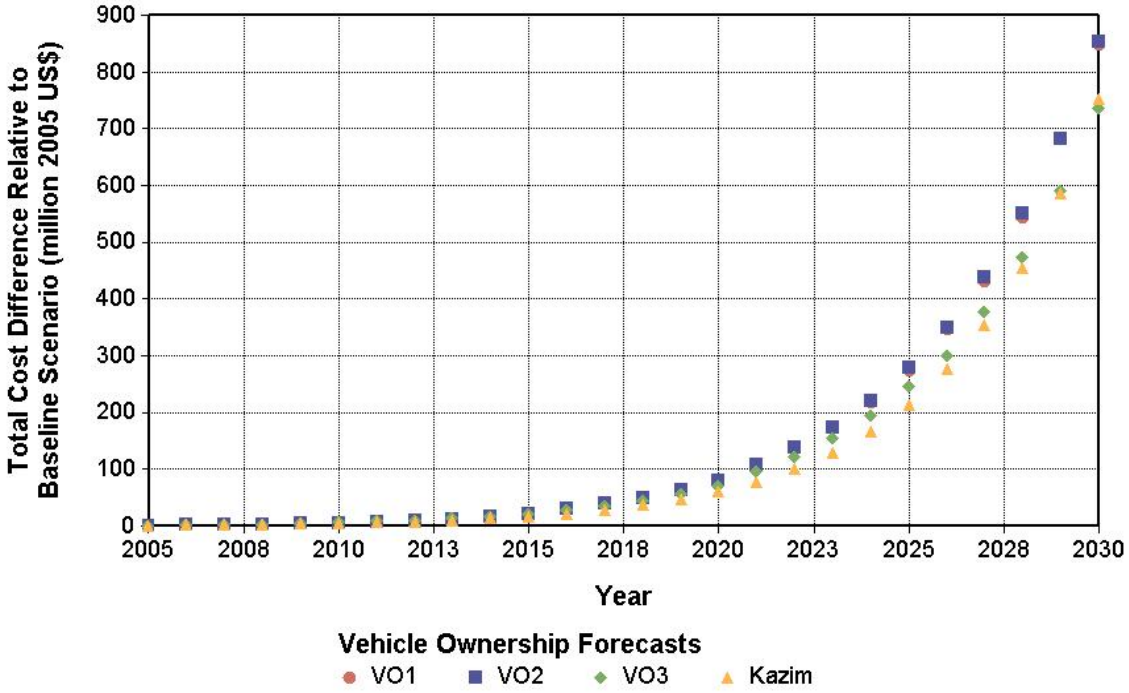
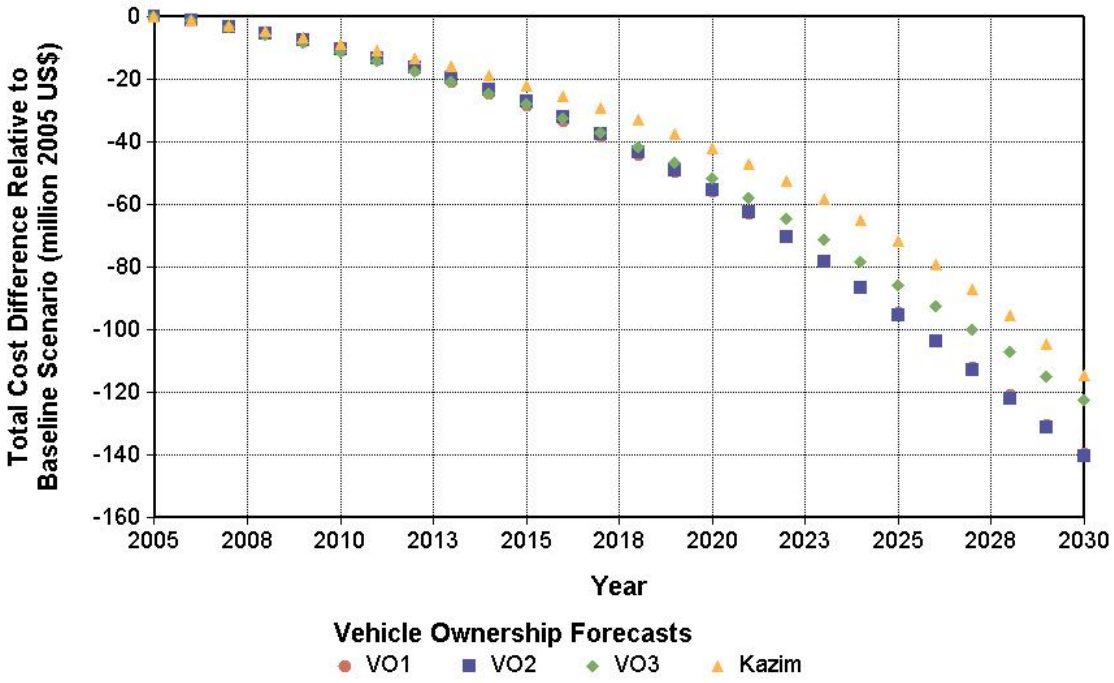


Figure 21. Range of Cost Difference between Baseline and Fuel Economy Scenarios



Cost-Effectiveness

While both the fuel economy and CNG scenarios reduce emissions of NO_x, PM and CO_2 from the baseline scenario, the fuel economy scenario is able to do so at a slightly negative cost, whereas the CNG scenario is associated with a larger, positive cost. Furthermore, the CNG scenario results in increased emissions of methane over the baseline scenario. Therefore, the fuel economy scenario is the more cost-effective option for reducing emissions from the passenger vehicle fleet.

Alternative Scenarios

Table 14 shows the impacts on emissions for two additional future scenarios. "CNG + FE," projects emissions reductions if both the fuel economy of gasoline vehicles were increased 10 percent and 10 percent of the 2030 fleet were CNG vehicles. "Constant distance, CNG + FE" demonstrates potential emissions reductions if instead of increasing over time, distance is held constant at 2005 levels (i.e., there is still growth in annual distance traveled in the baseline scenario under this assumption) in addition to incorporating CNG vehicles and fuel economy improvements. All scenarios besides the fuel economy scenario are more expensive than the baseline scenario. The "CNG, FE and Distance" scenario shows that if fuel economy improvements and CNG vehicle incorporation occurred in addition to holding average annual distance constant at 2005 values, significant emissions reductions could be achieved at a much lower cost than the CNG or CNG + FE scenarios alone.

Table 14. Relative Emissions in 2030 Vehicle Fleet Under Four Scenarios

Scenario	PM Emissions (metric tons)	NOx Emissions (metric tons)	CO_2 Emissions (million metric tons)	CH_4 Emissions (metric tons)	Relative Cost (million 2005 US$)
CNG	-79.8	-186.4	-0.913	+1487	$856.2
(95%CI)	*(-266,-11)*	*(-2778, +2133)*	*(-2.9, -0.173)*	*(+278, +4673)*	*(470,1080)*
%Change	**-9.1%**	**-1.5%**	**-5.3%**	**+242%**	
Fuel Economy	-82.2	-1124	-1.63	-57.3	-$139.5
(95%CI)	*(-261,-15)*	*(-3681,-201)*	*(-5.1, -0.309)*	*(-179,-11)*	*(-451,-25)*
%Change	**-9.3%**	**-9.3%**	**-9.5%**	**-9.3%**	
CNG + FE	-140	-1003	-2.09	+1449	$754.5
(95%CI)	*(-455,-24)*	*(-5247, +1111)*	*(-6.62,-0.392)*	*(+265, +4521)*	*(136,1044)*
%Change	**-15.9%**	**-8.3%**	**-12.2%**	**+236%**	
Constant Distance, CNG + FE	-370	-4494	-6.81	764	$364.7
(95%CI)	*(-1173,-69)*	*(-16K, - 690)*	*(-21.6,-1.3)*	*(+137,+2371)*	*(-1153, +934)*
%Change	**-42.0%**	**-37.3%**	**-39.6%**	**+124%**	

Sensitivity Analysis

Finally, a sensitivity analysis was conducted to determine the impact of a 25 percent increase or decrease in a number of variables on the outcomes of emissions, costs, and cost-effectiveness holding all other variables constant (ceteris paribus). The sensitivity analysis demonstrates which variables are most important when making the kinds of estimates discussed in this analysis. The results of the sensitivity analysis for costs and emissions are

shown in Tables 16, 17, and 18, respectively. Mean values are reported. Variables which cause the largest change in mean value of the outcome are shown in bold.

Table 15. Sensitivity Analysis of Relative Costs in 2030 for CNG and Fuel EE Scenarios

	CNG Scenario		Fuel Economy Scenario	
Original Value	$856		-$140	
Variables	-25%	+25%	-25%	+25%
Percent of LDTs	$939 *(10%)*	$772 *(-10%)*	-$136 *(-3%)*	-$144 *(3%)*
Breakdown of 2005 Fleet	**$642** ***(-25%)***	**$1,069** ***(25%)***	-$140 *(0%)*	-$140 *(0%)*
Annual Growth Rate of CNGVs	**$108** ***(-87%)***	**$6,135** ***(617%)***	-$140 *(0%)*	-$140 *(0%)*
Average Distance in 2005	$890 *(4%)*	$824 *(-4%)*	**-$105** ***(-25%)***	**-$175** ***(25%)***
Annual Growth in Distance	$868 *(1%)*	$841 *(-2%)*	-$128 *(-9%)*	-$154 *(10%)*
Average Fuel Economy in 2005	$811 *(-5%)*	$882 *(4%)*	**-$187** ***(33%)***	**-$112** ***(-20%)***
2005 Fuel Price	$889 *(4%)*	$882 *(-4%)*	**-$105** ***(-25%)***	**-$175** ***(25%)***
AFV Retail Cost	**$608** ***(-29%)***	**$1,103** ***(29%)***	-$140 *(0%)*	-$140 *(0%)*
Discount Rate	**$1154** ***(35%)***	**$636** ***(-26%)***	**-$189** ***(35%)***	**-$108** ***(-26%)***

Table 16. Sensitivity Analysis of Net Emissions Change of CNG Scenario
(metric tonnes)

		PM		NOx		CO_2 (thousands)		CH_4		CO_2e (thousands)	
	Original Value	-80.1		-225.6		-912.6		+1489		-875	
Variable		-25%	+25%	-25%	+25%	-25%	+25%	-25%	+25%	-25%	+25%
Percent of LDTs	New Value	-88	-72	-247	-202	-1000	-822	1632	1342	-960	-789
	% Change	*10%*	*-10%*	*9%*	*-10%*	*10%*	*-10%*	*10%*	*-10%*	*10%*	*-10%*
Breakdown of 2005 Fleet	New Value	-60	-100	-169	-282	-684	-1140	1117	1861	-656	-1094
	% Change	*-25%*	*25%*	*-25%*	*25%*	*-25%*	*25%*	*-25%*	*25%*	*-25%*	*25%*
Annual Growth Rate of CNGVs	New Value	**-14**	**-456**	**-39**	**-1283**	**-159**	**-5191**	**259**	**8471**	**-152**	**-4977**
	% Change	***-83%***	***469%***	***-83%***	***469%***	***-83%***	***469%***	***-83%***	***469%***	***-83%***	***469%***
Average Distance in 2005	**New Value**	**-59**	**-98**	**-100**	**-167**	**-684**	**-1140**	**1118**	**1863**	**-660**	**-1100**
	% Change	***-27%***	***22%***	***-56%***	***-26%***	***-25%***	***25%***	***-25%***	***25%***	***-25%***	***26%***
Annual Growth in Distance	New Value	-73	-88	-207	-245	-830	-1004	1343	1651	-796	-962
	% Change	*-9%*	*10%*	*-8%*	*9%*	*-9%*	*10%*	*-10%*	*11%*	*-9%*	*10%*
Average Fuel Economy in 2005	New Value	-107	-64	-301	-180	-1217	-730	1985	1191	-1167	-700
	% Change	*33%*	*-20%*	*33%*	*-20%*	*33%*	*-20%*	*33%*	*-20%*	*33%*	*-20%*
Emission Factors	**New Value**	**-60**	**-99**	**-133**	**-221**	**-684**	**-1141**	**1119**	**1865**	**-647 (CO_2)**	**-1103 (CO_2)**
	% Change	***-26%***	***24%***	***-41%***	***-2%***	***-25%***	***25%***	***-25%***	***25%***	***-26%***	***26%***
	New Value									-884 (CH_4)	-866 (CH_4)
	% Change									*1%*	*-1%*

Table 17. Sensitivity Analysis of Net Emissions Change of Fuel Economy Scenario
(metric tonnes)

		PM		NOx		CO_2 (thousands)		CH_4		CO_2e (thousands)	
	Original Value	-82		-1137		-1631		-57		-1632	
Variable		-25%	+25%	-25%	+25%	-25%	+25%	-25%	+25%	-25%	+25%
Percent of LDTs	New Value	-80	-85	-1106	-1170	-1585	-1676	-56	-59	-1586	-1678
	% Change	*-3%*	*3%*	*-3%*	*3%*	*-3%*	*3%*	*-3%*	*3%*	*-3%*	*3%*
Average Distance in 2005	New Value	**-62**	**-103**	**-842**	**-1403**	**-1223**	**-2039**	**-43**	**-71**	**-1230**	**-2051**
	% Change	***-25%***	***25%***	***-26%***	***23%***	***-25%***	***25%***	***-25%***	***25%***	***-25%***	***26%***
Annual Growth in Distance	New Value	-75	-90	-1036	-1248	-1485	-1790	-52	-63	-1486	-1791
	% Change	*-9%*	*10%*	*-9%*	*10%*	*-9%*	*10%*	*-9%*	*10%*	*-9%*	*10%*
Average Fuel Economy in 2005	New Value	**-110**	**-66**	**-1516**	**-910**	**-2173**	**-1304**	**-76**	**-46**	**-2176**	**-1305**
	% Change	***33%***	***-20%***	***33%***	***-20%***	***33%***	***-20%***	***15%***	***-20%***	***33%***	***-20%***
Emission Factors	New Value	-62	-103	-843	-1404	-1223	-2038	-43	-71	-1224 (CO_2)	-2039 (CO_2)
	% Change	*-25%*	*25%*	*-26%*	*23%*	*-25%*	*25%*	*-25%*	*25%*	*-25%*	*25%*

From the sensitivity analysis, it appears that changes in the annual growth rate of CNG vehicles have the largest effect on the predicted emissions, costs, and cost-effectiveness. However, several other variables also are important, including the percent of LDTs in the passenger fleet and the percentages of each fuel type in the fleet (fleet breakdown). For the cost sensitivity analysis, the discount factor and the price of fuel in 2005 are the variables that have the greatest effect on the model's predictions.

DISCUSSION

According to analysis, improving the average fuel economy of gasoline vehicles in the passenger vehicle fleet by 10 percent is projected to decrease emissions of NOx, PM, CO_2, and CH_4 more than changing 10 percent of the vehicle fleet to CNG vehicles by 2030. If exponential growth of CNG vehicles in the fleet were to continue past 2030, CNG vehicles would actually reduce PM emissions more than fuel economy improvements, but would not have the same effect on NOx or CO_2 equivalent emissions. Furthermore, this analysis shows that fuel economy improvements have a negative cost due to cost savings, whereas CNG vehicles are associated with a positive cost due to their high retail cost. The negative costs of fuel economy improvements are in part due to the assumption that shifting demand to smaller classes of vehicles will offset the additional retail cost of more efficient vehicles. If this assumption is relaxed, the fuel economy scenario may potentially have a slightly positive cost; however, the CNG scenario would still cost more because the retail premium of CNG vehicles is much higher than that for more efficient vehicles.

This analysis is intended to provide a simplified illustration of the future vehicle fleet in Abu Dhabi and the potential impact on air quality and GHG emissions of various changes to the baseline fleet. To do so, the analysis relies on a number of assumptions that increase uncertainty in the model. One such assumption is that CNG vehicles can reach 10 percent of the vehicle fleet by 2030. While this assumption allows for a clear demonstration of the potential impact of CNG vehicles on the fleet, it may be implausible in reality. A 10 percent increase in the average fuel economy of gasoline vehicles in the existing vehicle population

may also be implausible as consumer preference may demand larger vehicles rather than more efficient ones. In addition, the age distribution of the fleet is not considered as this study looks at the net change in the number of vehicles each year and not the vehicles sold or retirement rate of vehicles in the fleet. This assumption overlooks the replacement of CNG vehicles at the end of their lifetime, which may in turn underestimate the retail cost of the CNG scenario. Furthermore, this study did not examine volatile organic compound (VOC) emissions from incorporating CNG vehicles in the fleet, which are an important contributor to local air pollution. More comprehensive research in the future may include VOCs and potentially other air pollutants.

The cost analysis in this study also relies on a number of assumptions. For example, it is assumed that fuel subsidies will continue to stabilize the price of fuel in the UAE. In reality, it is likely that fuel prices will increase above the 2005 real price, therefore creating larger cost savings in the future. The cost analysis is from the perspective of drivers, and therefore does not consider costs to society of changes in the vehicle fleet and resulting emissions reductions. For example, in order for the large number of CNG vehicles in the CNG scenario to be sustained, more CNG refueling stations will be required in Abu Dhabi. Building this infrastructure will come at a large cost, although it will not necessarily be felt by consumers. The subsidized price of fuel does not take into account the real cost of fuel as well. Finally, there are several environmental and social externalities associated with vehicle fuel consumption that are not included in this analysis. These include the cost of additional morbidity and mortality from local air pollution and climate change, among others.

The scope of this analysis was necessarily limited due to data availability and time constraints. Despite these drawbacks, it remains a useful exercise to demonstrate the

potential emissions impacts of feasible policy decisions. Additionally, the conceptual framework and design of the model allows for future expansion to include more recent data, more Abu Dhabi-specific data, and further complexity in the model. To reduce uncertainty in this model, the most important data to collect are on the current passenger vehicle fleet, specifically of the annual growth rate of CNG vehicles, the average fuel economy of vehicles in the existing fleet, and the average annual distance traveled by vehicles in Abu Dhabi.

In order for changes in the vehicle fleet to have a measurable impact on transportation emissions in the UAE, two major forces must be at work. First, the political will must exist to encourage these changes in the vehicle fleet, thereby creating a technology "push." Abu Dhabi has already demonstrated support for CNG by installing a number of CNG distribution stations across Abu Dhabi, and should now focus on raising the average fuel economy of the vehicle fleet. The Abu Dhabi government can play a role in promoting fuel economy via financial incentives and other policy measures. Secondly, consumer demand must create a "technology pull" for increasing the number of CNG and more fuel efficient vehicles in the overall vehicle fleet. Research has shown that consumers tend to be myopic when it comes to increases in the purchase price of vehicles and possible inconveniences with refueling infrastructure for alternatively fueled vehicles. These obstacles to consumer demand may be overcome by careful construction of government policies that provide both financial incentives and infrastructure development to support the technological advancement of AFVs, as well as public outreach campaigns emphasizing the benefits of fuel efficiency and alternative technologies.

According to this analysis, fuel economy improvements dominate CNG vehicles in terms of cost-effectiveness at reducing emissions from passenger vehicles. This implies that

it would be more effective to focus on increasing the fuel economy of vehicles before attempting to incorporate alternatively fueled vehicles into the fleet. However, the problem is not that simple. Realistically, there is no one technology option that will solve the transportation emissions crisis on its own. Furthermore, fuel economy improvements can only go so far in reducing emissions before technological limitations are reached.

In the end, mitigating transportation emissions will require a myriad of changes in the vehicle fleet, including both diverse changes in vehicle technology as well as changes in personal driving behavior and in infrastructure. It is therefore recommended that Abu Dhabi focus primarily of increasing the average fuel economy of the vehicle fleet through procurement policies and incentives for consumers in the short term, but also encourage the incorporation of alternative fuel vehicles into the passenger fleet in the longer run. Finally, it is important to consider both the costs and the actual impact that alternative vehicles can have on reducing emissions in the vehicle fleet.

APPENDIX A

Table 18. Summary of All Inputs in Model

Variable	Description	Representation in Model	Reference
TOTAL NUMBER OF VEHICLES MODULE			
Population (pop)	Projection of the Abu Dhabi population from 2005-2030	See Table A1	ADDOT Appendix B, p. 201, 2009
Vehicle Ownership Forecasts (VO)	Three forecasts of vehicle ownership levels per 1000 people from 2007-2030: VO1, VO2, and VO3	See Table A1	ADDOT Appendix B, p. 203, 2009
Vehicle Demand Growth Rate (α)	Annual growth rate of personal vehicle demand for the UAE, based on data from 1980-2003	6%	Kazim, 2003
Number of Vehicles in 2005 (N_{2005})	Number of vehicles in Abu Dhabi in 2005, based on survey data	375,817	ADDOT Appendix B, p. 201, 2009
Number of Vehicles in 2006 (N_{2006})	Number of vehicles in Abu Dhabi in 2006, based on survey data	384,272	ADDOT Appendix B, p. 201, 2009
Total Number of Vehicles (N_{total})	Total number of vehicles in the passenger fleet under four VO projections: Kazim, VO1, VO2, VO3	$N_{Total,Kazim} = N_{2006} \times e^{\alpha(t-2006)}$ $N_{Total,VOi} = \frac{VO_i}{1000} \times Pop$ $i = 1,2,3$	Kazim, 2003; ADDOT, 2009
COMPOSITION OF VEHICLE FLEET MODULE			
Fleet Breakdown by Fuel Type in 2005 ($Fuel_{\%,,2005}$)	Percent of vehicles in 2005 that are fuelled by gasoline, diesel, and CNG		CTA& ORNL, 2009
Light Duty Trucks Percent ($LDT_{\%}$)	Percent of vehicles that are light duty trucks, based on the minimum, mean and maximum percentages of registered vehicles in	Triangular Distribution (23.7, 29.14, 31.2)	ADDOT, 2009

	Car	LDT
Gas	99.63	97.43
Diesel	0.30	2.5
CNG	0.07	0.07

	Abu Dhabi from 1997-2001			
Fleet Composition in 2005 ($comp_{2005}$)	Number of vehicles in the 2005 fleet by weight class and fuel type	If Car then $(1-LDT_{\%})\times N_{2005}\times Fuel_{\%,2005}$		
		If LDT then $(LDT_{\%})\times N_{2005}\times Fuel_{\%,2005}$		
CNG Growth Rate (β)	Annual growth rate of CNG vehicles in the fleet	Scenario	Percent	Kazim, 2003; Assumption
		Baseline	7.1	
		CNG	27.75	
		Fuel Economy	7.1	
Annual CNG Percent ($CNG_{\%}$)	Annual percent of CNG vehicles in the fleet	$\frac{N_{CNG,2005}\times e^{\beta(t-2005)}}{N_{Total,Kazim}}$		
Non-CNG Ratio (nCNG)	Percent of non-CNG vehicles that are gasoline and diesel in 2005	$nCNG_{fuel}=\frac{Fuel_{\%,2005}}{(1-CNG_{\%,2005})}$ where $Fuel_{\%,2005}$ is the percent of gasoline and diesel vehicles in 2005		
Composition of the Vehicle Fleet (comp)	Annual composition of the vehicle fleet by weight class and fuel type (number of vehicles)	CNG vehicles: $CNG_{\%}\times N_{total}$	Gas	Diesel
		Non-CNG LDTs: $[N_{total}\times(LDT_{\%}-CNG_{\%,LDT})]$	*97.5*	*2.5*
		Non-CNG Cars: $[N_{total}\times((1-LDT_{\%})-(CNG_{\%,Cars})]$	*99.7*	*0.3*
FUEL CONSUMPTION MODULE				
Distance in 2005 (D_{2005})	Average distance traveled per vehicle in 2005 (km) based on Kuwaiti survey data of 1570 households on daily km of vehicle operation (miles/year)	Lognormal Distribution		Koushki, 2007
		Mean	14,515	
		Standard Deviation	12,020	
Distance Growth Rate (D_{growth})	Annual growth in per vehicle distance traveled for cars, LDTs (%)	Car	1.3%	Singh et al., 2003
		LDT	1.9%	
Average Distance (D_{avg})	Average annual per vehicle distance traveled, 2005-2030 (mi/year)	$D_{2005}(1+D_{growth})^{t-2005}$		

Total Annual Distance (D_{total})	Total annual distance traveled by fleet (million mi/year)	$\frac{comp \times D_{avg}}{1{,}000{,}000}$			
2005 Fuel Economy (FE_{2005})	Average fuel economy of vehicles in fleet in 2005 (miles per gasoline gallon equivalent)		Car	LDT	Singh et al., 2003
		Gasoline	22.92	17.95	
		Diesel	33.23	21.71	
		CNG	24.66	16.45	
Increase in Gasoline Fuel Economy (FE_{growth})	Annual percentage increase of fuel economy of gasoline vehicles in the fleet	If Fuel Economy Scenario then 0.4%, otherwise 0			
Average Fuel Economy (FE_{avg})	Average annual per vehicle fuel economy from 2005 to 2030 (miles per gasoline gallon equivalent, mpgge)	Gasoline vehicles: $FE_{2005}(1+FE_{growth})^{t-2005}$			
		Diesel and CNG vehicles: FE_{2005}			
Annual Fuel Consumption Per Vehicle (FC_{avg})	Annual per vehicle fuel consumption from 2005-2030 (gallon of gasoline equivalent)	$\frac{1}{FE_{avg}} \times D_{avg}$			
Total Annual Fuel Consumption ($FC_{total,fuel}$)	Total annual fuel consumption of the passenger vehicle fleet from 2005-2030 by fuel type (million gge/year)	$comp \times \frac{1}{FE_{avg}} \times D_{avg}$			
Change in Fuel Consumption Relative to Baseline (ΔFC)	Difference in fuel consumption between CNG and fuel economy scenarios relative to baseline (gasoline gallon equivalents)	CNG scenario: $[FC_{CNG}-FC_{Baseline}]$x1,000,000			
		Fuel economy scenario: $[FC_{FE}-FC_{Baseline}]$x1,000,000			
EMISSIONS MODULE					
CO_2 Emission Factor (EF_{CO2})	Emission factor for CO_2 (g/gge)	(See Table 5)			EPA, 2005; GHG Protocol, 2010
NOx Emission Factor (EF_{NOx})	Emission factor for NOx (g/gge)	Uniform Distribution (See Table 6)			Mohamadabadi et al., 2009; Wang et al., 2007

PM Emission Factor (EF_{PM})	Emission factor for PM (g/gge)	Uniform Distribution (See Table 7)	Mohamadabadi et al., 2009; Wang et al., 2007
CH_4 Emission Factor (EF_{CH4})	Emission factor for CH_4 (g/gge)	Uniform Distribution (See Table 8)	Wang et al., 2007
Emissions by fuel type (E_{fuel})	Emissions of each scenario by fuel type and pollutant (tonnes)	$EF \times FC_{total,fuel} \times \frac{0.001 tonnes}{kg}$	
Total Emissions (E_{total})	Sum of emissions for all vehicle fuel types for each scenario (tonnes)	$\sum_{fuel} E_{fuel}$	
CO_2 Equivalent Emissions (E_{ghg})	CO_2 equivalent emissions of CO_2 and CH_4 using a 100 year global warming potential (GWP) of 25 for methane ($MMtCO_2e$)	$E_{CO_2} + 25 \times E_{CH_4}$	Forster et al., 2007
Change in CO_2 Equivalent Emissions (ΔE_{ghg})	Change in CO_2 equivalent emissions of fuel economy and CNG scenarios relative to baseline ($MMtCO_2e$)	CNG scenario: $E_{CO2,CNG} - E_{CO2,\ Baseline}$ Fuel economy scenario: $E_{CO2,FE} - E_{CO2,\ Baseline}$	
COST ANALYSIS MODULE			
Inflation Rate (i)	Annual inflation rate	2.5%	CIA Factbook
Discount Rate (r)	Nominal discount rate to adjust costs to 2005 US$	5%	
2005 Fuel Price ($P_{fuel,2005}$)	Average price of fuel in the UAE (US$/gasoline gallon equivalent)	Uniform Distribution: See Table 9	Chung, 2009; Daya, 2010; Carlisle, 2010
Fuel Price Projection (P_{fuel})	Projection of fuel prices from 2005 to 2030 (US$/gasoline gallon equivalent)	$P_{fuel,2005} \times (1+i)^{t-2005}$	
Change in Fuel Cost Relative to Baseline	Difference in annual fuel cost of CNG and fuel economy scenarios relative to baseline by	$\Delta FC \times P_{fuel}$	

(ΔCF_{fuel})	vehicle fuel type (million US$)		
Net Change in Fuel Cost (ΔCF)	Net change in annual fuel cost of CNG and fuel economy scenarios relative to baseline from 2005-2030, discounted to 2005 US$ (million US$)	$\frac{\sum_{fuel} \Delta CR_{CNG,\,fuel}}{(1+r)^{t-2005}}$	
New Vehicles (N_{new})	Number of new vehicles in fleet each year, which is the net change in the vehicle fleet	$comp_t - comp_{t-1}$	
Retail Cost Premium of Non-Gasoline Vehicles ($CR_{vehicles}$)	Additional retail cost of CNG and diesel vehicles above gasoline ICE vehicles (US$)	Uniform Distribution (See Table 9)	Singh et al., 2003; Mohamadabadi et al., 2009
CNG Change in Composition ($\Delta comp_{CNG}$)	Difference in the number of new vehicles of each type between the baseline and CNG scenarios	$N_{new,CNG} - N_{new,\,Baseline}$	
Retail Cost Premium of CNG Scenario ($\Delta CR_{CNG,fuel}$)	Annual retail cost premium of CNG scenario above baseline by vehicle fuel type (million US$)	$CR_{vehicles} \times (1+i)^{t-2005} \times \Delta comp_{CNG}$	
Net Retail Cost of CNG Scenario ($\Delta CR_{CNG,}$)	Sum of annual retail cost of CNG scenario across vehicle fuel types, discounted to 2005 US$ (million 2005 US$)	$\frac{\sum \Delta CR_{CNG,\,fuel}}{(1+r)^{t-2005}}$	
New Gasoline Vehicles in FE Scenario ($N_{new,gas}$)	Number of new gasoline vehicles in fleet each year under fuel economy scenario	$N_{gasoline,\,t} - N_{gasoline,t-1}$	
Retail Cost Premium of Efficient Vehicles ($\Delta CR_{FE,vehicle}$)	Additional retail cost of new efficient vehicles added to the fleet each year	0	Assumption

Net Retail Cost of Fuel Economy Scenario (ΔCR_{FEs})	Additional retail cost of vehicles in fuel economy scenario (million 2005 US$)	$\frac{N_{new,gas} \times \Delta CR_{FE,vehicles}}{(1+i)^{t-2005}}$	
OUTCOME VARIABLES			
Total Emissions Change (ΔE_{total})	Difference in emissions between CNG and fuel economy scenarios relative to baseline	CNG scenario: $E_{total,CNG} - E_{total,baseline}$	
		Fuel economy scenario: $E_{total,FE} - E_{total,baseline}$	
Total Cost Difference (ΔC_{total})	Total cost difference between fuel economy and CNG scenarios relative to baseline (million 2005 US$)	(ΔCR) + (ΔCF)	
Cost-Effectiveness (CE)	Cost per unit of emissions reduction of the CNG and fuel economy scenarios (million US$/tonne)	$\frac{\Delta C_{total}}{-\Delta E_{total}}$	Cohen et al., 2003; Yeh et al., 2009

APPENDIX B

Table 19. Population Data and Vehicle Ownership Forecasts from STMP (ADDOT, 2009)

Year	Population	VO1 (Vehicles/1000 people)	VO2 (Vehicles/1000 people)	VO3 (Vehicles/1000 people)
2007	1,484,769	309	302	317
2008	1,506,048	338	329	346
2009	1,527,327	367	353	379
2010	1,548,606	395	378	406
2011	1,569,884	422	401	435
2012	1,591,163	448	424	458
2013	1,612,442	472	448	478
2014	1,633,721	494	471	494
2015	1,655,000	514	493	508
2016	1,726,000	532	514	518
2017	1,797,000	548	534	526
2018	1,868,000	563	552	534
2019	1,939,000	575	568	540
2020	2,010,000	586	581	545
2021	2,119,000	596	593	549
2022	2,228,000	604	604	553
2023	2,337,000	611	612	556
2024	2,446,000	617	619	559
2025	2,555,000	622	625	562
2026	2,664,000	627	630	561
2027	2,773,000	630	634	561
2028	2,882,000	633	638	561
2029	2,991,000	636	640	561
2030	3,100,000	638	642	561

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