

ABSTRACT

KUO, PO-YAO. Evaluation of Freight Truck Anti-Idling Strategies for Reduction of Greenhouse Gas Emissions. (Under the direction of Dr. H. Christopher Frey.)

It is important to identify ways to reduce greenhouse gas (GHG) emissions in order to combat climate change. Freight trucks emit 5.5 percent of U.S. GHG emissions and one of key sources is long-haul sleeper cab truck engine idling. Some anti-idling strategies, such as auxiliary power unit (APU) and shore-power (SP), have been developed. The objective of this study is to assess the anti-idling techniques taking into account variability in of real-world; to develop a new methodology for measurement and evaluation of such techniques; and to obtain new data.

Anti-idling techniques as well as other strategies are assessed based on literature review. For robust assessment for specific situation, a methodology for quantifying real-world truck stop activities and fuel use and emission rates for the base engine and anti-idling techniques is developed. Quantified data are used to estimate avoided fuel use and emissions.

Thirty-three potential best practices for freight trucks are assessed. These practices could lead to 28 percent reduction of GHG emissions from 2003 to 2025. Some practices were estimated to have net cost savings concurrent with substantial GHG emission reductions. Sensitivity analysis was used to assess the effects of variability and uncertainty; for example, for APUs GHG emission reductions could vary from 0 to 5 percent. In order to more accurately assess the impact of APUs and SP, a detailed field study was executed.

A new methodology was developed to estimate real-world fuel use and emissions of twenty APU-equipped and SP-compatible trucks, divided equally between single drivers and

team drivers. Single drivers had 1,520 hours of rest stops per year, which were comparable to the literature estimates but more than those for team drivers. APUs for single and team drivers accounted for 59 and 25 percent, respectively, of idling hours. For two trucks, APUs accounted for 85 percent of idling hours. Double-dipping, which is simultaneous usage of the base engine and APU and defeats the purpose of the APU, accounted for 0.1 to 29% of idling hours. SP usage was seldom observed.

Energy use rates are estimated based on electronic control unit data for truck engines and electrical load measurement for APU and SP. Engine emission factors were measured using a portable emission measurement system. Indirect emission factors from SP are based on utility grid emission factors. Fuel use rates are typically lowest in mild weather and highest in very hot or cold weather. Compared to the base engine, fuel use and CO₂ emissions rates for the APU and SP are lower by 36 to 47 and 74 to 92 percent, respectively.

Taking into account the actual proportion of idling time for which the APU is used instead of the base engine, the avoided fuel use and CO₂ emissions for single and team drivers are 22 and 5 percent, respectively. The projected avoided fuel use and emissions are lower than those from literature sources. The difference is because of relatively low base engine idling fuel use and emissions rates, relatively high APU fuel use and emissions rates, lower idle reduction activity, and double-dipping. Because of low APU utilization rates, 17 of the 20 trucks have no net cost savings for the APU. Aggressive usage of SP, or APUs where SP is not available, elimination of double-dipping and decreased base engine RPM should be encouraged in order to enhance fuel use and emission reductions during idling. There is the need for real-world data and consistent methodology in order to assess anti-idling strategies.

Evaluation of Freight Truck Anti-Idling Strategies for
Reduction of Greenhouse Gas Emissions

by
Po-Yao Kuo

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APPROVED BY:

Dr. E. Downey Brill Jr.

Dr. Donald van der Vaart

Dr. Billy M. Williams

Chair of Advisory Committee
Dr. H. Christopher Frey

BIOGRAPHY

Po-Yao Kuo was born in Taichung, Taiwan. He earned his Bachelors of Science degree in Chemistry from National Taiwan University in 1991 and Master of Science degree in Environmental Engineering from Illinois Institute of Technology in 1998. After his graduation, he worked as an environmental engineer at an environmental technology consultant company, China Technical Consultants, Inc., in Taipei, Taiwan for two years. In 2000, he went to the National Policy Foundation for policy research regarding energy, climate change and air pollution. In August 2005, He came to North Carolina State University for his PhD degree in Environmental Engineering, where his research mainly focused on greenhouse gas emission inventories and reductions in energy use, greenhouse gas emissions and criteria pollutant emissions in transportation sector.

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PART I INTRODUCTION

1.1 Introduction

People face two important resource and environmental challenges in the 21st Century: 1) the depletion of petroleum fuel that cause high fuel price and impact our economy; and 2) the growth of greenhouse gas (GHG) emissions that increase concern regarding climate change that is one of the most serious threats to the environment. With these concerns, it is important to identify ways to reduce fuel consumption and GHG emissions.

Transport accounts for approximately 22 percent of global carbon dioxide (CO₂) emissions from fossil fuel combustion. The industrialized countries are responsible for 60 percent of total transport-related CO₂ emissions. The individual contributions of North America, OECD Europe and OECD Pacific countries to global transport-related CO₂ emissions from energy consumption are 34, 18 and 8 percent, respectively. As with total transport energy consumption, freight trucks of North America, OECD Europe and OECD Pacific countries are responsible for 24, 30 and 25 percent of their regional transport energy consumption, respectively, in 1998 (Lenzen et al., 2003).

Freight transportation is comprised of five major modes: truck, rail, air, water and pipeline. The freight transportation sector is responsible for approximately 8.2 percent of U.S. energy use and 9.2 percent of U.S. GHG emissions (BTS, 2005, FHWA, 2005, EPA, 2005). Freight trucks are estimated to consume 65 percent of freight transportation energy and contribute 60 percent of freight transportation GHG emissions. Thus, freight trucks are primary targets for deep reductions in freight transportation GHG emissions.

There are a growing number of strategies that are considered as potential best practices for reducing energy use and GHG emissions from freight trucking. However,

currently only a few studies point out limited technologies for which are applied or developed to achieve a certain potential in GHG emissions reductions from freight trucks. Few studies have complete insight into the potential for reduction in GHG emissions in freight trucking that can be attained. In order to make an estimate of the potential in the long-term, a comprehensive analysis of existing and emerging potential best practices is necessary. Thus, their potential reduction in energy use and GHG emissions as well as their cost-effectiveness can be assessed and compared.

There is expected to be substantial variability for the assessment results, and an individual adopter would or would not use a particular practice depending on real-world conditions. For example, some of truck anti-idling techniques, such as auxiliary power units (APUs), have been developed and assessed to be cost-effective strategies to avoid use of the base engine during rest stops (Frey and Kuo, 2007, Stodolsky, 2000). However, the assessment results for adopting these techniques may be strongly impacted by situation-sensitive key inputs, such as energy use rates and emissions factors for the base engines and anti-idling techniques as well as the operation hours for the anti-idling devices. There is a lack of real-world data for these key parameters in prior studies, which may be critical for the assessment. Case studies should be developed in order to quantify key parameters and make robust assessments that can help the decision-making for promoting and adoption of suitable practices.

This research presents a comprehensive analysis of potential best practices for reducing GHG emissions in freight transportation, and then focuses on a case study in order to confront and explore the limitation of the comprehensive analysis, such as variability and

uncertainties of key inputs. The comprehensive analysis includes characterization of potential best practices and the analysis of the effects and cost-effectiveness of implementing these strategies based on the data in literature. Some practices have been assessed as cost-effective strategies. For commercially available practices, the APUs have been assessed to be the cost-effective strategy with the highest estimated GHG emission reduction (Frey and Kuo, 2007). However, the variability and uncertainties of key inputs may be overlooked in the comprehensive analysis for the APU. A field study for implementing APUs has been developed to provide needed information, such as real-world base engine and APU fuel use and emission rates and truck stop activity patterns. These data have been used to evaluate the effects of selected anti-idling strategies, including APUs and on-board truck stop electrifications, in order to provide the real-world avoided fuel use and emissions. Thus, GHG emission reduction policies regarding truck anti-idling can be developed based on the real-world assessment results.

1.2 Objective

The key research objectives are:

- 1) Develop a comprehensive analysis for potential best practices in freight trucking in order to assess and compare the potential reductions in energy use and GHG emissions as well as cost-effectiveness;
- 2) Develop a methodology to quantify situation-specific key inputs for a field study regarding long-haul truck stop activity patterns for which anti-idling techniques

are adopted. This methodology is used to gain insights into the real-world truck stop activities impacted by selected anti-idling techniques;

- 3) Characterize the real-world energy use and emission rates during idling for base engine and selected anti-idling techniques and evaluate the real-world factors responsible for variability in the energy use and emission rates; and
- 4) Use estimated real-world energy use and emission rates and real-world truck stop activity data to quantify avoided fuel use and emissions associated with anti-idling techniques. The estimated results are used to evaluate the cost-effectiveness and payback periods of the auxiliary power units, the anti-idling device mainly used in the field study.

1.3 Organization

Part II describes a comprehensive study regarding potential best practices for greenhouse gas emissions reductions in freight trucking based on literature review. The effects of potential best practices on the reductions in energy use, refrigerant use and GHG emissions are assessed and compared. For those practices with sufficient information for quantitative cost assessments, the cost-effectiveness and payback periods are evaluated. The impacts of intermodal shift on GHG emissions reductions potential are also discussed.

Part III describes the development of a methodology of characterization of truck stop activity patterns for long-haul sleeper cab trucks for a field study. The field trucks are APU-equipped and compatible to shore-power (SP) systems, another type of anti-idling techniques. Under the impacts of these anti-idling devices, truck stop duration, frequency of specific

ranges of stop duration, and duration of usage for different power source choices while truck stops are estimated. The extended idling duration likely to be rest periods is also quantified.

Part IV quantifies the real-world fuel use and emission rates for the long-haul truck engines, APU and SP in the field study. A methodology is developed to estimate the fuel use rates and exhaust emissions factors taking into account variations of key factors in real-world conditions, such as engine RPM, ambient temperature, accessory load and the design of fuel saving functions.

Part V evaluates the effects of anti-idling techniques on real-world fuel use and emissions of idling long-haul trucks. The estimated fuel use rates and emissions factors data are incorporated with truck stop activity data to estimate avoided fuel use and emissions due to the implementation of anti-idling devices in the real-world conditions. The cost-effectiveness and payback periods of the APU are also assessed.

Part VI presents the conclusions of this study and the recommendations for further study based on the analysis results provided in Part III, IV and V.

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**PART II POTENTIAL BEST PRACTICES FOR REDUCING FREIGHT TRUCK
GREENHOUSE GAS (GHG) EMISSIONS**

Abstract

There has been a lack of a comprehensive source of comparative information regarding best practices for reducing freight truck fuel consumption, GHG emissions, or both. The goal of this work was to develop a practical survey of potential best practices based on literature review. Thirty-three potential best practices, categorized by eleven subgroups, are identified and assessed. There are varying degrees of information regarding each of these best practices, depending on their state of development. For each practice, reductions in fuel use and GHG emissions are estimated quantitatively. However, for only a small subset of five practices is sufficient information upon which to make quantitative assessments of cost-effectiveness. Some practices, such as off-board truck stop electrification, auxiliary power units (APUs), and hybrid vehicles, have the potential to produce significant net cost savings concurrent with substantial reductions in energy use and GHG emissions. To evaluate uncertainty as well as variability in context-specific conditions, sensitivity analyses were conducted for selected best practices. The sensitivity analyses illustrate varying degrees of confidence in the assessment results, which significantly impacts estimated GHG emissions reductions. If all of the identified best practices are implemented, by 2025 freight trucking GHG could be reduced by 28 percent compared to 2003, while fuel use could be reduced by 12 percent. Intermodal substitution of rail for trucking could lead to more substantial reductions in GHG emissions.

2.1 Introduction

Transport accounts for approximately 22 percent of global carbon dioxide (CO₂) emissions from fossil fuel combustion. The industrialized countries are responsible for 60 percent of total transport-related CO₂ emissions. The individual contributions of North America, OECD Europe and OECD Pacific countries to global transport-related CO₂ emissions from energy consumption are 34, 18 and 8 percent, respectively. As with total transport energy consumption, freight trucks of North America, OECD Europe and OECD Pacific countries are responsible for 24, 30 and 25 percent of their regional transport energy consumption, respectively, in 1998 (Lenzen et al., 2003).

Freight transportation is responsible for approximately 8.2 percent of U.S. energy use and 9.2 percent of U.S. greenhouse gas (GHG) emissions. Freight transportation includes five major modes of truck, rail, air, water, and pipeline. These five modes contribute 60, 6, 5, 13 and 16 percent, respectively, to freight transport GHG emissions (EPA, 2005, BTS, 2005). There is increasing interest in identifying ways to reduce fuel use and GHG emissions from freight transport. Because the truck mode is the largest contributor to overall U.S. freight fuel use and GHG emissions, this paper focuses on the truck mode.

Energy use for freight trucks could increase by 88% from 2003 to 2030, based on a long-term energy trend scenario of the U.S. Energy Information Administration (EIA, 2006). Because GHG emissions are largely based on energy use, GHG emissions are also likely to increase significantly, unless measures are taken to decrease such emissions.

There are a growing number of technological and operational strategies that are potential best practices for reducing energy use, GHG emissions, or both in freight trucking.

However, knowledge of these existing or developing potential best practices and their effectiveness at reducing greenhouse gas emissions is not widespread. The potential effects of implementing many potential best practices are currently unclear. Thus, a comprehensive analysis of these potential best practices for the truck mode is necessary in order to understand their potential for energy usage and GHG emissions reductions and their cost-effectiveness.

2.2 Research Objectives

The objectives of this paper are to: (i) identify existing or developing potential best practices for reducing GHG emissions for the truck mode; (ii) assess and quantify the maximum GHG emissions reductions from the identified potential best practices; and (iii) analyze the impacts of these potential best practices on total GHG emissions. Where sufficient data are available, the cost effectiveness of best practices is assessed. Sensitivity analysis is performed for selected examples in order to quantify the impacts of uncertainty and variability on measures of practice feasibility.

2.3 Methodology

The methodology includes reviewing literature to develop a list of potential best practices, assessing maximum GHG emissions reductions of individual practices and of multiple practices, assessing cost savings, performing sensitivity analysis, performing analysis of the impacts of practices on GHG emissions to 2025, and evaluating inter-modal substitutions.

Some practices are commercialized, while others are of potential future applicability if successfully developed; for simplicity, we refer to all potential best practices as “best practices.”

The scope of this work includes identify best practices for energy use reduction, GHG emissions reduction, and refrigerant usage reduction. For simplicity and brevity we simply use the term “GHG emissions reduction.” Reduction in energy use typically is highly correlated with reduction in emissions of some GHGs, such as CO₂ from fossil fuels.

2.3.1 Literature Review

Most data and information regarding fuel use, GHG emissions and cost effectiveness were taken from published technical and policy reports, books, and engineering journal papers, although some information was collected from websites. The entire literature review and additional details relevant to this paper are contained in a comprehensive report by Frey and Kuo (2007).

2.3.2 Identification of Best Practices

A list of existing or emerging best practices was developed based on the literature review. For each best practice, a quantitative estimate is made of the potential reduction in GHG emissions. The best practices were categorized by subgroups based on the factors that the practices can improve to reduce GHG emissions (e.g., idling, aerodynamic, rolling resistance, vehicle weight) or the technologies that trucks may apply to reduce GHG emissions (e.g., hybrid, alternative fuel).

2.3.3 GHG Emissions Reductions of Individual Best Practices in 2025

The potential reductions in GHG emissions for an individual best practice are estimated based on the difference in 2025 freight trucking emissions with and without the selected best practice. The expected maximum GHG emissions reductions of individual best practices were quantified based on an assumption that each best practice reaches a best estimate of maximum market penetration by 2025 without technical, practical and cost barriers. Actual market penetration may be lower than estimated, but the estimates provide a useful upper bound as to what might be achieved if adoption of such practices is encouraged. Reductions in GHG emissions of alternative fuel strategies are estimated based on life-cycle inventories.

2.3.4 Aggregated GHG Emissions Reductions for Multiple Best Practices in 2025

Aggregated GHG emissions reductions for a subgroup are estimated based on a simple linear combination of the reductions for multiple best practices within the subgroup, except in some situations. Within each subgroup, best practices for the same purpose, such as for anti-idling, are typically mutually exclusive because they cannot be used simultaneously. In such cases, only best practices with the highest potential reductions are used in the assessments. Some best practices could be implemented simultaneously but they may interact. An example is multiple techniques for reducing aerodynamic drag. In the absence of data regarding synergistic or antagonistic effects, a linear combination is assessed. Such situations are noted.

2.3.5 Assessments of Maximum Net Cost Savings of Individual Best Practices in 2025

The cost effectiveness of the best practices is analyzed for cases for which data are available. Such analyses were possible for only a limited number of practices because others do not have substantial information regarding their cost and reduction potential.

Total net cost savings of implementing best practices is the difference between annual energy or refrigerant costs savings and the annualized costs, the latter of which include levelized capital costs and annual operation and maintenance costs. Net savings per unit of GHG emissions reductions are estimated by normalizing total net savings with respect to GHG emissions reductions. A positive value of net savings means that the best practice will pay for itself over some period of time, whereas a negative value means that the annualized costs exceed savings associated with reductions in energy use or refrigerant use. A cost-effectiveness curve based on the net savings per unit of GHG emissions reductions versus cumulative annual GHG emissions reductions is developed.

2.3.6 Potential Reductions by 2025

Analysis of the impacts of best practices on total freight truck GHG emissions in 2025 includes development of Base Case and Alternative Scenarios of GHG emissions.

2.3.6.1 Base Case Scenario

The Base Case Scenario is based on estimated GHG emissions in 2003 and an energy trend scenario. The latter is based on EIA (EIA, 2006), which assumes that fuel economy of the truck mode will not be enhanced by technology progress over the next two decades. This

base case was selected because many of the fuel economy enhancements that EIA considers in its other scenarios are the same as many of the best practices considered here.

2.3.6.2 Alternative Scenario

An alternative scenario of freight truck GHG emissions is based on the assumption that all of the identified best practices are implemented. The scenario for aggregated GHG emissions reductions among multiple practices takes into account an estimated market share in 2025. Aggregated reductions in GHG emissions estimated from the implementation of the best practices are subtracted from the Base Case scenarios to arrive at the Alternative Scenario.

2.3.7 Sensitivity Analysis

Many best practices are not widely used. Thus, there is lack of knowledge as to the true values of key practice variables that impact assessments of reductions in GHG emissions, energy use, and refrigerant use, as well as costs, or such variables are subject to change because of fuel prices or context-specific conditions. Because such information is subject to uncertainty or variability, sensitivity analyses of key input assumption is used to infer the possible range of estimated GHG emissions reductions and cost-effectiveness. Sensitivity analysis was applied to three examples of best practices.

2.3.8 Intermodal Substitution

There are multiple freight transportation modes, including truck, rail, water, air, and pipeline. In some situations, it may be possible to substitute one mode for another for a given shipment,

either partially or fully. Compared to the truck mode, rail and water have lower GHG emission intensity (EPA, 2005, BTS, 2005). If it were possible to substitute some or all of a trucking trip with transport by rail or water-borne vessel, there could be a net reduction in GHG emissions. The reduction in GHG emissions from intermodal shifts from trucks to rail are discussed as an example.

2.4 Results

For the truck mode, 33 best practices are identified and their GHG emissions are quantified. For several of these, a detailed quantitative characterization of cost was possible and is described. The possible effects on total freight truck GHG emissions are evaluated based on comparison of base case and alternative scenarios. Sensitivity analysis is applied to several of the best practices to gain insight into the degree of confidence. Furthermore, the potential for inter-modal shifts to help reduce GHG emissions is assessed. More details regarding all 33 best practices and the related estimates are documented in Frey and Kuo (2007).

2.4.1 Identification of Best Practices and GHG Emissions Reductions

Of the 33 best practices, 19 are existing strategies and the others are in the developmental stage. Table 1 lists all of the best practices, sorted by 11 subgroups. These subgroups are briefly described:

- i. Anti-idling: Anti-idling techniques are used to avoid use of the base engine during rest stops for long-haul trucks equipped with sleeper cabs (Caceres et al., 2002, Stodolsky et al., 2000, Ang-Olson and Schroeer, 2002, Antares, 2005,

Saricks et al., 2003, Wallace, 2003, EPA, 2006). In the U.S. and other countries, sleeper cabs are used as a living compartment during mandatory rest stops. Off-board truck stop electrification (TSE) refers to modules that can be inserted into the window of a truck door and via which heat, cooling, and power are obtained. Truck-board TSE refers to the capability to connect a truck to “shore-power” in order to power electrically operated heating, ventilating, and air conditioning (HVAC) systems and other electrical auxiliary loads. Auxiliary power units (APUs) are comprised of a small diesel-generator set that can be used to generate electricity at any location, even if TSE is not available, in order to operate electrically powered HVAC systems and other auxiliary loads. A direct fire heater is a small diesel-fueled heater that is used to provide heating.

- ii. Air conditioning system improvement: Air conditioning system improvement reduces direct GHG emissions by reducing the rate of refrigerant leakage, substituting refrigerants that have lower global warming potential (GWP) if they leak, and reduces indirect GHG emissions due to energy consumed by the engine in order to run the air conditioning system (CARB, 2004).
- iii. Aerodynamic improvement: Aerodynamic drag is reduced by installing add-on devices or improving vehicle load profile, which increases truck fuel efficiency (Saricks et al., 2003, Coon and Visser, 2004). Many add-on devices are intended to streamline the exterior of the truck. Examples are deflectors installed on the top of the cab to improve the transition of airflow over the cab and over the trailer, and flares or skirts along the bottom of the truck. Other

devices are intended to reduce drag via other principles. For example, pneumatic blowing systems blow air at the trailer rear and planar boat tail plates reduce the formation of the wakes. Therefore, they can reduce aft-end aerodynamic drag. Load profile improvement applies to flat bed trucks and refers to configuring the placement of a load so as to improve the airflow over and around the load.

- iv. Tire rolling resistance improvement: Tire rolling resistance can be reduced by avoiding under-inflation of existing tires, use of alternative tires with low rolling resistance or use of pneumatic blowing, which blows air streams under the truck and provides a slight lift that reduces the loads on the wheels (Ang-Olson and Schroeer, 2002, Saricks et al., 2003, EPA, 2006). Reduced rolling resistance translates into improved fuel economy.
- v. Hybrid: Hybrid propulsion systems include a battery, electrical motors to assist with vehicle propulsion, and a capability to recover or recycle energy from braking and deceleration. Such systems increase fuel efficiency and are especially useful for trucks with a high fraction of stop-and-go transport activities (Langer, 2004, Zou et al., 2004), for which regenerative braking provides an added efficiency advantage.
- vi. Weight reduction: Reducing weight by using high-strength, light-weight materials reduces truck fuel consumption (Ang-Olson and Schroeer, 2002, Saricks et al., 2003).
- vii. Transmission improvement: Improving transmission systems by using advanced

high-efficiency technologies, such as the optimization of transmission engine-wheel speed ratios and reduction of mechanical losses, and low-viscosity lubricants have the potential to reduce mechanical losses and reduce energy consumption (Saricks et al., 2003, EPA, 2006).

- viii. Diesel engine improvement: The fuel efficiency of a diesel engine can be increased by reducing engine friction, increasing peak cylinder pressures, improving fuel injection rate and timing, using turbocharged, direct injection systems, and using thermoelectric technology to recover waste heat (Ang-Olson and Schroeer, 2002, Saricks et al., 2003, EPA, 2006, DOE, 2006).
- ix. Accessory load reduction: Accessory load can be reduced by full electrification of mechanically driven auxiliaries, such as gear- or belt-driven auxiliary, in order to reduce energy use (Saricks et al., 2003).
- x. Driver operation improvement: Improving driver operation behavior by implementing training and providing incentives can significantly reduce fuel use (Ang-Olson and Schroeer, 2002).
- xi. Alternative fuel: An alternative fuel such as biodiesel has the potential to reduce GHG emissions on a life cycle basis (Pang and Frey, 2006, NBB, 2004).

Potential reductions in GHG emissions, energy use, and refrigerant use by subgroup in 2025 are summarized in Table 1. Total GHG emissions reductions are mainly attributable to reductions in energy use. A small portion of emissions reductions are contributed by reductions in refrigerant use or leakage. These estimates take into account mutually

exclusive best practices as well as practices for which there are substantial unsolved technical or practical barriers that impede their feasibility. For example, five best practices in the anti-idling subgroup are mutually exclusive, and the estimate of the subgroup GHG emission reduction is based on one practice, auxiliary power units, alone.

2.4.2 Assessment Results for Best Practices by Subgroups

The two most important subgroups for GHG emissions reduction are diesel engine improvement and aerodynamic improvement. These two subgroups contribute approximately 29 and 16 percent, respectively, to the total truck mode GHG emissions reductions. The contributions of other subgroups vary from 3 to 10 percent.

Some subgroups include best practices with complex conditions, such as mutual exclusion and technological barriers, and their assessment results are calculated based on the following considerations:

- i. Anti-idling: Five best practices are mutually exclusive. The APU is chosen as the basis for the subgroup estimates because APUs provide power that can be used for a wide variety of heating, cooling, and auxiliary needs and thus are more versatile than direct fire heaters and truck stop electrification (Stodolsky et al., 2000).
- ii Air Conditioning System Improvement: Three alternative refrigerants that could be used as best practices are mutually exclusive, since only one refrigerant can be used in an air conditioning system. CO₂ is the first choice for a refrigerant because it has the lowest GWP compared to the other candidate refrigerants,

such as HFC-152a and hydrocarbon (CARB, 2004). Thus, the assessment results reported here are based on CO₂.

There is also interaction between enhanced air conditioning systems with respect to indirect emissions and low-GWP refrigerants. For example, a propane based refrigerant system may use 10% more energy for the air conditioning system operation and increase indirect GHG emissions. Thus, switching refrigerant may impact indirect GHG emissions for the system.

- iii Aerodynamic Improvement: Pneumatic aerodynamic drag reduction and planar boat tail plates on tractor-trailers are mutually exclusive because both of these best practices are installed on the tractor-trailer tails for aft-end drag reduction and cannot both be implemented on the same truck (Saricks, 2003, Coon, 2004). The reductions by the former are estimated to be higher than the reductions by the latter. Thus, the former is used as the basis for the analysis.

There is interaction between pneumatic aerodynamic drag reduction systems and some truck configurations. For example, the dimensions of the tractor-trailer gap may inhibit the reduction of aerodynamic drag achievable via pneumatic aerodynamic drag reduction system. However, there is no quantitative estimate for this interaction effect (LLNL, 2003).

- iv Tire Rolling Resistance Improvement: Wide-base tires and low rolling-resistance tires are mutually exclusive, since they cannot both be implemented on the same truck. Both of them can reduce energy use by the same magnitude. Thus, the results of the assessment are not sensitive to the choice between these

two approaches, and the estimates for the latter are used here to represent these two approaches.

- v Transmission Improvement: There is interaction between advanced transmissions and low-viscosity transmission lubricants. The former is designed to reduce internal friction, including the friction from gear surface roughness. The latter is also used to reduce gear contact friction. However, there is a lack of data with which to quantify the impact of the interaction, so a simple linear combination of the reductions is applied.
- vi Diesel Engine Improvement: Within five practices in this subgroup, there is an interaction between improved fuel injectors and turbocharged, direct injection to improved thermal management. The former improves the fuel injection systems for all trucks. The latter also improves the fuel injection system but focuses on medium-duty trucks. However, there is a lack of data with which to quantify the impact of the interaction. For the estimated reductions in energy use and GHG emissions for this subgroup, the improved fuel injectors are applied for heavy duty trucks and the turbocharged, direct injection is applied for medium duty trucks only.
- vii Accessory Load Reduction: Accessory load reduction can be achieved in part by conversion of mechanical auxiliary loads to electrically-operated ones. The same kinds of electrically-operated auxiliary components can be used for in combination with a variety of electric power supply systems. Alternative electrical supply systems can lead to reductions in overall truck energy use. For

example, electricity can be obtained via a small diesel engine with an alternator, or via a fuel-cell system. These two practices are mutually exclusive. The former can reduce GHG emissions more than the latter. Thus, the former is used as the basis for the analysis.

2.4.3 Quantitative Assessment for Cost-Effectiveness

There is sufficient information for five best practices upon which to make quantitative assessments for cost-effectiveness. These best practices include off-board truck stop electrification, auxiliary power units, direct-fire heaters, hybrid systems, and B20 biodiesel.

The GHG emissions reductions of these best practices vary from 0.33 to 4.27 percent. Table 2 provides a summary of quantitative estimates of reductions in 2025 GHG emissions and energy use, as well as regarding costs, for the five selected best practices. A cost-effectiveness curve for these five practices is given in Figure 1.

Four of the five best practices produce a net cost savings. These savings are the net result of substantial costs offset by substantial savings based on reduced energy usage. For B20 biodiesel, the net savings are negative, indicating that this practice does not pay for itself. Biodiesel fuel cost is higher than that for petroleum diesel (based on current typical experience) and thus there is a net increase in total costs. Overall, there is substantial variability in the cost-effectiveness of these best practices when normalized based on the GHG emissions reductions. Direct fire heaters appear to be the most cost-effective, whereas the use of B20 biodiesel appears to be the least cost effective. However, the APU, hybrid, and biodiesel practices have the potential to achieve substantially larger magnitudes of GHG

emissions reduction than the other two options. From a national policy perspective, consideration of the potential magnitude of reductions is important, whereas from an individual owner or operator perspective, consideration of cost savings and cost effectiveness may tend to be more important.

2.4.4 Sensitivity Analysis

To evaluate the potential of significantly over- or under-estimating GHG emissions reductions, sensitivity analyses were performed for the key inputs for each of three best practices: (1) APU; (2) hybrid trucks; and (3) B20 biodiesel. The key inputs selected for each of these three practices, and the ranges assigned to each, are given in Table 3.

The ranges of values of the inputs for the APU and hybrid system best practices represent possible inter-individual variability depending on characteristics of an individual truck, characteristic of an APU or routes driven by a truck. Thus, the ranges in GHG emissions reduction shown here are illustrative of differences that may occur for one truck or driver to another. For example, if an APU with high fuel use rate is implemented on a truck that has a high efficiency base engine with low fuel consumption at idle, GHG emissions might not change significantly. However, if the APU with low fuel use rate is implemented on a truck that has a base engine with high fuel consumption at idle, then GHG emissions could be reduced by 5 percent. Likewise, for the hybrid vehicles, there is variability in the GHG emissions reduction of 2.7 to 5.8 percent depending on the type of driving cycle, which might vary by truck route or driver.

In contrast, for biodiesel, the sensitivity analysis is based on uncertainty regarding the national biodiesel fuel production capacity and the estimates of net reductions in life cycle GHG emissions while biodiesel instead of petroleum diesel is used, leading to a substantial range of uncertainty, on a relative basis, in the estimated GHG emissions reduction. For example, the high end of the range, 17.7 percent, is approximately 24 times greater than the low end of the range, indicating a significant uncertainty in the impact of this best practice.

The wide ranges of variability or uncertainty in inputs for these three examples emphasizes the importance of recognizing and accounting for variability and uncertainty in GHG emissions reductions.

2.4.5 Potential Aggregated Reductions

Base Case and Alternative Scenarios of GHG emissions and energy use are illustrated in Figure 2. For the base case, energy use and GHG emissions are estimated to increase by 67 percent from 2003 to 2025. If all best practices are implemented with maximum market penetration rates, total GHG emissions could be reduced by 28 percent in 2025 compared to 2003 levels, and energy usage could be reduced by 12 percent. Aggressively implementing all best practices has the potential to not only stabilize, but also achieve a significant reduction of the truck mode GHG emissions in 2025 compared to the 2003 level. The reductions in energy use are not as significant as for GHG emissions. For example, alternative fuel can reduce GHG emissions but increase energy use based on life-cycle inventories. A fuel derived from renewable sources (e.g. biomass) can reduce GHG emissions released to the atmosphere, assuming that the amount of carbon sequestered by

biomass is equal to that emitted. However, a significant portion of energy for biodiesel fuel production is based on fossil fuel consumption.

Aggregated reductions in GHG emissions and energy use for the alternative versus base case scenarios are estimated to be 57 and 48 percent, respectively. The program goals of “The 21st Century Truck Program,” announced on April 21, 2000, are to double fuel efficiency of large trucks and triple fuel efficiency of medium and small trucks, which means that the overall program goal is a fuel use reduction of approximately 54 percent (DOE, 2000). The aggregated emissions reduction from implementation of multiple best practices is comparable to the goals implied by this program.

2.4.6 Intermodal Substitution

The typical unit GHG emissions per unit of freight activity of each of the freight modes range from 0.06 to 2.16 lb CO₂ per ton-mile, as illustrated in Figure 3 (EPA, 2005, BTS, 2005). As noted earlier, intermodal shifts from trucks to rail, if feasible, are attractive option for GHG emissions reductions. The GHG emissions per ton-mile for rail are 8 percent those of trucks, implying a maximum GHG emissions reduction of 92 percent if rail could substitute completely for trucking. The GHG emissions per ton-mile for ships are 17 percent those of trucks, implying a maximum GHG emissions reduction of 83 percent if intracoastal or inland waterborne transport could substitute completely for trucking.

However, whether freight can be shifted from trucks to rail or ships may depend on a number of factors. These factors include distance, availability of infrastructure (e.g., port terminals, rail/truck intermodal facilities), size of the cargo, schedule, durability of the cargo,

relative costs, and the need for new logistics systems. For example, some amount of truck activities, such as pick up and delivery, are likely to be needed even if most of the ton-miles involved rail. According to the estimate for a case study, 7 percent of the freight ton-miles require shipment by truck for pick up and delivery, with the balance shipped by rail.(Caceres, 2002) For this scenario, the rail-truck inter-modal shift would reduce GHG emissions by approximately 85 percent, instead of the maximum possible 92 percent. Of course, the actual reductions are also affected by implementation of best practices for GHG reduction in both the truck and rail modes, which can lead to a differing percentage difference for the inter-modal shift.

2.5 Conclusions

If current trends continue, U.S. energy use and GHG emissions for the truck mode could increase by 67 percent from 2003 to 2025. However, there are many potential best practices for reducing energy use and GHG emissions, which could combine to lead to a *reduction* in GHG emissions of 28 percent from 2003 to 2025, thereby reversing the current trend of growth in such emissions. Even larger percentage reductions are possible if intermodal shifts from trucks to rail are encouraged.

Many of the best practices, however, are in early stages of development or commercialization. Therefore, there is limited quantitative data upon which to base assessments of emissions reductions and cost. For several best practices for which adequate data are available, the normalized cost savings per unit of GHG emissions reduction was

highly variable. Thus, potential individual adopters of best practices should carefully compare their options but may find that in some cases the best practices pay for themselves.

From a national policy perspective, some best practices, such as B20 biodiesel, offer greater potential for large magnitudes in reduction of total GHG emissions, but may not be as cost-effective to an individual owner or operator. Thus, there may be targeted opportunities for a national government to promote research and development of such option in order to reduce their costs or to provide other incentives for their adoption.

The variability and uncertainty in estimates of GHG emissions reductions was assessed quantitatively based on a sensitivity analysis for selected best practices. In some cases, there is expected to be substantial variability in the conditions under which an individual truck owner or operator would use a particular best practice. In turn, this implies that the assessment and decision-making regarding adoption of such practices needs to be tailored to the situation of a particular potential adopter. A one-size-fits-all approach may not be appropriate. In other cases, there is uncertainty regarding the extent to which a particular best practice could be deployed, leading to national scale uncertainties in the amount of GHG emissions reduction that could be achieved.

If best practices are aggressively implemented, it is possible for there to be a net decrease in total GHG emissions from the freight truck mode over the next two decades, even if intermodal substitutions to rail do not occur. The aggregated emissions reduction from implementation of multiple best practices is comparable to the goals implied by the “The 21st Century Truck Program.”

In many cases, best practices for GHG emissions reductions for freight trucks may be a “no regrets” proposition, in that the owner or operator can realize a net cost savings. The complexity of options motivates the need for a guidebook of best practices that is aimed at the various stakeholders in decision making regarding adoption of best practices. A first edition of such a guidebook was developed as the basis for this paper. The guidebook should be updated as new information becomes available. Evaluating key assumptions (e.g., market penetration rates) that influence the selection of best practices via sensitivity analysis is also recommended for decision-making.

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Table 2. 1. A List of Potential Best Practices and Their Estimated 2025 Reductions in GHG Emissions, Energy Use and Refrigerant Use by Subgroups

Subgroup	I.D. No.	Brief Name of Best Practice	Developmental Status ^a	GHG Emissions Reductions for Individual Best Practice (%)	(A) ^b GHG Emissions Reductions (10 ⁶ Tons CO ₂ eq.) [%] ^c	(B) Energy Use Reductions		(C) Refrigerant Use Reductions (10 ⁶ Tons CO ₂ eq.) [%] ^c
						(B ₁) (10 ⁶ Tons CO ₂ eq.)	(B ₂) (10 ¹⁵ BTU) [%] ^c	
Anti-idling	1	Off-board Truck Stop Electrification	C	0.33	15.0 [3.6]	15.0	0.19 [4.5]	-
	2	Truck-board Truck Stop Electrification	C	0.39				
	3	Auxiliary Power Units	C	2.08				
	4	Direct-fired Heaters	C	1.05				
	5	Direct-fired Heaters with Thermal Storage Units	P	2.88				
Air Conditioning System Improvement	6	Enhanced Air Conditioning System I: Direct Emissions	P	0.88	19.1 [4.6]	1.3	0.02 [0.40]	17.8 ^d [100.0]
	7	Enhanced Air Conditioning System II: Indirect Emissions	C	0.18				
	8	Alternative Refrigerants: CO ₂	N	2.47				
	9	Alternative Refrigerants: HFC-152a	N	2.35				
	10	Alternative Refrigerants: HC	N	2.46				

Continued on Next Page

Table 2. 1. Continued

Subgroup	I.D. No.	Brief Name of Best Practice	Developmental Status ^a	GHG Emissions Reductions for Individual Best Practice (%)	(A) ^b GHG Emissions Reductions (10 ⁶ Tons CO ₂ eq.) [%] ^c	(B) Energy Use Reductions		(C) Refrigerant Use Reductions (10 ⁶ Tons CO ₂ eq.) [%] ^c
						(B ₁) (10 ⁶ Tons CO ₂ eq.)	(B ₂) (10 ¹⁵ BTU) [%] ^c	
Aerodynamic Improvement	11	Cab Top Deflector, Sloping Hood and Cab Side Flares	C	1.43	66.6 [16.2]	66.6	0.83 [20.0]	-
	12	Closing and Covering of Gap Between Tractor and Trailer, Aerodynamic Bumper, Underside Air Baffles, and Wheel Well Covers	C	2.37				
	13	Trailer Leading and Trailing Edge Curvatures	C	1.24				
	14	Pneumatic Aerodynamic Drag Reduction	N	2.17				
	15	Planar Boat Tail Plates on a Tractor-trailer	N	3.76				
	16	Vehicle Load Profile Improvement	C	0.43				
Tire Rolling Resistance Improvement	17	Automatic Tire Inflation Systems	C	0.56	28.3 [6.9]	28.3	0.35 [8.5]	-
	18	Wide-base Tires	C	2.03				
	19	Low-rolling-resistance Tires	C	2.83				
	20	Pneumatic Blowing to Reducing Rolling Resistance	N	0.54				
Hybrid	21	Hybrid trucks	N	3.40	24.5 [5.9]	24.5	0.3 [7.4]	-
Weight Reduction	22	Lightweight Materials	P	4.62	33.3 [8.1]	33.3	0.4 [10.0]	-
Transmission Improvement	23	Advanced Transmission	P	0.97	13.6 [3.3]	13.6	0.17 [4.1]	-
	24	Transmission Friction Reduction Through Low-Viscosity Lubricants	C	0.92				

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Table 2. 1. Continued

Subgroup	I.D. No.	Brief Name of Best Practice	Developmental Status ^a	GHG Emissions Reductions for Individual Best Practice (%)	(A) ^b GHG Emissions Reductions (10 ⁶ Tons CO ₂ eq.) [%] ^c	(B) Energy Use Reductions		(C) Refrigerant Use Reductions (10 ⁶ Tons CO ₂ eq.) [%] ^c
						(B ₁) (10 ⁶ Tons CO ₂ eq.)	(B ₂) (10 ¹⁵ BTU) [%] ^c	
Diesel Engine Improvement	25	Engine Friction Reduction Through Low-Viscosity Lubricants	C	1.81	118.31 [28.75]	118.3	1.47 [35.5]	-
	26	Increased Peak Cylinder Pressures	C	3.07				
	27	Improved Fuel Injectors	P	5.49				
	28	Turbocharged, Direct Injection to Improved Thermal Management	C	0.82				
	29	Thermoelectric Technology to Recovery Waste Heat	N	5.22				
Accessory Load Reduction	30	Electric Auxiliaries	C	1.43	39.6 [9.6]	39.6	0.49 [11.9]	-
	31	Fuel-cell-operated Auxiliaries	N	5.49				
Driver Operation Improvement	32	Truck Driver Incentive Program	C	3.10	22.3 [5.4]	22.3	0.28 [6.7]	-
Alternative Fuel	33	B20 Biodiesel Fuel for Trucks	C	4.27	30.8 [7.5]	-	-0.37 [-8.9]	-
Total Reduction					411.5 [100.0]	-	4.14, [100.0]	17.8 [100.0]

^aDevelopmental status: N = new concepts; P = pilot tests; C = commercially available systems

^bA is equal to B₁ plus C.

^c[%]: the percentage of the estimated total reduction attributable to each subgroup

^dGHG emissions reductions (i.e., 10⁶ tons CO₂ eq.) caused by refrigerant use reductions

Table 2. 2. Summary of GHG Emissions Reductions, Energy Use Reductions, Annualized Costs, Energy Cost Savings, Net Savings, and Unit Net Savings of Selected Best Practices

Practice Name	Off-board Truck Stop Electrification	Auxiliary Power Units	Direct-fire Heaters	Hybrid	B20 Biodiesel
Annual GHG Emissions Reductions (10 ⁶ ton CO ₂ eq./year)	2.4	15.0	7.6	24.5	30.8
Annual Energy Use Reduction (10 ¹² BTU /year)	27	185	94	300	-370
Unit GHG Emissions Reductions (10 ⁻³ lb CO ₂ eq./ton-mile)	11	66	34	130	29
Unit Energy Use Reduction (BTU /ton-mile)	60	409	207	804	-176
Annualized Cost (\$10 ⁶ /year)	570	3000	390	2430	3300
Annual Energy Cost Saving (\$10 ⁶ /year)	900	3400	1740	5600	0
Net Saving (\$10 ⁶ /year)	330	440	1350	3190	-3300
Net Savings per Unit of GHG Emissions Reductions (\$/ton CO ₂ eq.)	138	29	178	130	-108
Net Savings per Unit of Energy Use Reduction (\$/10 ⁶ BTU)	12	2.3	14	10.6	N/A ^a

^aThis practice has no energy use reduction due to an increase in energy use, and it has no net saving due to high annualized cost and no energy cost saving

Table 2. 3. Variable Ranges for Uncertainty Analysis

Best Practice	Selected Input	Range of Inputs			Estimated Sensitivity of GHG Emissions Reductions (%) ^a		
		Lower Bound	Base Case	Upper Bound	Lower Bound	Base Case	Upper Bound
Auxiliary Power Unit	Base Engine Idle Fuel Use	0.29 gallon/hr	0.85 gallon/hr	1.65 gallon/hr	0 ^b	2.1	5.0 ^c
	APU Fuel Use	0.1 gallon/hr	0.2 gallon/hr	0.45 gallon/hr			
Hybrid	Fuel Economy Gains for Different Drive Cycles	18%	33.4%	48%	2.7	3.5	5.8
B20 Biodiesel	B100 Biodiesel Production Capacity	1.7 billion gallons	7.8 billion gallons	15.2 billion gallons	0.75 ^d	4.3	17.7 ^e
	Net reduction in life cycle GHG emission	6%	7.4%	15.7%			

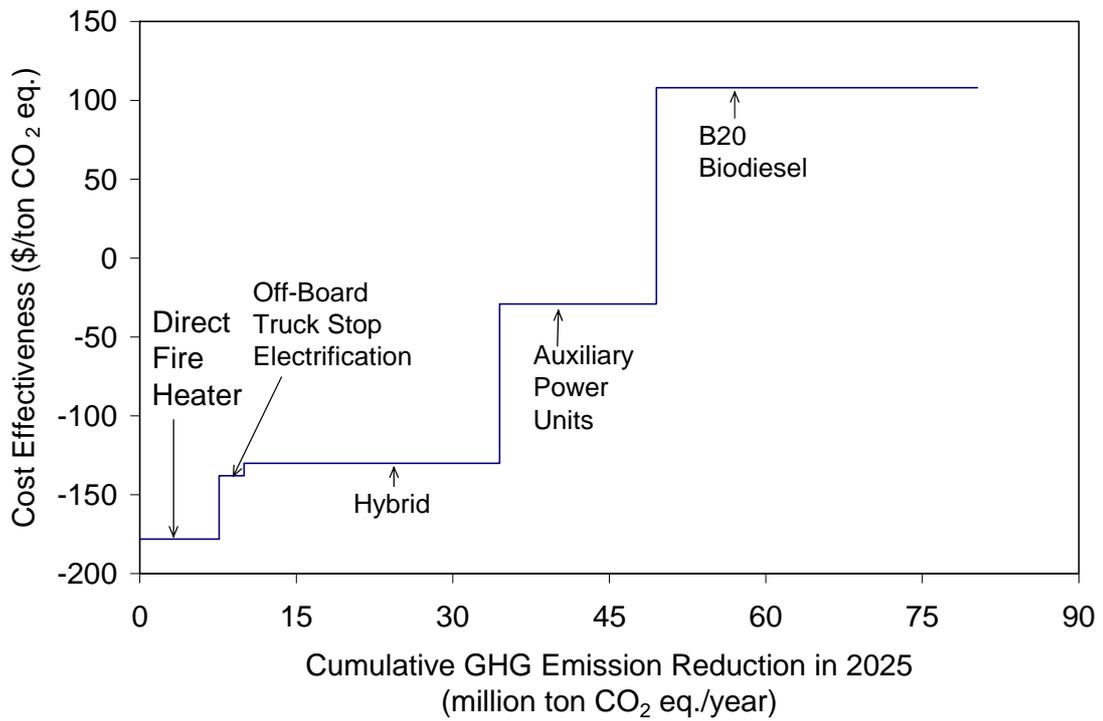
^a The percentage reduction when comparing total truck mode emissions with and without the indicated best practice

^b Based on lower bound of base engine fuel use and upper bound of APU fuel use. Negative values are excluded since an APU would not be used if it were to increase fuel consumption.

^c Based on upper bound of base engine fuel use and lower bound of APU fuel use

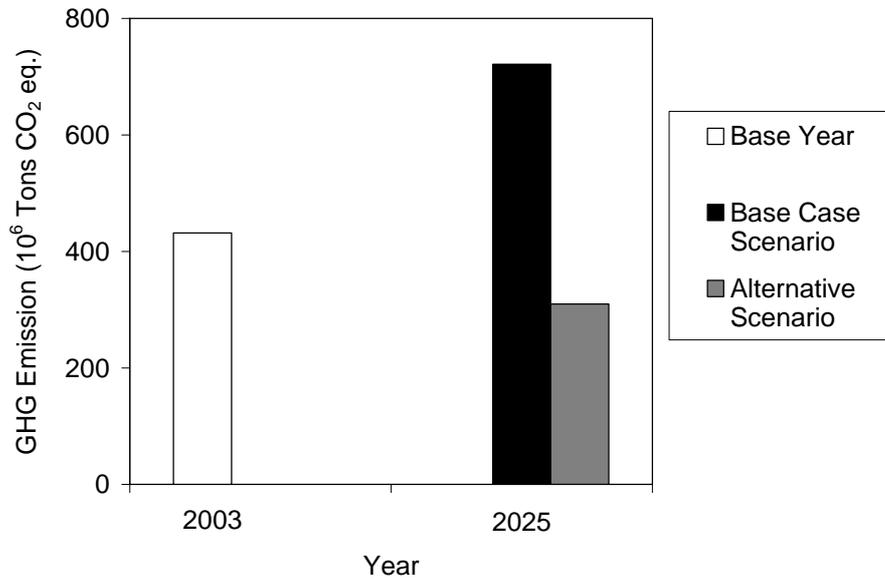
^d Based on lower bound of biodiesel production capacity and lower bound of net reduction in life cycle GHG emission.

^e Based on upper bound of biodiesel production capacity and upper bound of net reduction in life cycle GHG emission

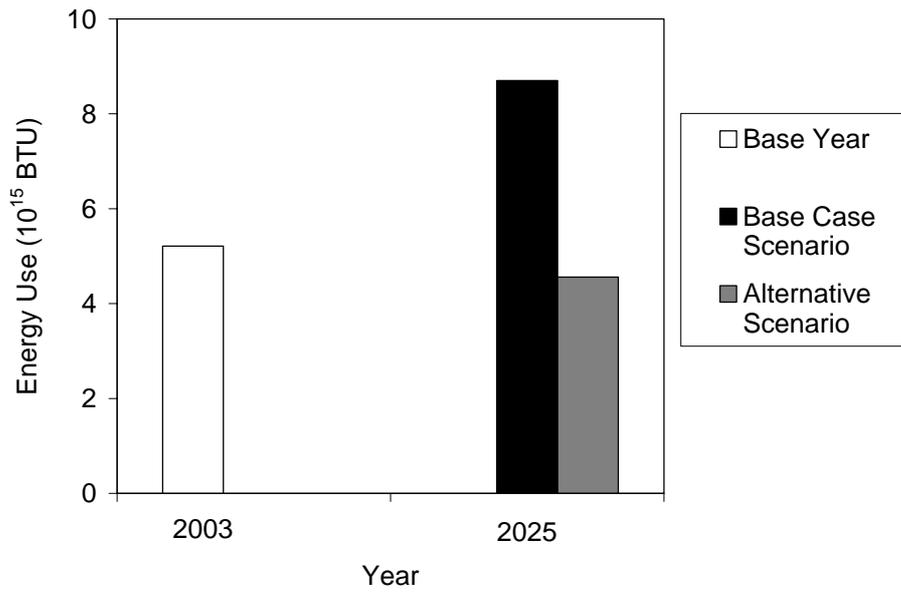


(Cost effectiveness for GHG emission reduction is equal to negative value of net savings per unit of GHG emissions reductions in Table 2)

Figure 2. 1. Cost-Effectiveness Curve for the Five Selected Best Practices



(a) Greenhouse Gas Emissions



(b) Energy Use

Figure 2. 2. A Comparison of Base Case and Alternative Scenarios of Greenhouse Gas Emissions and Energy Use for 2003 to 2025

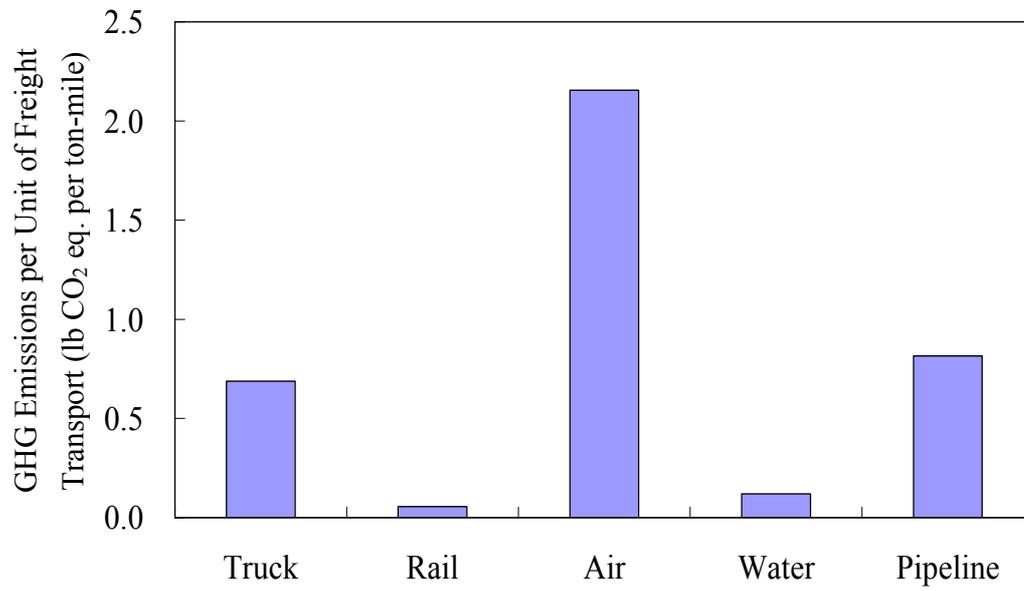


Figure 2. 3. Estimated GHG Emissions per Unit of Freight Transport of Each Mode

**PART III METHODOLOGY FOR CHARACTERIZATION OF LONG-HAUL
TRUCK IDLING ACTIVITY UNDER REAL-WORLD CONDITIONS**

Abstract

There is a need for real-world data to quantify the activity of long-haul sleeper cab trucks during extended idling in order to estimate baseline fuel use and emission rates, and to assess reductions achievable with idle reduction techniques such as Auxiliary Power Units (APUs) and shore-power (SP). A new methodology for obtaining such data is developed and demonstrated here. Twenty new APU-equipped and SP-capable in-service trucks, divided equally between single drivers of Fleet A and team-drivers of Fleet B, were monitored for more than one year. Data were collected from each truck using existing electronic control units, additional installed sensors, and a satellite uplink. The data were analyzed to quantify activity for each truck. For single drivers, there was an average of 2130 hours of idling per truck, of which 1,520 hours occurred for stops of ≥ 7 hours in duration. The APUs were used an average of 59 percent of time for all stops and 68 percent for stops of ≥ 7 hours. Team drivers averaged only 770 hours of total idling per truck and 29 percent overall APU usage. There was substantial inter-driver variability, demonstrating the need for adequate sample size in order to reliably characterize activity patterns.

3.1 Introduction

Long-haul truck drivers need to take rest stops required by Federal Hours-Of-Service (HOS) regulations (ATRI, 2006). These rest stops are intended to promote safety by reducing driver fatigue. Approximately 680,000 long-haul trucks are equipped with sleeper cabs (US Census Bureau, 2004). Sleeper cabs contain a small living environment with sleeping accommodations. Long-haul truck drivers tend to stay in cab compartments for rest periods. These cab compartments require heating, ventilation or air conditioning (HVAC), have small appliances such as refrigerators, and have electrical outlets to support other auxiliary loads. Typically, the heating, cooling, and power requirements for the sleeper cab during driver rest time are supplied by the base engine of the truck. The base engine might be run continuously for many hours during rest stops (EPA, 2004). Extended idling refers to periods of driver rest time during which the base engine is idling (Gaines et al., 2006). The drawbacks of extended idling include fuel consumption, pollutant emissions, noise and base engine wear (EPA, 2008).

Many states and local governments have passed or are considering anti-idling laws (CARB, 2008). EPA has developed a national idling reduction program under the SmartWay® Transport Partnership Program (EPA, 2008). Some anti-idling options involve

installation and operation of on-board systems, such as auxiliary power units (APU) and direct-fired heaters. Truck stop electrification includes “on-board” and “off-board” systems. On-board systems involve directly connecting the truck to a stationary source of electrical “shore” power. An “off-board” system is a module that fits into the window of the truck and via which the driver can obtain HVAC and electricity, such as IdleAire.

The average long-haul truck is estimated to idle from 1,460 to 1,800 hours annually for rest stops, depending on the study, and individual trucks are estimated to have annual extended idling that varies from 500 to 4,000 hours annually (ATRI, 2004, Lutsey *et al.*, 2004, and Gaines *et al.*, 2006). Much of this data depends on driver memory (or industry rules of thumb) when responding to surveys and thus may not be accurate. Alternatively, engine electronic control unit (ECU) data have been used to quantify total idling time (Huai *et al.*, 2006). Since the total idling time reported by the ECU represents a combination of in-traffic idling, idling for loading or unloading and extended idling, ECU data are likely to over-estimate extended idling. Thus, there is a need for a more rigorous methodology for quantifying extended idling.

Actual reductions in fuel use and emissions of anti-idling devices vary depending on actual hours of anti-idling device usage and the actual hours of base engine idling displaced

(EPA, 2004). A fleet preference survey concluded that 67% of truck drivers were satisfied with APU performance (ATRI, 2006). However, there is a lack of “real-world” data for quantifying the portion of idling time that is displaced by APU usage. Prior assessments typically estimated hours of anti-idling device usage based on estimated extended idling duration (EPA, 2004; EPA, 2008).

The focus of this paper is to develop methodology for quantifying different types of truck idling in order to support assessments of the impact of anti-idling technologies.

3.2 Research Objectives

The objectives of this project are to develop a methodology for: (i) collecting and screening real-world data from in-service trucks; (ii) categorizing stop scenarios; (iii) analyzing truck activity patterns while trucks are stopped; and (iv) estimating extended idling duration. The methodology is applied to an illustrative case study for two trucks as well as field data from 20 trucks.

3.3 Methodology

The methodology includes study design, data acquisition system, definition of key concepts,

categorization of stop scenarios, data screening, and data analysis.

3.3.1 Study Design

The study includes a field data collection component that has been implemented by Volvo Technology of North America and Volvo Trucks of North America. Volvo has instrumented 20 shore-power (SP) capable long-haul Volvo trucks with data acquisition systems. The 20 trucks are equally divided among Fleets A and B. The demonstration project includes evaluation of two different APUs, referred to here as APU-A and APU-B. For each of the two fleets, APU-A was installed on five trucks and APU-B was installed on five trucks. These trucks are privately owned. The driver logbooks are not available to the study team.

3.3.2 Data Acquisition System

Volvo has designed, installed, monitored, and maintained a data acquisition system for each of the 20 trucks. The data acquisition system is comprised of 4 major components: electronic control units (ECUs); additional sensors; a data logging system; and VolvoLink.

Each truck has electronic control units (ECUs) for the engine, climate control, lighting, and the instrument cluster. The ECUs provide data relevant to stop and idling

activity, such as cumulative base engine idle hours. However, they do not provide enough data to fully quantify such activity. Therefore, Volvo designed and installed additional sensors that monitor additional data, such as electricity usage of APU and SP systems and exterior temperature. The data from the supplemental sensors are input to a data logging system. The data logging system samples inputs at 6-hour, 1-hour or 15-minute increments, depending on the parameter. The collected data from the ECUs and additional sensors are consolidated and periodically transmitted (every 6 hours for each truck) via the satellite-based VolvoLink system.

3.3.3 Definition of Key Concepts

Key concepts that are the basis for the methodology and results are defined here.

- (i) **Idling:** Idling includes time periods when a truck is stationary at any location while the base engine is operating, including in-traffic idling, idling during initial starting, idling for loading or unloading, and extended idling during driver rest periods. Idling time is recorded by the engine ECU each time the truck idles for more than 120 seconds.
- (ii) **Stop:** A stop is characterized by zero road speed at a location for a period of 15

consecutive minutes or longer.

- (iii) Long-duration Idling: Long-duration idling is the operation of the base engine when not engaged in gear for a period greater than 15 consecutive minutes, except for in-traffic idling (EPA, 2004). As an approximation, long-duration idling is estimated based on idling for durations longer than 15 minutes because it is typically expected that most in-traffic-idling durations are shorter than 15 minutes.
- (iv) Extended Idling: Extended idling refers to the off-duty time period that a truck driver stays in a truck to take a rest as required by HOS regulations and during which the base engine is idling. The major difference between extended idling and long-duration idling is that the former is intended to refer only to driver rest time, but the latter refers to the combination of driver rest time and idling for loading or unloading. Although extended idling has been discussed often, it is not accurately quantified (Gaines *et al*, 2006).
- (v) Stop Duration: Stop duration is the combination of the duration of base engine idling, APU usage, and shore-power usage as well as the duration for which there is no power consumption from any source, when the combination of these durations is greater than or equal to 15 consecutive minutes.

- (vi) Combined Idling: Combined idling is the combination of base engine idle duration, APU usage duration, shore-power usage duration, and off-board system usage duration.
- (vii) Combined Long-duration Idling: Combined long-duration idling refers to periods of combined idling greater than or equal to 15 minutes.
- (viii) Combined Extended Idling: Combined extended idling refers to periods of combined idling greater than or equal to criteria for extended idling duration. Such criteria are introduced later based on analysis results.
- (ix) Cumulative Combined Extended Idling: Defines to the annual sum of all hours of combined extended idling for a truck.

3.3.4 Categorization of Stop Scenarios

A stop can include several types of activities, such as use of the base engine, APU, on-board electrification, off-board electrification, or no power source. There are seven stop scenarios:

Scenario 1. Base Engine: Truck base engine idles without using any anti-idling systems.

Scenario 2. APU & Base Engine: Base engine and APU are operated simultaneously.

Scenario 3. APU: Base engine is off and APU is operating.

Scenario 4. SP: Base engine is off and shore-power system is operating.

Scenario 5. SP & Base Engine: Base engine and shore-power systems are operated simultaneously.

Scenario 6. Off-Board: Base engine is off, no APU or on-board shore-power is used, but the truck is parked at an off-board-equipped location and the interior temperature indicates usage of a heater or A/C module.

Scenario 7. No Power: Base engine is off and no anti-idling system is used.

3.3.5 Data Analysis Process

This section illustrates the steps for data screening and analyzing truck activity patterns while trucks are stopped.

3.3.5.1 Data Screening Procedure

Data screening is a quality assurance procedure for reviewing collected data, determining whether any errors or problems exist, correcting errors or problems where possible, and removing invalid data if errors or problems cannot be corrected.

Data screening includes identification of misallocated data files, missing VIN, the

time at which transport service began, periods of missing data, mislabeled timestamps, missing parked status data while GPS data indicated a stop, and short-term movements within long-duration stops. If a data quality problem cannot be corrected, then such data are excluded. Most of the data screening procedure was implemented via a Visual Basic macro in Excel.

3.3.5.2 Analyzing Truck Activity Patterns While Trucks Were Stopped

Quantitative metrics for truck activity during stops were estimated using several Visual Basic macros. These metrics include vehicle stop duration, frequency of specific ranges of stop duration, and duration of usage for different power source choices based on the stop scenarios listed in Section 3.4. A conceptual flow chart for estimating these metrics is given in Figure 1.

3.3.6 Estimate of Cumulative Combined Extended Idling Duration

The cumulative combined extended idling duration is estimated by summing the durations of all combined long-duration idling greater than a duration criterion. The data were analyzed to infer possible criteria for defining combined extended idling. There are some short-

duration stops that are likely to be associated with loading/unloading. On the other hand, there are some longer-duration stops that are likely to be associated with rest periods.

The estimates of cumulative combined extended idling duration are compared with other data. The data in prior studies depend on either truck driver surveys or ECU-reported engine idling data for those trucks without APUs installed. ECU-reported engine idling plus APU usage hours in this study are assumed to be the same as the total amount of idling activity that would be reported by the ECU for a truck without an APU installed.

3.4 Results

Truck activity has been recorded for each of the 20 trucks. Data were screened to identify and either correct or remove data quality problems. The screened data were used to analyze truck activity patterns. Comprehensive analysis results for both fleets are summarized. For the purposes of demonstrating methodology, detailed results are given for two selected trucks.

3.4.1 Data Availability

The trucks entered commercial service between September 2006 and May 2007. For each truck, Table 1 reports the totals as of February 2008 (the end date of the field study) for

elapsed time in-service, accumulated miles, base engine operating time, base engine idling hours and APU usage time. For Fleet-A, the average truck has been in service for 10,900 hours, has 161,800 accumulated miles, and an annual equivalent of 2,130 hours of total ECU-reported idling plus APU usage hours. For Fleet-B, the average truck has been in service for 8,500 hours, has 114,100 accumulated miles, and an annual equivalent of 770 hours of total ECU-reported idling plus APU usage hours.

3.4.2 Data Quality and Data Screening

For 13 of the 20 trucks, data were missing for less than 2 percent of the total elapsed time since in-service. For four trucks, 4 to 8 percent of data were missing. For two trucks, 11 to 16 percent of data were missing. For one truck, 26 percent of data were missing. Missing data were typically due to data acquisition problems, such as data logger or antenna malfunction. The missing data occurred during on-road usage as well as idling. Therefore, it is not likely that the missing data are creating large biases when the available data are used to estimate the proportion of combined long-duration and combined extended idling relative to the total amount of time that data are successfully reported by the data acquisition system. Problems with missing data that were related to the data acquisition system were corrected in

the field at the next available opportunity by Volvo personnel.

3.4.3 Stop Activity Patterns

Quantitative stop activity metrics were estimated for all trucks of both fleets.

3.4.3.1 Number of Stops versus Stop Duration

In order to summarize overall stop and idling activity, the frequency distribution of the annualized number of stops per truck versus stop duration is illustrated in Figure 2 for both fleets. Most Fleet A trucks have a multimodal distribution of stop duration, with a peak in the frequency for very short duration stops and a second, lower, peak in the frequency for long duration stops. In contrast, the Fleet B trucks typically have a unimodal distribution in which the highest frequency of stop durations is for short stops. Most stops for all trucks had durations less than or equal to 3 hours. These stops may have been associated with traffic or with short duration loading or unloading.

Fleet-A trucks are predominately operated by a single driver. Most of the long duration stops of Fleet A trucks had average estimated durations between 5 and 14 hours. These longer duration stops are likely to include rest stops. While some of these stop

durations may not be fully consistent with HOS requirements, they may represent reality.

There were stop durations of 10 hours or longer which would be consistent with HOS requirements. While further information would be desirable to help interpret these data, such as the driver logbook, such information is not available.

Fleet-B trucks are predominantly operated by team drivers. Most stops of Fleet B trucks were shorter than 5 hours. It is likely that some of the rest periods for one driver occurred while the other driver operated the truck.

Rest stops appear to be associated with stop durations of 5 hours or more for Fleet A based on the multimodal frequency distribution of Figure 2a. However, it is possible that some loading/unloading stops may have durations around 5 hours. Thus, we assume 5 hours as the one criterion for the minimum duration of extended idling, and 7 hours as another criterion for a more conservative estimate.

3.4.3.2 Percentage of Time of Stop Scenarios versus Stop Duration

For all 20 trucks, the distributions of stop activity with respect to powered stop scenarios of usage of the base engine, APU and shore-power are illustrated in Figure 3. Examples of detailed distributions of stop activity with respect to stop scenarios for stop durations ranging

between 0.25 to 24 hours or more are quantified for two selected trucks in Figure 4.

Almost all Fleet A trucks, except Truck No. 6, had a similar activity pattern, as that shown in Figure 2a. For these trucks, there was a similar distribution of time in which either the base engine or APU were used for stop durations of approximately 5 to 14 hours. Thus, driver activity was similar among these trucks; however, the drivers made different choices regarding whether to meet their comfort needs using the base engine or the APU. As indicated in Figure 3, drivers for seven of the Fleet A trucks tended to use the APUs more frequently than the base engine. An example of the typical activity pattern for a Fleet A truck is shown in Figure 4a.

Annualized APU usage hours and the idle base engine hours for short and long stop durations for Fleet A trucks are summarized in Table 2. On average, APUs were used for 54 hours per truck annually for stops of 3 hours or less in duration, versus 1,010 hours per truck for stops of 7 hours or more. The APU usage hours were 27 percent and 66 percent of combined idling hours for these short and long duration stops, respectively. On average, 79 percent of all APU usage hours were for stop durations of 7 hours or more. Thus, the APUs were used more often than the base engine for long duration stops. For one case, the driver of Truck No. 3 strongly preferred to use the APU more than the base engine even for short

duration stops.

Almost all Fleet B trucks, except Truck No. 17, had a similar activity pattern to each other and to that shown in Figure 2b. These trucks had a relatively small number of longer stops compared to Fleet A. Truck No. 17 was the only truck for which the activity pattern had a multimodal distribution of the number of stops versus stop duration that was qualitatively similar to that for Fleet A trucks. It is possible that this truck was sometimes operated by a single driver.

Drivers of most Fleet B trucks, except for Truck No. 15, tended to use the base engine instead of the APU, as summarized in Figure 3 for all Fleet B trucks. An example of the typical activity pattern for a Fleet B truck is shown in Figure 4b.

The average annual APU operation hours for Fleet B were estimated to be 7 hours per truck for short stop durations and 97 hours per truck for long stop durations. Fleet B truck drivers tended to idle the base engine instead of using the APUs for both short and long stop durations, and on average used the APUs for only 25 percent of all combined idling hours.

Some amount of simultaneous use of both the APU and base engine was detected in almost all trucks. While this type of “double-dipping” is negligible for most trucks, there were 6 trucks with more than 25 hours of such usage. On-board shore-power system usage

and simultaneous use of on-board shore-power and base engine were estimated to be no more than 0.1 percent of time for each truck. There is no evidence that an off-board shore-power system (i.e. IdleAire) was used.

The longest durations for combined idling for most Fleet A trucks and Fleet B trucks were typically shorter than 24 and 14 hours, respectively. Stop durations of more than these ranges are usually without power of any kind.

3.4.4 Cumulative Combined Extended Idling

As noted earlier, combined extended idling is estimated based on two alternative thresholds, of 5 and 7 hours, respectively, for minimum duration. Table 3 summarizes the estimates of cumulative combined extended idling duration based on these thresholds.

For cumulative combined extended idling of 5 hours or more, the annual duration for Fleet A trucks ranged from 890 to 2150 hours, with an average of 1630 hours. For the more conservative threshold of 7 hours, the annual duration per truck ranged from 790 to 2100 hours, with an average of 1450 hours. The total hours associated with these two thresholds differ by only about 10 percent.

For Fleet B, the cumulative combined extended idling durations were substantially

smaller than for Fleet A, averaging only 330 and 250 hours per year per truck for the threshold values of 5 and 7 hours duration per combined idle event, respectively. However, there is considerable inter-truck or inter-driver variability. For example, the cumulative combined extended idle duration varies from 50 to 860 hour per truck within Fleet B, or by more than an order-of-magnitude, for the threshold of 5 hours.

ECU-reported idling plus APU usage hours include not only long stops during rest periods but also short stops during in-traffic idling and loading/unloading idling. As an approximation, we hypothesize that the duration of base engine idling plus APU usage is equivalent to the idling duration of a truck without an APU. Since the observed on-board and off-board TSE usage is negligible, the use of base engine and APU is assumed to be the combined idling duration. The cumulative combined idling for all stop durations for Fleets A and B averaged 2,130 and 770 hours per truck per year, respectively, which is significantly higher than estimated cumulative combined extended idling.

To provide a guideline regarding how much cumulative extended idling duration is replaced by APU instead of base engine usage, we estimate the percentage of APU usage relative to the cumulative duration of both base engine and APU usage. For Fleet A, the APU was used for 68 percent of cumulative combined extended idling of 7 hours or more,

whereas for Fleet B, the APU was used for only 29 percent of cumulative combined extended idling. For all stop durations, the APU was used for 59 percent of the average of 2130 hours of combined idling per Fleet A truck and 25 percent of the average of 770 hours of combined idling per Fleet B truck.

3.5 Conclusions

New methods have been developed for collecting and analyzing real-world data regarding long-haul truck stop activity and the choices among the base engine or several anti-idling devices. Stop activities have been identified, categorized, quantified and interpreted separately.

Most long duration stops likely to be rest periods were estimated to be from 5 to 14 hours. However, the drivers appear to differ in their preference for use of the base engine versus the APU during long duration stops. For stop durations indicative of rest stops, some of these types of stops may be associated with required HOS rest time, while others may not.

The total amount of annual combined extended idling duration for trucks operated primarily by single drivers averaged 1,450 hours per truck for stop durations of greater than 7 hours, which is comparable to literature estimates of 1,460 to 1,800 hours. However,

cumulative combined idling for all stop durations averaged 2,130 hours per truck.

For the team driven trucks, the annual average amount of combined extended idling was 250 hours per truck for stop durations of greater than 7 hours, and the total amount of combined idling for all stop duration averaged 770 hours per truck. These estimates are significantly lower than for the single driver trucks. Clearly, the team driver operated trucks have substantially less combined idling than single driver operated trucks.

There is substantial inter-truck and inter-driver variability in combined idling activity. Thus, it is important to base estimates on average over multiple trucks and not to rely on anecdotal data from individual or small numbers of trucks.

The percentage of combined extended idling to cumulative idling of all kinds is approximately 70 and 30 percent for single and team drivers, respectively. Some drivers use the APU for over 80 percent of combined idling. Thus, it is technically feasible to obtain high utilization levels. In order to increase cost effectiveness for fleets that use APUs, driver incentive programs should be developed to encourage this.

“Double-dipping” of simultaneous usage of the base engine and APU was significant for some trucks. This defeats the purpose of the APU, which is to reduce overall fuel consumption and emissions. On the other hand, we find that APUs are used instead of the

base engine not only for combined extended idling but for shorter duration stops as well.

This study provides more accurate and detailed idle activity data than has been available from driver surveys. Furthermore, this study illustrates the sensitivity of idling activity to driver logistics such as single versus team drivers, which needs to be considered not only in analyses of idling activity but by individual firms when estimating the economics of APUs for a particular situation.

Future work will involve measurements of fuel use and emissions of these engines, which will be combined with the activity data reported here in order to quantify avoided fuel use and emissions.

Although the combined idling activity data for this study are primarily for the APU and base engine, the methodology includes both on-board and off-board truck stop electrification. APU usage may not be allowed in some states; however, other anti-idling technologies, such as SP and TSE, will be. Thus, the methods developed here are recommended for quantifying activity patterns for additional trucks and should be extended to include other types of anti-idling methods (e.g. direct fired heaters) with appropriate instrumentation to supplement the ECU data.

3.6 Supporting Materials

Supporting materials are available in Appendix A. These include: (a) parameters available from the data acquisition system; (b) methodology for database construction; (c) steps for the data screening procedure; (d) the approach used for interpreting categorical data (e.g., APU engine on or off in each 15 minute sampling interval); (e) flow chart for categorization of stop scenarios; (f) details of variables and estimation methods used for analyzing truck activity patterns; (g) detailed figures for numbers of stops versus stop duration for each of the 20 trucks; and (h) detailed figures for percentage of time of stop scenarios versus stop duration for each of the 20 trucks.

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Table 3. 1. Total Elapsed Time, Total Hours of Reported Data, Accumulated Miles, Base Engine Hours, Base Engine Idling Hours and Auxiliary Power Unit Usage Hours for Twenty Field Trucks^a

Fleet ^b	Vehicle No.	Total Elapsed Time ^c (Hours)	Total Hours of Reported Data ^d (Hours)	Total Miles Traveled (Miles)	Actual Total Base Engine Hours (Hours)	Actual Base Engine Idling Hours (Hours)	Actual APU Usage Hours (Hours)	Annualized APU Usage Hours ^e (Hours)	Annualized Cumulative Combined Idling Hours ^{e,f} (Hours)	Percentage of Annualized APU Usage Hours to Annualized Cumulative Combined Idling Hours (%)
A	1	12997	12867	184484	5352	1895	485	330	1607	21
	2	12834	12702	204503	4411	736	2049	1413	1916	74
	3	12815	11442	183022	3910	445	2671	2045	2349	87
	4	8738	8724	126328	2746	456	826	829	1286	64
	5	12631	12568	209322	4831	971	2317	1615	2289	71
	6	9862	9829	152611	4122	1492	1777	1584	2909	54
	7	8762	6486	112527	2799	816	1150	1553	2368	66
	8	7151	6847	83685	2355	847	666	852	1889	45
	9	11487	11375	186985	5702	2306	573	441	2200	20
	10	11265	11216	174117	3599	463	2762	2157	2518	86
	Avg.	10854	10406	161758	3983	1043	1528	1282	2133	59
B	11	9511	8776	145305	3535	944	46	46	916	5
	12	7176	7169	100885	2722	805	38	46	1028	4
	13	7254	7245	90543	2054	397	10	13	492	3
	14	8871	8833	103533	2558	695	29	28	714	4
	15	7309	7237	84821	1934	471	444	537	1102	49
	16	9530	9073	114875	2474	389	358	345	703	49
	17	9348	9348	112154	2380	516	591	554	1037	53
	18	8345	6998	134702	2878	409	113	142	571	25
	19	9018	8334	119531	2347	260	41	43	296	15
	20	8983	8977	134429	2959	492	355	346	826	42
	Avg.	8535	8199	114078	2584	538	203	210	769	25

Continued on Next Page

Table 3. 1. Continued

^aThe data for total elapsed time, total miles traveled, total base engine hours and base engine idling hours are from the electronic control unit (ECU), but the data for the APU are recorded by installed sensors monitoring the status of the APU

^bFleet A typically used individual drivers. Fleet B typically uses a pair of team drivers

^cThe data for all parameters are through February 28, 2008

^dTotal elapsed time since truck started service minus total hours of missing data

^eAnnualized data = (actual data) × (8760/ total elapsed time)

^fTotal combined idling hours include ECU-reported base engine idling plus APU usage hours

Table 3. 2. Annualized Auxiliary Power Unit Usage Hours and the Idle Base Engine Hours for Short and Long Stop Durations for 20 Trucks^a

Fleet	Vehicle No.	Stop Durations between 0.25 and 3 hours			Stop Durations \geq 7 hours			Percentage of Total APU Usage That Occurs for \geq 7 Hours ^c (%)
		APU Usage Hours (Hours) (A)	Idle Base Engine Hours (Hours) (B)	Percentage of APU Usage Hours to Combined Long-Duration Idling ^b $[A/(A+B) \times 100\%]$	APU Usage Hours (Hours) (C)	Idle Base Engine Hours (Hours) (D)	Percentage of APU Usage Hours to Combined Long-Duration Idling ^b $[C/(C+D) \times 100\%]$	
A	1	34	217	14	265	854	24	80
	2	30	123	20	1259	183	87	89
	3	238	50	83	1342	106	93	66
	4	24	144	14	663	119	85	80
	5	45	166	21	1402	253	85	87
	6	53	154	26	953	998	49	60
	7	31	251	11	1392	529	72	90
	8	20	259	7	613	551	53	72
	9	18	142	11	368	1373	21	83
	10	45	24	66	1850	103	95	86
	Ave.	54	153	27	1011	507	66	79
B	11	1	455	0.3	17	642	3	37
	12	0	472	0.0	9	543	2	20
	13	1	422	0.2	3	260	1	22
	14	11	416	2.5	7	242	3	24
	15	0	164	0.3	451	294	61	84
	16	15	226	6.3	52	196	21	15
	17	7	101	6.7	268	295	48	48
	18	4	301	1.3	18	189	9	13
	19	1	304	0.4	18	96	16	43
	20	27	296	8.4	126	213	37	36
Ave.	7	316	2.6	97	297	20	34	

^a Exclude the APU usage hours and idle base engine hours while the base engines idled and the APUs operated simultaneously

^b Combined long-duration idling is the sum of APU usage hours and idle base engine hours

^c APU usage hours for stop durations \geq 7 hours divided by total APU usage hours, which are summarized in Table 1

Table 3. 3. Comparison of Estimated Annual Extended Idling to Annual Electronic Control Unit (ECU)-Reported Idling

Fleet	Truck No.	Cumulative Combined Extended Idling Duration (Hours)		Cumulative Combined Idling Hours ^a (C)	Percentage of Cumulative Combined Extended Idling to All Combined Idling (%)		Percentage of all APU Usage that Occurs During Stops \geq 7 Hours ^b
		Duration \geq 5 hours (A)	Duration \geq 7 hours (B)		Duration \geq 5 hours (D = A/C)	Duration \geq 7 hours (E = B/C)	
A	1	1119	847	1607	70	53	31
	2	1537	1464	1916	80	76	86
	3	1717	1515	2349	73	65	89
	4	886	785	1286	69	61	84
	5	1776	1690	2289	78	74	83
	6	2144	1618	2910	74	56	59
	7	1960	1852	2368	83	78	75
	8	1290	1045	1889	68	55	59
	9	1736	1610	2200	79	73	23
	10	2145	2109	2518	85	84	88
	Average	1631	1454	2133	76	67	68
B	11	330	155	916	36	17	11
	12	241	172	1028	23	17	5
	13	106	81	492	22	16	3
	14	71	65	714	10	9	10
	15	863	742	1102	78	67	61
	16	339	127	703	48	18	41
	17	812	810	1037	78	78	33
	18	89	73	571	16	13	24
	19	47	47	296	16	16	39
	20	371	196	826	45	24	64
	Average	327	247	769	37	28	29

^aThese annualized data include ECU-reported base engine idling plus APU usage hours and are from Table 1

^bAnnual APU usage hours for stop durations \geq 7 hours (from Table 2) divided by annual extended idling for stop durations \geq 7 hours

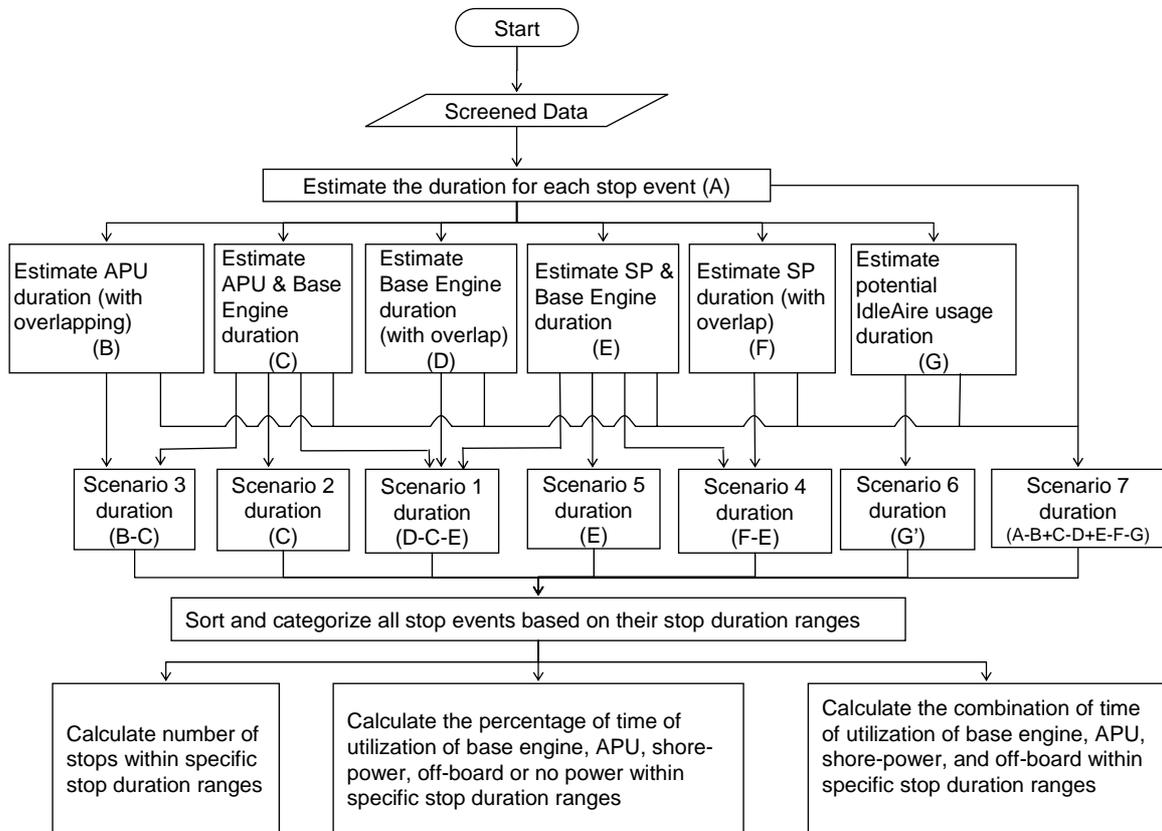
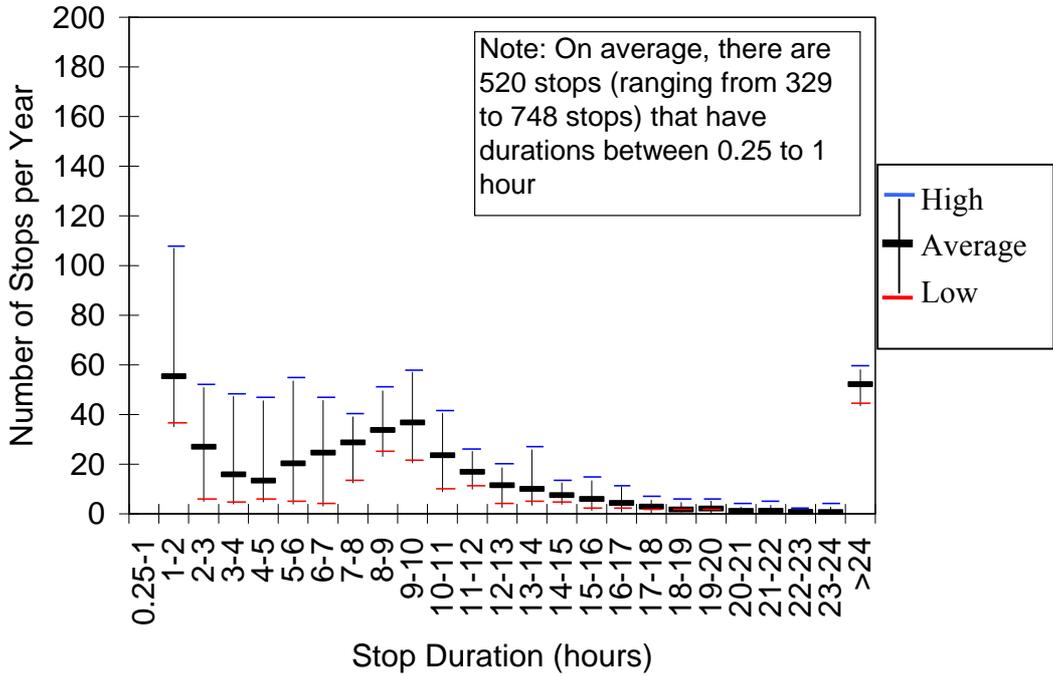
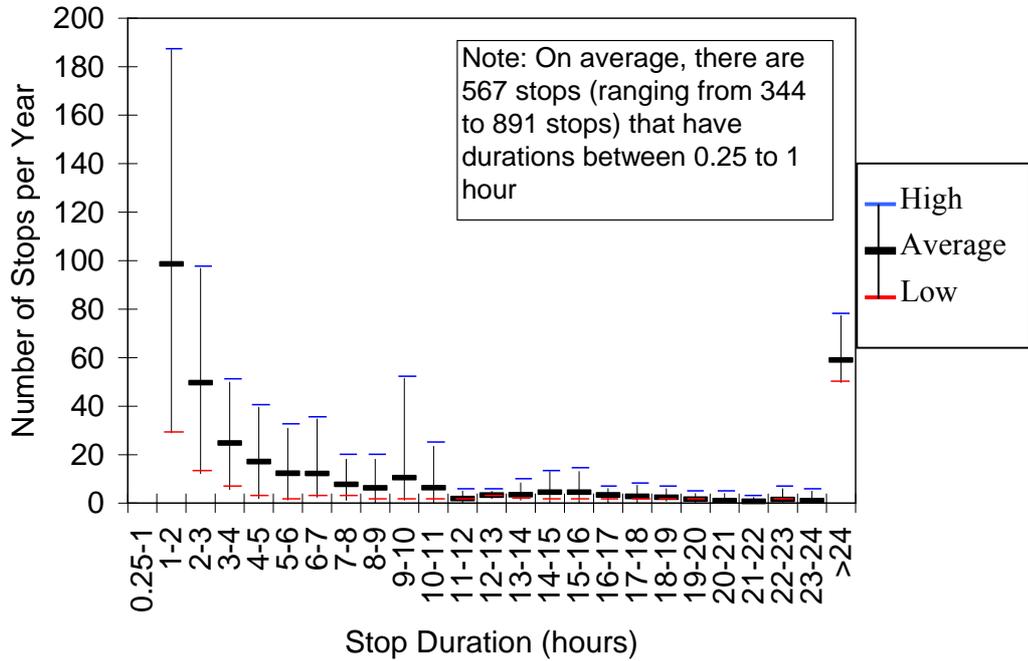


Figure 3. 1. Flow Chart for Calculation Steps and Sequence for Quantifying Activity during a Stop

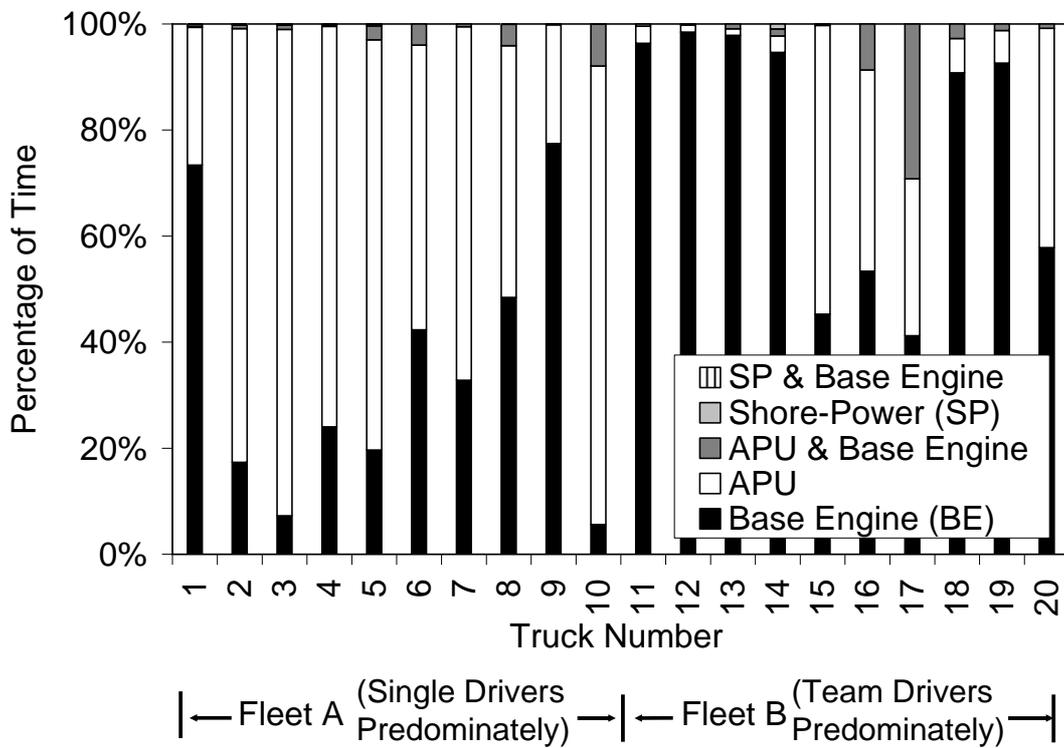


(a) Fleet A (Predominately Single Driver)



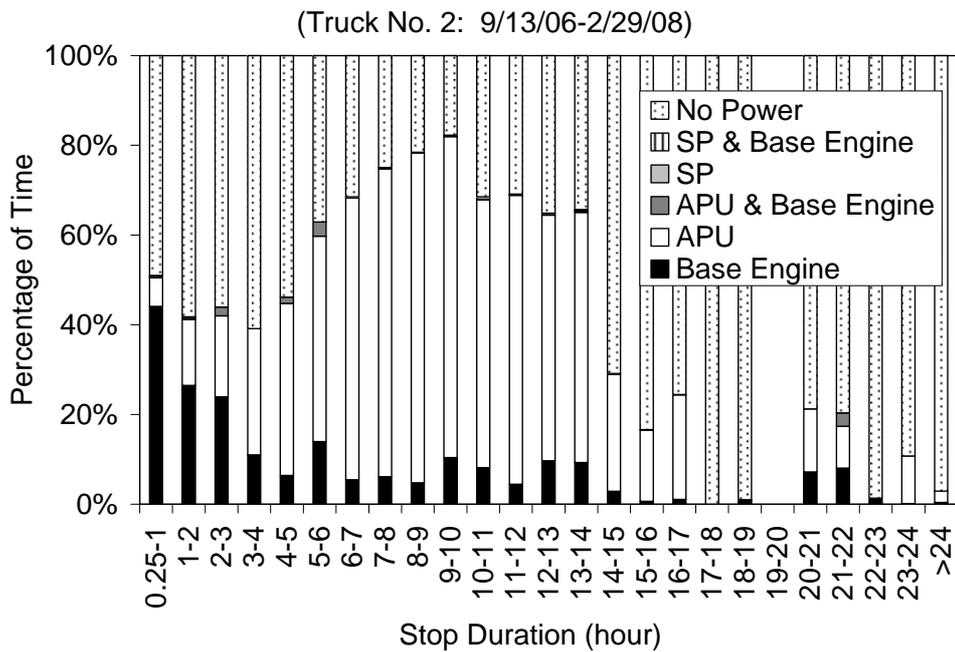
(b) Fleet B (Predominately Team Driver)

Figure 3. 2. Annualized Number of Stops per Truck versus Stop Duration for Both Fleets

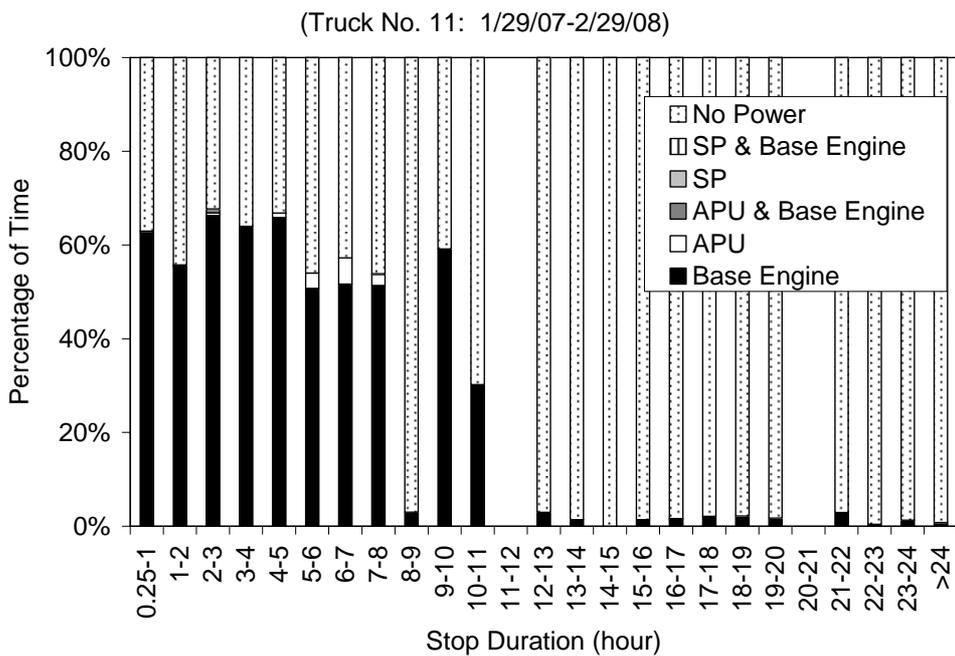


(Note: For stops ≥ 0.25 hours)

Figure 3. 3. Percentage of Time of Powered Stop Scenarios for 20 Field Trucks



(a) Example of a Single Driver-Operated Truck: Truck No. 2



(b) Example of a Team Driver-Operated Truck: Truck No. 11

Figure 3. 4. Percentage of Time of Stop Scenarios versus Stop Duration for Trucks Operated by Single and Team Drivers (SP = Shore-power; APU = Auxiliary Power Unit)

**PART IV REAL-WORLD ENERGY USE AND EMISSION RATES FOR IDLING
LONG-HAUL TRUCKS AND SELECTED IDLE REDUCTION TECHNOLOGIES**

Abstract

Long-haul freight trucks typically idle for more than 2,000 hours per year, including rest stops, motivating interest in idle reduction techniques such as auxiliary power units (APUs) and shore-power (SP). Real-world energy use and emissions for truck engines, APUs, and SP are quantified. Fuel or energy use rates are estimated based on electronic control unit (ECU) data for truck engines and electrical load measurements for APU engines and SP systems. Engine emission factors were measured using a portable emission measurement system. Indirect emissions from SP are based on average utility grid emission factors. Base engine fuel use and APU or SP electrical load were analyzed for 20 trucks monitored for more than one year during 2.76 million miles of activity within 42 U.S. states. The average base engine fuel use rate typically varied from 0.46 to 0.65 gal/hr. The average APU fuel use rate varied from 0.24 to 0.41 gal/hr. Fuel use rates are typically lowest in mild weather and highest in very hot or cold weather and depend also on engine RPM. Compared to the base engine, APU fuel use and emissions of CO₂ and SO₂ are lower by 36 to 47 percent, depending on the system and ambient conditions. NO_x emissions are lower by 80 to 90 percent. Reductions in PM, CO, and hydrocarbon emissions vary from approximately 10 to over 50 percent. SP leads to more substantial fuel use and emissions reductions, except for SO₂. The actual reductions achievable in practice will be lower, since only a fraction of base engine usage is likely to be replaced by either APU, SP, or both. Recommendations are made for reducing base engine fuel use and emissions, accounting for variability in fuel use

and emissions rates, and for further work to quantify real-world avoided fuel use and emissions.

4.1 Introduction

Long distance truck drivers are required by Federal Hours of Service (HOS) regulations to take mandatory rest stops in order to promote safety by reducing driver fatigue. Long distance trucks typically have a sleeper compartment whose heating, cooling, and power requirements are supplied by the diesel-fueled base engine. During rest stops, engines are typically run for continuous periods of many hours. The U.S. Environmental Protection Agency (EPA) estimates that idling long-haul truck engines consume 960 million gallons of fuel and emit 11 million tons of carbon dioxide (CO₂), 180,000 tons of oxides of nitrogen (NO_x), and 5,000 tons of particulate matter (PM) per year (Lim, 2002; EPA, 2008).

The United States National Energy Policy 2001 has targeted reductions in heavy-duty truck idling in order to reduce fuel use and emissions (NEPD, 2001). Various anti-idling devices have been developed to provide cab comfort and electricity, but currently they are not widely deployed (Lindsey and Kim, 2005).

Anti-idling devices include mobile and stationary options. Mobile options include on-board systems such as auxiliary power units (APUs) and direct-fired heaters. Stationary options, such as truck stop electrification (TSE), require connecting the truck to a “shore-based” facility. TSE systems include “on-board” and “off-board” systems. On-board systems involve connecting the truck to a stationary source of electrical power, and are referred to as shore-power (SP) systems. An “off-board” system is a module that fits into the window of the truck and via which the driver can obtain HVAC and electricity (EPA, 2008).

The potential economic and environmental benefits of anti-idling devices depend on reductions in the real-world fuel use and emissions compared to avoided base engine usage.

Fuel use rates and emission factors for the base engines, APUs and SP vary significantly due to inter-vehicle or inter-device variations, ambient weather conditions, operation conditions, driver behavior, and the electricity energy mix. Prior studies have estimated the idling fuel use and emissions rates for NO_x, hydrocarbons (HC), carbon monoxide (CO), CO₂ and PM for the base engines of more than 100 trucks, which range from 1975 to 2005 model years, based on laboratory tests (Brodrick et al., 2002; Khan et al., 2006; Lim, 2002; Lutsey et al., 2004; McCormick et al., 2000; Stodolsky et al., 2000; Storey et al., 2003). For example, a climate-controlled chamber test program run by EPA measured fuel use and emissions rates for idling heavy-duty diesel trucks at three different ambient temperatures (0 °F, 65 °F and 90 °F) and at idle speeds from 600 to 1,200 RPM (Lim, 2002). However, there is a lack of data on the effect of variability in real-world conditions, such as the variations in ambient temperature, engine RPM, cab size, solar radiation and accessory load, on base engine fuel use and emissions.

There is significant variability among available data for the fuel use rates for different types of APUs, ranging from 0.13 to 0.45 gal/hr, primarily based on information provided by APU vendors or, less frequently, independent parties (Cummins, 2008; EPA, 2008; Idlebuster, 2008; Kohler, 2008a; Kohler, 2008b; Lim, 2002; Pony Pack, 2008; Stodolsky et al., 2000). The testing methods for these data are usually not reported. There is no standard testing method for quantifying APU fuel use rates. Moreover, the real-world fuel use rates and emission factors for the APUs are influenced by inter-device variations and real-world conditions, such as weather (Caterpillar, 2006), but these impacts are not well-quantified.

The benefits of off-board TSE and SP systems with respect to energy savings and emissions reduction have been evaluated in several demonstration projects (ANTARES, 2005; Lindsey and Kim, 2005; Perrot, 2004). The number of new trucks manufactured to be compatible with SP is increasing. Only a small portion of truck idling is conducted at truck stops equipped with TSE facilities. The analyses for the TSE demonstration projects were site-oriented, not truck-oriented, so there is a lack of data regarding the connection time to the TSE systems for individual trucks.

4.2 Research Objectives

The objectives of this paper are to: (i) characterize the real-world, in-use energy use and emission rates during idling for base engines, APU engines and shore-power; and (ii) identify and evaluate the real-world factors responsible for variability in these energy use and emission rates.

4.3 Methodology

The methodology includes: (1) field data collection; (2) estimation of fuel use rates for the base engines; (3) estimation of fuel use rates for APUs; (4) emissions measurements and estimation of emission factors for the base and APU engines; (5) estimation of energy use rates and emission factors for shore-power; and (6) sensitivity analysis for fuel use rates with respect to base engine speeds and weather conditions.

4.3.1 Field Data Collection

The methodology is applied to 20 trucks for which field data have been collected.

4.3.1.1 Study Design

Twenty new Volvo long-haul sleeper cab trucks for interstate freight shipments have been placed into commercial service. These trucks include 10 of Fleet A and 10 of Fleet B. Both fleets are equipped with 2006 Volvo VED12 12.1 liter engines. The Fleet A engines are rated at 465 hp versus 435 hp for Fleet B. The difference in rating is attributed to differences in timing and duration of fuel injection. Fleet A has 375 ft³ Volvo VNL 780 sleeper cabs with black exterior paint; whereas Fleet B has 200 ft³ Volvo VNM 630 sleeper cabs with white exterior paint. All trucks are shore-power compatible. These engines comply with EPA's 2004 Heavy Duty Diesel emissions requirements for highway vehicles.

Each fleet has 5 trucks with diesel-powered APU system A and 5 trucks with diesel-powered APU system B. Both APU systems are equipped with 2006 Kubota Z482 0.48 liter engines. The engines are rated at 10.9 hp @ 3,600 RPM and 7.4 hp @ 2,400 RPM. For APU A, the 3,600 RPM setting is used, and for APU B, the 2,400 RPM setting is used. These differences in RPM are because of the generator specifications. APU-A has a direct-driven 6 kW generator and APU-B has a belt-driven 4 kW generator. The Kubota engines are reported by the manufacturer to comply with the 2005 Tier II emission standards applicable to nonroad engines.

The HVAC system for APU-A has an "ECONO" mode setting that cycles the engine on and off based upon heating or cooling demand. APU-B does not have this feature.

The Fleet A trucks are predominantly operated by single drivers. The Fleet B trucks are predominantly operated by a team of two drivers: one driver rests while the other drives.

4.3.1.2 Data Acquisition System

The data acquisition system for each truck includes: (i) electronic control units (ECUs) that provide data relevant to moving or idling activity; (ii) additional sensors that monitor data not available via the ECUs, such as electricity usage of APUs; (iii) a data logging system that continuously samples and logs data; and (iv) VolvoLink, which provides satellite communications and data transmission between the truck and the fleet office. The data are consolidated and transmitted via VolvoLink once every 6 hours.

4.3.2 Fuel Use Rates for the Base Engines

Base engine idle fuel use rates are reported by the ECU. These data are hourly average values with 0.0625 gal/hr resolution. Idle fuel use rates as well as emission rates are a function of ambient temperature and engine speed (Pekula et al., 2003). Regression equations for idle fuel use rates versus ambient temperature and engine speed were developed. Ambient temperature was monitored by temperatures sensors installed on the lower exterior of the field trucks. Solar irradiation was also measured on each truck. Based on a separate experiment conducted by Volvo, data were recorded for actual ambient temperature, solar irradiation, and observed truck exterior temperature. These data were used to develop a correction factor for actual versus observed exterior temperature at a function of

solar irradiation. However, the measured temperature, and hence the load on the air conditioning system, is also influenced by thermal radiation from pavement.

The default engine idle speed setting was 600 RPM. This speed can be reset by the driver. From a nationwide truck driver survey, some drivers prefer to increase this set point for many reasons, whether real or perceived. Examples of cited reasons include reduction of engine noise and vibration, improved oil circulation and pressure, and maintenance of sufficiently high engine temperature at very cold ambient temperature. However, idle fuel consumption increases as RPM increases (Lutsey, 2004). Idle fuel use rates have a linear relationship with engine speed (Pekula et al., 2003). A linear regression for idle fuel use rate versus engine speed was developed based on ECU data.

4.3.3 Fuel Use Rates for the Auxiliary Power Units

APU fuel use rates are a function of electrical loads (Caterpillar, 2006). Bench tests for APU fuel use rate versus electrical load was conducted for APU-A and APU-B. Fuel flow was measured using an AVL PLU 401/108 Universal Fuel Meter. Electrical loads were provided by a combination of several 500W (nominal) halogen lights and a 3kW (nominal) electric resistance heater. “Nominal” versus “actual” electrical loads were measured by determining the actual resistive power (Amps x Volts) consumed by the various available loads.

Electrical loads were applied in steps up to the maximum capacity of the APU generators (6 kW for APU-A and 4 kW for APU-B). Prior to starting measurements, each APU was brought up to operating temperature, as indicated by an open coolant thermostat or at least one cycle of the engine cooling fan. After reaching a steady state condition at each load level,

APU fuel use rate was observed for a minimum of three minutes. APU coolant temperature at each step was monitored for consistency to verify steady state operation. From these data, fitted curves were developed for fuel use rate versus electrical load for each type of APU.

The real-world APU electrical loads for each truck were measured and reported every 15 minutes by the data acquisition system. From the real world load and bench test fuel use data, hourly average real-world APU fuel use rates are estimated.

4.3.4 Emissions Factors for the Base Engines and Auxiliary Power Units

This section describes the emission measurement system instrumentation, measurement procedure, and data analysis for estimating emissions factors.

4.3.4.1 Portable Emission Measurement System

Fuel-based emission factors for the base engine and each type of APU were measured using a Portable Emission Measurement System (PEMS). PEMS offers the advantage of low cost, ease of use and applicability in real-world situations (Frey et al., 2002). The PEMS used here is an OEM-2100 Montana system, manufactured by Clean Air Technologies International, Inc. (CATI, 2003). NO and O₂ are measured by electrochemical sensors. HC, CO and CO₂ are measured by a nondispersive infrared (NDIR) sensor. Exhaust concentrations are reported on a second-by-second basis. In some cases, HC and CO concentrations from diesel engine are below the practical detection limits of this instrument, which are approximately 20 ppm and 0.02 vol% for HC and CO, respectively (Frey et al.,

2007). When mean modal emission concentrations are below the detection limits, there is less confidence in the stability of the mean values.

The PEMS was calibrated with a cylinder gas before the test, and also self-calibrated periodically by using ambient air as a reference. The PEMS was warmed up for more than 45 minutes before making measurements. A detailed assessment of the PEMS precision and accuracy is reported elsewhere (Battelle, 2003).

4.3.4.2 Base Engines

Lim (2002) reported that base engine emissions are less stable during the first three hours of operation than after longer time periods. Therefore, the base engine was operated for three hours before collecting exhaust measurements. The tested engine is the same as the 465 hp version used in Fleet A and similar to that used in Fleet B. The base engine emissions were measured at 660 rpm, which was the default setting for the tested engine, with and without air conditioning load.

4.3.4.3 Auxiliary Power Units

The APU emissions were measured using the PEMS while electrical loads were varied. Electrical loads were applied in steps up to 4.4 kW for APU-A and 3.0 kW for APU-B, using the combinations of several 500W (nominal) halogen lights.

4.3.4.4 Emission Factors

Fuel-based emission factors are estimated based on fuel properties and emissions measurements using the Montana PEMS. The Montana PEMS uses a light scattering sensor to measure opacity, which produces semi-quantitative values for PM concentrations and does not represent accurate mass emission rates. Thus, PM emission factors for the base and APU engines were estimated based on other data (Khan et al., 2006; Storey et al., 2003; Stodolsky et al., 2000).

Time-based emission factors in grams of pollutants emitted per hour were estimated based on the product of the fuel-based emission factors (g/gallon) and the diesel fuel use rate (gallons per hour).

4.3.5 Energy Use Rates and Emission Factors for Shore-Power Systems

4.3.5.1 Energy Use Rates

Energy use rates for shore-power were estimated based on electricity consumed and the relationship between primary energy and electricity. The electricity consumption for the SP systems was monitored by sensors installed as part of the data acquisition system. The ratio of primary energy input to electricity output was estimated based on 2006 U.S. national data from the Energy Information Agency (EIA, 2007a).

4.3.5.2 Emission Factors

Indirect power plant NO_x, SO₂ and CO₂ emission factors were estimated based on national mass emissions and total end-use electricity consumed in the U.S. in 2006(EIA, 2007a;

2007b). HC, CO and PM emission factors were estimated based on similar 2001 data, which are the most recent available national data (EPA, 2007a; EIA, 2002).

4.3.6 Comparison of Energy Use and Emissions Rates for Base Engines, Auxiliary Power Units, and Shore Power

To enable comparisons on a consistent base, fuel use and emission rates are estimated for the base engines, APU engines, and SP for two weather scenarios: mild and high temperature.

The temperature ranges for the selected weather scenarios and corresponding accessory loads and energy use rates are based on the range of observations from the field study.

4.4 Results and Discussion

4.4.1 Field Data Availability and Quality

The trucks entered commercial service between September 2006 and May 2007. The end date of the field study was February 2008. The average truck was in service for 10,900 hours for Fleet A and 8,500 hours for Fleet B. Combined, the 20 trucks accumulated 2.76 million miles and operated in 42 states within the continental U.S. On an annualized basis, the cumulative combined idling duration, which includes the sum of all stop activities powered using the base engine, APU, or SP, averaged 2,130 hours per truck for Fleet A and 780 hours per truck for Fleet B. The difference in these averages is attributable to the different freight operations between Fleet A and Fleet B, as well as single versus team drivers. Fleet A drivers used the the APUs for 59% of powered stop activities versus only 25% for Fleet B drivers. More than 25 hours of simultaneous “double-dipping” use of both the APU and base

engine was detected in 6 trucks, which defeats the purpose of the APU for reducing fuel consumption and emissions. More detail on the activity data is given by Frey *et al.* (2008).

Missing data for most trucks are less than 2 percent of the total elapsed time since in-service. The missing data occur during periods of on-road usage as well as during period of stop activity. Thus, missing data do not create large biases for the estimation of truck stop activities, fuel use and exhaust emissions.

The two fleets have approximately similar frequency distributions of observed temperatures associated with base engine usage. The 95 percent range of variability in observed temperatures associated with base engine usage is 1 °C to 41 °C for Fleet A and -1 °C to 47 °C for Fleet B. Fleet A had a slightly higher proportion of time (35 percent versus 30 percent) at temperatures over 30 °C. However, when the temperature was over 30 °C, Fleet B had a higher partial average temperature by 3 °C. Thus, overall, there were not substantial differences in the distribution of ambient temperatures experienced by the two fleets when the base engine was used.

In contrast, the temperature distributions were somewhat different between the two fleets when the APU engine was used. For Fleet A, approximately 25 percent of APU usages was for temperatures greater than 30 °C, versus less than 10 percent for Fleet B. Conversely, Fleet B had a higher proportion of time of temperatures less than 10 °C (approximately 25 percent versus 15 percent) compared to Fleet A. On average, Fleet A APU usage was associated with 4.5 °C higher ambient temperature than for Fleet B.

4.4.2 Measured Fuel and Energy Use Rates

Base engine fuel use rate during idle is highly variable. The 95 percent range of variability in fuel use rate is 0.40 to 0.63 gal/hr for Fleet A and 0.25 to 1.00 gal/hr for Fleet B. Fleet A trucks operated at a mean engine idle speed of 601 RPM, with a standard deviation of 20 RPM. Fleet B trucks operated at a mean engine idle speed of 700 RPM, with a standard deviation of 74 RPM. Thus, Fleet B tended to operate with a wider range of variation in engine idle speed, leading to more variation in fuel use rate.

On average, idle fuel use rates for Fleets A and B are approximately 0.55 and 0.51 gallon/hour, respectively. These rates are significantly lower than values of 0.8 to 1.0 gallons/hours typically assumed elsewhere (Lim, 2002; Lutsey et al.; 2004Stodolsky, 2000).

Fleet A trucks tended to have higher average idle fuel use rates than Fleet B trucks because of darker exterior paint, which leads to higher cooling load, and larger interior volume, which leads to higher loads for both cooling and heating.

4.4.2.1 Fleet A Base Engine Fuel Use

Eighty percent of the idle engine speed data for eight Fleet A trucks are at approximately 600 RPM. To assess the variation in engine fuel use rate versus ambient temperature, an estimate was made of the ambient temperature. The observed truck outer temperatures were corrected based on actual ambient temperature and solar irradiation:

$$T = -0.198 + 0.988T_o - 0.0028I \quad (1)$$

$$(n = 9483, R^2 = 0.987, p\text{-value} < 0.001)$$

Where

$T =$ Estimated ambient temperature ($^{\circ}\text{C}$)

$T_o =$ Observed truck outer temperature ($^{\circ}\text{C}$)

$I =$ Solar irradiation (W/m^2)

As expected, the observed temperature is reasonably accurate under no irradiation but is overestimated with irradiation.

Equation (1) does not include a correction for the impact of thermal radiation from pavement (Yavuzturk et al., 2005). Such a correction is not practical without site-specific data for pavement types, which were not available. For example, the outer temperature was observed to be 130°F for a truck parked near Dallas, Texas on August 15, 2007. The actual highest ambient temperature in that area on that day was only 102°F . Thus, very high values of reported outer temperature are interpreted as a qualitative relative indicator of cooling demand, rather than as accurate ambient temperatures.

At 600 RPM, the average fuel use rate is found to be a weak function of estimated ambient temperature.

$$E_{F,600}^A = 5.05 \times 10^{-5} T^2 + 9.65 \times 10^{-3} T + 0.478 \quad (2)$$

$$(R^2 = 0.384; n = 3734; p\text{-value} < 0.001)$$

Where

$E_{F,600}^A =$ Fleet A base engine mass fuel use rate at 600 RPM (gal/hr)

As expected, average fuel use rate is highest at high estimated ambient temperatures, because of high air conditioning load. At moderate to low temperature, fuel use rate is relatively insensitive to temperature.

There were two trucks that operated at various engine speeds. Based on data from Truck Nos. 3 and 10, an adjustment in fuel use rate is developed as a function of engine RPM:

$$\Delta E_{F,N}^A = 1.31 \times 10^{-3} N - 0.872 \quad (3)$$

$$(R^2 = 0.474; n = 359; p\text{-value} < 0.001)$$

Where

$$\Delta E_{F,N}^A = \text{Fleet A base engine idle fuel correction term impacted by engine speeds (RPM)}$$

$$N = \text{Engine speed (RPM)}$$

As engine RPM increases, fuel use rate increases, as expected. The average fuel use rate at idle is estimated as:

$$E_F^A = E_{F,600}^A + \Delta E_{F,N}^A \quad (4)$$

Where

$$E_F^A = \text{Fleet A base engine mass fuel use rate (gal/hr)}$$

4.4.2.2 Fleet B Base Engine Fuel Use

For Fleet B, the same methodology as for Fleet A was used to estimate idle fuel use rate; however, the results were slightly different. Most often, Fleet B trucks had an idle engine RPM set point of 690 RPM, not 600 RPM as for Fleet A. This was the case for 80 percent of the data from six of the Fleet B trucks. The average fuel use rate under these conditions is weakly sensitive to ambient temperature:

$$E_{F,690}^B = 6.54 \times 10^{-5} T^2 - 2.10 \times 10^{-3} T + 0.480 \quad (5)$$

$$(R^2 = 0.148; n = 959; p\text{-value} < 0.001)$$

Where

$$E_{F,690}^B = \text{Fleet B base engine mass fuel use rate at 690 RPM (gal/hr)}$$

The Fleet B results more clearly show the expected trend in which average fuel use rate is highest at very low or high temperature and lowest at moderate temperature.

The engine speed was more highly variable for Truck Nos. 13, 16, 18 and 19. For these trucks, engine RPM varied from 590 to 990 RPM. The difference in fuel use relative to 690 RPM is estimated as:

$$\Delta E_{F,N}^B = 1.52 \times 10^{-3} N - 1.04 \quad (6)$$

$$(R^2 = 0.899; n = 227; p\text{-value} < 0.001)$$

Where

$$\Delta E_{F,N}^B = \text{Fleet B base engine idle fuel correction term impacted by engine speeds (RPM)}$$

As expected, average fuel use increases with RPM.

For Fleet B, the sensitivity of average fuel use rate to ambient temperature and engine RPM is given by:

$$E_F^B = E_{F,690}^B + \Delta E_{F,N}^B \quad (7)$$

Where

$$E_F^B = \text{Fleet B base engine mass fuel use rate (gal/hr)}$$

For each fleet, average fuel consumption rate varies with respect to ambient temperature. At a given ambient temperature, and particularly at high ambient temperatures, Fleet A trucks consume more fuel. The average fuel consumption rates vary from 0.47 to 0.65 gal/hr for Fleet A, or by 38%, over a range of temperatures. For Fleet B, the average fuel consumption rates vary from 0.46 to 0.58 gal/hr for Fleet B, or by 26%. The Fleet A trucks have higher fuel use rate even though they typically operate at lower RPM than for Fleet B. This is attributed to the larger heating and cooling load for the Fleet A cabs.

4.4.2.3 Auxiliary Power Unit Engine Fuel Use

The bench test results for APU fuel use versus electrical load are given in Figure 1. The two APUs have a similar fuel consumption rate of 0.45 gal/hr at a load of approximately 3 kW. However, APU-A is more fuel efficient at higher load whereas APU-B is more fuel efficient at lower load. Although both APUs use the same engine, they operate at different RPM. High engine RPM may increase engine mechanical friction but decrease fuel-air ratio that slightly increase engine indicated efficiency (the ratio of total work within the engine to consumed fuel energy), and the increase of engine load may decrease mechanical friction and increase indicated efficiency slightly (Rakopoulos, 1997). Thus, APU-A has higher fuel use rates than APU-B at low load probably because of higher mechanical friction attributed to higher engine RPM. At high APU load, mechanical friction decreases and indicated efficiency increases, which leads to lower fuel use rates for APU-A than those for APU-B.

For APU-A, the distribution of electrical load is approximately bimodal, with one cluster of values representing loads of less than 1,000 W and another cluster with loads as high as 3,000 W or slightly higher. The latter most likely represent full load for the air conditioner, whereas the former likely represent loads impacted by the HVAC “ECONO” mode function. The average load for Fleet A was 800 W versus only 470 W for Fleet B. These loads correspond to fuel consumption rates of 0.31 and 0.30 gal/hr, respectively. The higher average load for Fleet A is attributed to: (a) larger cab size; (b) darker exterior color; and (c) a higher proportion of time (57 percent versus 47 percent) spent at temperatures of 20 °C or more.

For APU-B, there is a continuous rather than multimodal distribution of electrical load, with loads rarely exceeding 2,000 W for either fleet. The average electrical load for APU-B for Fleet A was 680 W versus 610 W for Fleet B. These correspond to fuel flow rates of 0.26 and 0.26 gal/hr, respectively. As expected, Fleet A had a higher average load than Fleet B for APU B, but the relative difference is less than that for APU A. The Fleet B trucks with APU B had a larger proportion of time (29 percent versus 12 percent) spent at temperatures of less than 10 °C than the Fleet A trucks with APU B, which affects heating load.

Overall, there are larger differences in fuel use rates when comparing the two APUs than when comparing the two fleets. The main differences between APU-A versus APU-B are engine RPM, direct versus belt drive, and the “ECONO” mode function that is paired only with APU-A. There were also differences in the temperature distributions for each Fleet and APU combination.

For each combination of Fleet and APU, field data were analyzed to assess the average electrical load versus estimated ambient temperature, as shown in Figure 2. The purpose here is to estimate electrical load for situations in which only the APU is used to provide power. Therefore, observed instances of “double-dipping,” in which both the base engine and APU were used simultaneously, were excluded from this analysis. For example, Truck No. 10 had 179 hours of double dipping, and Truck No. 6 had 110 hours, on an annualized basis. APU average loads during double dipping typically are lower than when the base engine is not in use.

APU electrical load was found to be a weak function of ambient temperature. The trend lines were obtained from linear regression and have p-values below 0.001. The R^2 values

vary between 0.04 to 0.22 among the four cases shown in Figure 2. Although there are some quantitative differences in estimated average load at a given temperature, the qualitative trends are similar among each group and have the expected minimum load at moderate temperatures and high loads at extreme temperatures.

4.4.2.4 Shore-Power System Energy Use

In order to deliver 1 kWh of electricity to an end-user, the average primary energy consumption in the U.S. is 10,810 BTU (EIA, 2007a), taking into account conversion and transmission losses.

The activities for SP usage were not significant. The only observed SP usage was to maintain charge of the truck battery during long stops. SP could be used to provide electrical power for the same purposes as that provided by APUs. Thus, for comparison purposes, indirect energy use and emission rates for SP are estimated using similar ranges of electrical load as observed for the APUs.

4.4.3 Measured Emission Factors for the Base Engines and Auxiliary Power Units

The emission test results and the corresponding fuel- and time-based emission factors for the base and APU engines are summarized in Table 1. The base and APU engine emission factors for NO_x, HC, CO, and opacity-based PM are from measurements using the PEMS. Since the PEMS provides only relative comparisons of PM levels, the absolute PM emission rate was estimated based on data from the literature.

For the base engine, the fuel-based emission factors were similar for load (A/C on) and no load (A/C off). The differences in the fuel-based emission factors for HC and CO are not significant, since these emission factors are based on average exhaust concentrations that are below the gas analyzer detection limits. The small variations in the opacity-based PM data indicate that there is no significant relative difference in fuel-based PM emission rate as a function of load.

For the APU engines, the fuel-based NO_x emission rate increases with load for APU-A and is less sensitive to load for APU-B. The NO_x emission rates for the two APU engines are of comparable magnitude, but differ at any given comparable load. This is attributed to differences in engine RPM. The trends in fuel-based emission rates for HC and CO are similar for both engines, but these average emission factors are based on average concentrations that are below the gas analyzer detection limit; hence, the differences between the engines are not considered to be significant. The opacity data from the PEMS indicates that there may be a weak dependence of fuel-based PM emission rate on fuel flow rate. A fuel based emission rate for PM is inferred from the literature.

4.4.4 Energy-Based Emission Factors for Shore Power

Energy-based NO_x, HC, CO, CO₂, PM and SO₂ emission factors for SP are estimated to be 1.00, 0.015, 0.12, 644, 0.18 and 2.49 g/kWh, respectively, based on total emissions from electricity production divided by total electricity end use. These results are based on the national U.S. power generation mix, which includes 49.9 percent coal, 1.7 percent oil, 18.3 percent natural gas, 20.0 percent nuclear, 9.3 percent renewable energy, and 0.8 percent other.

The energy-based and mass per time emission factors for the SP systems with electrical loads ranging from 0 to 3 kW are summarized in Table 1. The emission factors for SP are expressed for an equivalent gallon of diesel fuel to enable comparisons with the base and APU engines.

4.4.5 Comparison of Energy Use and Emissions Rates for Base Engines, Auxiliary Power Units, and Shore Power

In order to directly compare the energy use and emission rates between the base engine, APUs, and SP, two scenarios were developed. A “mild temperature” scenario is based on the energy use and emission rates typical of temperatures ranging from 10 °C to 20 °C, whereas a “high temperature” scenario is based on temperatures of 30 °C or more. The typical average load for the former is approximately 500 W, versus 2,000 W for the latter. The results for these scenarios are given in Table 2.

Since the base engine fuel-based emission factors are relatively insensitive to load, an average of these emission factors is used in combination with the observed base engine fuel use rates from the field study in order to estimate time-based emission rates. The APU emission rates are estimated for a given fuel flow based on curve fits for fuel-based emission rate versus fuel flow. Shore-power energy-based emission rates are a constant per unit of electricity consumed, regardless of load. The fuel or energy-based emission rates are multiplied by fuel or energy use rate to estimate time-based emissions rates.

At mild temperature, APU usage instead of the base engine leads to an 80 to 90 percent reduction in NO_x emissions, 36 to 47 percent reduction in CO₂ emissions and fuel use, and 10

to 25 percent reduction in PM emissions. The estimated percent reductions in HC and CO emissions are based on average concentrations below detection limits. Thus, although these data indicate a possible reduction in HC emissions, and a reduction in CO emissions for APU-B, they are not conclusive. On the other hand, the emission rates of HC and CO from diesel engines are typically low, and the pollutants of more substantial concern from such engines are typically NO_x, PM, and CO₂.

At high temperature, the estimated relative emissions reductions for the APU versus base engines are slightly lower than for the mild temperature case, but the magnitude of the emissions reductions is higher. For example, NO_x emissions are lower by 78 to 88 percent, which is a slightly lower percentage than for the mild temperature case, but these reductions are with respect to a higher magnitude of base engine emissions of 92 g/hr versus 72 g/hr. Likewise, the reductions in CO₂ and PM emissions are similar on a relative basis but higher on an absolute basis.

Compared to the base engine, shore-power will produce larger reductions in emissions than can be achieved with APUs, on both a relative and absolute basis. For the high temperature scenario, SP consumes 74 percent less energy and produces 79 percent lower CO₂ emissions, while achieving NO_x reductions of 98 percent and PM reductions of 75 percent. The disadvantage of SP is that it leads to higher emissions of SO₂. When compared to APUs rather than the base engine, SP has substantial reductions in energy use and emissions, except for SO₂. Of course, the SO₂ emissions from power plants have been the subject of increasingly stringent regulation, and over time these emissions are likely to continue to decrease.

4.4.6 Benchmarking Measured Data

4.4.6.1 Fuel Use Rates and Emission Factors for the Base Engine

In order to evaluate the fuel use and emission rates measured or estimated here, they were compared to other reported values, which range from 0.29 to 1.65 gal/hr (Brodrick et al., 2002; Khan et al., 2006; Lim, 2002; Lutsey et al., 2004; McCormick et al., 2000; Stodolsky et al., 2000; Storey et al., 2003). Although the conventional wisdom is that trucks typically consume 1 gallon per hour at idle, both other reported data and this study demonstrate that actual idle fuel use may be much lower, depending on the engine. The fuel use and emission rates estimated here are within the range of values reported elsewhere, and are deemed to be reasonable.

4.4.6.2 Auxiliary Power Unit Fuel Use Rates

APU fuel use rates reported elsewhere range from approximately 0.1 to 0.45 gal/hour, depending on the make and model of the APU and either load or ambient conditions (Cummins, 2008; EPA, 2008; Idlebuster, 2008; Kohler, 2008a; Kohler, 2008b; Lim, 2002; Pony Pack, 2008). The measured APU fuel use rates are generally at the upper range of or higher than these other reported values, depending on load. There is not as yet a consistent methodology by which vendors measure or certify their reported fuel consumption rates. Thus, a direct comparison is not possible.

4.4.6.3 Auxiliary Power Unit Emission Factors

The APU emission factors measured or estimated in this study are compared to other reported values (Lim, 2002; Storey et al.; Stodolsky et al., 2000). The fuel-based emission factors are similar for HC, CO and PM, and similar or lower for NO_x. For example, when converted to a fuel basis, the reported NO_x emission factors range from 36 to 64 g/gallon. The measured NO_x emission factors for APU B are from 50 to 55 g/gallon for most loads of interest. The measured NO_x emission factors for APU B are of the same order of magnitude but somewhat lower, at approximately 20 g/gallon. On a per time basis, the estimated APU emission rates of 5 to 25 g/hour compare with values from 7 to 42 g/hour reported elsewhere. On a per time basis, the CO₂ emission rates tend to be higher because of the higher fuel consumption. The time-based emission rates of the other pollutants are comparable to the other reported values.

4.5 Conclusions

Differences in base engine speeds, ambient weather conditions, accessory loads, or combinations of these, as applicable, can have significant effects on energy use and emissions rates for the base engines, APUs and SP systems. New methods have been developed for estimating fuel or energy use rates and emission factors taking into account variations of key factors in real-world conditions.

Most drivers for Fleets A and B tended to idle the base engines at low RPM of approximately 600 and 690 RPM, respectively, with average base engine fuel use rates of 0.46 to 0.65 gal/hr, depending on variations in ambient temperature. These are much lower

than typically reported values of 0.8 to 1 gal/hr. The estimated average APU fuel use rates typically ranged from 0.24 to 0.41 gal/hr, depending on variations in electrical load impacted by ambient temperature, which are higher than the typically reported values of approximately 0.2 gal/hr. Thus, the magnitudes of reduction in fuel use for the APUs are lower than the other reported values, and APUs may be not as an attractive idle reduction option here as prior studies imply.

The base engine and APU fuel use rates during cold and hot weather cases are generally higher than those during mild weather cases, which are similar to the trends reported in literature.

The base and APU engines for Fleet A tend to consume more fuel than those for Fleet B by 8% for the base engine and by 4 to 7% for the APUs. Higher fuel use rates for Fleet A are attributed to higher accessory loads for cooling and heating because of the cab size and, in the case of cooling load, exterior temperature. The APU electrical load is influenced by factors such as “ECONO” model of the HVAC system.

The use of APU instead of base engines leads to significant 36 to 47 percent reductions in fuel use and emissions of CO₂ and SO₂ under various loads. The 80 to 90 percent reductions in NO_x emissions are more substantial. PM emissions are reduced by a modest but significant 10 to 25 percent. There may also be significant reductions in emissions of HC and CO, but these data were typically below the PEMS detection limit and thus are not deemed to be statistically significant.

The use of SP instead of the base engine leads to 75 to 93 percent reductions in energy use and CO₂ emissions. Except for SO₂, the reductions in emissions of other pollutants are much larger for SP than for APU usage when compared to the base engine.

The overall reductions in fuel use and emissions for the substitution of either APUs or SP instead of the base engine will be less than the estimates here, which are based on comparison of one hour of operation of each power source. For example, the field data imply that the APU is used by single drivers for an average of 59% of idling and by team drivers for an average of only 25% of idling. The actual reductions will depend on the portion of idling time for which the anti-idling devices are used, as well as the ambient conditions during which they are used.

The wide ranges of variability in base engine fuel use rates imply the importance of accounting for variability in engine speed and ambient temperature.

The user-setting for base engine idle RPM is shown to have a significant effect on base engine fuel use during idle. A key implication is that the base engine idle RPM should be set as low as possible in order to conserve fuel. When purchasing trucks, owners should consider the choice of exterior color and cab size, with a preference for lighter and smaller, respectively, given their influence on idle fuel consumption.

The two APUs compared in this study used the same engine but have different efficiencies as a result of the RPM setting and integration with the generator. Since APU loads were found to typically be less than 3 kW, the configuration for APU-B will typically be more fuel efficient than that for APU-A. For example, percentage reductions in fuel use for APU B versus APU A at 500 W, 1,000 W and 2,000 W are 17, 13 and 4 percent. Thus,

appropriate matching of APU characteristics to expected load patterns can help in reducing fuel consumption.

On average, fuel use rates for the APU engines are lower than those for the base engines, leading to a net reduction in fuel use. However, the field trucks have relatively low base engine idle fuel use rates compared to those reported elsewhere, whereas the APU engine fuel use rates are higher than assumed in most other studies. Therefore, the fuel use savings and emissions reductions that would be projected from these results will typically be lower than those based on other sources.

The high frequency of double-dipping for some trucks defeats the purpose of the APU for reducing fuel consumption and emissions. Double-dipping should be discouraged in order to achieve the fuel use and emissions reductions that are possible if the APU is used instead of the base engine.

As new base engines that are subject to increasingly stringent emissions standards enter the onroad fleet, the relative advantage of APUs or SP may be decreased with respect to emission rates, especially for NO_x and PM. However, the advantages with respect to reduced fuel use and CO₂ emissions are likely to remain. Additional data would be useful regarding the idle emission rates of newer base engines. Furthermore, the effect of alternative fuels such as B20 biodiesel on both base and APU engine emissions should be assessed.

Some states, such as California, will not allow the use of APUs without advanced emission control devices. However, trucks often stop at locations that are not served by SP or other types of TSE. Thus, for trucks that spend most of their operation time outside of the currently limited number of states or localities where APU use is not allowed, APUs may still

be an idle reduction technology worth considering, given their portability and applicability at any location other than those excluded by law or regulation.

The estimated real-world fuel use rates and emissions factors will be used to quantify avoided fuel use and emissions in the real-world conditions for the observed Fleets A and B, and to assess the cost effectiveness of idle reduction using APUs. The methods developed here are recommended for the measurements and certification of the APU fuel use rates versus electrical load in order to have a direct comparison among various APUs. The methods developed here should be adopted to assess other idle reduction options, such as off-board TSE and direct fire heaters.

4.6 Supporting Information

Supporting information is available in Appendix B that includes more detail regarding: (a) the distribution of ambient temperature for the base engine and APUs for each Fleet; (b) the fuel use rates for the base engines of Fleets A and B; (c) the average APU electrical loads versus temperature; (d) the emission measurements for the base and APU engines; (e) benchmark comparisons of measured fuel use and emission rates versus values reported elsewhere; and (f) sensitivity analysis of base and APU engine fuel use rate with respect to base engine RPM and ambient temperature.

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Table 4. 1. Energy Use and Emission Rates for Base Engine, Auxiliary Power Unit and Electricity from Shore Power

Emission Source	Load (kW)	Energy Use Rate (gal eq./hr)	Fuel-or Energy-Based Emission Factor (g/gal eq.)				Time-Based Emission Factor					
			NO _x	HC ^d	CO ^d	PM ^e	NO _x (g/hr)	HC ^d (g/hr)	CO ^d (g/hr)	CO ₂ ^f (kg/hr)	PM ^e (g/hr)	SO ₂ ^g (g/hr)
Base Engine (2006, 465 hp 12 liter Volvo VED12 Engine, 660 RPM) ^{a,b}	Low (A/C off)	0.56	160	6.2	31.9	2.4	89.4	3.5	17.8	5.7	1.3	0.029
	High (A/C on)	0.71	142	5.5	21.8		101	3.9	15.5	7.2	1.7	0.037
APU-A (2006, 10.9 hp @3,600RPM, 0.48 liter Kubota Z482 engine, 6 kW generator) ^b	0	0.28	18.4	6.0	83.0	3.3	5.2	1.7	23.3	2.9	0.93	0.015
	0.9	0.32	24.1	4.6	56.0		7.8	1.5	18.1	3.3	1.1	0.017
	1.8	0.37	29.3	2.8	40.0		10.9	1.0	14.8	3.8	1.2	0.019
	2.7	0.43	34.6	3.6	28.0		14.8	1.5	12.0	4.4	1.4	0.022
	3.5	0.48	42.5	3.6	21.3		20.5	1.7	10.3	4.9	1.6	0.025
	4.4	0.55	44.4	3.5	19.0		24.5	1.9	10.5	5.6	1.8	0.029
APU-B (2006, 7.4 hp @2,400 RPM, 0.48 liter Kubota Z482 engine, 4 kW generator)	0	0.22	49.5	5.9	36.2	3.3	11.0	1.3	8.1	2.3	0.74	0.012
	1.1	0.29	57.5	4.3	22.0		16.6	1.2	6.4	2.9	1.0	0.015
	2.1	0.36	55.6	2.5	15.4		20.3	0.90	5.6	3.7	1.2	0.019
	3.0	0.46	54.6	1.6	14.0		25.0	0.72	6.4	4.7	1.5	0.024
Shore-Power ^c	0	0	12.8	0.20	1.6	2.3	0	0	0	0	0	0
	3.0	0.23					3.0	0.047	0.37	1.9	0.53	7.5

^a The tested engine is the same as those for Fleet A, but has a higher RPM set point of 660 RPM vs. 600 RPM for most Fleet A trucks. The engines for Fleet B are the same engine model as the tested engine but are rated at 435 hp instead of 465 hp.

^b The emission rates for the base engine without air conditioning load and for APU-A for an electrical load of 2.7 kW were measured twice to assess repeatability. The reported data in this table are the average values of the repeated tests. More detail is given in the Supporting Information.

^c For electricity used by shore-power system, indirect power plant NO_x, SO₂ and CO₂ emission factors were estimated based on national mass emissions and total end-use electricity consumed in the U.S. in 2006 (EIA, 2007a; 2007b). HC, CO and PM emission factors were estimated based on similar 2001 data, which are the most recent available national data (EIA, 2002; EPA, 2007a) To enable comparison energy use for the SP systems to diesel fuel use of the truck or APU engines, the primary energy consumption for electricity usage was converted to an equivalent diesel basis using a fuel heating value of 138,690 BTU/gallon. For each kWh of electricity delivered via the SP system, an average

Table 4.1. Continued

of 10,810 BTU of primary energy was used (EIA, 2007a). Hence, an energy equivalent of 0.078 gallons of diesel fuel are used per kWh consumed.

^d For numbers that are italicized, the average exhaust concentrations from the measurements are below the detection limits of 20 ppm for HC and 200 ppm for CO. For these numbers, there is less confidence in the stability of the mean values (Zhao and Frey, 2004).

^e The Montana PEMS uses a light scattering sensor to measure opacity, which produces semi-quantitative values for PM concentrations and does not represent accurate mass emission rates. Fuel-based and time-based PM emission factors for the APUs are estimated based on data from Khan et al., 2006, Storey et al., 2003 and Stodolsky et al., 2000 (Khan et al., 2006; Stodolsky, 2000; Storey, 2003).

^f Fuel-based CO₂ emission factors for the base and APU engines are approximately 10.2 kg per gallon of diesel fuel, since more than 99 percent of the carbon in the fuel is emitted as CO₂; energy-based CO₂ emission factor for the SP is approximately 8.26 kg per gallon equivalent based on national average emission factor for power plants

^g The SO₂ emission factor for the base and APU engines is based on the average sulfur content of ultra low sulfur diesel (ULSD) for the last quarter of 2006 and the first three quarters of 2007, which is 8.1 ppm (EPA, 2007b). Fuel-based SO₂ emission factor for the base and APU engines is approximately 0.052 gram per gallon of diesel fuel. Energy-based SO₂ emission factor for the SP system, based on national mass emissions from power plant and total end-use electricity consumed, is approximately 32.0 gram per gallon eq. of diesel fuel.

Table 4. 2. Comparison of Energy Use and Emission Rates for the Base Engine, Auxiliary Power Unit and Electricity Used by Shore-Power Systems for Selected Mild and High Ambient Temperature Scenarios

Source	Mild Temperature Scenario ^a							High Temperature Scenario ^a						
	Energy Use (gal eq./hr)	NO _x (g/hr)	HC ^b (g/hr)	CO ^b (g/hr)	CO ₂ (kg/hr)	PM (g/hr)	SO ₂ (g/hr)	Energy Use (gal eq./hr)	NO _x (g/hr)	HC ^b (g/hr)	CO ^b (g/hr)	CO ₂ (kg/hr)	PM (g/hr)	SO ₂ (g/hr)
Base Engine (BE)	0.47	72.2	2.8	13.4	4.8	1.1	0.024	0.60	92.2	3.6	17.1	6.1	1.4	0.031
APU-A	0.30	6.3	1.4	20.4	3.0	1.0	0.016	0.38	11.5	1.5	13.9	3.9	1.3	0.020
APU-B	0.25	13.4	1.3	7.2	2.5	0.8	0.013	0.36	20.2	1.0	6.3	3.6	1.2	0.019
Shore-Power (SP)	0.039	0.50	0.008	0.061	0.32	0.088	1.2	0.16	2.0	0.031	0.24	1.3	0.35	5.0
Comparison	Percent Reduction for Mild Temperature Scenario (%)							Percent Reduction for High Temperature Scenario (%)						
APU-A vs. BE	36	91	49	-53	36	10	36	37	88	57	19	37	11	37
APU-B vs. BE	47	81	55	46	47	25	47	40	78	73	63	40	16	40
SP vs. BE	92	99	99.7	99.5	93	92	-5000	74	98	99	99	79	75	-16000
SP vs. APU-A	87	92	99	99.7	89	91	-7800	59	83	98	98	67	72	-25000
SP vs. APU-B	84	96	99	99	87	89	-9500	57	90	97	96	65	71	-27000

^aThe mild weather scenario (a temperature range of 10 to 20°C) has a low accessory load of 0.5 kW and the high scenario (a temperature range of 38°C or higher) has a high accessory load of 2 kW based on typical values for APU electrical load. The data used here are from the emission tests reported in Table 1.

^bFor numbers that are italicized, the estimates are based on average exhaust concentrations from the measurements below the detection limits of 20 ppm for HC and 200 ppm for CO. For these numbers, there is less confidence in the stability of the mean values.

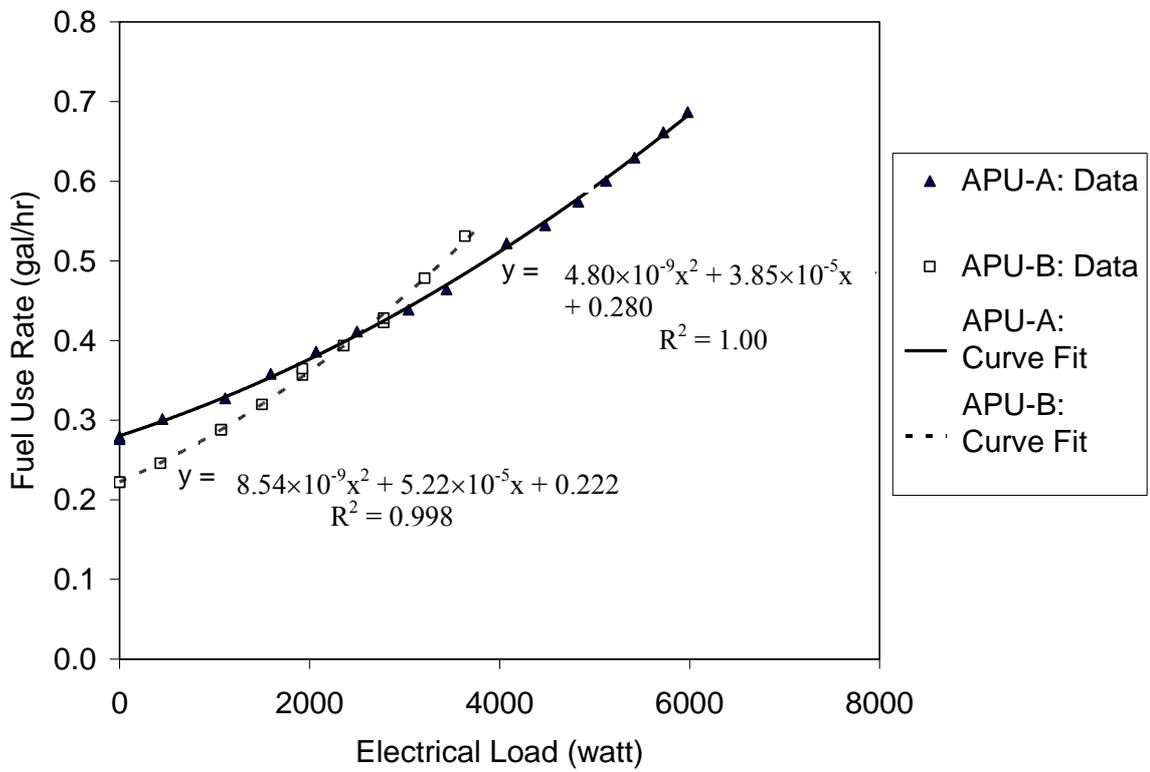
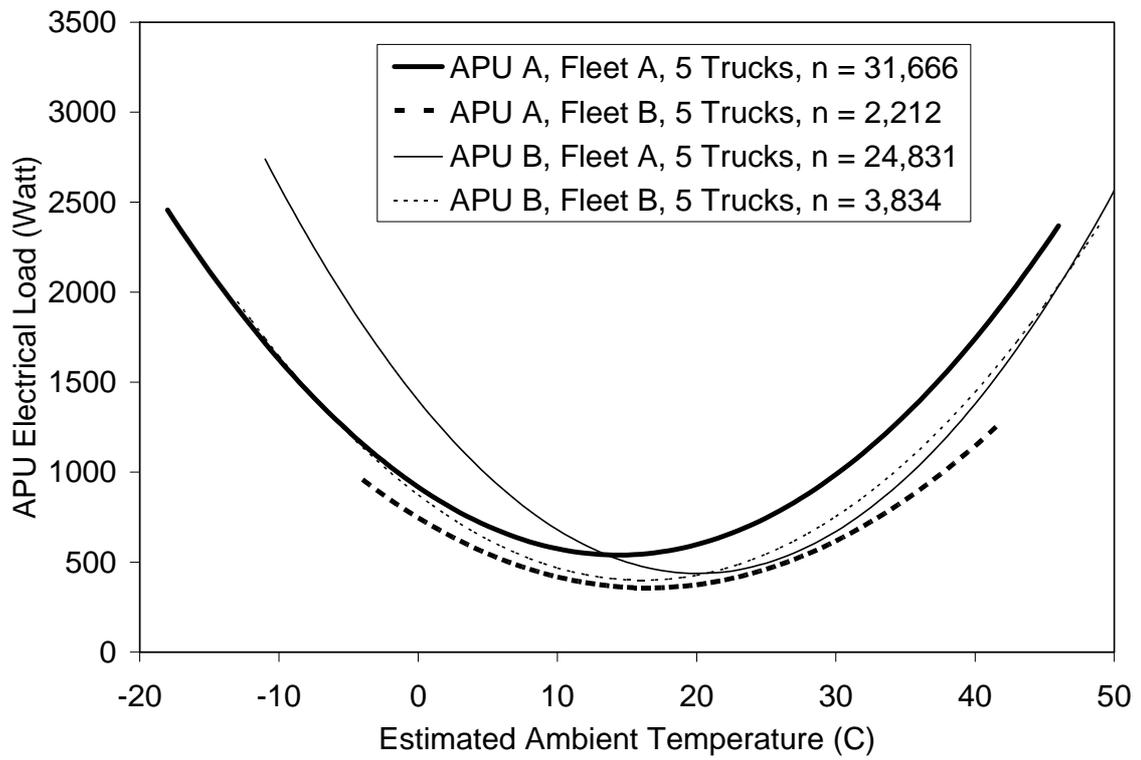


Figure 4. 1. Auxiliary Power Unit Fuel Use Rates versus Electrical Loads for APU Systems A and B



(Note: APU electrical loads during double-dipping were excluded)

Figure 4. 2. Average Trends in Auxiliary Power Unit Electrical Load versus Ambient Temperature

**PART V EFFECTS OF IDLE REDUCTION TECHNOLOGIES ON REAL WORLD
FUEL USE AND EXHAUST EMISSIONS OF IDLING LONG-HAUL TRUCKS**

Abstract

Fuel use and emissions due to long-haul trucks idling for rest stops are nationwide energy and environmental issues in the US. The effects of idle reduction techniques, including auxiliary power unit (APU) and shore-power (SP), on real-world fuel use and emissions of trucks are the first time to be evaluated. Twenty APU-equipped and SP-compatible trucks are divided equally between single drivers of Fleet A and team drivers of Fleet B. A methodology for estimating avoided fuel use and emissions, based on the quantification of truck stop activities and fuel use and emission rates, was developed. Single drivers had significantly more stops that were likely to be rest stops and more APU usage duration than team drivers. Driver preference for APU versus base engine varied. The SP has limited acceptance by drivers. Base engine fuel use and emission rates varied depending on ambient temperature. APU and SP energy use and emission rates varied depending on electrical load. Avoided annual average fuel use and CO₂ emissions are 22 and 5 percent, respectively, for Fleets A and B. Avoided annual average NO_x emissions are 47 and 12 percent. The projected avoided fuel use and emissions are lower than those from literature sources. The differences is because of relatively low base engine idling fuel use and emissions, relatively high APU fuel use and emissions, lower idle reduction activity, and double-dipping activity. Significant APU operation during short duration stops provides new insight into potential further fuel and emissions savings for such systems. Fuel penalty due to APU weight may defeat the purpose of the APU. Most trucks have no net cost savings and long or no payback

periods. Encouraging the usage of the usage of the APU and SP aggressively is needed in order to enhance their potentials in energy savings and emissions reductions.

5.1 Introduction

There are 680,000 long-haul freight trucks with sleeper cabs in the United States (US Census Bureau, 2004). Long-haul freight truck drivers need to take rest stops under the Federal Hours of Service (HOS) regulation in order to reduce driver fatigue (ATRI, 2006). During in-cab rest periods, drivers usually idle the base engines to power the heating, ventilating, and air conditioning (HVAC) system, and provide power for small appliances, such as refrigerators, and electrical outlets.

The average long-haul truck is estimated to idle from 1,460 to 1,800 hours annually for rest stops, varying from 500 to 4,000 hours annually (ATRI, 2004; Lutsey et al., 2004; Gaines et al., 2006). The U.S. Environmental Protection Agency (EPA) estimates that idling long-haul truck engines consume approximately 960 million gallons of diesel fuel and emit 10.9 million tons of CO₂, 180,000 tons of nitrogen oxides (NO_x) and 5,000 tons of particles (PM) annually during idle (Lim, 2002; EPA, 2008).

Anti-idling strategies include mobile options, such as generator-based auxiliary power units (APUs), and stationary options, such as truck stop electrification (TSE) (EPA, 2008). Generator-based APUs are small diesel engine-generator sets that can supply power for electrical HVAC, and auxiliary loads. On-board TSE systems, referred to as shore-power (SP) systems, allow trucks to directly connect to a stationary source of electricity. An off-board TSE system provides electricity and HVAC via a module that fits in a truck window.

Fuel savings and emission reductions of anti-idling devices vary depending on the hours of base engine idling displaced, hours of anti-idling device usage, and energy use and emissions rates for base engines versus the device (EPA, 2004a). However, there is a lack of

“real-world” quantitative data for anti-idling device usage hours (EPA, 2004; EPA, 2008; Gaines et al., 2006).

Base engine fuel use and emission rates are highly variable from one engine to another. For example, idle fuel use varied from 0.29 to 1.17 gallons per hour among 75 trucks, and the emission rates of NO_x, HC, CO and PM varied by more than an order-of-magnitude (Khan et al., 2006). Sources of variability include year, make, and model of the truck engine and ambient weather conditions. EPA reports that base engine fuel use rates vary from 0.4 to 1.7 gallon per hour and that NO_x emission rates range from 55 to 329 grams per hour during idle depending on engine size, engine speed, ambient temperatures and accessory loads (Lim, 2002). Thus, in order to accurately assess idle fuel use and emission rates in the real-world, it is necessary to account for factors such as these.

Furthermore, data for APU fuel use and emissions are limited. Real-world fuel use and emission rates for APUs are impacted by: inter-device variations; real-world conditions, such as weather; and hours of use of the idle reduction technology (Caterpillar, 2006; EPA, 2004a). However, these inputs are poorly quantified.

Based on available data, the reduction in fuel use and emission rates for APUs versus base engines on a per hour basis, assuming complete substitution of one for the other, is: 50 to 80% for fuel use, CO₂ emissions, and NO_x emissions; 57 to 97% in HC emissions; 51 to 91% in CO emissions; and -20% (an increase) to 95% in PM emission (EPA, 2004a; Lim, 2002; Storey et al., 2003; Stodolsky et al., 2000).

The economics of APUs are sensitive to the annual avoided fuel use compared to the base engine, which depends on the difference in fuel use rates between the two engines.

Many studies appear to use high values for base engine fuel use (e.g. 1.0 gal/hr) and low values for APU fuel use (e.g. 0.2 gal/hr), combined with assumed but uncertain hours of substitution of APU usage for that of the base engine, which leads to estimated payback periods of 1.4 to 4.3 years (Stodolsky et al., 2000). Given the variability in fuel use rates of engine and their sensitivity to real-world conditions, there is a need for real-world data to support such analysis.

The energy savings and emissions reductions for off-board TSE and SP systems have been studied, but these site-oriented analyses do not provide truck-oriented data, such as the portion of truck idling conducted at truck stops equipped with TSE facilities (Antares, 2005; Lindsey and Kim, 2005; Perrot et al., 2004).

A demonstration project for implementing selected APU systems has been developed to provide needed “real-world” information, such as truck idling activity patterns as well as fuel use rates and emissions factors. Methods for quantifying real-world truck stop activities and estimating real-world fuel use rates and emissions factors for the base engine and selected idle reduction technologies have been developed and applied in previous work (Frey et al., 2008; Frey and Kuo, 2008). Here, we use the recently estimated real-world fuel use rates and emission factors, combined with real-world activity data, to quantify the real-world avoided fuel use and emissions associated with APUs and SP. Payback periods for the APUs are estimated based on real-world avoided fuel use. The estimates are compared with the literature.

5.2 Methodology

The methodology includes: (a) study design; (b) field data acquisition; (c) categorization of stop scenarios and quantification of stop activity patterns; (d) estimation of fuel use rates and emissions factors; (e) quantification of avoided fuel use and emissions; and (f) assessment of simple payback periods.

5.2.1 Study Design

Activity data were collected for 20 new APU-equipped and SP-compatible Volvo long-haul sleeper cab trucks that were placed into commercial interstate freight service between August 2006 and February 2007. These trucks include 10 of Fleet A equipped with 2006 Volvo VED12 12.1 liter engines rated at 465 hp and 375 ft³ black sleeper cabs and 10 of Fleet B equipped with the same engine rated at 435 hp and 200 ft³ white sleeper cabs. These engines comply with EPA's 2004 Heavy Duty Diesel emissions requirements for highway vehicles. Each fleet has 5 trucks with APU system A and 5 trucks with APU system B. Both APU systems are equipped with 2006 Kubota Z482 0.48 liter engines complying with the 2005 Tier II emission standards applicable to nonroad engines. The engine is rated at 10.9 hp @3,600 RPM and 7.4 hp @2,400 RPM. APU A uses the higher RPM while APU B uses the lower RPM for compatibility with their respective generators. The Fleet A trucks are predominately operated by single drivers. The Fleet B trucks are predominately operated by a team of two drivers, who alternate rest periods while the other drives.

5.2.2 Field Data Acquisition

Each truck has been equipped with a data acquisition system, including: (i) a data logging system that collects data from electronic control units (ECUs) and from additional sensors; and (ii) Volvo Link, which transmits data from trucks to a central data repository via satellite. Details of the data acquisition system and data quality assurance and analyses procedures are reported by Frey *et al.* (2008).

5.2.3 Stop Scenarios and Activity Patterns

Vehicle data have been analyzed based on following scenario categories: (i) base engine is idling; (ii) base and APU engines are operating simultaneously; (iii) APU is operating; (iv) SP system is operating; (v) base engine and SP system are operating simultaneously; (vi) off-board TSE system is operating; and (vii) truck base engine is off without using any anti-idling system.

Quantitative metrics for truck activity during stops are estimated from field data using macros. These metrics include the duration for each stop event, the number of stops within specific stop duration ranges, and the duration for different power source choices during each stop. Cumulative combined extended idling is quantified based on the sum of total powered stop activities with stop durations greater than a duration criterion of 7 hours. This criterion is based on the lower bound for the rest stops inferred from frequency distributions of the number of stops versus stop durations for each truck (Frey *et al.*, 2008). For simplicity and brevity we simply use the term “extended idling” to refer to these durations of powered stop activities.

5.2.4 Fuel Use and Emissions Rates

A methodology for estimation of fuel use rates and exhaust emissions factors for the base engines, APUs and SP systems is reported in detail elsewhere (Frey and Kuo, 2008) and briefly summarized here. Base engine fuel use rates vary depending on ambient temperature and engine speed (Pekula, 2003). Regression equations for base engine idling fuel use rates versus ambient temperature and engine speed were developed based on ECU data.

APU fuel use rates vary depending on electrical load (Caterpillar, 2006). Fuel use rate for each APU was measured as a function of electrical load on the generator (Frey and Kuo, 2008). Real-world APU fuel use rates are estimated based on electrical loads for each truck monitored by the data acquisition system.

Fuel-based emission factors for the base and APU engines were estimated based on fuel properties and emissions measurements using a Portable Emission Measurement System (PEMS). The PEMS used is an OEM-2100 Montana system. Details of PEMS instrumentation and measurement procedure are reported by Frey and Kuo (2008). The emissions for a base engine of the same make, model and horsepower as that for the Fleet A trucks was tested with and without accessory load. The base engine for Fleet B has the same make, model but slightly lower horsepower. Time-based emission factors are estimated by the products of fuel-based emission factors and fuel use rates. Because the opacity measured by the Montana PEMS provides only semi-quantitative values for PM concentrations, emission factors for PM were estimated by averaging data from the literature (Khan et al., 2006; Storey et al., 2003).

Two APU engine-generator sets were tested, corresponding to the systems used in the field trucks. Fuel-based emission factors were measured using PEMS. Mass per time emission factors are estimated using fuel consumption rate. PM emission factors were estimated based on data from the literature (Stodolsky et al., 2000; Storey et al., 2003).

Energy use rates for the SP systems are based on electricity consumed by the truck and the relationship between primary energy and electricity for power plants (EIA, 2007a).

Energy-based emission factors for production of electricity consumed by the SP systems are estimated based on energy consumed to generate electricity and total emissions for generating electricity (EIA, 2007a; EIA, 2007b; EIA, 2002; EPA, 2007) .

5.2.5 Avoided Fuel Use and Emissions

Real world fuel or energy use rates and exhaust emissions factors are incorporated with stop activity data to estimate fuel use and emissions with or without APUs or SP system usage for the field trucks. The ambient temperatures, APU electrical loads and SP electrical loads were monitored and recorded for the field trucks. Based on these data, real-world fuel use rates and emissions factors are estimated. The durations of various power choices for all stops are determined by analysis of the truck activity data. The conventional wisdom is that the APUs are used to reduce base engine extended idling. However, some drivers also used the APUs even for short duration stops (Frey et al., 2008). Thus, avoided fuel use and emissions for the APU or SP are quantified based on two ranges of stop activity: total duration of all stops and extended idling durations only.

Fuel use and emissions are quantified for four scenarios: “actual;” “base engine;” “best driver;” and “shore-power.”

The base engine scenario assumes that the base engine is used for all power needs during a stop.

The actual scenario is based on the observed field data and takes into account the amount of time in which the base engine, APU, and shore power were actually used during a stop. The estimates of fuel use and emissions are reported on an equivalent annualized basis for each truck.

Some instances of “double-dipping,” which refers to the use of two power sources simultaneously during a stop, have been observed (Frey et al., 2008). An example of double-dipping is the use of both the base engine and the APU, perhaps to more rapidly cool the interior of the cab by running both the base and APU air conditioning systems simultaneously or to use the APU to provide 120 VAC for appliances. Double-dipping defeats the purpose of using the APU or SP as an alternative, not supplement, to the base engine. The actual scenario also takes into account observed durations of double-dipping.

Avoided fuel use and emissions are quantified by comparing the actual scenario to the base engine scenario.

The “best driver” scenario assumes that all field trucks reach the same percentage of reduction in fuel use as that with the highest fuel use reduction among all Fleets A and B trucks.

The “shore-power” scenario is based on the electrical load for the actual scenario but assumes that shore-power is used instead of the APU. Avoided fuel use and emissions are

quantified by comparing the shore-power to the base engine scenario.

5.2.6 Payback Periods

To evaluate whether idle reduction techniques make economic sense, net savings per unit of energy use reduction and simple payback periods are estimated. Net cost savings per unit of energy use reduction, which is used to examine the economic benefit of energy reduction due to the utilization of the APUs, are estimated based on the net cost savings divided by avoided fuel use. Net cost savings is annual energy cost saving minus annualized cost. Annualized cost is the product of the capital cost and the fixed charge factor plus annual non-fuel O & M cost.

Simple payback periods, which are used to evaluate the needed time to recover its initial investment, for the APUs are estimated based on the number of years required to recoup the initial costs of the APUs as a result of net annual fuel cost savings. Net annual cost savings is the difference between annual fuel costs savings and annual non-fuel operation and maintenance costs. Such estimates are based on a discount rate of zero. Consideration of the discount rates lead to longer payback periods.

5.3 Results and Discussion

Truck activity has been recorded for each of the 20 trucks. Each truck began commercial service on a different date. Data were collected for each truck for 10 to 18 months through February 29, 2008. The trucks accumulated a total of 2.8 million miles and operated in 42 states of the United States.

5.3.1 Stop Activity Patterns

Most stops had durations less than or equal to 1 hour, which are likely to be associated with traffic or with short duration loading or unloading. Aside from these very short stops, there are relatively high frequencies of stop durations of approximately 7 or more hours for the single driver trucks. These are most likely to be rest stops. Most stops of team driver trucks are shorter than 5 hours.

All Fleet A trucks have a similar distribution of time in which either the base engine or APU are used for stop durations of approximately 5 to 14 hours. However, drivers made different choices regarding whether to meet their comfort needs using the base engine or the APU. Drivers for eight of the Fleet A trucks preferred to use the APUs during extended idling, while drivers for eight of the Fleet B trucks used the APU more often for such stops. The preferences for drivers during all stops versus extended idling are similar. APUs are used for both short and long duration stops for some trucks.

For Fleet B, most trucks, except Truck No. 15, have much less APU usage time compared to the total time of the base engine idling.

Simultaneous use of the APU and base engine was detected in all trucks, accounting for an annualized 1 to 178 hours per truck in Fleet A and 2 to 272 hours per truck in Fleet B. Use of on-board shore-power was less than 0.1% of total stop activities for each truck. The limited actual use of SP is attributed to lack of availability of TSE at locations where the drivers stopped or lack of driver's preference. When SP was used, it appears to have been

used only to maintain the charge of the vehicle's battery. Use of off-board shore-power (i.e. IdleAire) was not detected.

The annual average amount of annual extended idling for trucks operated primarily by single and team drivers is estimated to be 1,450 and 250 hours per truck, respectively. The proportion of APU usage during extended idling for single versus team driver trucks is estimated to be 67 and 28 percent, respectively.

5.3.2 Fuel Use and Emission Rates

Average fuel use rates are typically highest at extreme ambient temperature and lowest at moderate temperature. At mild temperatures, ranging from 10 to 20 °C and with a typical 500 W electrical load, the average fuel use rates for APU-A, APU-B and SP are lower than those for the base engine by 0.17, 0.22 and 0.43 equivalent gal/hr, respectively. For temperatures of 30 °C or more, which have typical electrical loads of 2,000 W, the average fuel use rates for the APU-A, APU-B and SP are lower than those for the base engine by 0.22, 0.24 and 0.44 equivalent gal/hr, respectively. The average trends of fuel use rates of the base engines, APU and SP vary depending on ambient temperature, as shown in Figure 1. On average, fuel use rates for the APUs and SP are lower than those for the base engines, which lead to a net fuel use reduction.

The estimated emission factors for NO_x, HC, CO, CO₂, and PM for the base engine, APU and SP systems vary with respect to each engine or power source and as a function of load, which in turn is influenced by ambient temperature. In general, the base engine tends to have the highest emission rates and the SP systems have the lowest emission rates, except

for SO₂. The APU emission rates are lower than for the base engine but higher than for SP, except for SO₂. APU usage instead of the base engine leads to 36 to 47 percent lower fuel use and CO₂ emissions, 78 to 91 percent lower NO_x emissions, and 10 to 25 percent lower PM emissions. Although data for HC and CO emissions indicate a possible reduction in emissions for the APUs versus base engine, except for CO emissions for APU-A, they are not conclusive because these data are based on average concentrations below detection limits.

SP usage instead of the base engine leads to 74 to 92 percent lower fuel use, 79 to 93 percent lower CO₂ emissions, 98 to 99 percent lower NO_x emissions, 75 to 92 percent lower PM emissions, but 50 to 160 times greater SO₂ emissions. Data for HC and CO emissions indicate a significant reduction in emissions for the SP versus base engine, although the magnitudes of reduction are not conclusive because of the base engine measurement data below detection limits.

5.3.3 Avoided Fuel Use and Emissions

5.3.3.1 Actual Scenario versus Base Engine Scenario

In order to assess the real world avoided fuel use and emissions for APUs and SP versus base engines, the actual and base engine scenarios are compared.

For Fleet A, the annual average idling for all stop durations and extended idling are 2,130 and 1,450 hours, respectively. For Fleet B, the averages are 770 and 250 hours, respectively. The annual average and range of avoided fuel use and emissions for all stop durations and extended idling are summarized in Table 1. The CO₂ and NO_x emissions from these scenarios for each truck of both fleets are given in Figures 2 and 3, respectively. The

difference between the estimates for two scenarios is avoided fuel use or emissions. More than 97% of the avoided fuel use is attributable to usage of the APU. Thus, the actual scenario is equivalent to an APU usage scenario.

For Fleet A, the use of anti-idling devices (primarily the APU) for all stop durations leads to 72 to 416 gallons of avoided fuel use per year, which reduces idling fuel use by 8 to 28 percent. For extended idling, there are 46 to 388 gallons of avoided fuel use per year, with a fuel use reduction of 11 to 38 percent.

For Fleet B, average avoided fuel use for all stops and extended idling are -4 to 89 and -7 to 75 gallons per year, which is significantly less than for Fleet A. Negative values of avoided fuel use are attributed to a significant cumulative duration (over 270 hours per year) of double-dipping. Without double-dipping, avoided fuel use for all trucks would have positive values.

For all stop durations, avoided annual average fuel use and CO₂ emissions are 22 and 5 percent, respectively, for Fleets A and B, which are significantly lower than literature estimates of 50 to 80 percent. The differences in real world versus previously estimated avoided fuel use and emissions are because of differences in fuel use rates and emissions factors, lower hours of idle reduction activity, and significant amount of double-dipping activity, which accounts for 0.1 to 29 percent of cumulative powered stop duration.

Avoided annual average NO_x emissions for all stops are 47 and 12 percent for Fleets A and B, respectively, which are significantly lower than literature estimates of 70 to 90 percent. For Fleet B, the reductions in fuel use and emissions are only minor, because the

activity pattern of team drivers typically involves less long duration idling and lower APU utilization rates than for single drivers.

Based on literature values for national idle base engine and APU fuel use rates, national average annual avoided fuel use could be as high as 480 to 770 million gallons per year (Lim, 2002; EPA, 2008). Based on results from Fleet A for single drivers, the estimated national annual avoided fuel use would be projected at only 130 million gallons. The projected reduction in fuel use for team drivers is far lower; however, the proportion of onroad trucks that have team drivers is not known. Thus, the EPA reported estimates appear to be optimistic in that they assume that all trucks in the onroad fleet would have similar performance. Conversely, the sample of trucks in this study is not a nationally representative sample. However, the trucks observed here represent a proportion of those on the road. Therefore, an accurate estimate of the national potential for avoided fuel use and emissions should take into account variability within the onroad fleet and among APU systems.

Based on literature emission factors, national average annual avoided NO_x and PM emissions could be 130,000 to 160,000 and -1,000 (an increase) to 4,800 tons per year, respectively. Based on results from the single driver trucks, the estimated national annual avoided NO_x and PM emissions are 42,000 and 130 tons, respectively. Thus, both the avoided emissions as well as fuel use are sensitive to truck and APU characteristics, as well as driver behavior.

5.3.3.2 Shore-Power Scenario versus Base Engine Scenario

For shore-power versus base engine scenarios, the average and range of avoided fuel use and emissions for all stop durations are summarized in Table 2. For Fleet A and all stop durations, the estimated reduction in fuel use is 154 to 893 equivalent gallons per year, or 17 to 73 percent. For Fleet B, the fuel use reduction is 3 to 230 equivalent gallons per year, or by 0 to 40 percent. Avoided annual average energy use and CO₂ emissions for all stops are 48 and 13 percent for Fleets A and B, respectively. Avoided annual average NO_x emissions for all stops for shore-power scenario are 54 and 15 percent for Fleets A and B, respectively.

The avoided energy use and emissions for shore-power are significantly higher than those for APU usage, except for SO₂. However, shore-power facilities are not yet widely available at the locations where truck drivers take their rest stops.

5.3.3.3 Best Driver Scenario versus Base Engine Scenario

The best driver who aggressively uses the APU reduces fuel use by 30.7%, which is 30% higher than the average value of Fleets A and 5.6 times of that of Fleet B, based on the comparison between the actual scenario and the base engine scenario. Thus, the best driver scenario for all stop durations leads to 221 to 482 and 76 to 233 gallons of avoided fuel use per year for Fleets A and B, respectively. Avoided annual average fuel use for the best driver scenario is 352 and 158 gallons for Fleets A and B, respectively, which are higher than 261 and 25 gallons, respectively, for those for the actual scenario.

For Fleet A, the average avoided fuel use for the shore-power scenario is 57% higher than that for the best driver scenario and 130% higher than that for the actual scenario. For Fleet B, the average avoided fuel use for the best driver scenario is 130% higher than that for the shore-power scenario and 540% higher than that for the actual scenario. The shore-power scenario and best driver scenario lead to the highest avoided fuel use for single drivers and team drivers, respectively. Thus, encouraging the usage of the shore-power is the most useful strategy for reducing idle fuel use for single drivers and encouraging the usage of the idle reduction devices aggressively is the most useful strategy for reducing idle fuel use for team drivers.

5.3.4 Payback Periods

To evaluate the potential economic benefits of APUs, the net cost savings per unit of energy use reduction and simple payback periods are estimated. Furthermore, to evaluate variability and uncertainty in key measures of economic feasibility, a sensitivity analysis is performed taking into account variation in factors such as fuel price, capital cost, and non-fuel operating and maintenance (O&M) cost.

Only three trucks have positive net cost savings per unit of energy use reduction in the scenario of low APU capital cost and \$8 per gallon of diesel fuel price. Most trucks have no net cost savings per unit of energy use reduction due to low avoided fuel use.

In general, simple payback periods for all trucks ranges from 6 years to no payback period because of no net saving, which are significantly longer than literature estimates, which are 1.4 to 4.3 years (Stodolsky et al., 2000). Even for the scenario of low APU capital

cost and \$8 per gallon of diesel fuel price, the shortest simple payback periods are 3 years. If discount rate and fuel penalty due to APU weight is considered, longer payback periods are expected.

Since no net cost saving or long payback periods, field trucks need to either install more fuel-efficient APUs compared to APU-A and APU-B or use the APUs more aggressively in order to get net cost savings and short payback periods.

5.4 Implications and Recommendations

Avoided fuel use and emissions attributable to the APUs for the trucks operated by single drivers are significantly higher than those by team drivers. Both estimates are lower than those from literature sources, which lead to longer payback periods than literature estimates. Furthermore, new base engines complying with the EPA and California emission standards for 2007 and later model year highway heavy-duty vehicles have low NO_x and PM emissions, which lead to lower emissions reductions while the APUs are adopted. However, the advantages with respect to reduced fuel use and CO₂ emissions are likely to remain. The new APU also needs to comply with Tier 4 emission standards after 2008. Furthermore, trucks operated in California with 2008 and later model year APU need to control PM emissions by routing APU exhaust through the PM filter for the base engine or having a PM filter on the APU. These new emission standards decrease the potential environmental benefits and increase the capital and operation cost for the APU. Further research and development for the APUs or their alternative is necessary in order to reduce their cost, fuel use and emissions effectively.

SP has the potential to reduce the fuel use and emissions more than APUs, especially for the trucks operated by single drivers. However, the SP facilities are not widely available, and there is a lack of sufficient cost information for the cost-effectiveness analysis for the SP. More demonstration projects are needed in order to promote the development of the SP. Further research regarding the net cost savings for the SP is also required in order to assess its cost-effectiveness.

The differences in real world versus previously estimated avoided fuel use and emissions is because of differences in fuel use rates and emissions factors, lower idle reduction activity, and the significant amount of double-dipping duration. The net cost savings per unit of energy use reduction could be increased and the payback period for single drivers could be decreased by company policies that reward drivers for increased use of the APU instead of the base engine. The trucks operated by team drivers should consider choosing other idle reduction option because it is almost impossible for them to have net cost saving for the use of the APU. “Double dipping” usage of both the base engine and APU occurs in the real world and incentives need to be developed to discourage this.

The methodology developed here can be adapted to assess other idle reduction options, such as direct-fire heater. More detailed analysis of avoided emissions as a function of stop duration, location, and ambient condition will be conducted.

5.5 Supporting Information

Supporting information is available in Appendix C that includes more detail regarding: (a) truck and auxiliary power unit specifications; (b) distribution of locations of all truck

activities for Fleets A and B for all data collected over multiple seasons; (c) duration of time among powered stop scenarios for all 20 field trucks; (d) energy use rates and emission factors for the base engine, auxiliary power unit and shore-power; (e) avoided energy use and emissions for actual versus base engine scenarios; (f) avoided energy use and emissions for shore-power versus base engine scenarios; (g) fuel penalty due to APU weight and adjusted avoided fuel use; and (h) sensitivity analysis for net savings per unit of energy use reduction and simple payback periods.

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Table 5. 1. Absolute Amount of Avoided Energy Use and Emissions for All Stop Durations and for Extended Idling Duration for Actual versus Base Engine Scenarios

Fleet	APU	Stop Activity Range		Avoided Fuel Use (gal/yr)	Avoided CO ₂ Emissions (kg/yr)	Avoided NO _x Emissions (kg/yr)	Avoided HC Emissions ^c (g/yr)	Avoided CO Emissions ^c (g/yr)	Avoided PM Emissions (g/yr)
A	APU-A	All Stop Duration ^a	Average	241	2460	89	<i>2000</i>	<i>-5600</i>	190
			Range	72 to 374	737 to 3830	25 to 142	<i>603 to 3140</i>	<i>-10000 to -970</i>	67 to 265
		Extended Idling Duration ^b	Average	194	1990	72	<i>1620</i>	<i>-4700</i>	149
			Range	46 to 273	472 to 2790	17 to 100	<i>401 to 2250</i>	<i>-7500 to -880</i>	34 to 218
	APU-B	All Stop Duration ^a	Average	281	2850	78	<i>2120</i>	<i>8540</i>	335
			Range	115 to 416	1170 to 4230	29 to 106	<i>784 to 3190</i>	<i>3240 to 13200</i>	166 to 576
		Extended Idling Duration ^b	Average	237	2400	66	<i>1790</i>	<i>7200</i>	280
			Range	96 to 388	979 to 3940	24 to 99	<i>657 to 2970</i>	<i>2710 to 12300</i>	140 to 539
B	APU-A	All Stop Duration ^a	Average	20	202	8	<i>168</i>	<i>-950</i>	9
			Range	1 to 89	10 to 910	1 to 35	<i>16 to 735</i>	<i>-3900 to 4</i>	-3 to 53
		Extended Idling Duration ^b	Average	17	171	7	<i>138</i>	<i>-690</i>	11
			Range	1 to 75	6 to 773	0 to 30	<i>4 to 627</i>	<i>-3300 to 42</i>	0 to 45
	APU-B	All Stop Duration ^a	Average	30	299	11	<i>246</i>	<i>860</i>	4
			Range	-4 to 71	-43 to 723	1 to 20	<i>32 to 560</i>	<i>-200 to 2240</i>	-140 to 86
		Extended Idling Duration ^b	Average	10	99	5	<i>95</i>	<i>272</i>	-15
			Range	-7 to 31	-68 to 314	1 to 12	<i>22 to 225</i>	<i>-270 to 900</i>	-140 to 37

^aAll stop durations: Annual sum of all hours of the combination of the duration of base engine idle, APU usage and shore-power usage.

^bExtended Idling Duration: Annual sum of all hours of the combination of the duration of base engine idle, APU usage and shore-power usage excluding stops shorter than 7 hours.

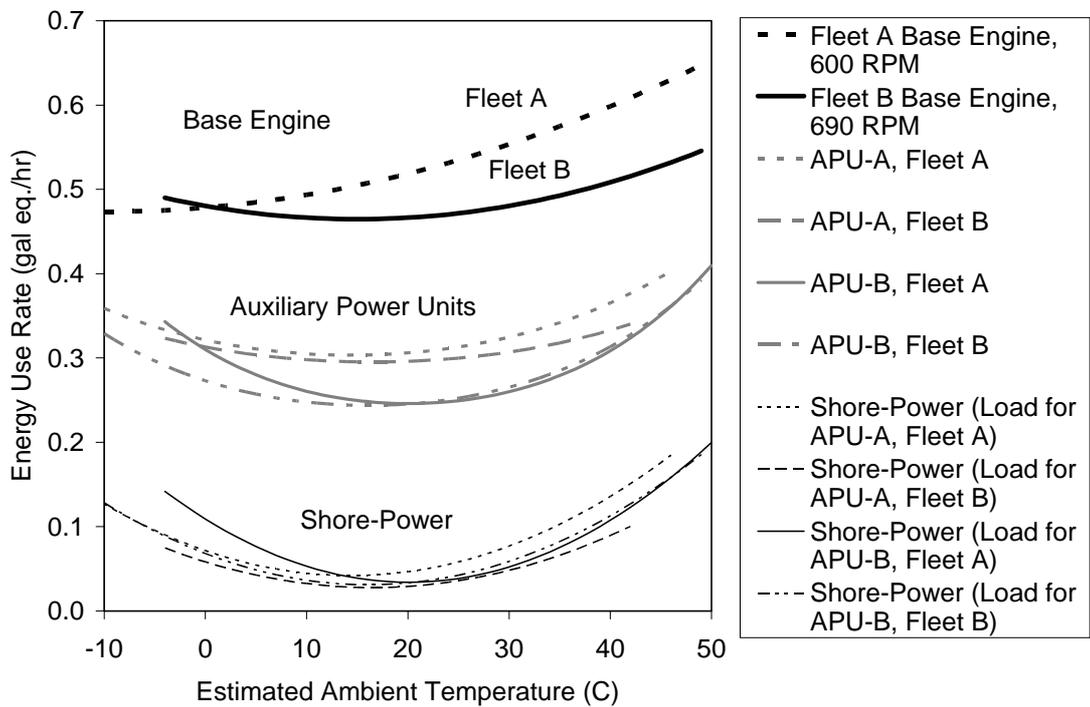
^cFor numbers that are italicized, the estimates are based on average exhaust concentrations from measurements below the detection limits of 20 ppm for HC and 200 ppm for CO. For these numbers, there is less confidence in the stability of the mean values

Table 5. 2. Absolute Amount of Avoided Energy Use and Emissions for All Stop Durations for Shore-Power versus Base Engine Scenarios^a

		Avoided Energy Use (gal eq./yr)	Avoided NOx Emission (kg/yr)	Avoided HC Emission (g/yr) ^b	Avoided CO Emission (g/yr) ^b	Avoided CO ₂ Emission (kg/yr)	Avoided PM Emission (g/yr)
Fleet A, APU-A	Average	552	97	<i>3788</i>	<i>18039</i>	5767	1312
	Range	154 to 893	28 to 155	<i>1081 to 6071</i>	<i>5145 to 28919</i>	1617 to 9318	368 to 2124
Fleet A, APU-B	Average	554	95	<i>3718</i>	<i>17714</i>	5769	1318
	Range	208 to 763	34 to 132	<i>1340 to 5143</i>	<i>6390 to 24501</i>	2149 to 7946	495 to 1814
Fleet B, APU-A	Average	53	9	<i>348</i>	<i>1661</i>	548	126
	Range	3 to 230	1 to 38	<i>36 to 1498</i>	<i>171 to 7142</i>	37 to 2381	8 to 547
Fleet B, APU-B	Average	86	15	<i>581</i>	<i>2770</i>	894	204
	Range	10 to 143	2 to 25	<i>72 to 972</i>	<i>344 to 4629</i>	108 to 1486	25 to 341

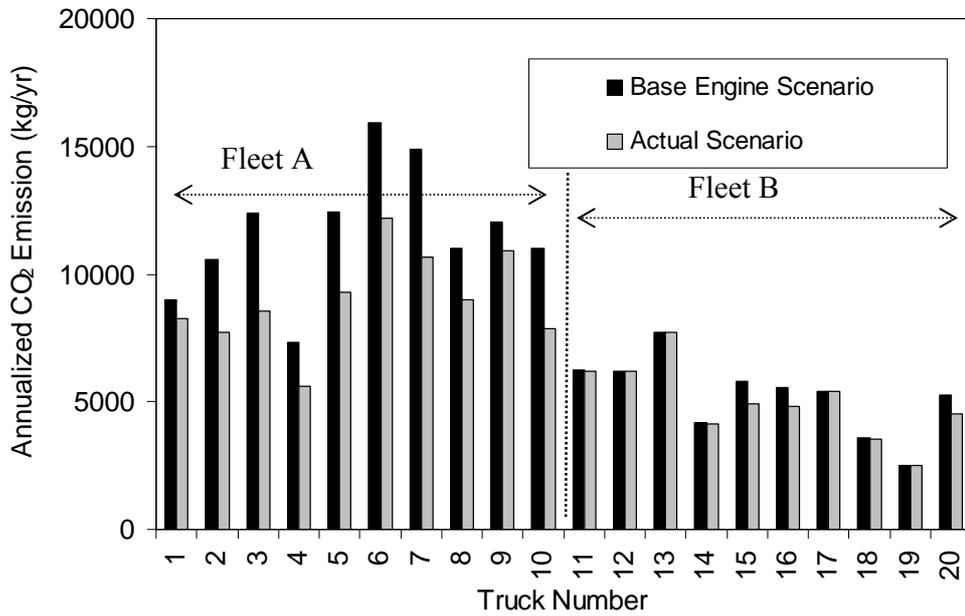
^aAll stop durations: Annual sum of all hours of the combination of the duration of base engine idle, APU usage and shore-power usage.

^bFor numbers that are italicized, the estimates are based on average exhaust concentrations from measurements below the detection limits of 20 ppm for HC and 200 ppm for CO. For these numbers, there is less confidence in the stability of the mean values.

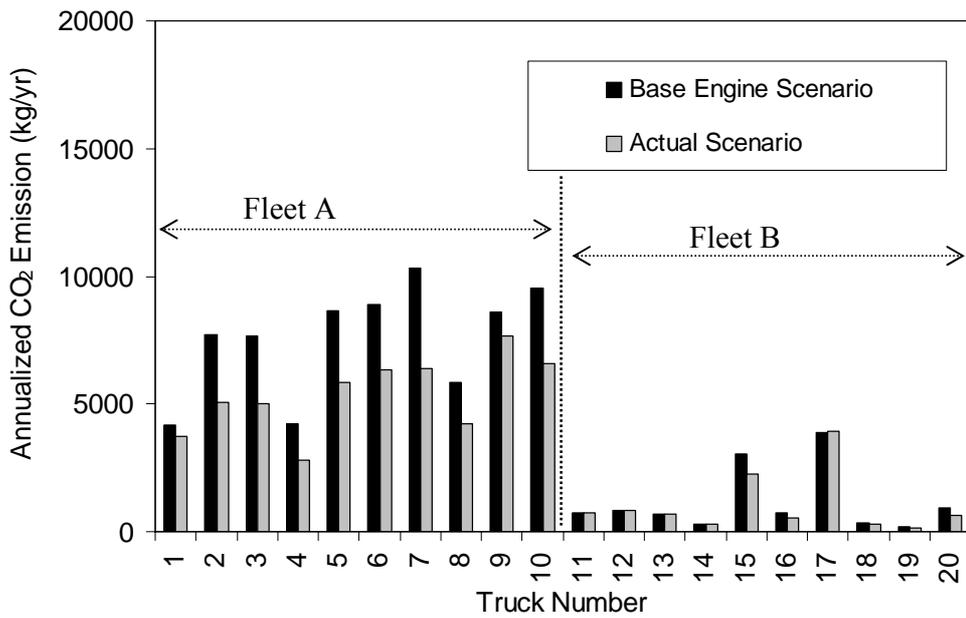


(Note: About 138,690 BTU of primary energy input for electricity production is equal to one diesel gallon equivalent)

Figure 5. 1. Average Trends of Energy Use Rates versus Ambient Temperature for Base Engine, Auxiliary Power Unit and Shore-Power for 20 Field Trucks

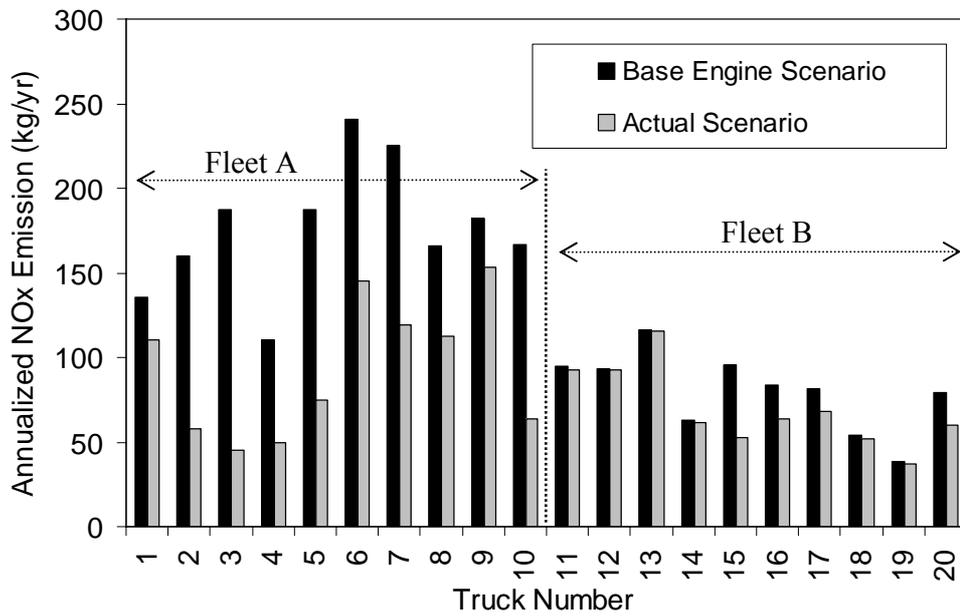


(a) All Stop Durations

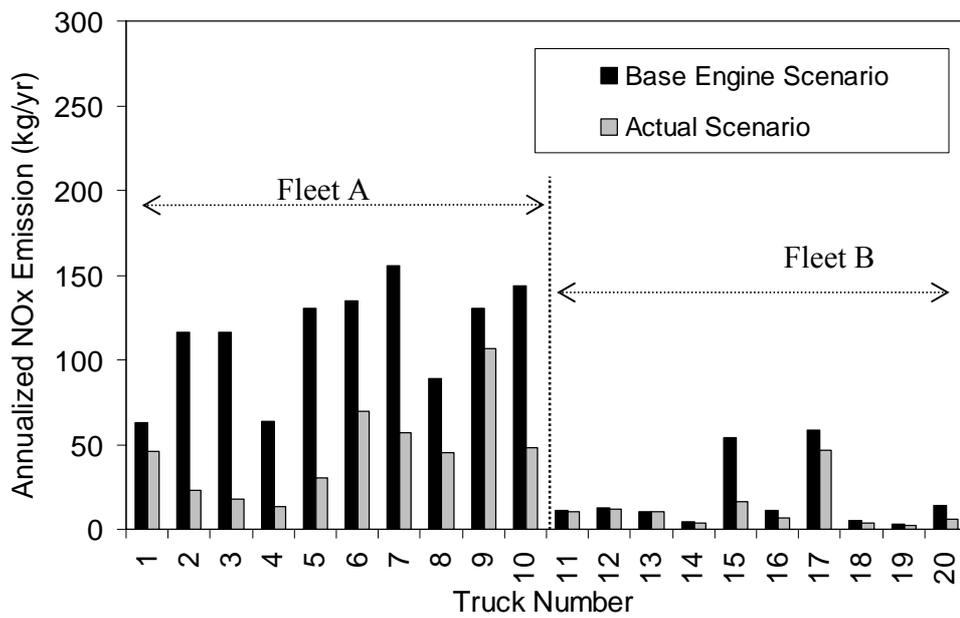


(b) Extended Idling Durations

Figure 5. 2. Annualized CO₂ Emissions During All Stops and Extended Idling for Base Engine and Actual Scenarios



(a) All Stop Durations



(b) Extended Idling Durations

Figure 5. 3. Annualized NO_x Emissions During All Stops and Extended Idling for Base Engine and Actual Scenarios

PART VI CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This section presents key conclusions.

6.1.1 Comprehensive Analysis for Potential Best Practices for Reducing Greenhouse Gas Emissions in Freight Trucking

Based on the projection of current trends, U.S. energy use and GHG emissions in freight trucking could increase by 67 percent from 2003 to 2025. Aggressive implementation of potential best practices could combine to lead to a *reduction* in GHG emissions of 28 percent from 2003 to 2025, thereby reversing the current trend of growth in such emissions. Even larger percentage reductions (as high as 85 percent) are possible if intermodal shifts (e.g. substitute rail for truck) are encouraged.

There is limited quantitative cost data upon which to base assessments of potential best practices. For five best practices for which adequate cost data are available, a few offered net cost savings, while others had net cost increases. Some potential best practices may lead to “no regrets” net cost savings to an operator, but some potential best practices with large magnitudes of reduction may not be cost-effective.

Based on the sensitivity analyses, there is expected to be substantial variability in performance and cost of a particular best practice under different conditions.

6.1.2 Field Study for the Impacts of Selected Idle Reduction Techniques on Fuel Use and Emissions for Long-Haul Trucks

This study develops the first methods to quantify long-haul truck activity patterns while

trucks stop and to estimate fuel use rates and emission factors for the base engine and anti-idling devices taking into account variations of key factors from field study. These results lead to more accurate estimation of avoided fuel use and emissions while anti-idling techniques are implemented in the real-world conditions than those from literature sources.

Most long duration stops likely to be extended idling duration for rest periods were estimated to be from 5 to 14 hours. The drivers appeared to differ in their preference for use of the base engine versus the APU. The APUs for some drivers were used instead of the base engine not only for combined extended idling but for shorter duration stops as well. Thus, it is technically feasible to obtain high utilization levels. Double-dipping is simultaneous usage of the base engine and APU, which defeats the purpose of the APU. Double dipping accounted for 0.1 to 7.9% and 0.2 to 29% for single and team drivers, respectively, of time for all powered stops. APU average loads during double dipping typically are lower than when the base engine is not in use. Double-dipping usually involves using the base engine for basic heating or cooling needs and using the APU for other accessory loads.

SP system usage was observed to be less than 0.1 percent of time for all stops for each truck. This may be attributable to lack of SP facilities at the locations where trucks were stopped for extended idling, which included parking lots. Thus, the APU was used more often than the SP. However, the measured electrical loads for the APU are indicative of the loads that could be supplied by SP if such facilities had been available.

The total annual combined extended idling duration for trucks operated primarily by single drivers averaged 1,450 hours per truck, which is comparable to literature estimates.

For the team driven trucks, the annual average amount of combined extended idling was significantly lower than that for the single driver trucks.

Differences in base and APU characteristics, engine speeds, ambient weather conditions, accessory loads, double-dipping or combinations of these, as applicable, can have significant effects on fuel use and emission rates for the base and APU engines. Previous EPA studies estimated fuel use and emission rates without considering the variability of truck and APU characteristics (e.g., cab size and exterior paint and APU system design) and APU engine speed. Their studies did not have accurate estimates for annual APU utilization hours per truck, and did not address the questions of whether the APU operated in mild weather and whether double-dipping activity existed and had the effects on APU electrical load. These issues are quantified for the first time. Typically, APU fuel use and emissions were not measured and reported on a consistent basis. Methods for APU fuel use and emissions rates versus accessory load are developed here for the first time.

Fuel use rates for the base and APU engines are typically lowest in mild weather and highest in very hot or cold weather and depend also on engine RPM. Most Fleets A and B drivers tended to idle the base engines at low RPM ranging from 600 to 690 RPM. Average base engine fuel use rates range from 0.46 to 0.65 gal/hr, depending on ambient temperature. These are much lower than typically reported values of 0.8 to 1 gal/hr. The estimated average APU fuel use rates typically ranged from 0.24 to 0.41 gal/hr, depending on variations in engine RPM, APU system design, and electrical load impacted by ambient temperature, the HVAC “ECONO” mode function for APU-A, and double-dipping. These fuel use rates are higher than the reported values of approximately 0.2 gal/hr in literature.

The base and APU engines for Fleet A tend to consume more fuel than those for Fleet B. Higher fuel use rates for Fleet A are attributed to higher accessory loads because of the larger cab size, darker exterior paint and higher exterior temperature.

Energy use and emission rates for the APU and SP are typically lower than those for the base engines. Without considering the impacts of actual idle reduction hours and double-dipping hours, the use of APU instead of base engines could lead to significant 36 to 47 percent reductions in fuel use and CO₂ emissions under various loads. Compared to the base engine, SP fuel use and CO₂ emissions are lower by 74 to 92 percent.

Avoided fuel use and emissions are quantified by comparing the actual scenario, which is based on the observed field data, to the base engine scenario, which assumes that the base engine is used for all power needs. Avoided annual average fuel use and CO₂ emissions for all stops for actual versus base engine scenarios are 22 percent for single drivers and 5 percent for team drivers. For the “best driver” truck among all field trucks, the use of anti-idling devices (primarily the APU) for all stop durations reduces idling fuel use by 31 percent. The fuel use savings and emissions reductions projected from the field study results are significantly lower than those from literature sources, such as 50 to 80 percent of fuel use and CO₂ emission reductions in previous EPA studies. The differences in real world versus previously estimated avoided fuel use and emissions is because of relatively low base engine idling fuel use and emissions, relatively higher APU fuel use and emissions, lower idle reduction activity, and double-dipping activity.

Previous EPA studies recognized the variability in idle reduction activity but ignored the existence of double-dipping activity. Furthermore, EPA estimated avoided fuel use and

emission based on the assumption that idle reduction duration equal to total rest periods. Their estimates did not quantify the effects of variability in idle reduction activity because there was a lack of real-world data. The actual effects of idle reduction techniques on real-world fuel use and emissions of trucks are the first time to be accurately quantified. Based on literature values, national annual avoided fuel use attributable to the usage of the APU could be as high as 480 to 770 million gallons. These estimates appeared to be optimistic. Conversely, based on results from Fleet A for single drivers, the national avoided fuel use would be projected at only 130 million gallons. Although these sample trucks is not a nationally representative sample, they represent a proportion of those on the road.

As new base engines that are subject to increasingly stringent emissions standards enter the onroad fleet, the relative advantage of APUs or SP may be decreased with respect to emission rates, especially for NO_x and PM. However, the advantages with respect to reduced fuel use and CO₂ emissions are likely to remain.

6.2 Recommendations

Potential individual adopters of best practices should carefully compare their options in order to evaluate if the best practices pay for themselves or not. Some best practices with large magnitudes of reduction may not be cost-effective, and governments should promote research, development, and demonstration (RD&D) to foster these best practices.

Developing tools, such as web-based decision tree and a decision tool, to support decision making regarding best practices are also recommended. A decision tree is helpful when faced with a complex multistage decision problem. There is also a critical need to develop a

decision tool that allows stakeholders to compare multiple best practices on the same basis of important assumptions for a specific situation.

The field study illustrates that assessment and decision-making needs to be tailored to the situation of a particular adopter. Some key inputs which may not be recognized by prior laboratory studies can be identified and their impacts can be quantified by field studies. Based on the results of the field study, an accurate estimate of the potential avoided fuel use and emissions should take into account variability with the onroad fleet and among idle reduction techniques. Evaluating key assumptions that influence the selection of potential best practices via field studies and sensitivity analysis is recommended for decision-making for all identified potential best practices in freight trucking.

The sensitivity of idling activity to driver logistics such as single versus team drivers is illustrated, which needs to be considered by individual firms when estimating the economics of APUs for a particular situation.

It is important to base estimates on average over multiple trucks and not to rely on anecdotal data from small numbers of trucks. In order to increase cost effectiveness for fleets that use APUs, driver incentive programs should be developed to encourage low engine RPM and high APU utilization levels and discourage double-dipping. When purchasing trucks, owners should consider the choice of exterior color and cab size, with a preference for lighter and smaller, respectively, given their influence on idle fuel consumption.

As new base engines that are subject to increasingly stringent emissions standards enter the onroad fleet, additional data would be useful regarding the idle emission rates of newer base engines. APU fuel use versus accessory load should be measured and reported with a

standard way, and the methods developed for this study is recommended. Furthermore, the effect of alternative fuels, such as B20 biodiesel, on engine emissions should be assessed.

New emission standards for the base and APU engines and the restriction of APU usage in some states, such as California, may decrease the potential environmental benefits and increase the capital and operation cost for the APU. Thus, future research and development of the APU is necessary in order to control its emissions effectively and decrease its cost. In contrast, the SP system has the potential to reduce the fuel use and emissions more than the APU and can be deployed in the states with restricted emission standards. However, its high infrastructure cost and relative low access rate may inhibit its developmental potential. More SP demonstration projects and further research regarding the utilization patterns and cost-effectiveness are recommended.

Furthermore, the methods developed here are recommended for quantifying activity patterns and avoided fuel use and emissions for additional trucks and should be extended to include other types of anti-idling methods (e.g. direct fired heaters) with appropriate instrumentation to supplement the ECU data.

More detailed analysis of avoided emissions as a function of stop duration, location, and ambient condition for field study are recommended for future work. There are some limitations for field study. For example, a truck for which engine RPM was not adjustable was used for emission tests. NO_x emission data are sensitive to ambient temperature but no suitable data to make correction. Further study should modify these methods in order to get insight of the variations of emissions due to the change of RPM and ambient temperature.

APPENDIX A

INTRODUCTION

These supporting materials provide supplemental text, tables and figures to further describe the methods for truck stop activity analysis and the results for individual trucks. The information is provided in Sections as follow:

- A. Parameters Available from the Data Acquisition System;
- B. Methodology for Database Construction;
- C. Steps for Data Screening Procedure;
- D. The Approach Used for Interpreting Categorical Data (e.g., APU Engine on or off in Each 15 Minute Sampling Interval);
- E. Flow Chart for Categorization of Stop Scenarios;
- F. Details of Variables and Estimation Methods Used for Analyzing Truck Activity Patterns;
- G. Detailed Figures for Numbers of Stops versus Stop Duration for Each of the 20 Trucks; and
- H. Detailed Figures for Percentage of Time of Stop Scenarios versus Stop Duration for Each of the 20 Trucks.

Section A. Parameters Available from the Data Acquisition System

The available data from the data acquisition system, including GPS coordinates, ECU data for various vehicle systems such as the engine, and additional data from the supplemental sensors and data logger, are listed and defined in Table A-1.

TABLE A-1. Parameters Available from the Data Acquisition System

Frequency	Parameter	Description
Recorded at 6-hour Increments	Total Miles Traveled	Odometer reading at the end of the 6-hour long data grouping
	Total Base Engine Hours	Accumulated base engine operating hours at the end of the 6-hour long data grouping
	VIN	Truck (vehicle) identification number
Recorded at 1-hour Increments	Timestamp	One-hour-interval time stamp, which is the end time of the hour long data grouping
	Latitude and Longitude	The GPS data (latitude and longitude) received at time of timestamp
	Total Base Engine Hours at Idle	Accumulated idle hours with base engine on at time of timestamp; at idle is determined by zero road speed detected for a time period longer than 120 seconds while the base engine is operating
	Total Base Engine Fuel Use at Idle	Accumulated idle fuel use with base engine on at time of timestamp
	Average Base Engine Fuel Rate at Idle	Amount of fuel consumed by base engine per unit of time at idle; it is only calculated when the base engine is determined to be at idle
	StdDev, Base Engine Fuel rate at Idle	Standard Deviation (over the hour period) of fuel rate at idle
	Average Base Engine Speed at Idle	Average base engine speed at idle; it is only calculated when the base engine is determined to be at idle
	StdDev, Base Engine speed at Idle	Standard Deviation (over the hour period) of engine idle speed at idle
	Cab Interior Temperature	Upper bunk, lower bunk and driver compartment temperatures (°C)
	Outdoor Temperature	Outdoor temperature (°C)
	Relative Humidity	Relative humidity of outdoor atmosphere (%)
	Sunload	Solar radiation (W/m ²)
	DC Battery Volts	Voltage of battery output
	DC Current	DC Currents (Amps DC) supplied / consumed by the APU and/or battery chargers
ShorePower Voltage	Average AC Voltage present at ShorePower inlet (only calculated when voltage \geq 70 VACrms)	

Continued on next page

Table A-1. Continued

Frequency	Parameter	Description
Recorded at 15-minute Increments	Truck Parked Status ^a	A categorical parameter that indicates if road speed is zero (no moving) or not
	Ignition Key Status ^a	A categorical parameter that indicates if the truck ignition key is on or not
	APU Status ^a	A categorical parameter that indicates if APU is on or not
	APU A/C Status ^a	A categorical parameter that indicates if APU A/C system is on or not
	APU Heater Status ^a	A categorical parameter that indicates if APU heater system is on or not
	Truck A/C Compressor Status ^a	A categorical parameter that indicates if truck A/C compressor is engaged or not
	APU-A EconoMode Status ^a	A categorical parameter that indicates if APU-A EconoMode function is on or not; in Econo Mode APU-A operated only when cab temperature out of set-up range
	Electrical Energy Supplied by APU	Energy supplied by the APU in units of kWh for energy consumed by A/C, heater, battery charger, and indoor and outdoor receptacles
	Electrical Energy Supplied by Shore-power	On-board shore-power in units of kWh for energy consumed by A/C, heater, battery charger, and indoor receptacles

^a These parameters are categorical and reported each 15 minutes; they are sampled at 2 minute intervals plus change-of-state . They have been recorded with four discrete values, “ON entire time,” “Changed more ON,” “Changed more OFF,” and “OFF entire time” for individual 15-minute periods. They are explained in the section on “Interpreting Categorical Data.”

Section B. Methodology for Database Construction

Data files are received by the VolvoLink server. Each binary data file contains 6-hours of data. Volvo Technology collected the data from each of the 20 trucks every month.

Approximately 120 binary data files are received each month for each truck.

North Carolina State University (NCSU) downloaded the binary data files for 20 trucks from Volvo's ftp site every month. Binary data files were converted to comma separated format files by using a converter developed by Volvo. Multiple months of binary data files for each truck were converted together to form a single comma separated format data file for each truck. Macros programmed in Visual Basic were used for data analysis. Only parameters regarding truck activity patterns while trucks were stopped were analyzed.

Section C. Steps for Data Screening Procedure

The steps for the data screening procedure, including the identification of misallocated data files, missing VIN, the time at which transport service began, periods of missing data, mislabeled timestamps, missing parked status data while GPS data indicated a stop, and short-term movements within long-duration stops, are described in Table C-1. These steps, except the first three steps, were implemented via a Visual Basic macro in Excel.

TABLE C-1. Steps for Data Screening Procedure

Step	Step Description
Identifying Misallocated Data Files	Every month, approximately 120 binary data files are downloaded for each truck. These files are allocated to a separate folder for each truck. After the initial allocation, the VINs recorded in each file are checked. If the VINs are for a different truck, then the file is reallocated to the proper folder for that truck.
Identifying Missing VIN	There were some 6-hour data files for which VIN data were unavailable. The VIN can be recognized by comparing timestamp patterns of data sets for which VINs are missing with timestamp patterns of data sets for which the VINs is reported. The correct VIN for each truck is input to the data file.
Identifying the Time at Which Transport Service Began	The time at which transport service began is estimated based on the first occurrence of transport activity in which a truck drove several hours, stopped several hours to comply with requirements of hours-of-service regulations, and then drove several hours again. Transport activity is determined based on changes in GPS coordinates, base engine hours, and miles traveled data.
Identifying Periods of Missing Data	There were some periods of time for which data were missing. By comparing timestamps before and after the loss of data, the periods of missing data were identified. An Excel macro was developed to automatically identify the existence of missing data and the duration of these periods. The total hours of reported data exclude periods of missing data.
Identifying Mislabeled Timestamp	A mislabeled time stamp occurs immediately after a vehicle completely loses battery power, such as during maintenance or repair operations. In such situations, the timer of the data logger resets to its factory default value, and does not get updated to the correct time until the next GPS fix is obtained. Thus, there is a time period of an hour with an incorrect time stamp. These infrequent time periods are identified using a macro that searches for inconsistencies in time stamps. Such periods are flagged for manual review and correction by the data analyst.
Identifying Missing Parked Status Data while GPS Data Indicated A Stop	Parked status data are used to infer the occurrence of a stop for which location does not change for multiple time periods. Although GPS data could also be used for this purpose, parked status is reported every 15 minutes, whereas GPS data are reported every hour. However, some parked status data were missing. When parked status data are missing, GPS data are used as a secondary parameter for identifying a stop. GPS data are subject to drift because of changes in atmospheric conditions and imprecision. A change in distance of 20 meters or less for consecutive hourly GPS readings was judged to represent no real movement of the vehicle. Missing parked status data within such an hour were imputed to be parked “on.” An Excel macro was developed to automatically identify and adjust missing parked status data.
Identifying Short-term Truck Movements within Long-duration Stops	Some short-duration movements within a long-duration stop have been identified. For example, a truck might move a short distance during one hour, as indicated by a significant but small change in GPS coordinates (e.g., 50 meters), and by a parked status “Changed more on” or “Changed more off” during as few as one 15 minute interval whereas parked status is “On” for all other 15 minute intervals during a longer time period, such as 24 hours. The small movement could be a repositioning to a different parking space in the same truck stop or might be a transition from loading/unloading to a rest stop at an origin or destination. In these cases, the short-term movement was noted but the entire time period that the truck spent at the general location was considered as one stop, not two separate stops An Excel macro was developed to automatically identify and adjust these short-term movement events.

Section D. The Approach Used for Interpreting Categorical Data

Several parameters are categorical, and they are reported at 15 minute intervals. These parameters include parked status, ignition key status, truck A/C compressor status, APU status, APU A/C status, APU heater status, and APU-A Economode status. Judgment is needed to interpret these categorical data and to convert them into quantitative estimates of durations. These categorical parameters have been recorded with four discrete values, “ON entire time,” “Changed more ON,” “Changed more OFF,” and “OFF entire time” for individual 15-minute periods. “ON entire time” means that the parameter was on for the entire 15-minute (0.25 hours) period. “Changed more ON” means that the parameter was on for most of the 15-minute period, but that it changed between on and off at least once during the time period. As a simplifying assumption, the parameter is assumed to be on for 75% of the time period, or 0.1875 hours. “Changed more OFF” means that the status changed between on and off at least once, but that most of the time period the parameter was off. As a simplifying assumption, the parameter is assumed to be on for 25% of the time period, or 0.0625 hours. “OFF entire time” means that the parameter status was “off” for the entire 15-minute period. A Visual Basic macro was developed to automatically convert these categorical data to quantitative time estimates.

Section E. Flow Chart for Categorization of Stop Scenarios

There are seven stop scenarios as shown in Figure E-1. The steps for categorizing these stop scenarios from the raw data are also illustrated in Figure E-1.

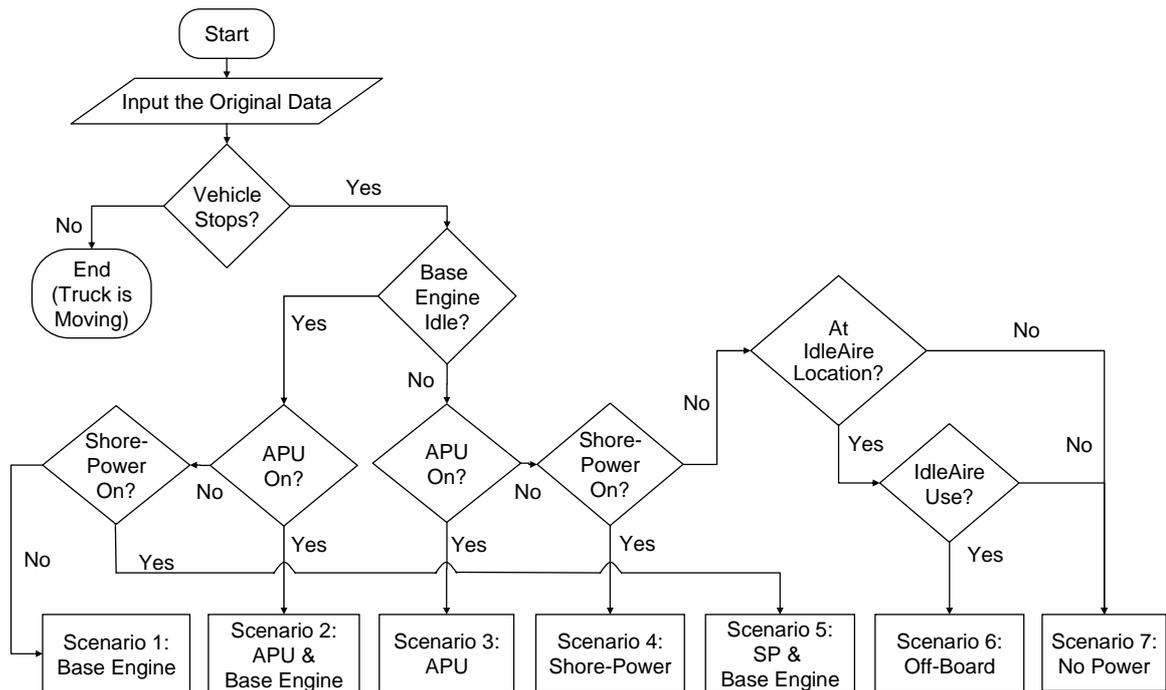


FIGURE E-1. Flow Chart for Categorization of Stop Scenarios

Section F. Details of Variables and Estimation Methods Used for Analyzing Truck

Activity Patterns

Quantitative metrics for truck activity during stops were estimated using several Visual Basic macros. These metrics include vehicle stop duration, frequency of specific ranges of stop duration, and duration for different power source choices. The macros for quantifying these metrics are described in Table F-1 of Section F.

TABLE F-1. Details of Variables and Estimation Methods Used for Analyzing Truck Activity Patterns

Variable	Estimation Methods	Note
Stop Duration	Stop duration was estimated by summing the number of consecutive 15 minute time periods for which parked status was “on.”	The minimum value of estimated vehicle stop duration was 15 minutes.
Frequency of a Stop Duration Range	The number of stops within a specific stop duration range (e.g., 7 to 8 hours duration) was estimated by sorting and counting stop events based on the values of their stop duration.	
Base Engine Idling Duration	Base Engine Idling Duration refers to situations in which only the base engine was used during idling. This variable was estimated as the difference between the total stop duration for a stop and the amount of time during that stop that the ignition key was in the “off” position. In addition, time periods in which both the base engine and another idling method were in use (e.g., APU, shore power), as explained below, were subtracted from the total base engine idling duration to arrive at a duration of only base engine usage during a stop.	Although there is a J1587 parameter for cumulative hours of base engine idling, this parameter is reported once per hour, not 15 minutes.
APU Usage Duration (APU)	APU Usage Duration was estimated by summing the estimated time of usage for the APU for each 15 minute period that is included in a stop duration. For APU-A, there is an “economy mode” setting that cycles the APU on or off while the APU system is on call. The entire time period that the economy mode setting is on is used as the estimate of APU usage duration. The APU Usage Duration excludes periods of time that the APU is used in combination with another technology, such as the base engine.	
Duration of Overlapping Base Engine Idling and APU Usage (APU & Base Engine)	The duration of overlapping use of both the base engine and the APU system was estimated for each 15 minute time period based on the sum of the usage time estimated for each system minus the 15 minute duration of the time period. For example, if both the base engine and APU were used for 75% of a 15 minute period (“changed more on”) then the estimated duration of overlapping usage is $11 + 11 - 15 = 7$ minutes.	The APU and base engine might be used simultaneously to initially cool-down the cabin by using the HVAC systems of both the truck and the APU system.
Shore-power Usage Duration (SP)	Shore-power was assumed to be used for an entire 15 minute period if there was an indication of power consumption from shore power during that period. The total time period of shore power usage during a stop was estimated by summing all 15 minute time periods in which shore power was used. However, time periods of overlapping usage of the base engine were excluded from the shore power duration and are reported separately.	

Continued on next page

TABLE F-1. Continued

Variable	Estimation Methods	Note
Duration of Overlapping Base Engine Idling and Shore-power Usage (SP & Base Engine)	The duration of overlapping use of both the base engine and the shore-power system was estimated for each 15 minute time period based on the sum of the usage time estimated for each system minus the 15 minute duration of the time period.	
Possible Duration for Off-board Usage (e.g. IdleAire)	The possible duration for off-board system usage was determined base on comparison of GPS data of each vehicle stop with GPS data of IdleAire-equipped locations. If a truck stopped at an IdleAire-equipped location and cab temperature was lower than outdoor temperature in summer or cab temperature was 10°C higher than outdoor temperature in winter, the off-board system was presumed to be in use.	As of February 2008, 132 truck stops were equipped IdleAire Systems
Duration for Truck Ignition Key off without Using Any Anti-idling System (No Power)	$(\text{No Power}) = (\text{Duration of Vehicle Stop}) - (\text{Base Engine}) - (\text{APU}) + (\text{APU \& Base Engine}) - (\text{SP}) + (\text{SP \& Base Engine}) - (\text{Off-Board})$	

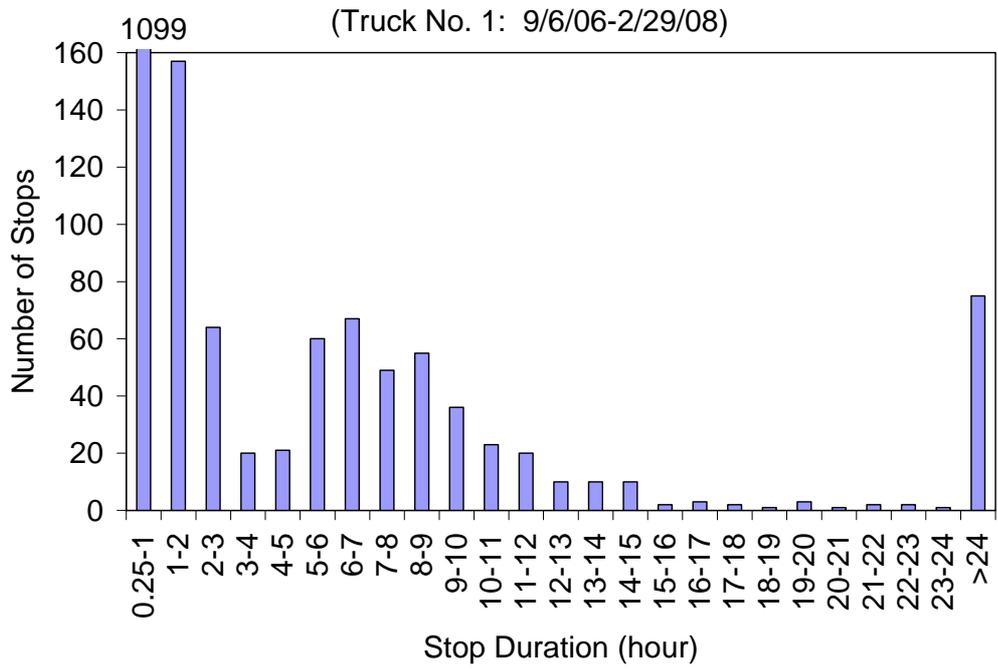
Section G. Detailed Figures for Numbers of Stops versus Stop Duration for Each of the

20 Trucks

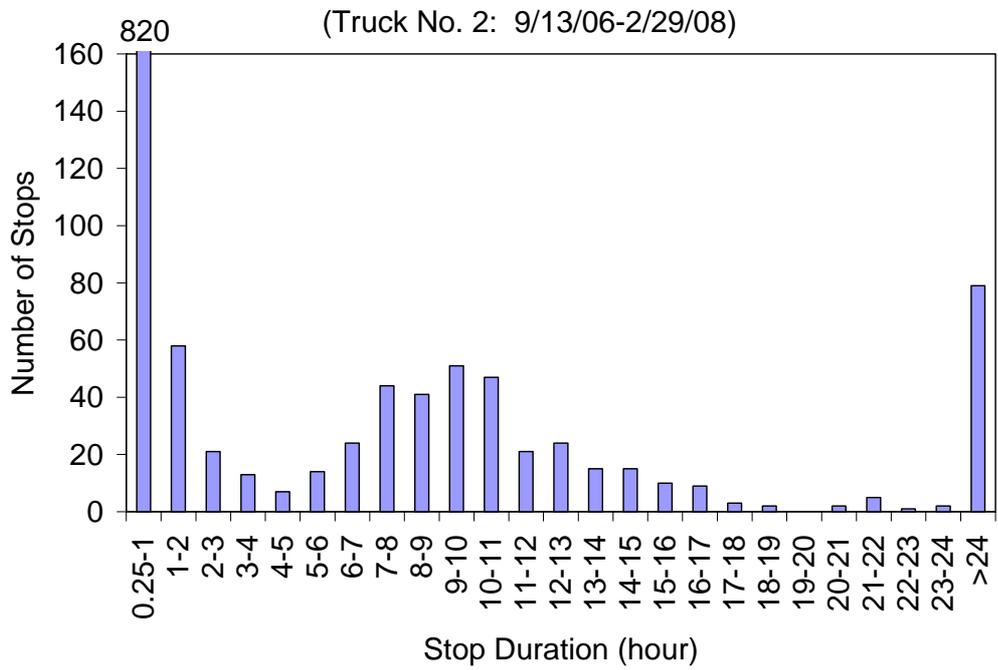
The frequency distributions of the number of stops versus stop duration for each of the 20 trucks are illustrated in Figure G(a) to (j) for Fleet A and G(k) to (t) for Fleet B.

Most Fleet A trucks had a multimodal distribution of stop duration, with a peak in the frequency of very short duration stops and a second, lower, peak in the frequency of long duration stops. Most short duration stops had durations less than or equal to 3 hours. Most long duration stops had average estimated durations between 5 and 14 hours. An exception is that one Fleet A truck (Truck No. 6) had more stops with durations between 3 and 7 hours than those with durations between 7 and 14 hours.

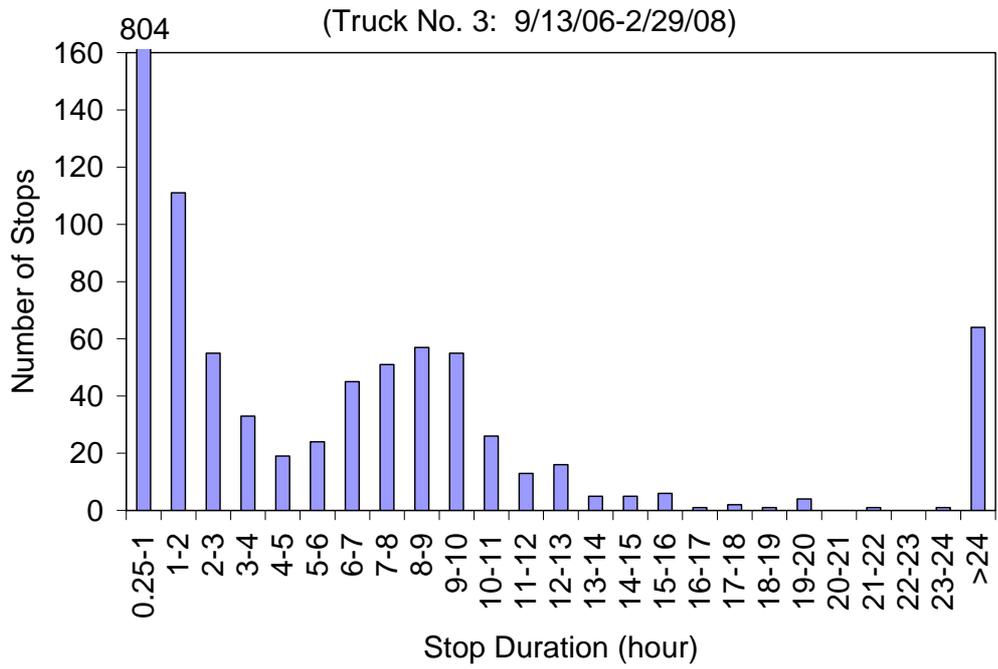
Most Fleet B trucks had a unimodal distribution in which the highest frequency of stop durations is for short stops which were shorter than 5 hours. .



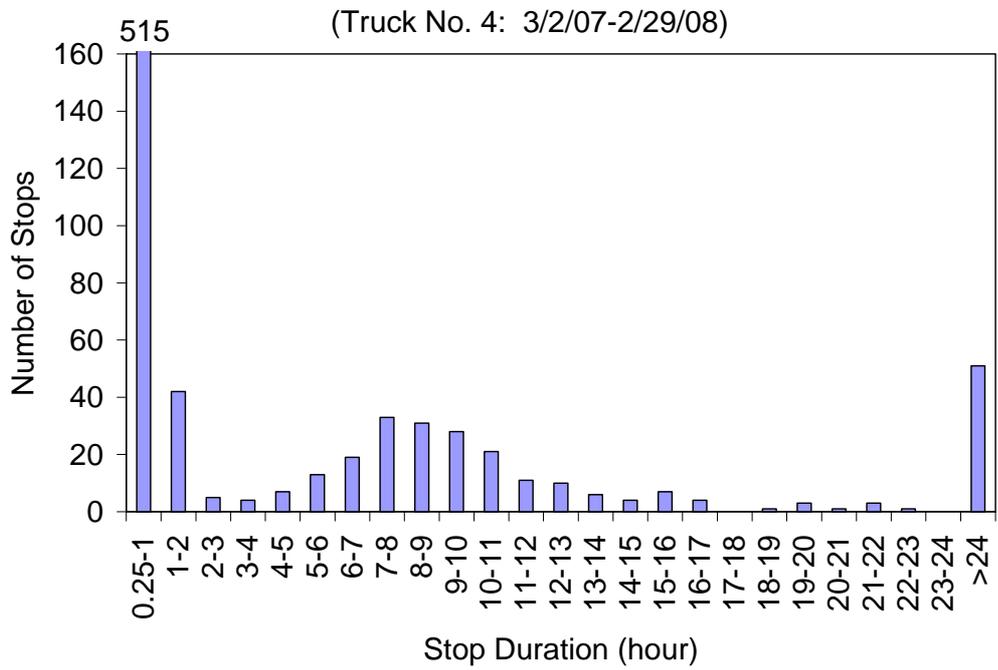
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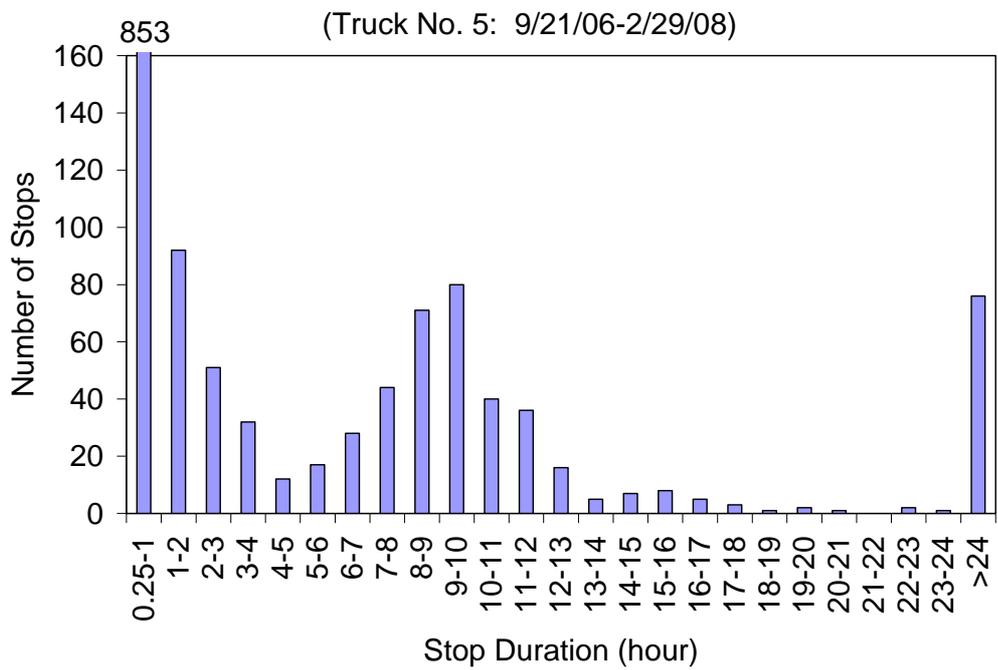
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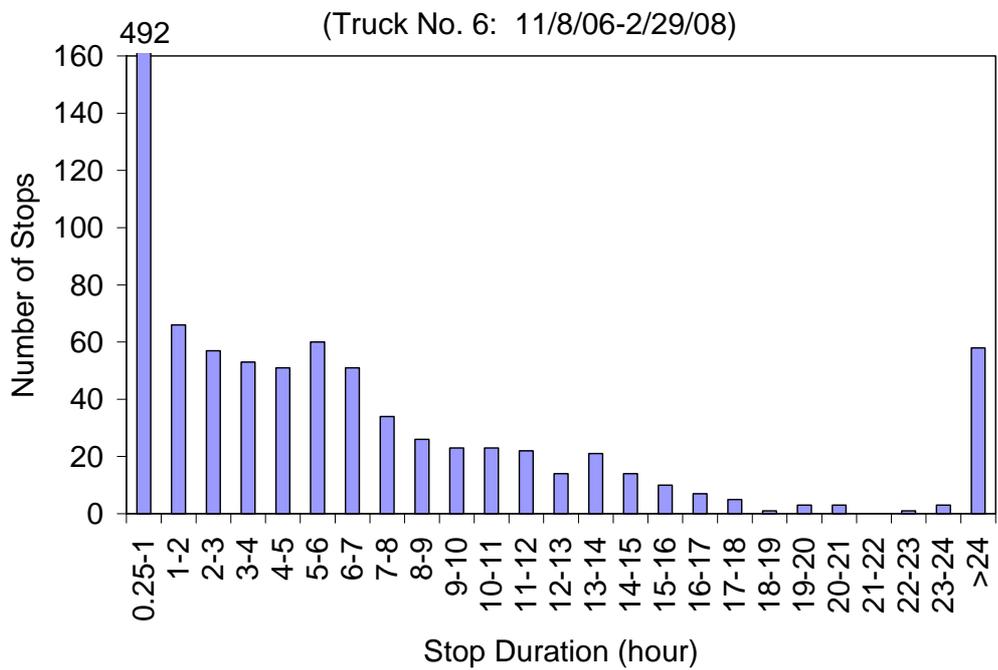
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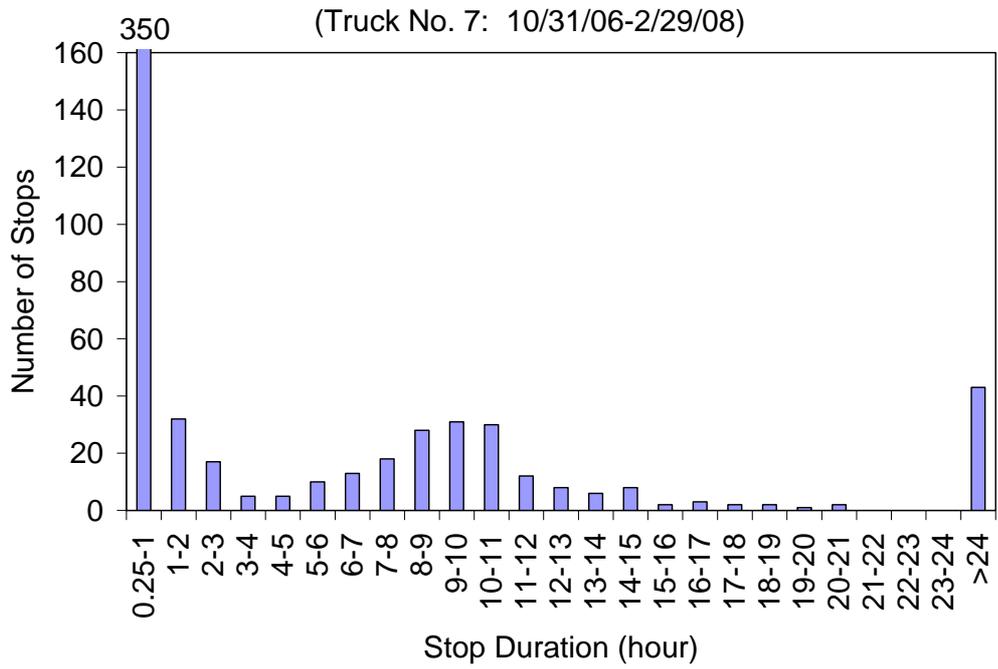
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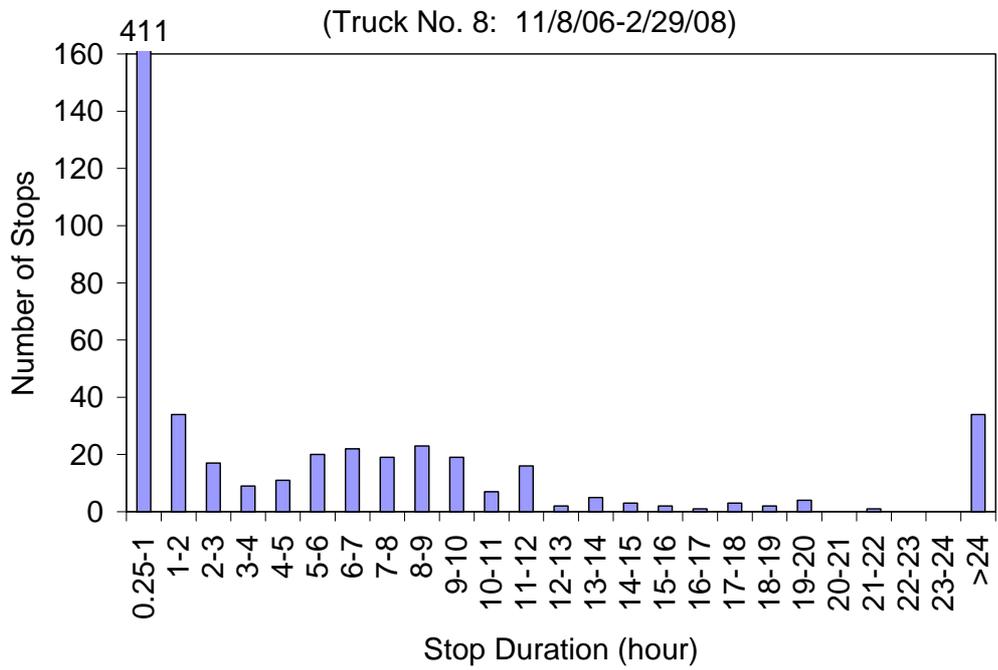
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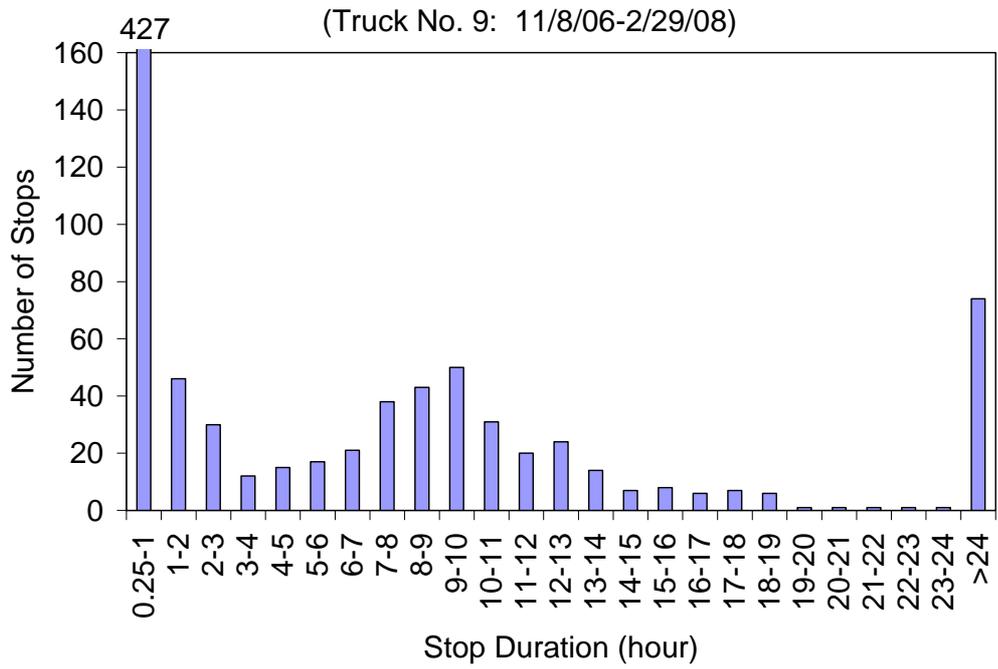
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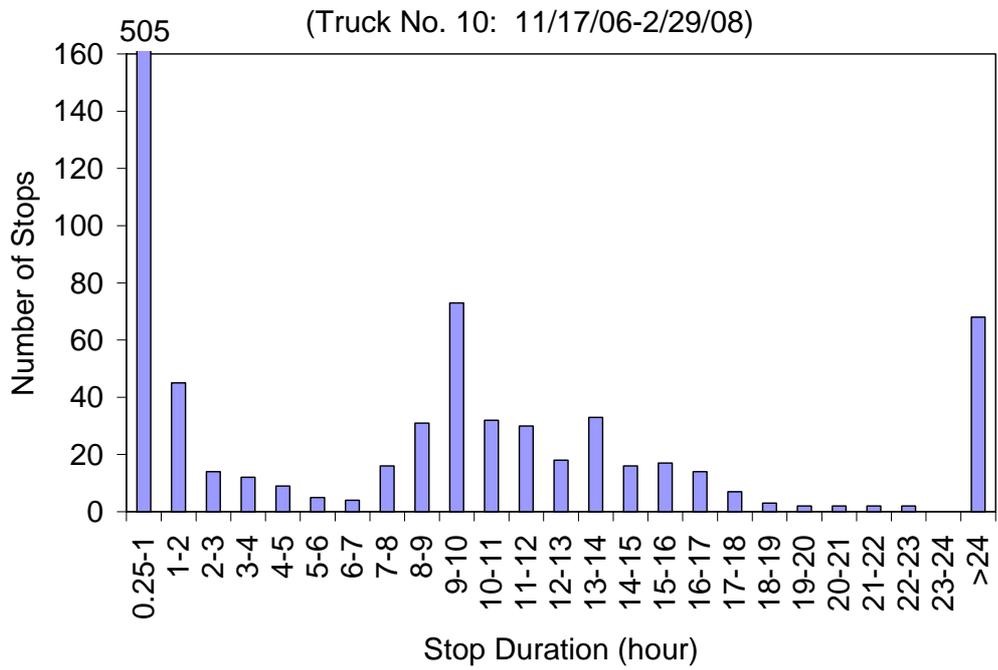
(g)



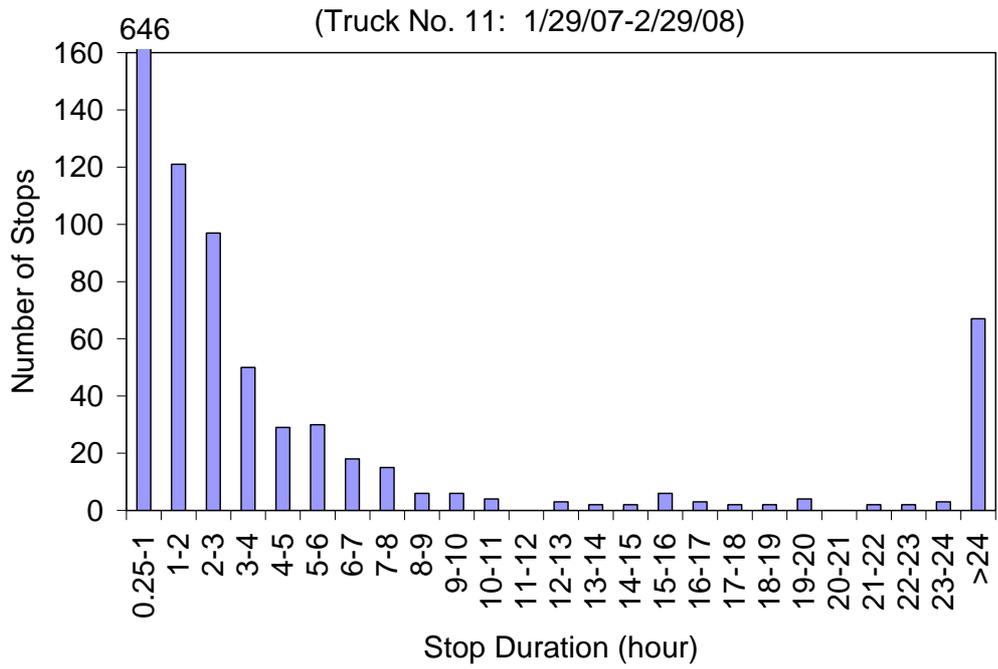
(h)



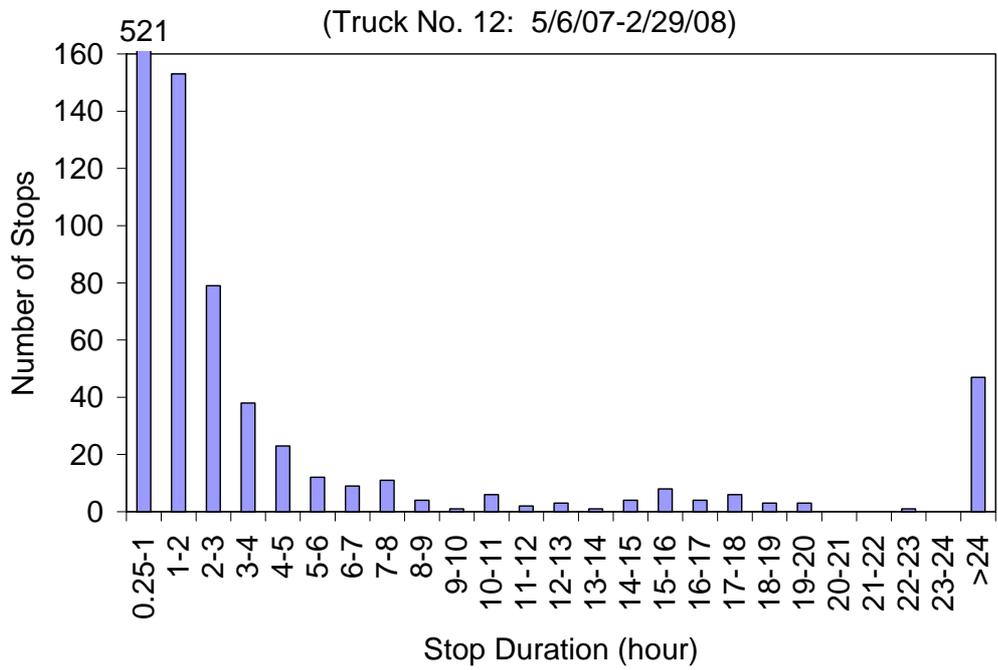
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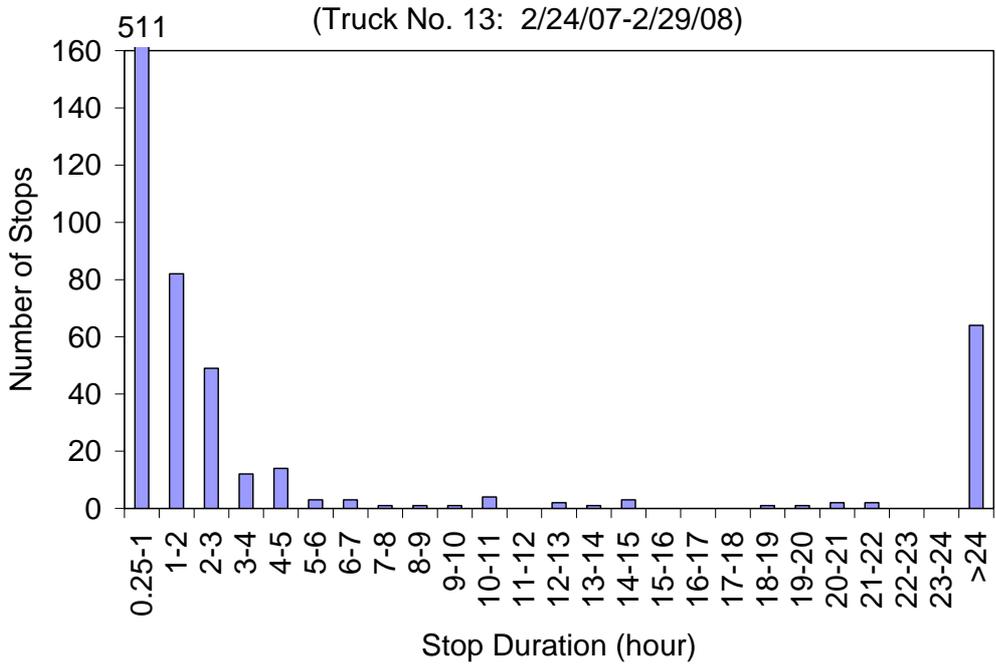
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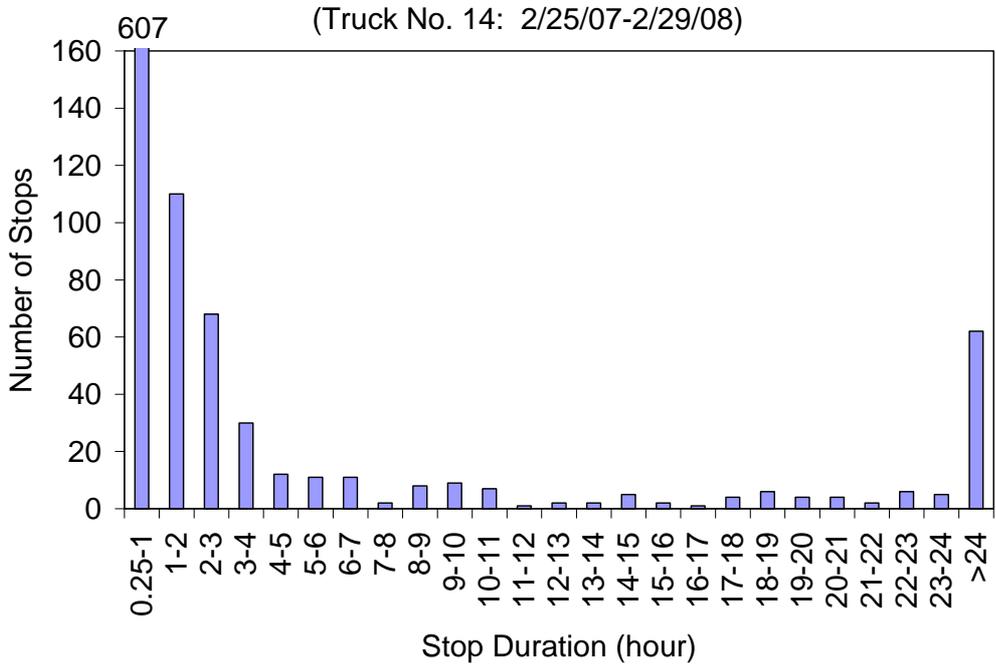
(k)



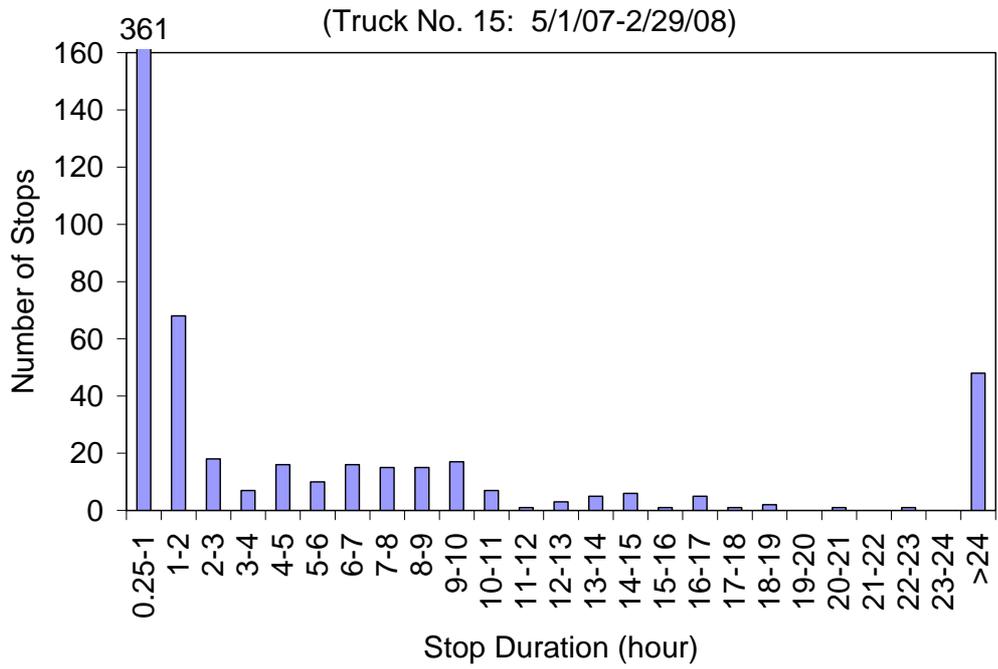
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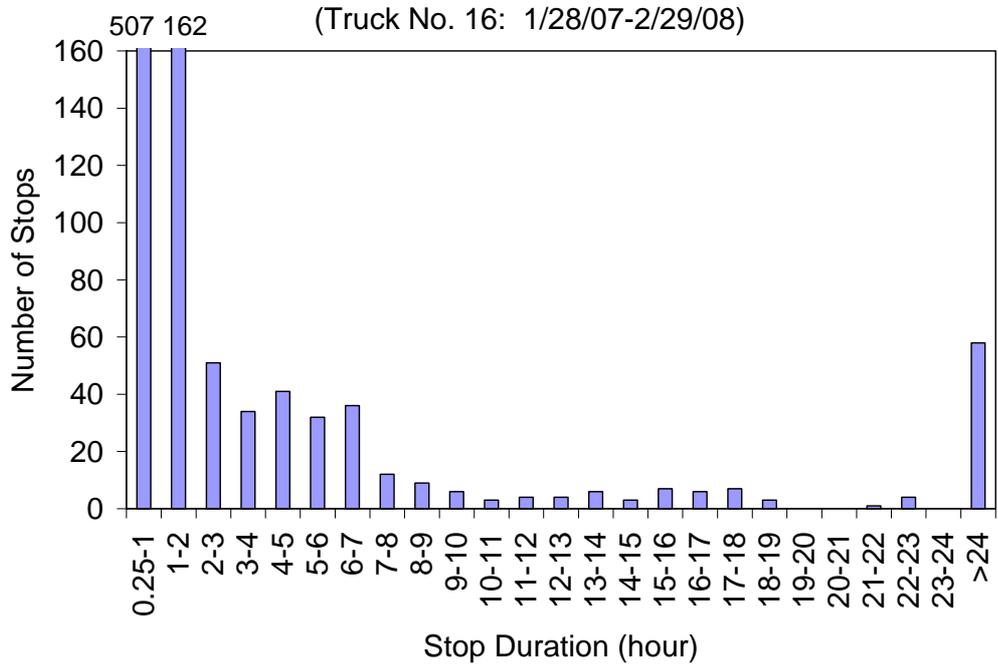
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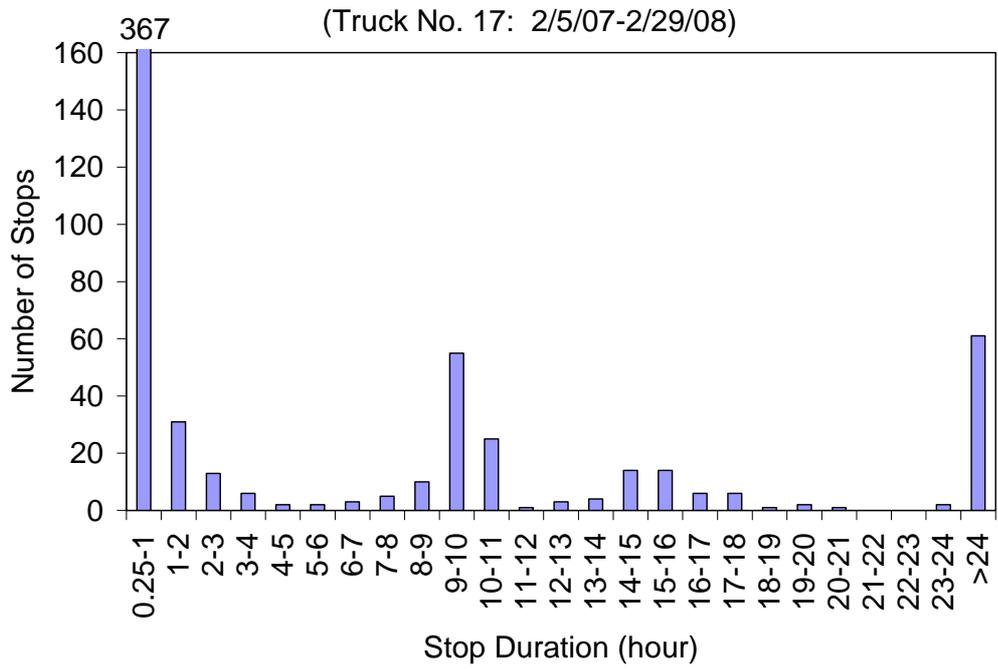
(n)



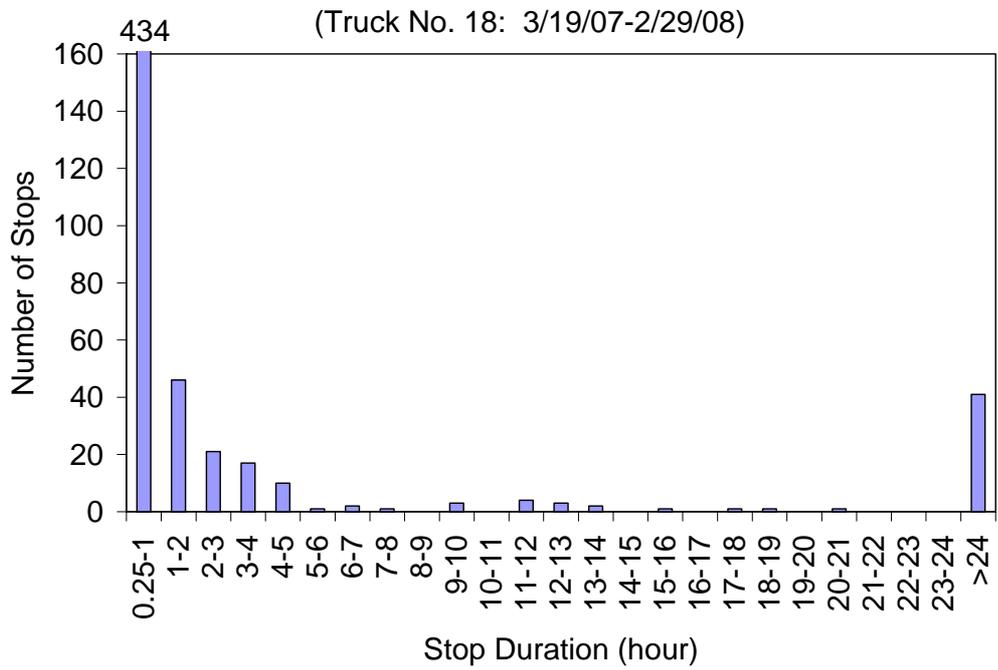
(o)



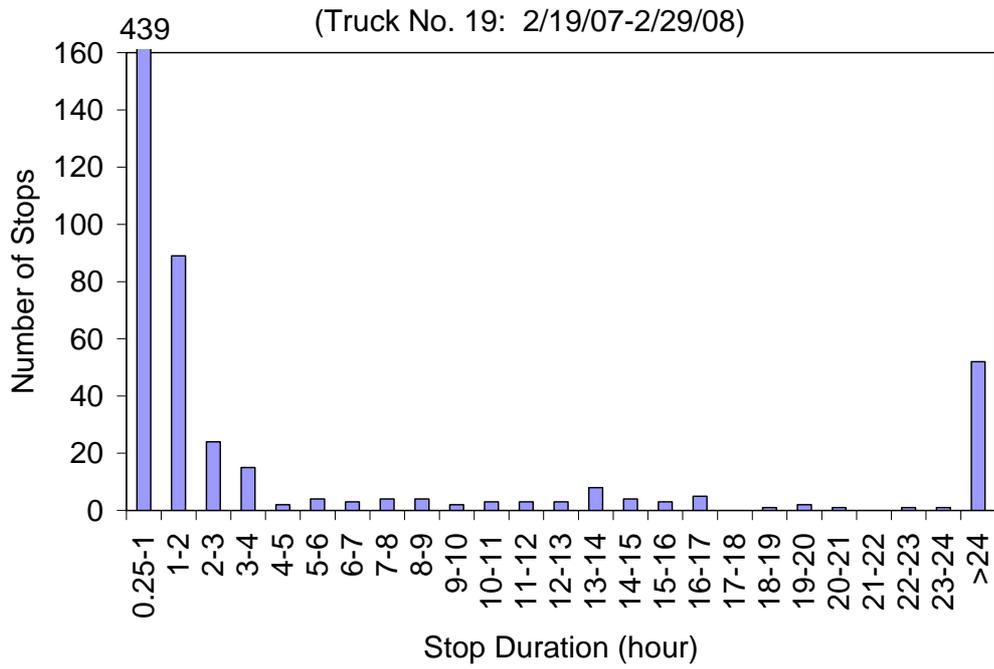
(p)



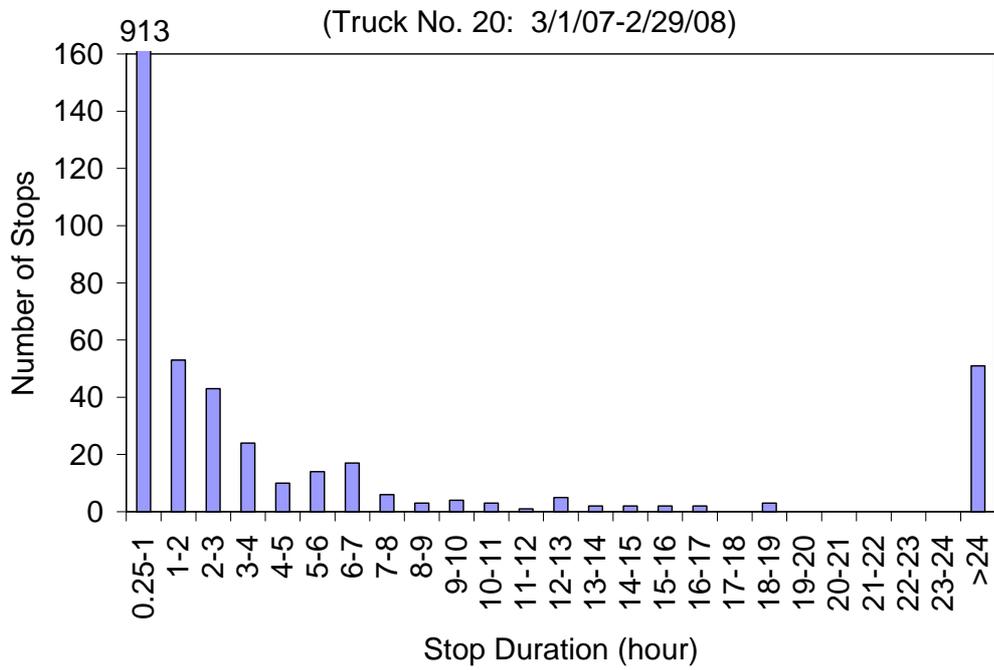
(q)



(r)



(s)



(t)

Figure G-1. Numbers of Stops versus Stop Duration for Each of the 20 Trucks

Section H. Detailed Figures for Percentage of Time of Stop Scenarios versus Stop

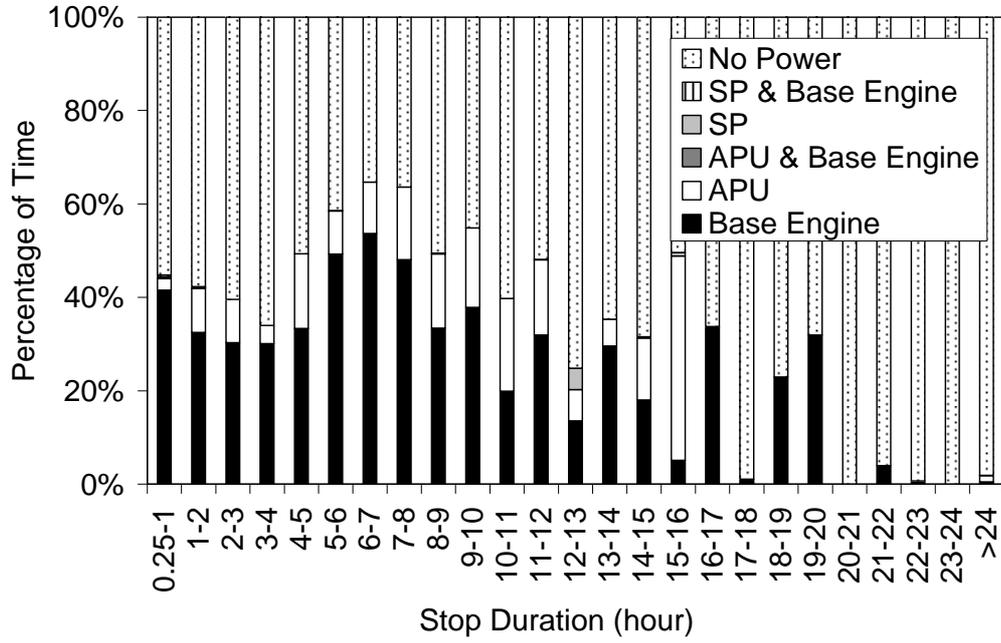
Duration for Each of the 20 Trucks

For all 20 trucks, the distributions of stop activity with respect to stop scenarios of usage of the base engine, APU and shore-power and no power for stop durations ranging between 0.25 to 24 hours or more are quantified and illustrated in Figure H (a) to (t).

Seven Fleet-A trucks tended to use the APUs whereas the base engines were frequently used for 3 Fleet-A trucks. Seven Fleet-B trucks tended to use the base engines but the APUs were frequently used for 3 Fleet-B trucks for long duration stops. Single drivers prefer to use the APUs but team drivers prefer to idle the base engines.

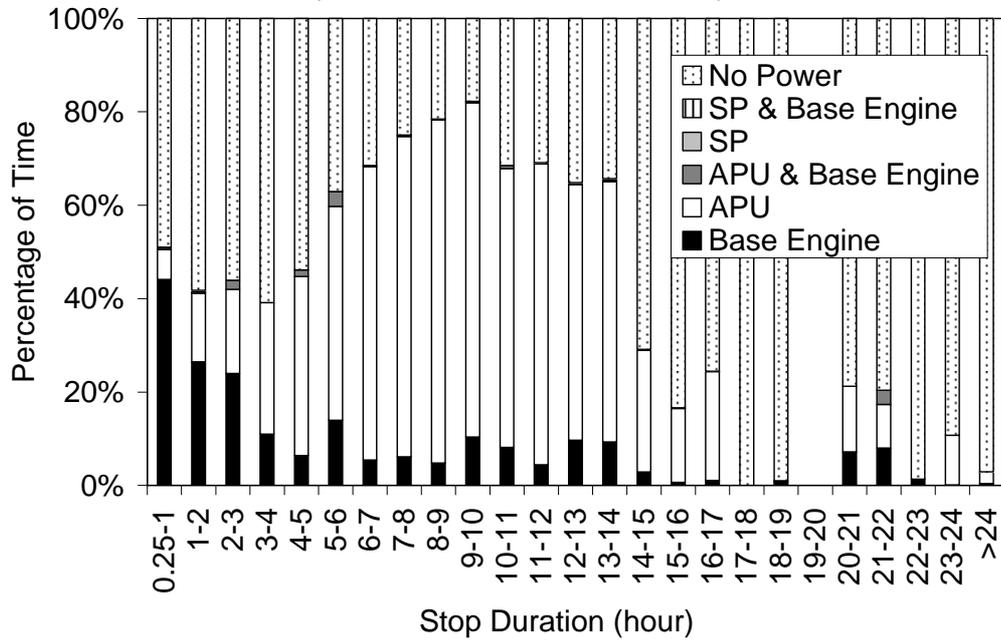
Simultaneous use of the APU and base engine accounted more than 25 hours of annual usage for 6 trucks. On-board shore-power system usage and simultaneous use of on-board shore-power and base engine were estimated to be less than 0.1 percent of time for all 20 trucks. There is no evidence that an off-board shore-power system (i.e. IdleAire) was used.

(Truck No. 1: 9/6/06-2/29/08)



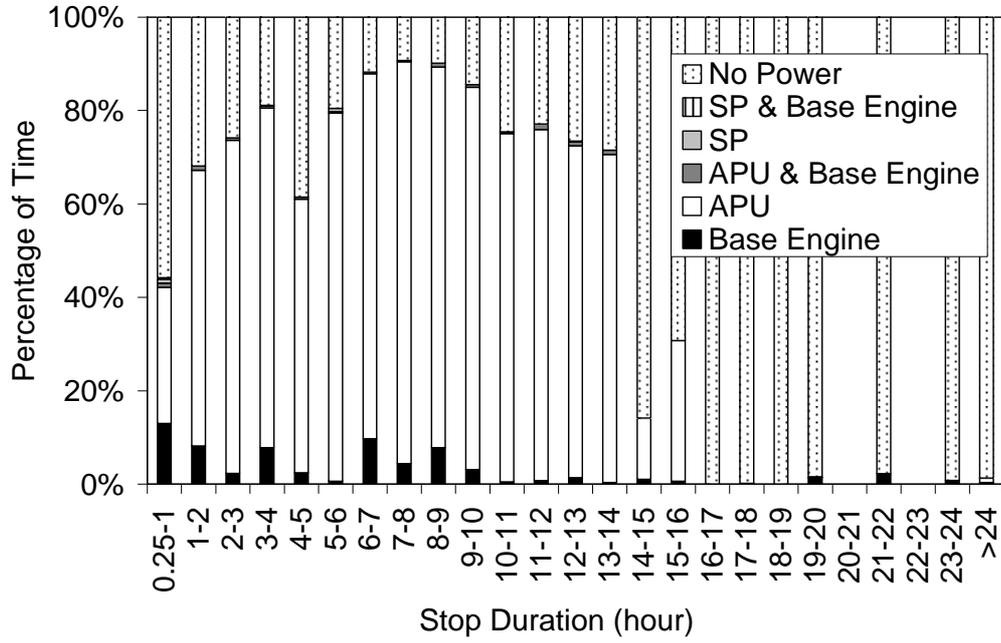
(a)

(Truck No. 2: 9/13/06-2/29/08)



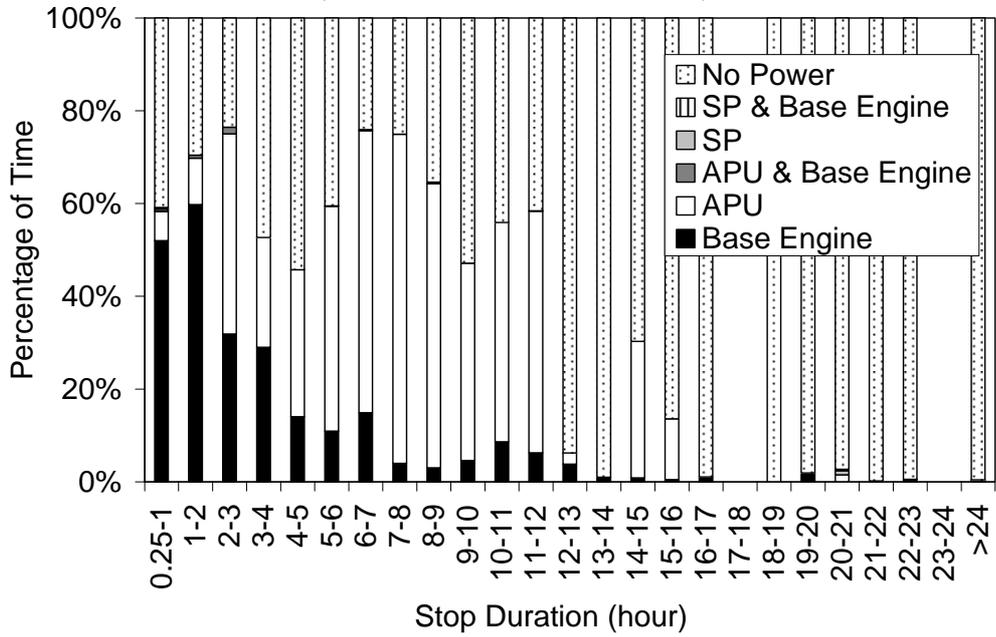
(b)

(Truck No. 3: 9/13/06-2/29/08)



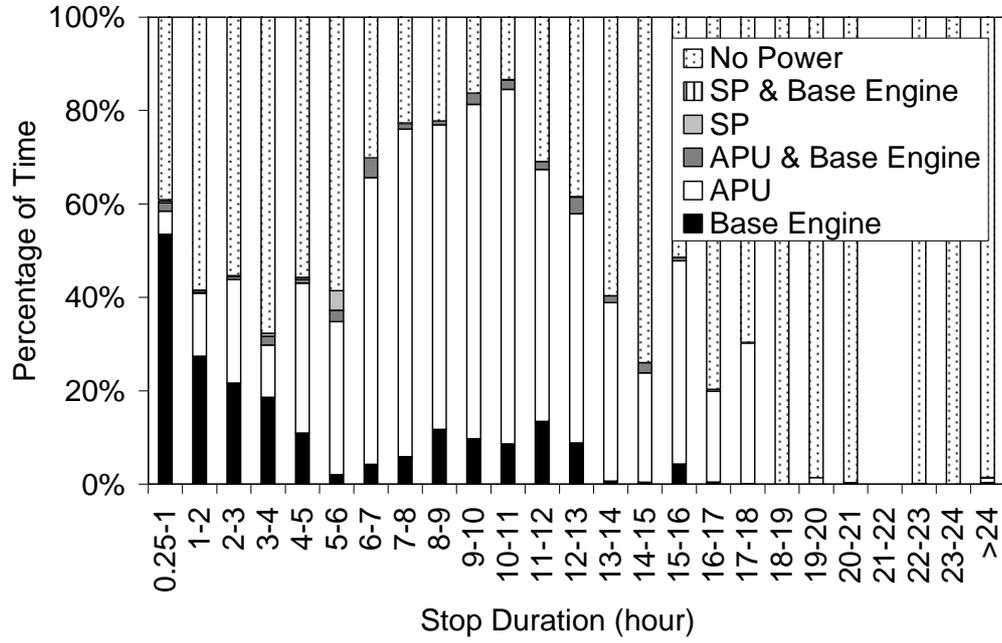
(c)

(Truck No. 4: 3/2/07-2/29/08)



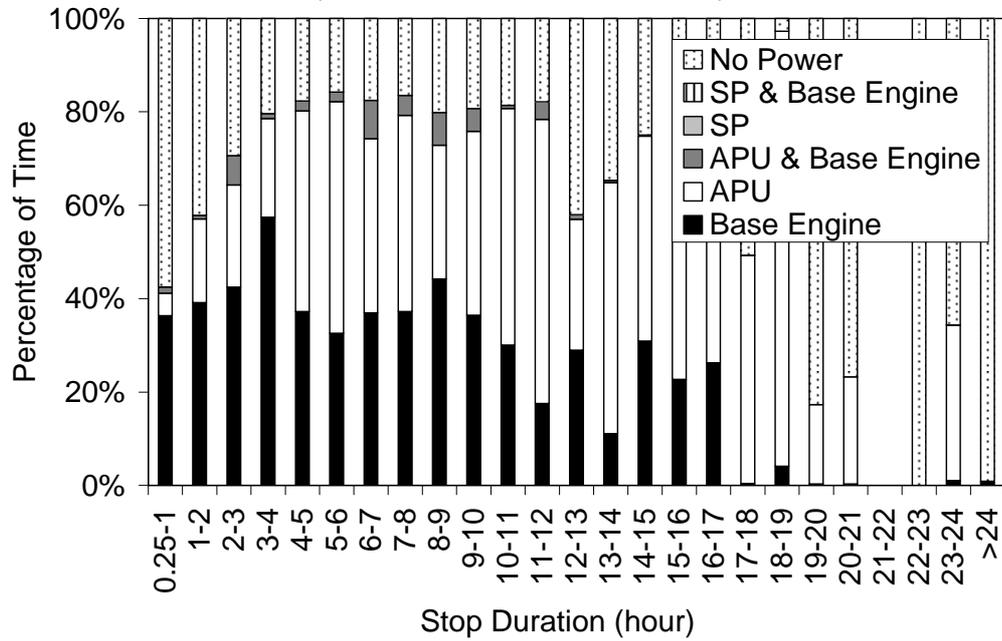
(d)

(Truck No. 5: 9/21/06-2/29/08)



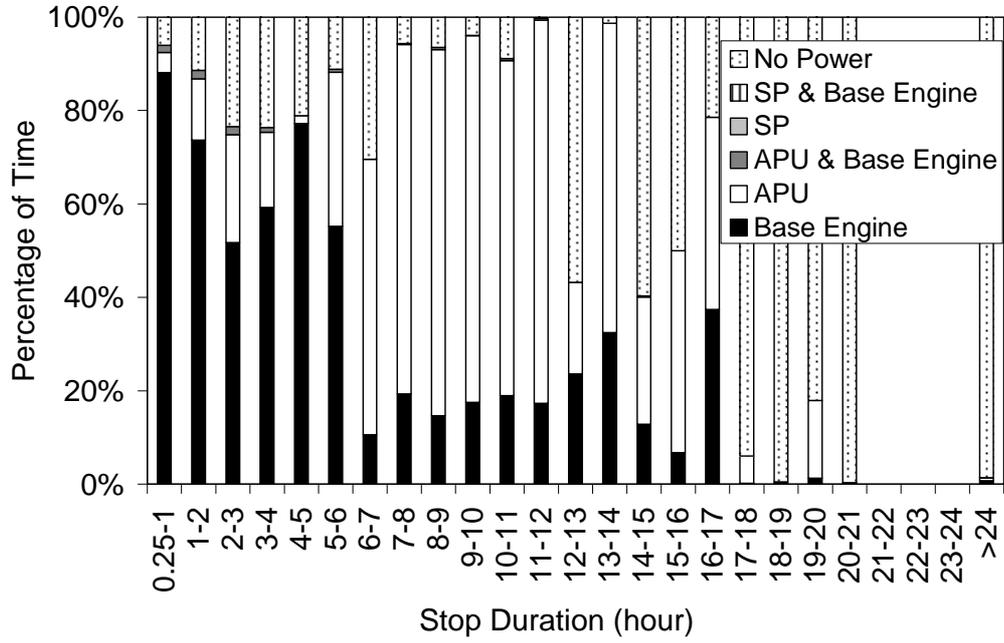
(e)

(Truck No. 6: 11/8/06-2/29/08)



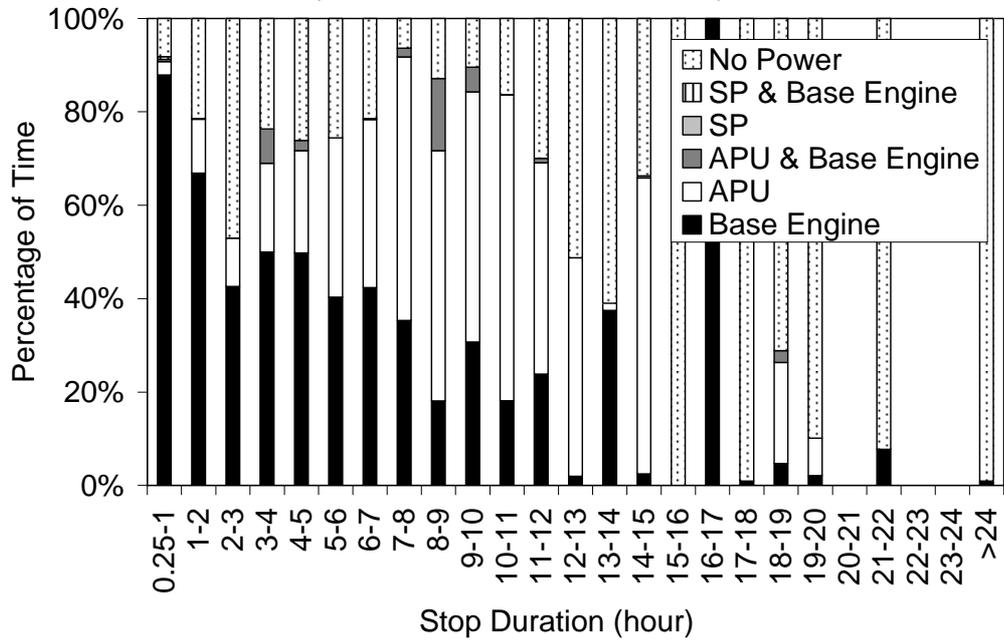
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(Truck No. 7: 10/31/06-2/29/08)



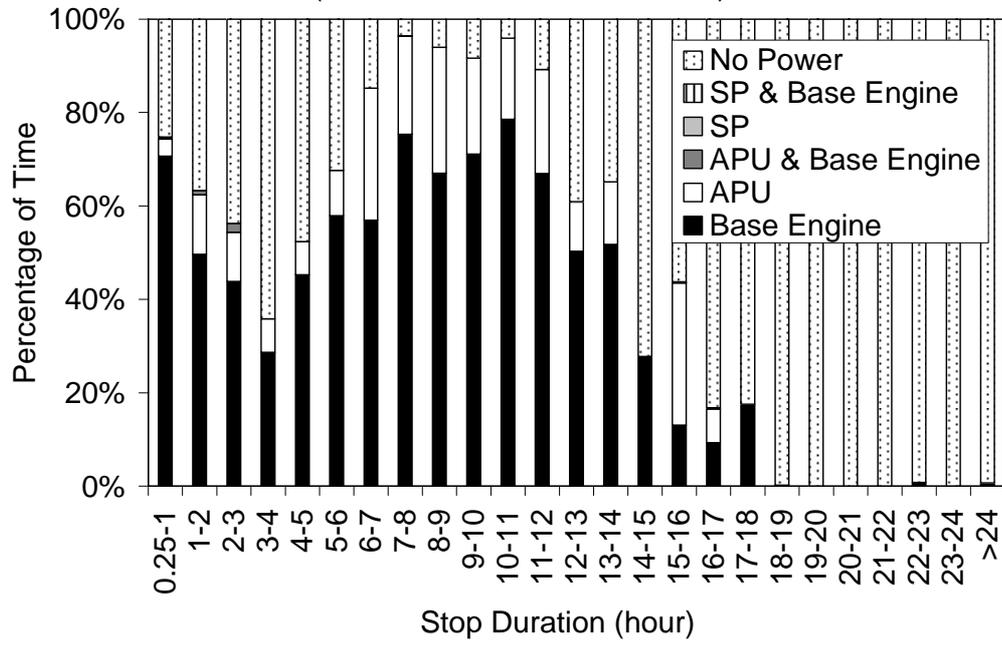
(g)

(Truck No. 8: 11/8/06-2/29/08)



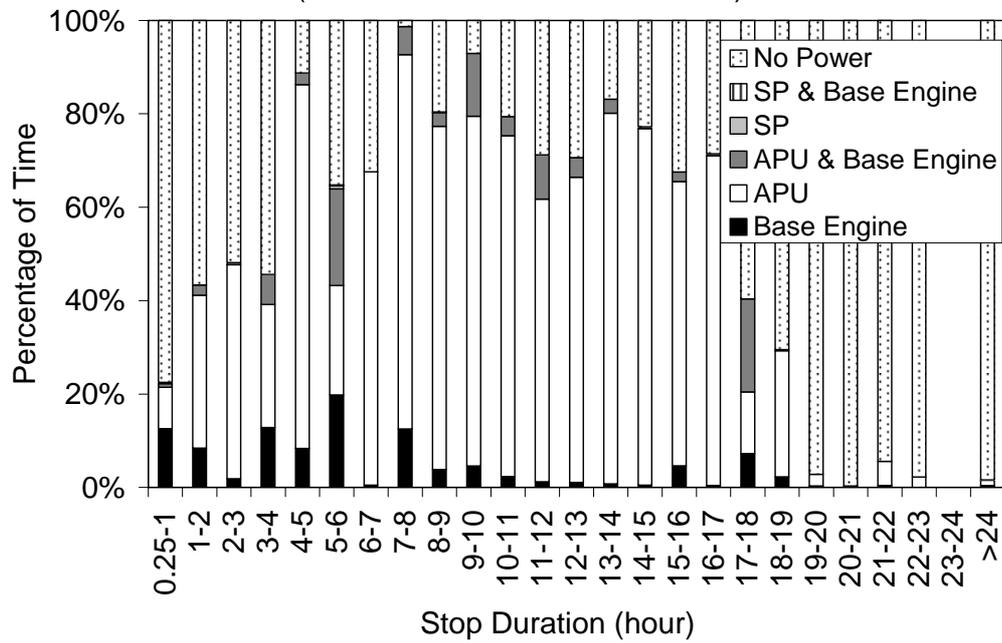
(h)

(Truck No. 9: 11/8/06-2/29/08)



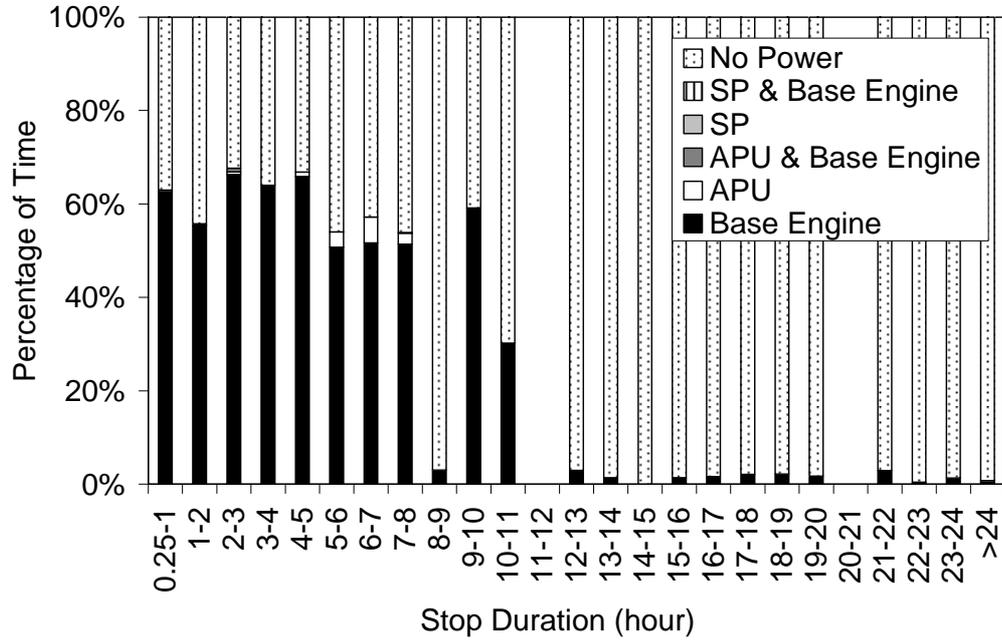
(i)

(Truck No. 10: 11/17/06-2/29/08)



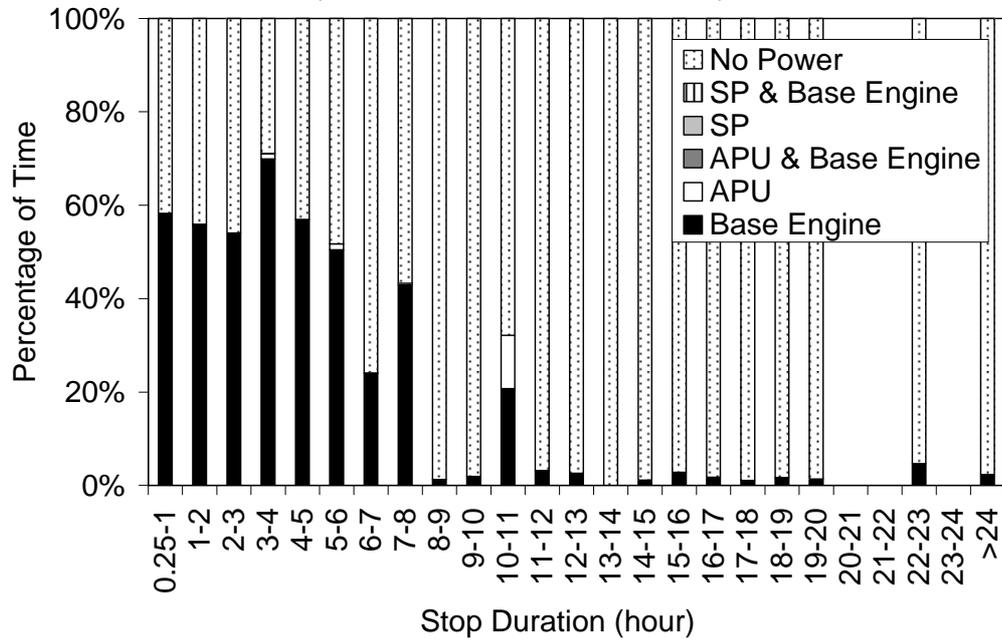
(j)

(Truck No. 11: 1/29/07-2/29/08)



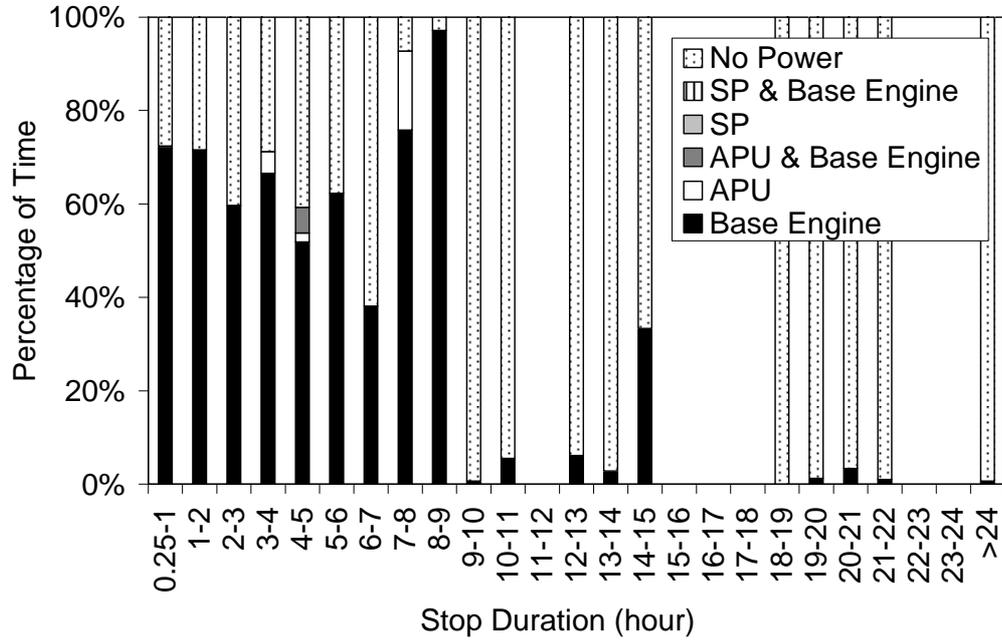
(k)

(Truck No. 12: 5/6/07-2/29/08)



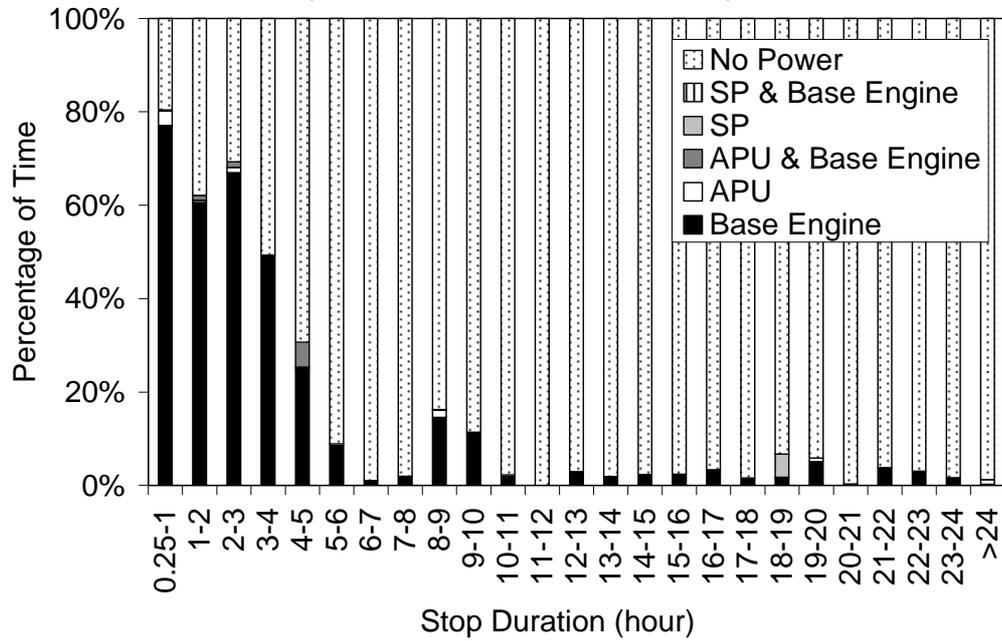
(l)

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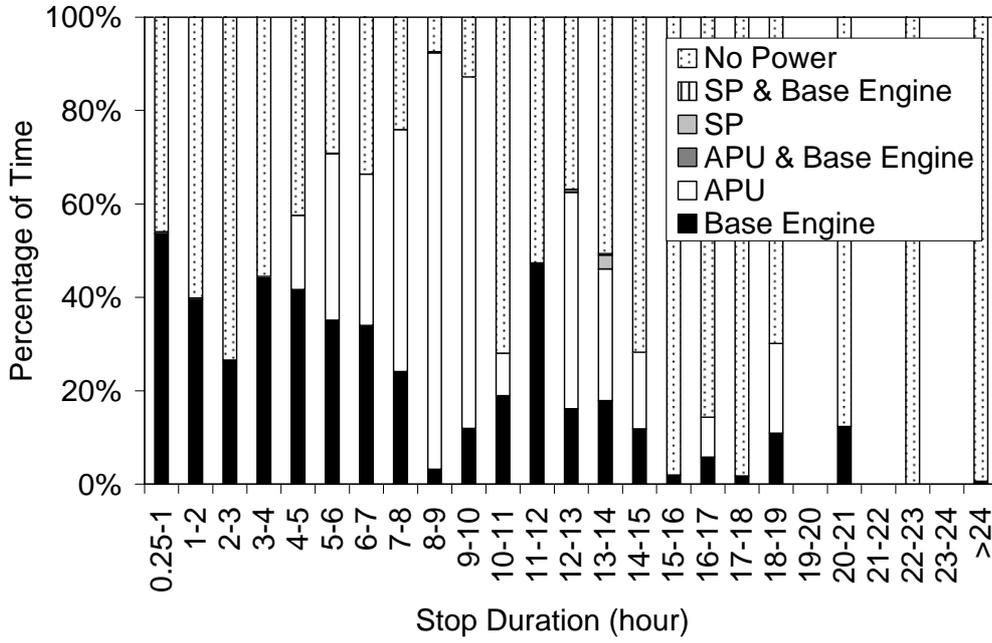
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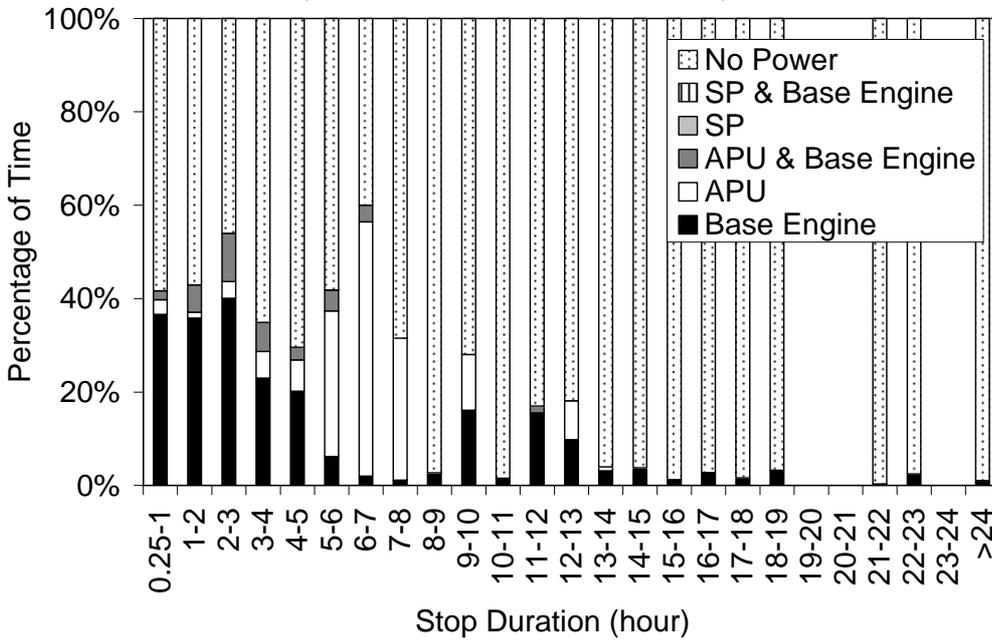
(n)

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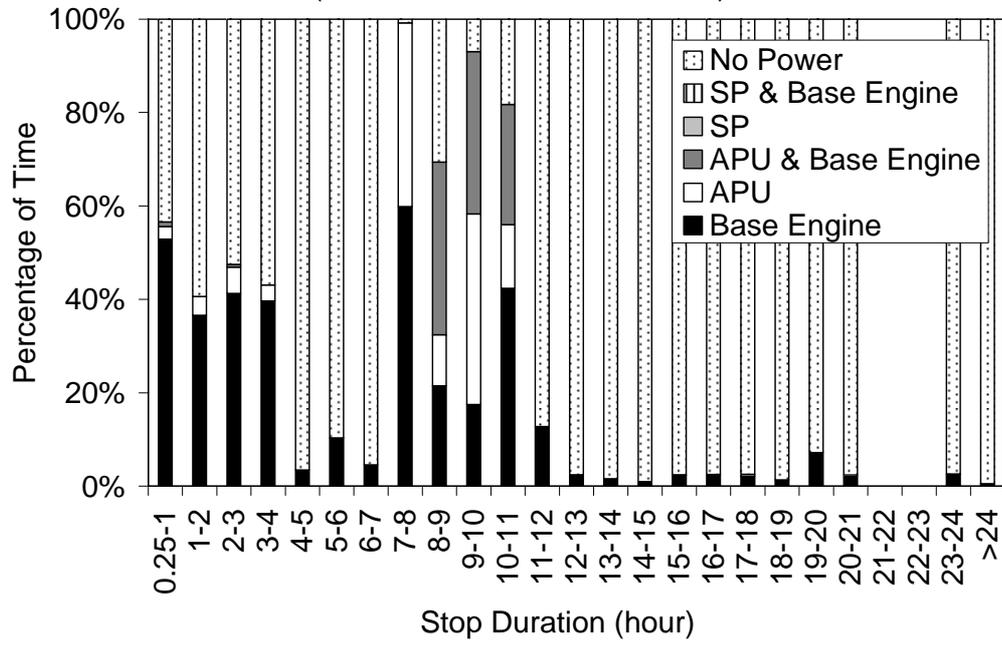
(o)

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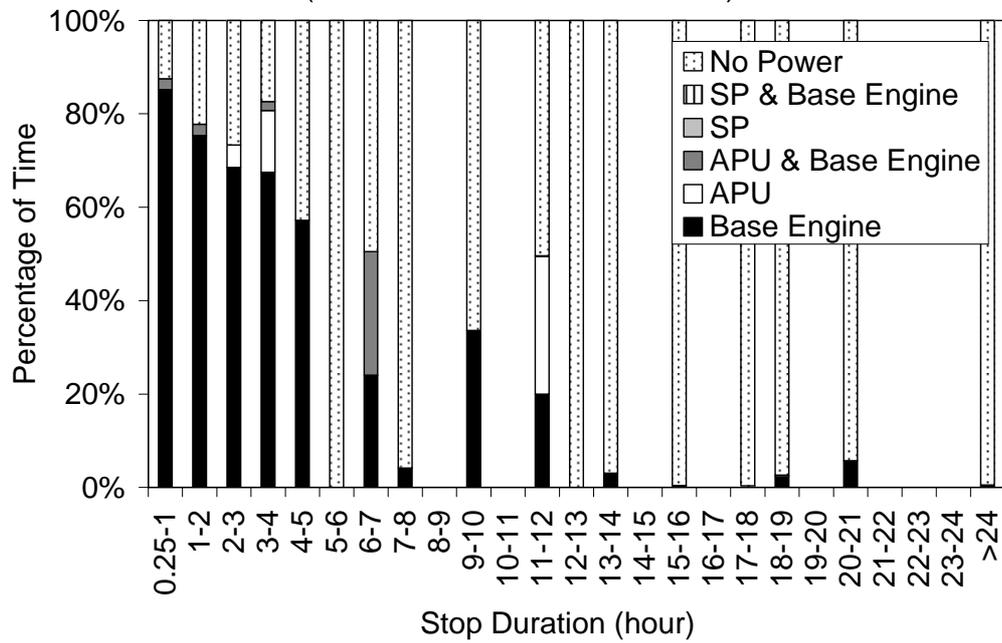
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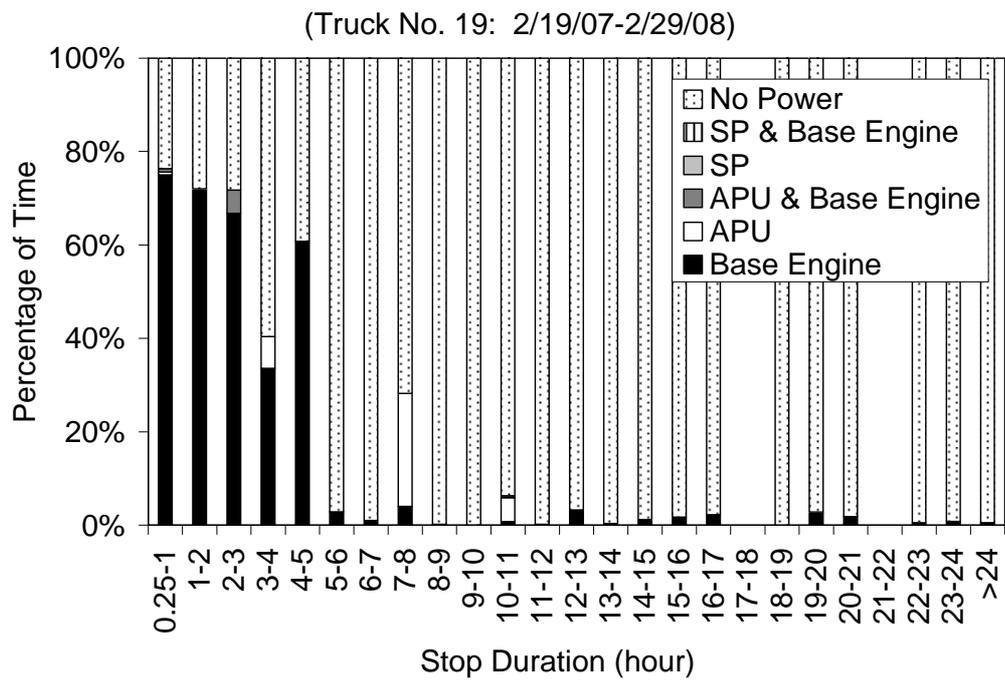


(q)

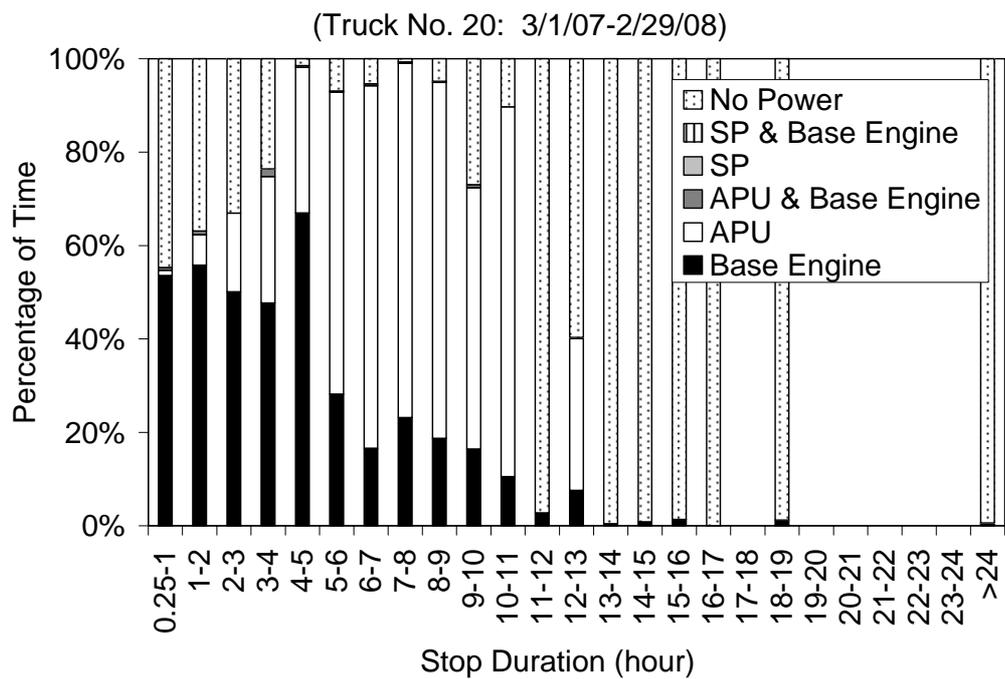
(Truck No. 18: 3/19/07-2/29/08)



(r)



(s)



(t)

Figure H-1. Percentage of Time of Stop Scenarios versus Stop Duration for Each of Trucks

APPENDIX B

INTRODUCTION

This Supporting Information supplements the Part IV of the main text. The information is provided in Sections as follow:

- A. The distribution of ambient temperature for the base engine and APUs for each Fleet;
- B. The fuel use rates for the base engines of Fleets A and B;
- C. The average APU electrical loads versus temperature;
- D. The emission measurements for the base and APU engines;
- E. Benchmark comparisons of measured fuel use and emission rates versus values reported elsewhere; and
- F. Sensitivity analysis of base and APU engine fuel use rate with respect to base engine RPM and ambient temperature.

Section A. Comparison of Ambient Temperature Observations for Fleets A and B

The purpose of this section is to compare the distribution of ambient temperature observed for each Fleet in order to help interpret differences in engine idle fuel consumption between the two fleets.

Since the primary comparison between the two Fleets is based on base engine idling at 600 RPM for Fleet A and 690 RPM for Fleet B, a cumulative distribution function (CDF) of the distribution of observed ambient temperatures under these conditions is given in Figure A-1.

The percentage of time of total base engine idle duration versus ambient temperature ranges and average ambient temperature for each temperature range for each fleet is summarized in Table A-1.

Fleet A has a higher frequency of temperatures greater than 20 °C: for Fleet A, 61.1 percent of base engine idling occurs at temperatures of 20 °C or more, versus only 51.8 percent of base engine idling for Fleet B. On the other hand, Fleet B experienced higher extreme temperatures than Fleet A. The partial average temperature for temperatures over 30 °C was 3.2 degrees higher for Fleet B than for Fleet A. Fleet B experienced a slightly higher proportion of cold temperatures than Fleet A.

Overall, the data in Figure A-1 and Table A-1 do not lead to a clear conclusion regarding which fleet is expected to have higher average base idle fuel use rate, if all other factors (including engine power rating and idle RPM setting) were the same. Fleet A has higher average temperatures most of the time, but does not have extreme temperatures as low or as high as that for Fleet B.

To gain further insight regarding the variation in ambient temperatures for the two fleets, a map of the GPS position data for both fleets is shown in Figure A-2. This map includes all truck activities using the base engine, the APU, or both. The data imply that Fleet A tends to operate mainly in Southeastern states such as North Carolina, South Carolina, Georgia, Florida, and Alabama, as well as other southern states such as Mississippi, Louisiana, and Texas, among others. There is some travel by Fleet A trucks as far north as Michigan and Connecticut, for example, but these activities represent a small proportion of the total fleet movements. Based on the locations of Fleet A trucks, one can expect a wide range of ambient temperatures.

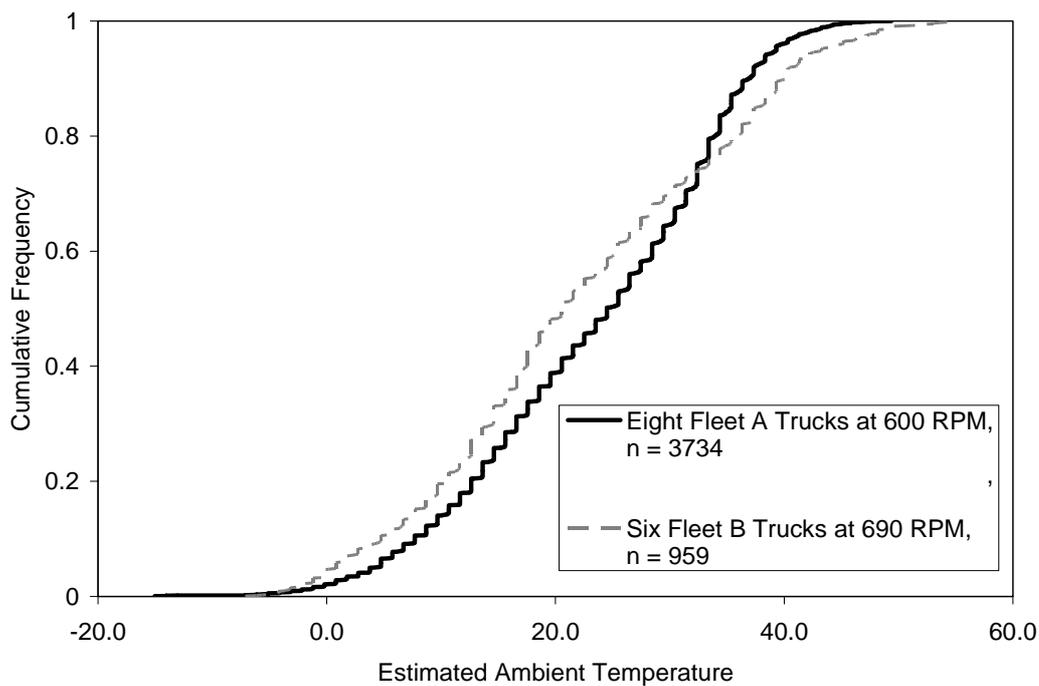


Figure A-1. Comparisons of Cumulative Frequency of Estimated Ambient Temperature for Fleet A at 600 RPM and Fleet B at 690 RPM

Table A-1. Percentage of Total Base Engine Idle Time and Partial Average Temperatures versus Ambient Temperature Range^a

Temperature Range (°C)	≤ 10		10-20		20-30		≥ 30	
	Percentage of Time (%)	Average Temperature (°C)	Percentage of Time (%)	Average Temperature (°C)	Percentage of Time (%)	Average Temperature (°C)	Percentage of Time (%)	Average Temperature (°C)
Fleet A	14.0	4.7	24.9	15.3	25.7	25.3	35.4	35.2
Fleet B	19.6	4.0	28.6	15.3	21.6	24.8	30.2	38.4
Temperature Difference (°C)		0.7		0.0		0.5		-3.2

^a Base engine events with idle duration longer than one hour per stop only

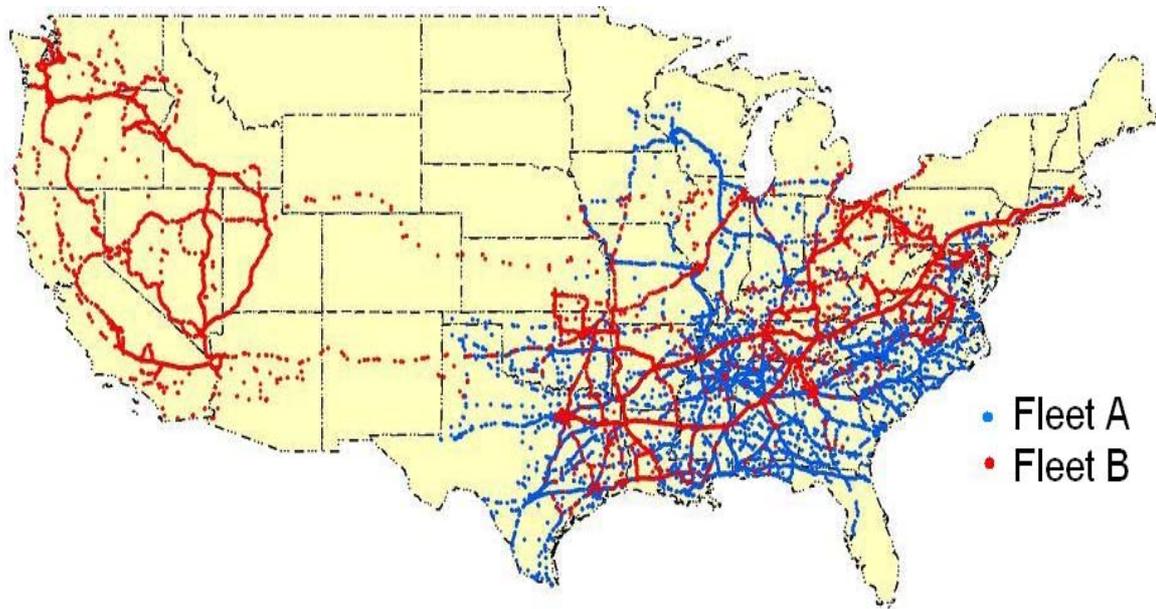


Figure A-2. Distribution of Locations of All Truck Activities for Fleets A and B for all Data Collected over Multiple Seasons.

Fleet B trucks operated in the mid-Atlantic region that overlaps with much of Fleet A's operations, as well as in Texas. However, Fleet B trucks also operated out of a hub in Arizona, and as a result traveled the west coast in California, Oregon, and Washington as well as neighboring states such as Utah and Nevada. Fleet B trucks also may have had more operations in some northeastern or upper Midwestern states such as Pennsylvania and Ohio. These activity patterns are consistent with the wider extremes of temperatures observed for Fleet B versus Fleet A for both very cold and very hot conditions.

Whereas the comparisons of Figure A-1 and Table A-1 focus on the observed temperature distribution when the base engine was used for idling, a comparison was also made for the observed temperature distributions when the APU engines were used for idling. These comparisons are summarized as CDFs for each fleet and each type of APU in Figure A-2. Table A-2 provides the proportion of time spent in various temperature ranges and the partial average temperature in each range.

From the CDFs, it is apparent that when the APU was used, Fleet A generally experienced higher temperatures than Fleet B. In particular, APU usage for Fleet A was associated with a higher proportion of time spent at temperatures of 30 °C or more, compared to Fleet B. Both fleets have approximately similar proportions of time spent at temperatures of 20 to 30 °C for each type of APU. Fleet B has a higher proportion of time spent at temperatures of less than 10 °C for each type of APU. These comparisons suggest that, if all else were equal (i.e. exterior paint color, interior volume), one would expect higher average fuel use from the APUs for Fleet A at high temperature and higher average fuel use from the APUs of Fleet B at lower temperature. However, since the Fleet A trucks have a

significantly larger interior volume, the heating load, as well as the cooling load, for Fleet A will tend to be higher in all cases.

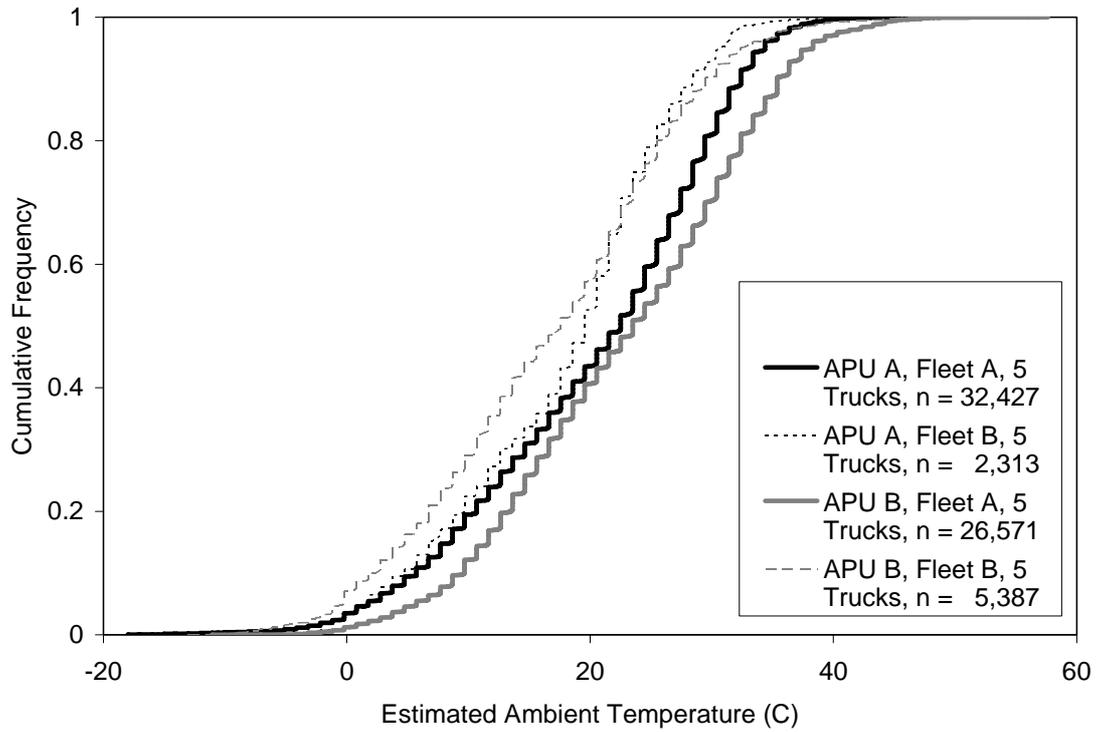


Figure A-3. Comparisons of Cumulative Frequency of Ambient Temperature for Each Combination of Auxiliary Power Unit and Fleet under the Real-World Condition

Table A-2. Percentage of Total APU Operation Time and Partial Average Temperatures versus Ambient Temperature Range

Temperature Range (°C)	10		10-20		20-30		≥ 30	
	Percentage of Time (%)	Average Temperature (°C)	Percentage of Time (%)	Average Temperature (°C)	Percentage of Time (%)	Average Temperature (°C)	Percentage of Time (%)	Average Temperature (°C)
APU-A, Fleet A	19.5	4.3	24.0	15.2	37.5	25.4	19.0	33.0
APU-A, Fleet B	22.4	4.8	30.2	15.9	40.1	23.9	7.3	32.1
APU-B, Fleet A	12.1	5.8	28.5	15.3	29.7	25.4	29.7	34.8
APU-B, Fleet B	29.1	3.7	28.4	14.9	32.7	24.4	9.8	34.0

SECTION B. Fuel Use Rates of Base Engines for Fleets A and B

Base engine fuel use rate during idle is highly variable. The 95 percent range of variability in fuel use rate is 0.40 to 0.63 gal/hr for Fleet A and 0.25 to 1.00 gal/hr for Fleet B. Fleet A trucks operated at a mean engine idle speed of 601 RPM, with a standard deviation of 20 RPM. Fleet B trucks operated at a mean engine idle speed of 700 RPM, with a standard deviation of 74 RPM. Thus, Fleet B tended to operate with a wider range of variation in engine idle speed, leading to more variation in fuel use rate.

On average, idle fuel use rates for Fleets A and B are approximately 0.55 and 0.51 gallon/hour, respectively. These rates are significantly lower than values of 0.8 to 1.0 gallons/hours typically assumed elsewhere (Lim, 2002; Lutsey et al., 2004; Stodolsky, 2000).

Fleet A trucks tended to have higher average idle fuel use rates than Fleet B trucks because of darker exterior paint, which leads to higher cooling load, and larger interior volume, which leads to higher loads for both cooling and heating.

Fleet A Base Engine Fuel Use

Eighty percent of the idle engine speed data for eight Fleet A trucks are at approximately 600 RPM. This value is at the lower bound of the engine speed distribution from a nationwide truck driver survey, which ranged from 600 to 1,200 RPM (Lutsey, 2004). Thus, in most cases, the idle fuel use rates for Fleet A trucks are not sensitive to engine speeds but are sensitive to ambient temperatures.

The observed truck outer temperatures were corrected based on actual ambient temperature and solar irradiation:

$$T = -0.198 + 0.988T_o - 0.0028I \quad (\text{B-1})$$

$$(n = 9483, R^2 = 0.987, \text{p-value} < 0.001)$$

Where

T = Estimated ambient temperature ($^{\circ}\text{C}$)

T_o = Observed truck outer temperature ($^{\circ}\text{C}$)

I = Solar irradiation (W/m^2)

The first two terms of the equation correct the observed temperature when solar irradiation is zero (e.g. at night) and the third term accounts for the average effect of solar irradiation on the observed temperature. As expected, the observed temperature is reasonably accurate under no irradiation but is overestimated with irradiation.

Equation (B-1) does not include a correction for the impact of thermal radiation from pavement. Such a correction is not practical without site-specific data for pavement types, which were not available. The observed extreme high temperatures are typically influenced by heat transfer from hot pavement (Yavuzturk, 2005). For example, the outer temperature was observed to be 130°F for a truck parked near Dallas, Texas on August 15, 2007. The actual highest ambient temperature in that area on that day was only 102°F . Thus, very high values of reported outer temperature are interpreted as a qualitative relative indicator of cooling demand, rather than as accurate ambient temperatures.

At 600 RPM, the average fuel use rate is found to be a weak function of estimated ambient temperature.

$$E_{F,600}^A = 5.05 \times 10^{-5} T^2 + 9.65 \times 10^{-3} T + 0.478 \quad (\text{B-2})$$

$$(R^2 = 0.384; n = 3734; p\text{-value} < 0.001)$$

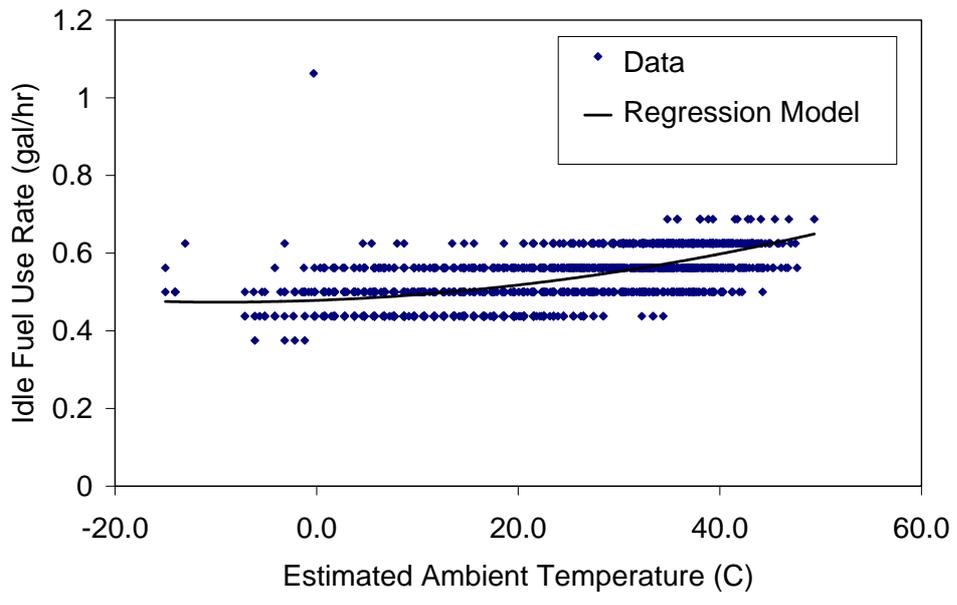
Where

$$E_{F,600}^A = \text{Fleet A base engine mass fuel use rate at 600 RPM (gal/hr)}$$

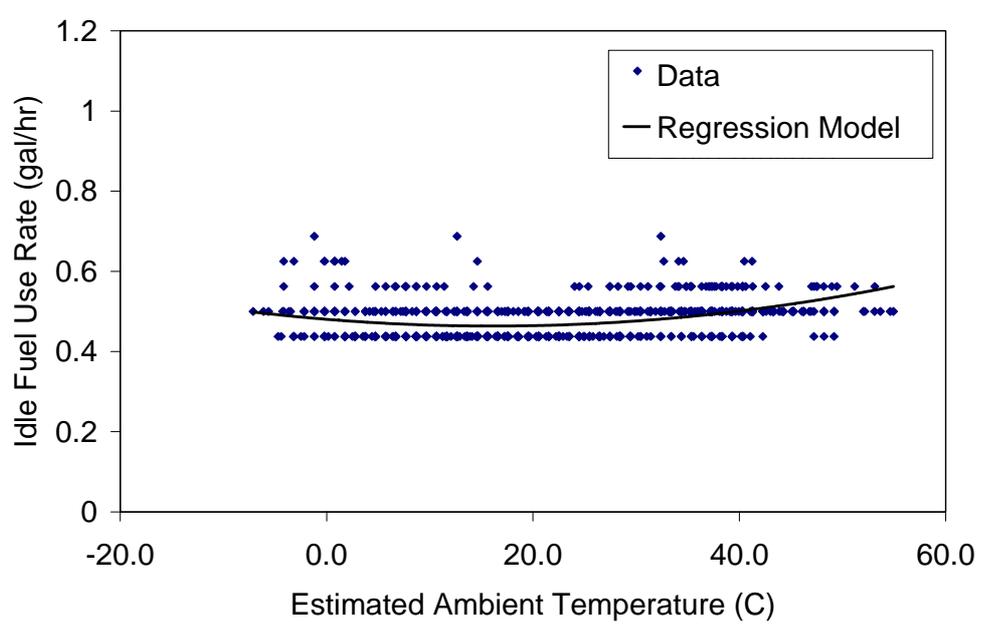
As expected, average fuel use rate is highest at high estimated ambient temperatures, because of high air conditioning load. At moderate to low temperature, fuel use rate is relatively insensitive to temperature. The results are shown in Figure B-1(a).

During very cold or hot weather, base engines are reported to have higher idle fuel use rates than during mild weather (Lim, 2002; Caterpillar, 2006; Pejula, 2003). In this case, the expected trend is observed at high exterior temperature. At low temperature, where cabin heating is needed, there is only a very small change in average fuel use rate compared to intermediate temperature. Perhaps the heating fan load is low and sufficient heat is provided by the engine such that a significant increase in engine fuel use is not needed at low temperature.

There were two trucks that operated at various engine speeds. Based on data from Truck Nos. 3 and 10, an adjustment in fuel use rate is developed as a function of engine RPM:



(a) Eight Fleet A Trucks at 600 RPM



(b) Six Fleet B Trucks at 690 RPM

Figure B-1. Base Engine Idle Fuel Use Rates versus Ambient Temperatures

$$\Delta E_{F,N}^A = 1.31 \times 10^{-3} N - 0.872 \quad (\text{B-3})$$

$$(R^2 = 0.474; n = 359; p\text{-value} < 0.001)$$

Where

$\Delta E_{F,N}^A$ = Fleet A base engine idle fuel correction term impacted by
engine speeds (RPM)

N = Engine speed (RPM)

As engine RPM increases, fuel use rate increases, as expected. For Fleet A trucks, the average fuel use rate at idle can be estimated as a function of ambient temperature and engine speed:

$$E_F^A = E_{F,600}^A + \Delta E_{F,N}^A \quad (\text{B-4})$$

Where

E_F^A = Fleet A base engine mass fuel use rate (gal/hr)

For Truck No. 3, there was a very weak ($R^2 = 0.073$, $p = 0.035$) relationship between average RPM and exterior temperature, and for Truck No. 10, the relationship was not statistically significant ($R^2 = 0.0014$, $p = 0.83$). Thus, engine RPM is treated here as an independent variable chosen by the driver.

Fleet B Base Engine Fuel Use

For Fleet B, the same methodology as for Fleet A was used to estimate idle fuel use rate; however, the results were slightly different. Most often, Fleet B trucks had an idle engine RPM set point of 690 RPM, not 600 RPM as for Fleet A. This was the case for 80 percent of the data from six of the Fleet B trucks. As shown in Figure B-1(b), the average fuel use rate under these conditions is weakly sensitive to ambient temperature:

$$E_{F,690}^B = 6.54 \times 10^{-5} T^2 - 2.10 \times 10^{-3} T + 0.480 \quad (\text{B-5})$$

$$(R^2 = 0.148; n = 959; p\text{-value} < 0.001)$$

Where

$$E_{F,690}^B = \text{Fleet B base engine mass fuel use rate at 690 RPM (gal/hr)}$$

The Fleet B results more clearly show the expected trend in which average fuel use rate is highest at very low or high temperature and lowest at moderate temperature.

The engine speed was more highly variable for four Fleet B trucks, which include Trucks Nos. 13, 16, 18 and 19. For these trucks, engine RPM varied from 590 to 990 RPM.

The difference in fuel use relative to 690 RPM is estimated as:

$$\Delta E_{F,N}^B = 1.52 \times 10^{-3} N - 1.04 \quad (\text{B-6})$$

$$(R^2 = 0.899; n = 227; p\text{-value} < 0.001)$$

Where

$\Delta E_{F,N}^B =$ Fleet B base engine idle fuel correction term impacted by engine speeds (RPM)

As expected, average fuel use increases with RPM.

For Fleet B, the sensitivity of average fuel use rate to ambient temperature and engine RPM is given by:

$$E_F^B = E_{F,690}^B + \Delta E_{F,N}^B \quad (\text{B-7})$$

Where

$E_F^B =$ Fleet B base engine mass fuel use rate (gal/hr)

Engine speed for Fleet B trucks was found to be a very weak function of ambient temperature. For three of the four trucks with variable engine speeds, the R^2 for RPM versus temperature was 0.18 or lower. Thus, there is not a strongly definitive pattern regarding the driver's choice of an idle RPM set point versus ambient temperature.

For each fleet, average fuel consumption rate varies with respect to ambient temperature. At a given ambient temperature, and particularly at high ambient temperatures, Fleet A trucks consume more fuel. Based on Figure B-1, the average fuel consumption rates vary from 0.47 to 0.65 gal/hr for Fleet A, or by 38%, over a range of temperatures. For Fleet B,

the average fuel consumption rates vary from 0.46 to 0.58 gal/hr for Fleet B, or by 26%. The Fleet A trucks have higher fuel use rate even though they typically operate at lower RPM than for Fleet B. This is attributed to the larger heating and cooling load for the Fleet A cabs.

SECTION C. Average APU Electrical Load versus Temperature

The purpose of this section is to evaluate the field data for the trend between APU electrical load and ambient temperature. This evaluation is done for four sets of trucks: (a) Fleet A with APU A; (b) Fleet A with APU B; (c) Fleet B with APU A; and (d) Fleet B with APU B. For each fleet, a polynomial regression equation was used to summarize the average trend in electrical load versus estimated ambient temperature. The initial result for this evaluation is shown in Figure B-1.

Figure C-1 has the expected result that electrical load is lowest at mild ambient temperatures of approximately 10 to 20 °C, and that electrical load increases either as temperatures become colder than the mild range or hotter. Furthermore, the comparisons for three of the sets of trucks and APUs appear to cluster together. For example, at high temperature, the results for Fleet A with APU A and for Fleet B with both types of APUs seem to be within a relatively narrow range. However, for the set of Fleet A trucks with APU B, the minimum electrical load occurs at a very high temperature of approximately 25 °C and the load at very high temperature is much lower than for the other sets. Thus, these results appear to be inconsistent. The reason for this inconsistency was explored.

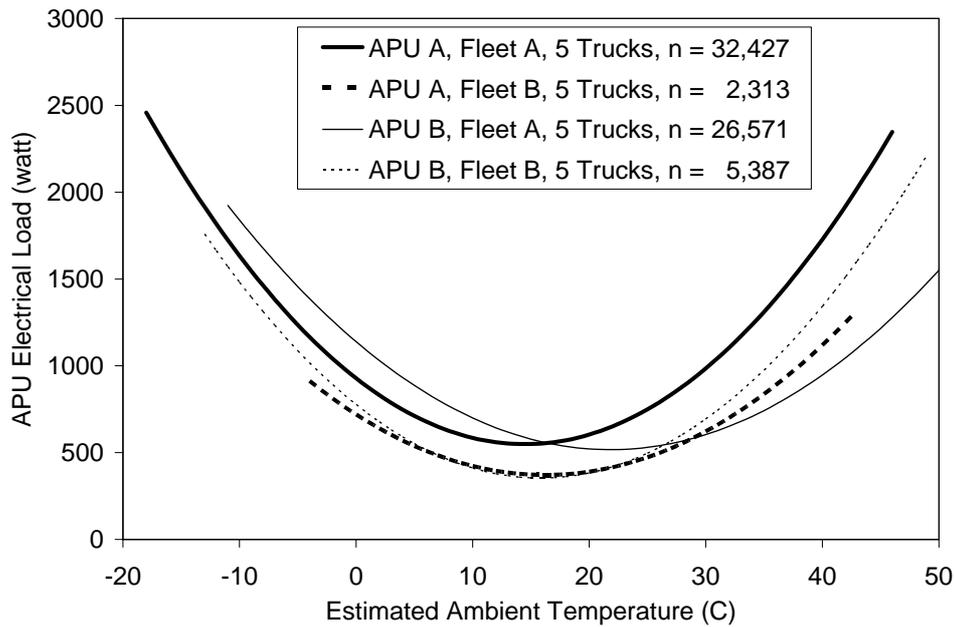


Figure C-1. Preliminary Estimate of Average APU Electrical Load versus Estimated Ambient Temperature for Four Sets of Trucks Based on Fleet and Type of APU.

For the purpose of diagnosing why the average results from Truck Nos. 6-10 of Fleet A have a different load versus temperature pattern than for the other sets of trucks, a more detailed analysis was performed for the APU electrical load of each of these five trucks versus estimated ambient temperature. This analysis is shown in Figure C-2.

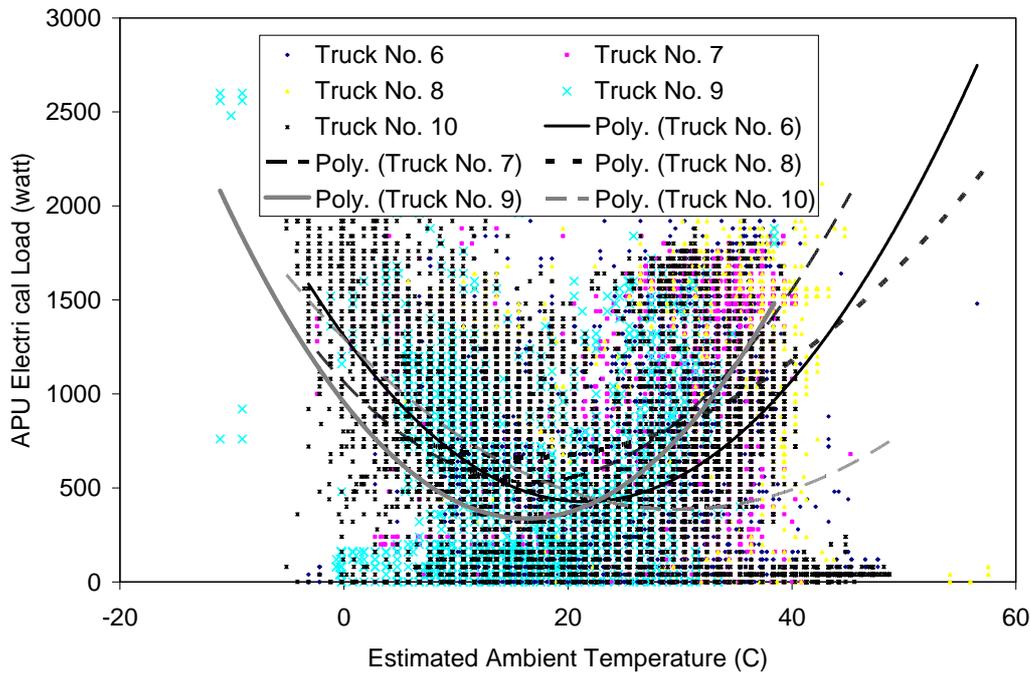


Figure C-2. Average Trends in Auxiliary Power Unit Electrical Load versus Ambient Temperature Truck Nos. 6-10 of Fleet A with APU-B

Truck Nos. 6 to 9 have similar distributions of average electrical load versus ambient temperature, and appear to be clustered together. However, the result for Truck No. 10 is clearly different than those of the other four trucks. Upon further investigation, Truck No. 10 was found to have a high proportion of time spent “double-dipping.” This refers to simultaneous use of both the APU and base engine. For Truck No. 10, there were 179 hours of double dipping activity, versus an average of only 32 hours of such activity for all other Fleet A trucks.

In order to assess the affect of double-dipping on APU electrical load, it is necessary to consider the characteristics of the electrical system of the trucks. The base engine

generates 12 volt direct current (VDC) power that is available via power ports. However, many accessories that a driver may wish to use for comfort, such as a coffeemaker or microwave, operate on 120 volt alternating current (VAC). The trucks do not have a power inverter to convert 12 VDC to 120 VAC. However, the base engine can power the heating and air conditioning systems that are integrated with the base engine.

Conversely, the APU generates 120 VAC power, which is available via conventional electrical receptacles in the truck. The APU can also power a separate electrically operated HVAC system. Thus, if both the base engine and APU are used simultaneously, it is possible to operate two HVAC systems. A driver might want to do this, for example, to help rapidly cool the interior space if the space had been unconditioned during hot weather. However, only the APU system can be used to operate loads that require 120 VAC.

The data for Truck No. 10 imply that at very high temperature, the APU system had a much lower electrical load than for the other trucks. This result is consistent with a scenario in which both the base engine and APU engine are used simultaneously, and in which the base engine air conditioning system is providing most or all of the cooling required. The APU is probably being used only for other electrical loads, which would be consistent with the relatively low electrical load of about 500 W. Furthermore, a load of about 500 W is typical of mild temperature operations for the other trucks, when neither heat nor cooling is required.

Figure C-3 illustrates the average electrical load for four sets of trucks based on fleet and type of APU with respect to ranges of temperature during double-dipping. Most trucks have lower average electrical loads during double-dipping than those excluding the data

during double-dipping at any given temperature range. Thus, the load levels for most trucks are approximately consistent with little to no usage of the electrically operated HVAC system. In contrast, Truck No. 13 has much higher average electrical loads, implying that the drivers of this truck operated two HVAC systems for the tractor and APU simultaneously sometimes.

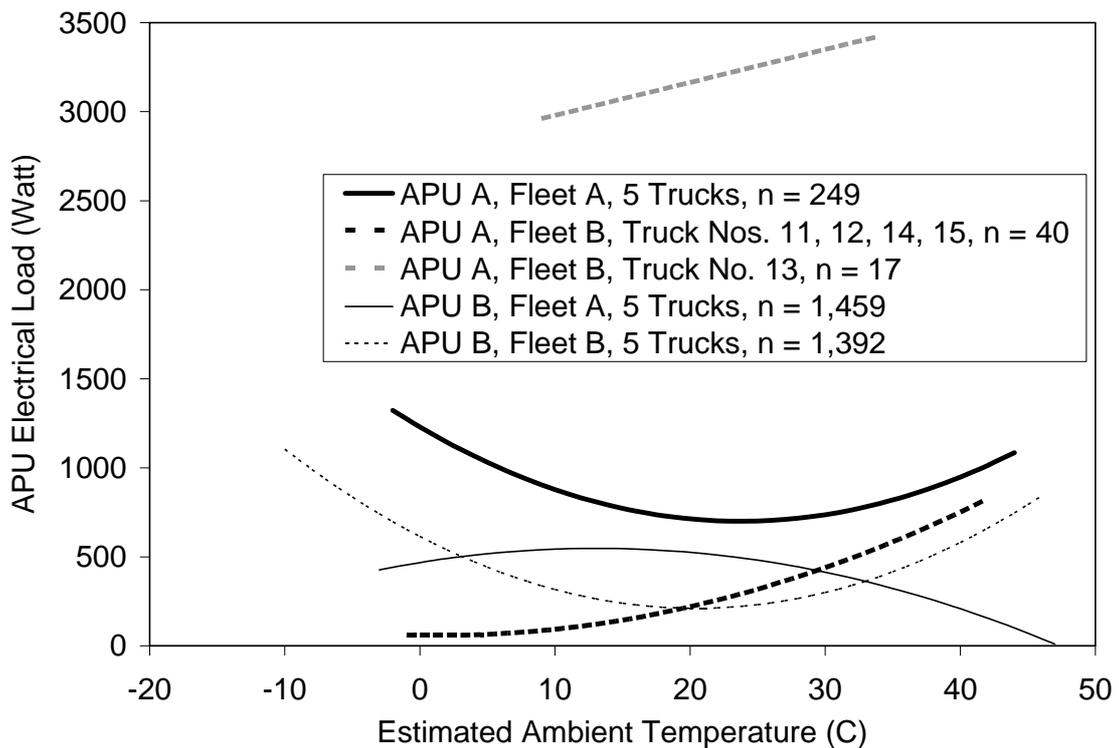


Figure C-3. Average Trends in Auxiliary Power Unit Electrical Load versus Ambient Temperature for the Data during Double-Dipping

Because double-dipping is counter-productive to the intended use of the APU, a decision was made to exclude the data during double-dipping from the analysis of average electrical load versus ambient temperature for the situation in which the APU, and not the base engine, is used to supply space conditioning needs. The resulting comparison of

average electrical load versus ambient temperature is given in Figure C-4. This is also shown as Figure 3 in the main paper. With double-dipping data excluded, the average trends for all sets of trucks are similar.

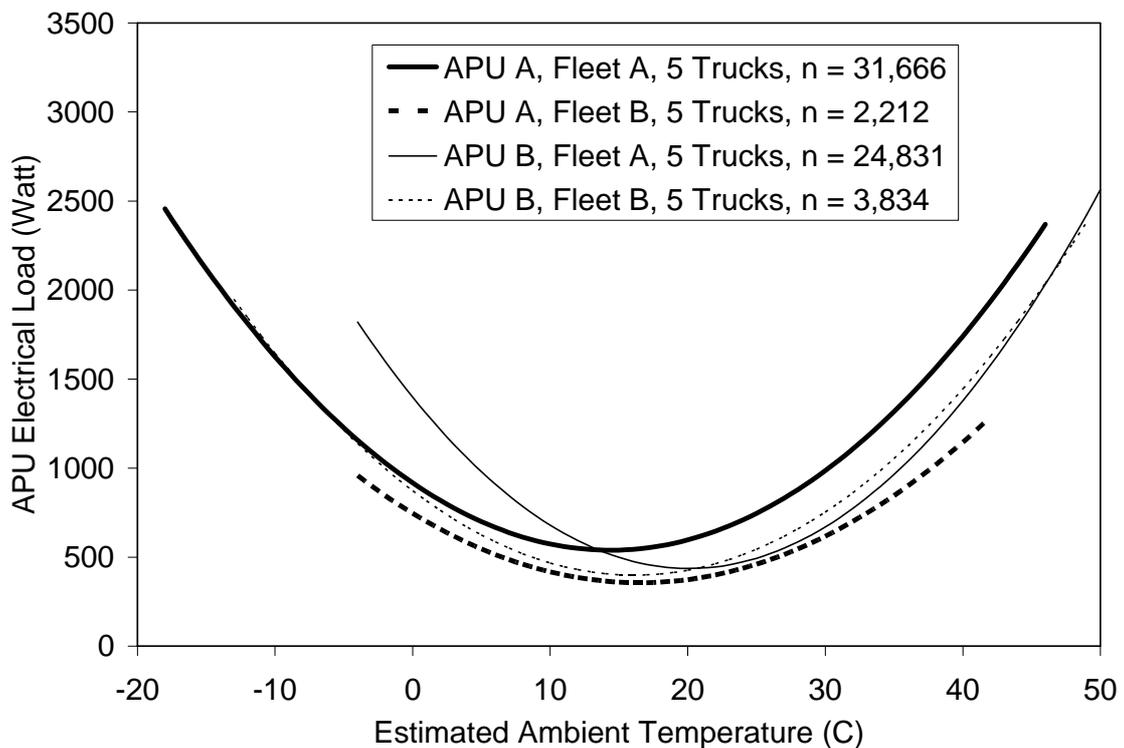


Figure C-4. Average Trends in Auxiliary Power Unit Electrical Load versus Ambient Temperature Excluding Data during Double-Dipping

Based on the APU fuel use rate versus electrical load given in Figure 2 and average APU electrical load given in Figure C-4, average fuel use rates versus ambient temperature are estimated. The comparison of average fuel use rates versus ambient temperature for each combination of Fleet and APU is given in Figure C-5. The results clearly show the expected trend in which average fuel use rates for both APU engines are highest at very low or high

temperature and lowest at moderate temperature. There are larger differences in fuel use rates when comparing the two APUs than when comparing the two fleets. Even though the average trends in APU electrical load versus ambient temperature for APU-A are similar to those for APU-B, the fuel use rates for APU-A are higher than those for APU-B, especially during mild weather.

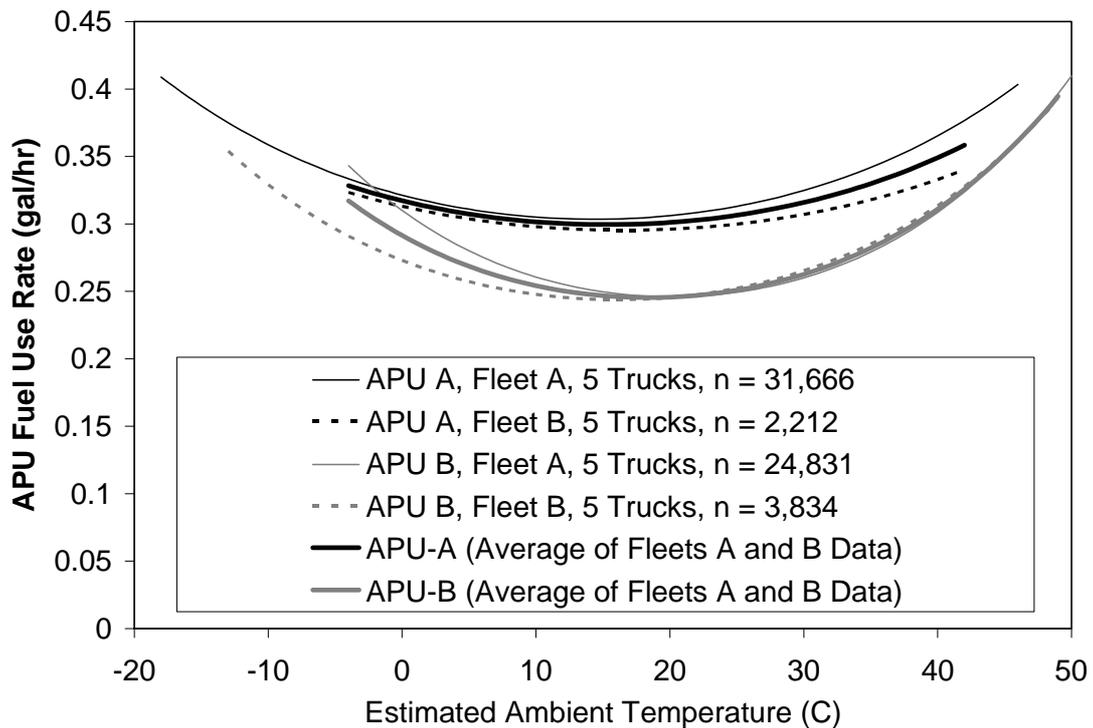


Figure C-5. Auxiliary Power Unit Fuel Use Rates versus Ambient Temperature

SECTION D. Emissions Measurements for the Base Engine and Auxiliary Power Units

Fuel-based emission factors are estimated based on fuel properties, the fraction of carbon allocated among exhaust CO₂, CO and HC, and the molar ratio of exhaust NO (as NO₂) to CO₂. Diesel fuel contains 86.9 weight percent of carbon and 13.1 weight percent of hydrogen, and has a density of 3,212 grams per gallon (Lim, 2002). Exhaust emissions were measured using a Portable Emission Measurement System (PEMS). The results of emission concentration measurements for the tested base engine and two types of the APUs are summarized in Tables D-1.

Table D-1. Exhaust Concentration Measurements for the Base Engine and Auxiliary Power Units^a

Source	Load (kW)	Diesel Fuel Use Rate (gallon/hr)	Average NO Concentration (ppm)	Average HC Concentration [ppm]	Average CO Concentration [ppm]	Average CO ₂ Concentration [ppm]
Base Engine	659.4 rpm, A/C Off	0.57	222	9	67	15000
	660.0 rpm, A/C off	0.55	221	9	79	14700
	659.9 rpm, A/C On	0.71	270	11	69	20700
APU-A	0	0.28	62	21	453	35000
	948	0.32	96	19	361	41500
	1842	0.37	136	13	300	48400
	2727	0.43	183	16	222	54600
	2727	0.43	179	22	250	54400
	3516	0.48	233	21	194	59000
	4380	0.55	260	22	185	63000
APU-B	0	0.22	147	18	178	31800
	1100	0.29	218	17	139	40800
	2070	0.36	265	12	122	51200
	3040	0.46	330	10	141	65200

^aFor numbers that are italicized, the average exhaust concentrations from the measurements are below the detection limits of 20 ppm for HC and 200 ppm (0.02 vol-%) for CO. For these numbers, there is less confidence in the stability of the mean values (Zhao and Frey, 2004).

Most of the average exhaust measurements of HC and CO were below the detection limits of 20 ppm and 200 ppm, respectively (Frey et al., 2007). When the average is below the detection limit, there is less confidence in the stability of the mean values (Zhao and Frey, 2004). Such situations do not imply that the data are useless, but that they should be interpreted with care. Average concentrations that are below the detection limit are shown in italicized font style in Table D-1.

To assess repeatability, the emission rates for the base engine without air conditioning load and for APU-A for an electrical load of 2.7 kW were measured twice. The differences in the emission concentrations for NO and CO₂ for the repeatability tests are less than 2% for both base engine and APU. With good test repeatability, the measurement quality was assured for these pollutants.

As expected, fuel use rate increases with load for all three tested engines. The exhaust concentration of CO₂ increases monotonically with load, indicating that the air-to-fuel ratio decreases with load. The exhaust concentration of NO increases monotonically with load. The average exhaust concentration tends to decrease with load; however, for the base engine and APU B these results are not considered to provide a significant insight regarding trend since these averages are below the detection limit. For APU A, the average exhaust concentrations for CO at low load are above the detection limit. Thus, it is clear that CO concentration is higher at low load than at high load for this engine. For HC, the average concentrations are above the detection limit for a few loads for APU A. However, overall the data are consistent with no significant trend in HC concentration versus load.

The fuel-based and time-based emission factors for APU A are given in Figure D-1. The fuel-based emission factors increase with load for NO and decrease with load for CO. For HC, the trend is not significant. A relative indication of PM emission rate based on the light scattering detection method of the PEMS implies that the fuel-based PM emission rate is not very sensitive to engine load. For the time-based emission factors, NO and CO emission rates are highly sensitive to load. The HC and PM emission rates are weakly or not significantly sensitive to load.

The results for APU B, shown in Figure D-2, are qualitatively similar to those for APU A with a few exceptions. The fuel-based NO emission rate is not sensitive to load. The time-based emission rates for HC and PM appear to be more sensitive to load.

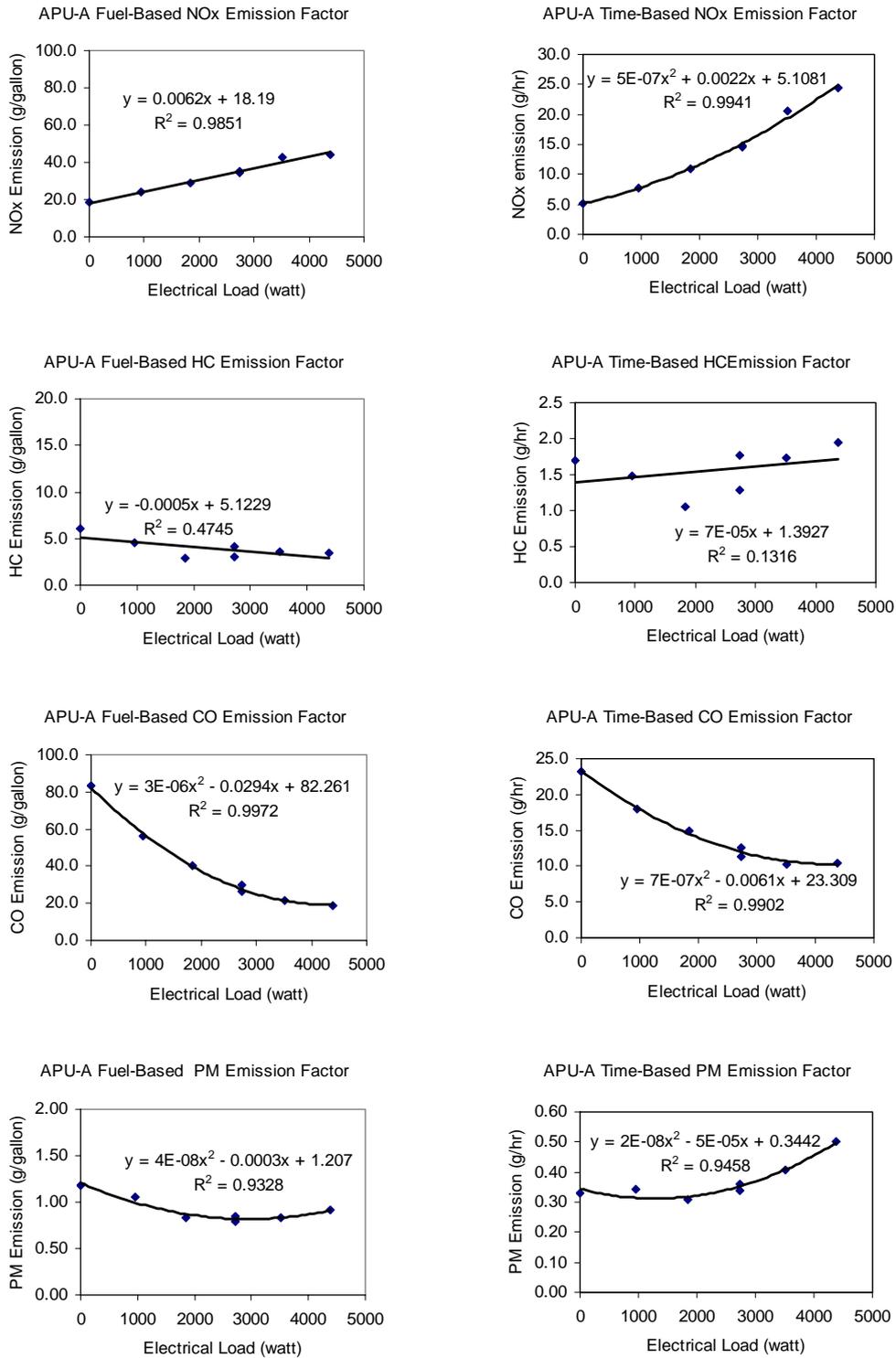


Figure D-1. Fuel-Based and Time-Based Emission Factors for APU A

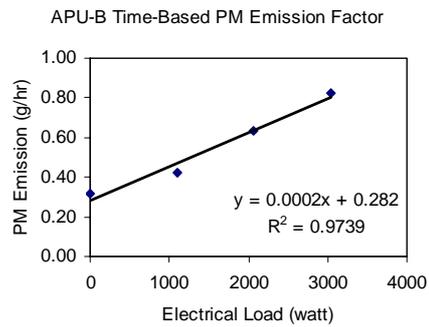
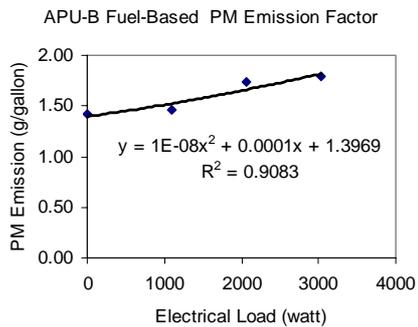
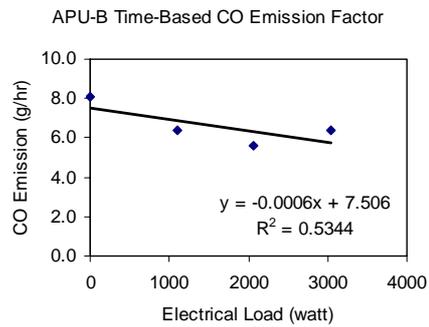
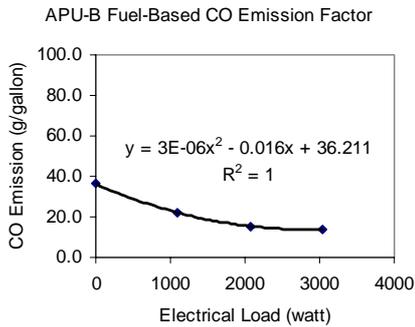
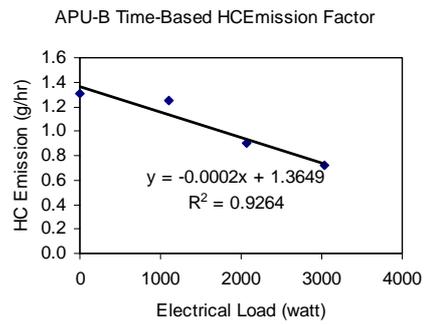
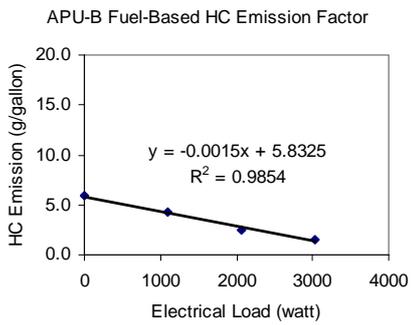
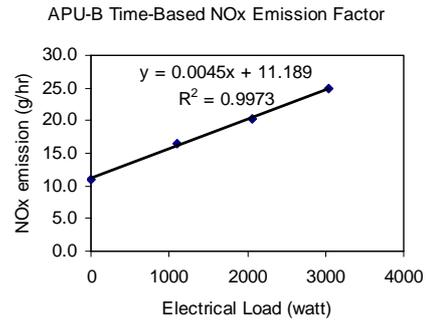
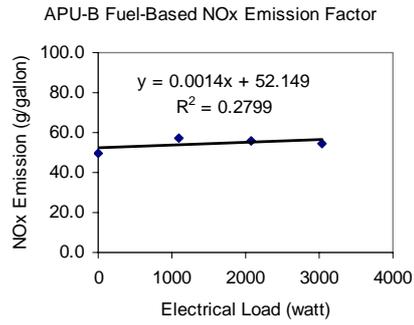


Figure D-2. Fuel-Based and Time-Based Emission Factors for APU B

Section E. Benchmark Comparisons of Measured Fuel Use and Emission Rate Data

Fuel Use Rates and Emission Factors for the Base Engine

For purposes of this study, ECU-reported fuel use rates are used as the basis for the data.

ECU-reported fuel use rates were compared to actual fuel use rates as measured by an AVL PLU 401/108 Universal Fuel Meter, and the differences were found to be within $\pm 5\%$ over a variety of idle RPMs and idle loads.

In order to evaluate the fuel use rates estimated here, they are compared to other reported values, which range from 0.29 to 1.65 gal/hr. The comparisons for the base engine are given in Table E-1. Although the conventional wisdom is that trucks typically consume 1 gallon per hour at idle, both other reported data and this study demonstrate that actual idle fuel use may be much lower, depending on the engine. The fuel use and emission rates estimated here are within the range of values reported elsewhere, and are deemed to be reasonable.

Auxiliary Power Unit Fuel Use Rates

Comparisons of APU fuel use rates measured here to those reported elsewhere are given in Figure E-1. These values range from approximately 0.1 to 0.45 gal/hour, depending on the make and model of the APU and either load or ambient conditions. The measured APU fuel use rates are generally at the upper range of other reported values, depending on load. There is not as yet a consistent methodology by which vendors measure or certify their reported fuel consumption rates.

An EPA-conducted study tested an APU with the same engine model and RPM as those for APU-A. The main difference between the EPA-tested APU and the APU-A is the integration of the APU with the HVAC systems. The EPA-tested APU has its own compressor and condenser, but utilizes existing truck cooling and heating systems, such as evaporator, coolant, heater cores, fan, and blowers of tractors. The APU-A system, on the other hand, has an independent cooling and heating system. The APU fuel use rates at hot weather estimated by EPA were 0.23 gal/hr,¹ which was significantly lower than 0.38 gal/hr of fuel use rates for APU-A at hot weather. This implies that the integrated APU system may be more fuel-efficient than the independent APU system, but further evaluation is needed to characterize and verify this.

Auxiliary Power Unit Emission Factors

The APU emission factors measured or estimated in this study are compared to other reported values in Table E-2. The fuel-based emission factors are similar for HC, CO and PM, and similar or lower for NO_x. For example, when converted to a fuel basis, the reported NO_x emission factors range from 36 to 64 g/gallon. The measured NO_x emission factors for APU B are from 50 to 55 g/gallon for most loads of interest. The measured NO_x emission factors for APU B are of the same order of magnitude but somewhat lower, at approximately 20 g/gallon. On a per time basis, the estimated APU emission rates of 5 to 25 g/hour compare with values from 7 to 42 g/hour reported elsewhere. On a per time basis, the CO₂ emission rates tend to be higher because of the higher fuel consumption. The time-based emission rates of the other pollutants are comparable to the other reported values.

Table E-1. Comparison of Base Engine Idle Fuel Use Rates and Emission Factors

Source	Fuel Use Rate (gal/hr)	NO _x Emission Factor (g/hr)	HC Emission Factor (g/hr)	CO Emission Factor (g/hr)	CO ₂ Emission Factor (kg/hr)	PM Emission Factor (g/hr)	Engine Characteristics	Comments
This Study	0.46-0.65	71-100	2.8-3.9	13.1-18.5	4.7-6.6	1.1-1.5 ^a	2006 Volvo VED-12; 465 HP (Fleet A)/ 435 HP (Fleet B); 12.13 L	20 vehicles
Khan et al., 2006	0.29-1.17	4-196	1-95	4-85	avg. 4.5-4.6	N.D.-16	Engine model year: 1974-2004; engine power: 200-530 HP	75 vehicles, 600 rpm
Lim, 2002; Storey et al., 2003	0.39-1.65	20-329	N/A	N/A	3.9-16.6	0.8-20.6	Engine model year: 1990-2000; engine power: 370-500 HP	9 vehicles, vary depending on engine size, engine speed, ambient temperatures and accessory loads
Stodolsky et al., 2000	1.0	55.0-56.7	12.5-12.6	94.0-94.6	10.4	2.57	N/A	With heating or A/C
Brodrick et al., 2002	0.36-0.93	103-254	1.4-86.4	14.6-189.7	4.0-9.7	N/A	1999 Freightliner Century Class truck with 450 HP engine	1 truck, Idling after cruise or transient at 600 rpm without A/C; Idling at 600 or 1050 rpm with A/C
McCormick et al., 2000	N/A	63-115	3.6-12.5	43.6-128.3	N/A	1.0-2.2	Engine model year: 1989-1999; engine power: 175-450 HP; 7.3-12.7 L	12 trucks at 1609 meters above sea level
Lutsey et al., 2004	0.5-1.7	N/A	N/A	N/A	N/A	N/A	N/A	A nationwide survey for long-haul truck drivers ; engine speeds vary from 500 rpm to 1,300 rpm

^a PM emission factors are estimated based on data from Khan et al., 2006 and Storey et al., 2003

Table E-2. Comparison of Auxiliary Power Unit Fuel Use Rates and Emission Factors

Source	Description	Fuel Use Rate (gal/hr)	Fuel-Based Emission Factor (g/gal)				Time-Based Emission Factor				
			NO _x	HC	CO	PM	NO _x (g/hr)	HC (g/hr)	CO (g/hr)	CO ₂ (kg/hr)	PM (g/hr)
This study	APU-A, 0.48 L, Electrical load: 0-3 kW	0.28-0.45	18.4-20.1	3.6-6.0	29.2-83.0	3.3 ^a	5.1-16.2	1.4-1.6	11.3-23.3	2.8-4.5	0.9-1.5 ^a
	APU-B, 0.48 L, Electrical load: 0-3 kW	0.22-0.45	49.5-54.6	1.6-5.9	14.0-36.2	3.3 ^a	11.2-24.7	0.8-1.4	5.7-7.5	2.3-4.6	0.7-1.5 ^a
Lim, 2002; Storey, 2003	Pony Pack APU, ambient temperature: 0°F and 90°F	0.2-0.23	36.3-43.5	N/A	N/A	2.2-4.2	7-11	N/A	N/A	2.05-2.35	0.5-1
Stodolsky et al., 2000	Pony Pack APU, vendor data	0.08-0.3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Pony Pack APU, 0.47 L, Winter/Summer	0.18/N/A	64/N/A	2.7/N/A	42/N/A	3.8/N/A	12/23	0.5/0.9	7.5/15	1.87/N/A	0.69/1.4
	Pony Pack APU, 0.39 L, Year-round	N/A	N/A	N/A	N/A	N/A	41.5	9.7	35.9	N/A	3.1

^a PM emission factors are estimated based on data from Storey et al., 2003 and Stodolsky et al., 2000

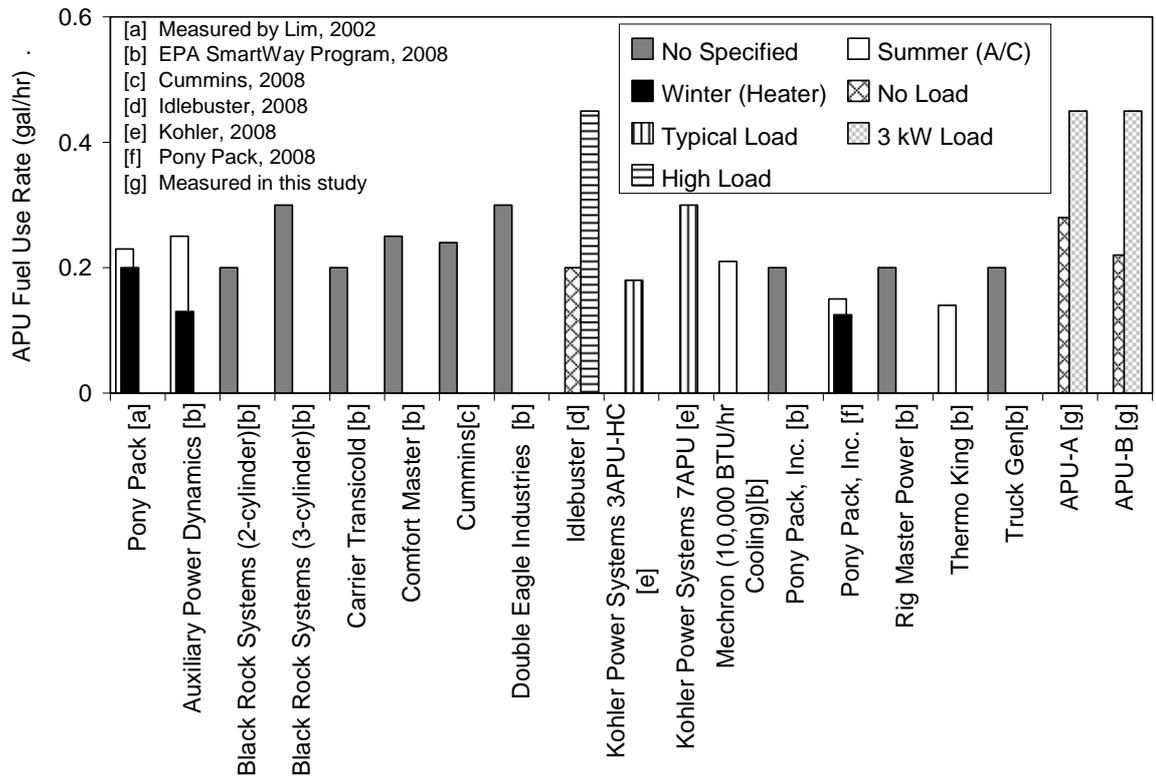


Figure E-1. Comparison of Auxiliary Power Unit Fuel Use Rates

Section F. Sensitivity Analysis of Fuel Use Rates for the Base Engines and APUs

Sensitivity analysis was applied to assess the possible ranges of variability in estimated the fuel use rates for the base and APU engines under real-world conditions. The ranges of the inputs were determined based on the observed data for the fleets.

The key inputs selected for the sensitivity analysis for potential fuel use reduction for APU usage are engine speeds for the base engine and ambient temperatures for the base engine and the APU.

For the base engines of each fleet, three RPM values are selected in order to represent a range of typical observed settings. These include 590, 700, and 940 RPM for Fleet A and 600, 680, and 1,000 RPM for Fleet B. For each combination of Fleet and RPM setting, the average fuel use rate is shown in Figure F-1 only for the range of temperatures actually observed.

There is substantial variability in fuel use rates for the base engine with respect to engine speed. For example, the fuel use rate for Fleet B at high RPM and hot weather is about 3 times of that at low RPM and mild weather. The variations in engine speed have more significant effects on fuel use than the variations in ambient temperature. For example, the fuel use rate for Fleet B at high RPM and hot weather is about 2.5 times of that at low RPM and hot weather.

Variations in base engine speed have significant effects on the differences between the fuel use rates of the base versus APU engines. For example, at a high temperature of 38°C, the fuel use rates for the base engines of Fleets A and B are higher than that for the APU

engines by 64-69 percent. However, at the same temperature but low base engine RPM, the difference is only 5 to 39 percent.

There is variability in base and APU engine fuel use rates with respect to ambient temperature. For example, the base engine fuel use rate for Fleet B at low RPM and high temperature is about 11 percent higher of that at the same RPM and mild temperature (of 15°C). The APU fuel use rates at high temperature are 13 to 16 percent higher than at mild temperature.

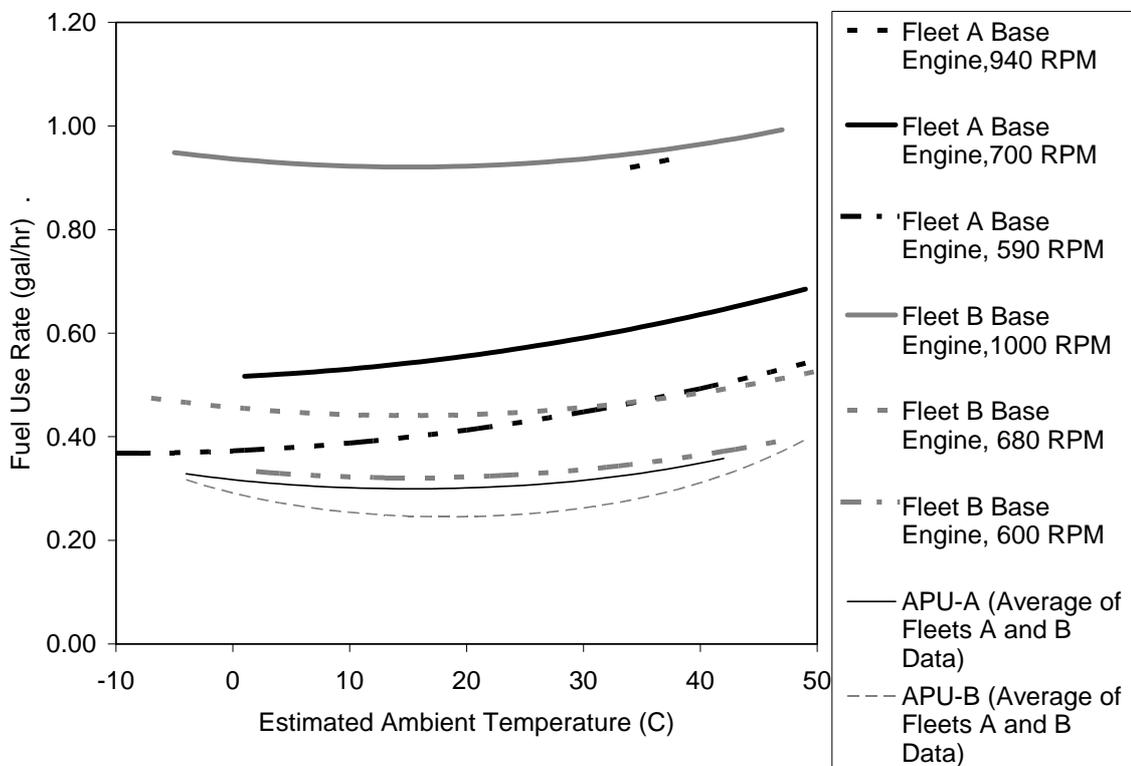


Figure F-1. Sensitivity of Base and Auxiliary Power Unit Engine Fuel Use Rates to Ambient Temperature

APPENDIX C

INTRODUCTION

This Supporting Information supplements the Part V of the main text. The information is provided in Sections as follow:

- A. Truck and auxiliary power unit specifications;
- B. Distribution of locations of all truck activities for Fleets A and B for all data collected over multiple seasons;
- C. Distribution of time among powered stop scenarios for all 20 field trucks;
- D. Energy use rates and emission factors for the base engine, auxiliary power unit and shore-power;
- E. Avoided energy use and emissions for actual versus base engine scenarios;
- F. Avoided energy use and emissions for shore-power versus base engine scenarios;
- G. Fuel penalty due to APU weight and adjusted avoided fuel use; and
- H. Sensitivity analysis for net savings per unit of energy use reduction and simple payback periods

Section A. Truck and Auxiliary Power Unit Specifications

The field study includes twenty new Volvo long-haul sleeper cab trucks for interstate freight shipments. These trucks include 10 of Fleet A and 10 of Fleet B. Both fleets are equipped with 2006 Volvo VED12 12.1 liter engines. The Fleet A engines are rated at 465 hp versus 435 hp for Fleet B. The difference in rating is attributed to differences in timing and duration of fuel injection. Fleet A has 375 ft³ Volvo VNL 780 sleeper cabs with black exterior paint; whereas Fleet B has 200 ft³ Volvo VNM 630 sleeper cabs with white exterior paint. All trucks are equipped with Auxiliary Power Units (APUs) and are shore-power compatible. These engines comply with EPA's 2004 Heavy Duty Diesel emissions requirements for diesel highway vehicles. The specifications of these trucks and their APU units are summarized in Table A-1.

Each fleet has 5 trucks with diesel-powered APU system A and 5 trucks with diesel-powered APU system B. Both APU systems are equipped with 2006 Kubota Z482 0.48 liter engines. The engines are rated at 10.9 hp @3,600 RPM and 7.4 hp @2,400 RPM. For APU A, the 3,600 RPM setting is used, and for APU B, the 2,400 RPM setting is used. These differences in RPM are because of the generator specifications. APU-A has a direct-driven 6 kW generator and APU-B has a belt-driven 4 kW generator. The Kubota engines are reported by the manufacturer to comply with the 2005 Tier II emission standards applicable to nonroad engines. The HVAC system for APU-A has an "ECONO" mode setting that cycles the engine on and off based upon heating or cooling demand. APU-B does not have this feature. .

Table A-1. Truck and Auxiliary Power Unit Specifications

Fleet or APU Type	Specifications	Engine	Note
Fleet A	Volvo VNL 780 sleeper cab, 375 cubic feet	2006 VED12 (465 hp @ 1,800 RPM, 12.1 liters)	Black vehicle body; complies with EPA's Tier II standards for diesel highway vehicles
Fleet B	Volvo VNM 630 sleeper cab, 200 cubic feet	2006 VED12 (435 hp @ 1,800 RPM, 12.1 liters)	White vehicle body; complies with EPA's Tier II standards for diesel highway vehicles
APU-A	Direct-drive 6kW 120Vac generator; 14K BTU/hr HVAC system	2006 Kubota Z482 (10.9 hp @3,600 RPM, 0.48 liters)	ECONO mode in which APU cycles on and off to save fuel; complies with 2005 Tier II emission standards applicable to nonroad engines
APU-B	Belt-drive 4kW 120Vac generator; 14K BTU/hr HVAC system	2006 Kubota Z482 (7.4 hp @2,400 RPM, 0.48 liters)	Complies with 2005 Tier II emission standards applicable to nonroad engines

Section B. Distribution of Locations of All Truck Activities for Fleets A and B for all Data Collected over Multiple Seasons

To gain further insight regarding the variation in ambient temperatures for the two fleets, a map of the GPS position data for both fleets is shown in Figure B-1. This map includes all truck activities using the base engine, the APU, or both. The trucks operated for over 2.8 million miles in 42 states during the data collection period, which ranged from September 2006 to February 2008.

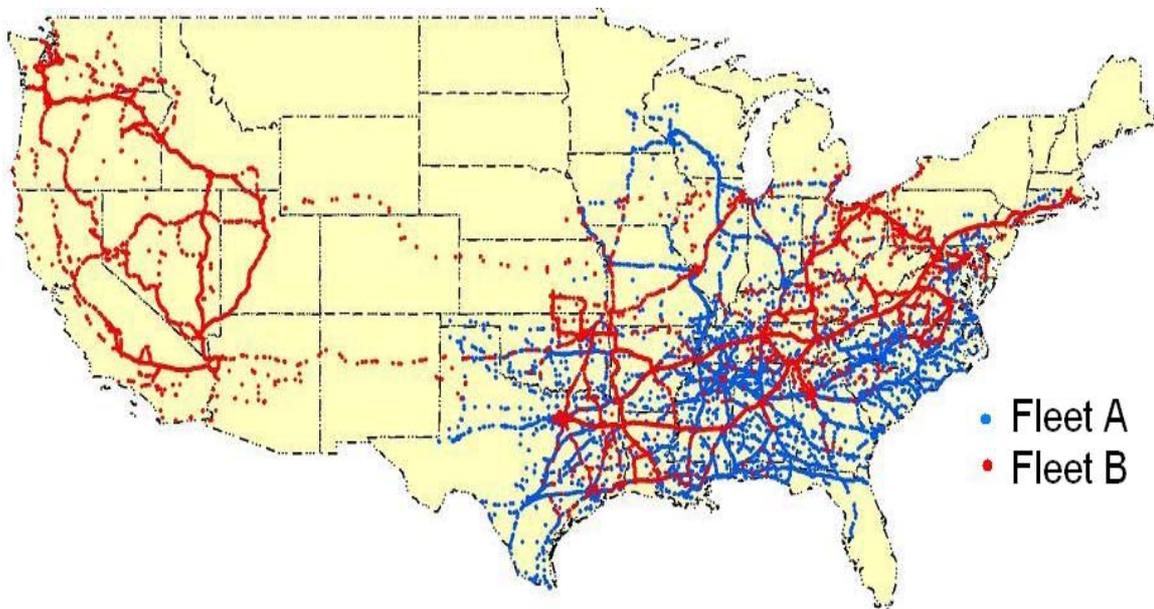


Figure B-1. Distribution of Locations of All Truck Activities for Fleets A and B for all Data Collected over Multiple Seasons.

The data imply that Fleet A tends to operate mainly in Southeastern states such as North Carolina, South Carolina, Georgia, Florida, and Alabama, as well as other southern

states such as Mississippi, Louisiana, and Texas, among others. There is some travel by Fleet A trucks as far north as Michigan and Connecticut, for example, but these activities represent a small proportion of the total fleet movements. Based on the locations of Fleet A trucks, one can expect a wide range of ambient temperatures.

Fleet B trucks operated in the mid-Atlantic region that overlaps with much of Fleet A's operations, as well as in Texas. However, Fleet B trucks also operated out of a hub in Arizona, and as a result traveled the west coast in California, Oregon, and Washington as well as neighboring states such as Utah and Nevada. Fleet B trucks also may have had more operations in some northeastern or upper Midwestern states such as Pennsylvania and Ohio. These activity patterns are consistent with the wider extremes of temperatures observed for Fleet B versus Fleet A for both very cold and very hot conditions.

Section C. Distribution of Time among Powered Stop Scenarios

Drivers are making different choices regarding whether to meet their comfort needs using the base engine or the APU. As shown in Figure C-1, drivers for three of the Fleet A trucks prefer to use the base engine during all stops, while drivers for seven of the Fleet A trucks tend to use the APU more often for such stops. One truck uses the APU intensively even when the stop duration is less than 3 hours. For Fleet B, most trucks, except Truck No. 15, have the total time of the APU usage shorter than the total time of the base engine idling.

Simultaneous use of APU and base engine was detected in 6 trucks, with those occurrences accounting more than 25 hours of annual usage per truck. The results imply that these types of activities may be significant during the test periods for some trucks, which cause negative impacts on fuel use savings for truck APUs.

On-board shore-power system was less used. When shorepower was used, the electrical load was only about 100 W, which implies usage of shorepower to maintain the charge of batteries in the truck. Use of off-board shore-power system (i.e. IdleAire) was not detected.

As shown in Figure C-1 and C-2, the preferences regarding the source of power during idle for a given driver during all stops versus extended idling are similar. Drivers for eight of the Fleet A trucks prefer to use the APUs during extended idling, while drivers for eight of the Fleet B trucks tend to use the base engines more often for such stops.

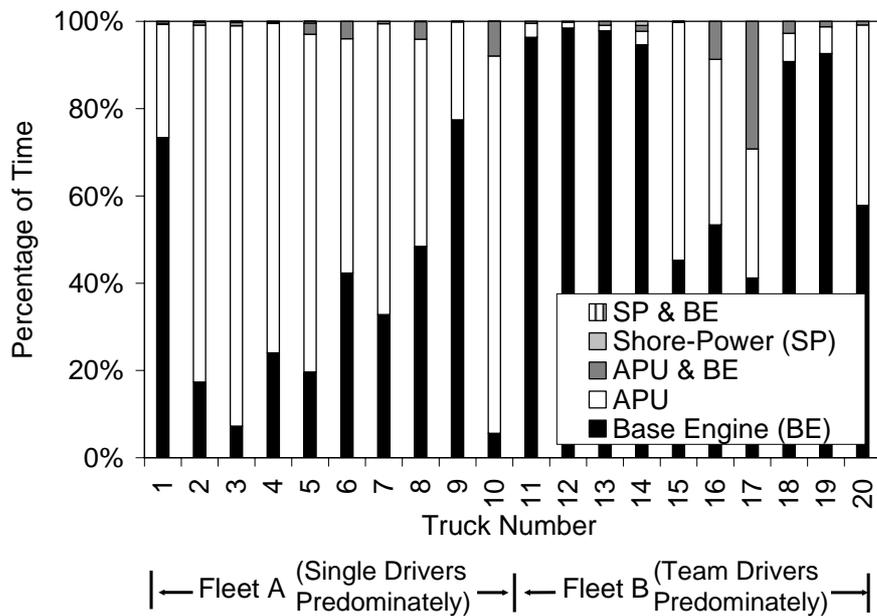


Figure C-1 Percentage of Time of Powered Stop Scenarios for All Stop Durations for 20

Field Trucks

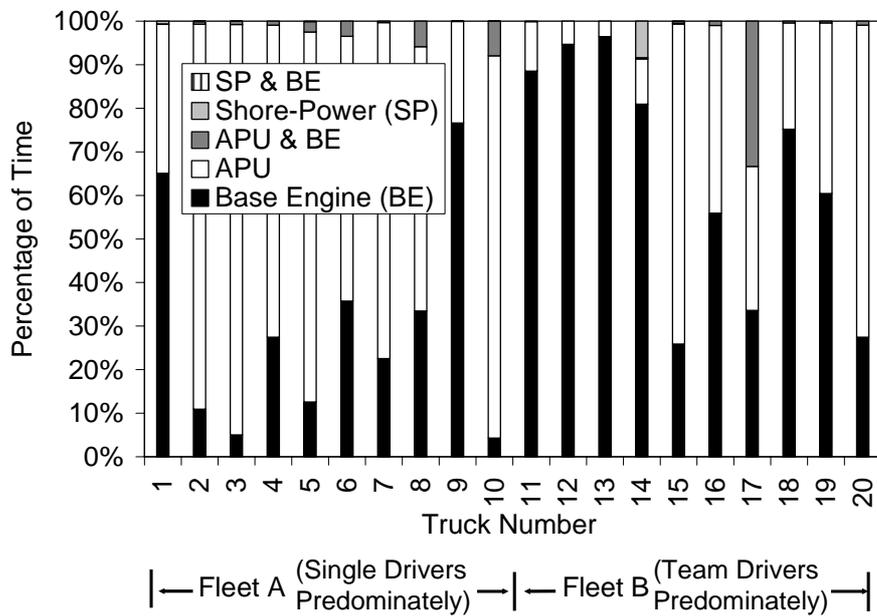


Figure C-2 Percentage of Time of Powered Stop Scenarios for Extended Idling Durations for 20 Field Trucks

Section D. Energy Use Rates and Emission Factors for the Base Engine, Auxiliary Power Unit and Shore-Power

In order to directly compare the energy use and emission rates between the base engine, APUs, and SP, two scenarios were developed. A “mild temperature” scenario is based on the energy use and emission rates typical of temperatures ranging from 10 °C to 20 °C, whereas a “high temperature” scenario is based on temperatures of 30 °C or more. The typical average load for the former is approximately 500 W, versus 2,000 W for the latter. The results for these scenarios are given in Table D-1.

Table D-1. Energy Use Rates and Emissions Factors for the Base Engine, Auxiliary Power Unit and Shore-Power

Source	Mild Temperature Scenario ^a							High Temperature Scenario ^a						
	Energy Use (gal eq./hr)	NO _x (g/hr)	HC ^b (g/hr)	CO ^b (g/hr)	CO ₂ (kg/hr)	PM (g/hr)	SO ₂ (g/hr)	Energy Use (gal eq./hr)	NO _x (g/hr)	HC ^b (g/hr)	CO ^b (g/hr)	CO ₂ (kg/hr)	PM (g/hr)	SO ₂ (g/hr)
Base Engine (BE)	0.47	72.2	2.8	13.4	4.8	1.1	0.024	0.60	92.2	3.6	17.1	6.1	1.4	0.031
APU-A	0.30	6.3	1.4	20.4	3.0	1.0	0.016	0.38	11.5	1.5	13.9	3.9	1.3	0.020
APU-B	0.25	13.4	1.3	7.2	2.5	0.8	0.013	0.36	20.2	1.0	6.3	3.6	1.2	0.019
Shore-Power (SP)	0.039	0.50	0.008	0.061	0.32	0.088	1.2	0.16	2.0	0.031	0.24	1.3	0.35	5.0

^aThe mild weather scenario (a temperature range of 10 to 20°C) has a low accessory load of 0.5 kW and the high scenario (a temperature range of 38°C or higher) has a high accessory load of 2 kW based on typical values for APU electrical load. The data used here are from the emission tests reported in Frey and Kuo (2008).

^bFor numbers that are italicized, the estimates are based on average exhaust concentrations from measurements below the detection limits of 20 ppm for HC and 200 ppm for CO. For these numbers, there is less confidence in the stability of the mean values.

Since the base engine fuel-based emission factors are relatively insensitive to load, an average of these emission factors is used in combination with the observed base engine fuel

use rates from the field study in order to estimate time-based emission rates. The APU emission rates are estimated for a given fuel flow based on curve fits for fuel-based emission rate versus fuel flow. Shore-power energy-based emission rates are a constant per unit of electricity consumed, regardless of load. The fuel or energy-based emission rates are multiplied by fuel or energy use rate to estimate time-based emissions rates.

At mild temperature, APU usage instead of the base engine leads to an 80 to 90 percent reduction in NO_x emissions, 36 to 47 percent reduction in CO₂ emissions and fuel use, and 10 to 25 percent reduction in PM emissions. The estimated percent reductions in HC and CO emissions are based on average concentrations below detection limits. Thus, although these data indicate a possible reduction in HC emissions, and a reduction in CO emissions for APU-B, they are not conclusive. On the other hand, the emission rates of HC and CO from diesel engines are typically low, and the pollutants of more substantial concern from such engines are typically NO_x, PM, and CO₂.

At high temperature, the estimated relative emissions reductions for the APU versus base engines are slightly lower than for the mild temperature case, but the magnitude of the emissions reductions is higher. For example, NO_x emissions are lower by 78 to 88 percent, which is a slightly lower percentage than for the mild temperature case, but these reductions are with respect to a higher magnitude of base engine emissions of 92 g/hr versus 72 g/hr. Likewise, the reductions in CO₂ and PM emissions are similar on a relative basis but higher on an absolute basis.

Compared to the base engine, shore-power will produce larger reductions in emissions than can be achieved with APUs, on both a relative and absolute basis. For the high

temperature scenario, SP consumes 74 percent less energy and produces 79 percent lower CO₂ emissions, while achieving NO_x reductions of 98 percent and PM reductions of 75 percent. The disadvantage of SP is that it leads to higher emissions of SO₂. When compared to APUs rather than the base engine, SP has substantial reductions in energy use and emissions, except for SO₂. Of course, the SO₂ emissions from power plants have been the subject of increasingly stringent regulation, and over time these emissions are likely to continue to decrease.

Section E. Avoided Energy Use and Emissions for Actual Scenario versus Base Engine Scenario

In order to assess the real world avoided fuel use and emissions for the observed usage of APUs and SP versus base engine, the actual and base engine scenarios are compared. The differences between these scenarios are the avoided fuel use or emissions attributable to the usage of the APU and SP in real world conditions.

The average and range of avoided fuel use and emissions for all stop durations and extended idling durations are summarized in Tables E-1 and E-2. Table E-1 provides the percentage reduction in fuel use and emissions, and Table E-2 provides the amount of avoided fuel use and emissions. Table E-2 is also shown as Table 1 in the main paper. The avoided fuel use attributable to the APU operation and those attributable to the SP operation are summarized in Table E-3 as an example for the portions of the contribution from the APU and SP. The APUs were used predominately in the real world conditions. Hence, this comparison is effectively one for real-world APU usage versus the base engine, since SP usage was negligible.

Table E-1 Percentage of Avoided Energy Use and Emissions for All Stop Durations and for Extended Idling Duration for Actual Scenario versus Base Engine Scenario

Fleet	APU	Stop Activity Range		Avoided Fuel Use (%)	Avoided CO ₂ Emissions (%)	Avoided NO _x Emissions (%)	Avoided HC Emissions ^c (%)	Avoided CO Emissions ^c (%)	Avoided PM Emissions (%)
A	APU-A	All Stop Duration ^a	Average	23	23	55	32	-18	8
			Range	8 to 31	8 to 31	19 to 76	11 to 43	-29 to -4	3 to 10
		Extended Idling Duration ^b	Average	29	29	70	41	-24	9
			Range	11 to 34	11 to 34	27 to 85	16 to 48	-35 to -8	3 to 12
	APU-B	All Stop Duration ^a	Average	22	22	39	28	23	11
			Range	10 to 28	10 to 28	16 to 62	11 to 38	10 to 32	6 to 17
		Extended Idling Duration ^b	Average	27	27	49	35	29	14
			Range	11 to 38	11 to 38	18 to 67	13 to 49	11 to 43	7 to 22
B	APU-A	All Stop Duration ^a	Average	3	4	9	5	-6	1
			Range	0 to 16	0 to 16	1 to 40	0 to 22	-24 to 0	0 to 4
		Extended Idling Duration ^b	Average	8	8	20	11	-9	3
			Range	1 to 25	1 to 25	1 to 65	1 to 35	-39 to 5	0 to 8
	APU-B	All Stop Duration ^a	Average	6	6	15	8	6	0
			Range	-1 to 14	-1 to 14	4 to 25	2 to 17	-1 to 14	-11 to 7
		Extended Idling Duration ^b	Average	17	17	34	22	17	5
			Range	-2 to 33	-2 to 33	20 to 60	3 to 41	-3 to 34	-16 to 17

^aAll stop duration: Annual sum of all hours of the combination of the duration of base engine idle, APU usage and shore-power usage

^bExtended Idling Duration: Annual sum of all hours of the combination of the duration of base engine idle, APU usage and shore-power usage excluding stops shorter than the criterion for extended idling duration, which is 7 hours

^cFor numbers that are italicized, the estimates are based on average exhaust concentrations from measurements below the detection limits of 20 ppm for HC and 200 ppm for CO. For these numbers, there is less confidence in the stability of the mean values.

Table E-2 Absolute Amount of Avoided Energy Use and Emissions for All Stop Durations and for Extended Idling Duration for Actual Scenario versus Base Engine Scenario

Fleet	APU	Stop Activity Range		Avoided Fuel Use (gal/yr)	Avoided CO ₂ Emissions (kg/yr)	Avoided NO _x Emissions (kg/yr)	Avoided HC Emissions ^c (g/yr)	Avoided CO Emissions ^c (g/yr)	Avoided PM Emissions (g/yr)
A	APU-A	All Stop Duration ^a	Average	241	2460	89	2000	-5600	190
			Range	72 to 374	737 to 3830	25 to 142	603 to 3140	-10000 to -970	67 to 265
		Extended Idling Duration ^b	Average	194	1990	72	1620	-4700	149
			Range	46 to 273	472 to 2790	17 to 100	401 to 2250	-7500 to -880	34 to 218
	APU-B	All Stop Duration ^a	Average	281	2850	78	2120	8540	335
			Range	115 to 416	1170 to 4230	29 to 106	784 to 3190	3240 to 13200	166 to 576
		Extended Idling Duration ^b	Average	237	2400	66	1790	7200	280
			Range	96 to 388	979 to 3940	24 to 99	657 to 2970	2710 to 12300	140 to 539
B	APU-A	All Stop Duration ^a	Average	20	202	8	168	-950	9
			Range	1 to 89	10 to 910	1 to 35	16 to 735	-3900 to 4	-3 to 53
		Extended Idling Duration ^b	Average	17	171	7	138	-690	11
			Range	1 to 75	6 to 773	0 to 30	4 to 627	-3300 to 42	0 to 45
	APU-B	All Stop Duration ^a	Average	30	299	11	246	860	4
			Range	-4 to 71	-43 to 723	1 to 20	32 to 560	-200 to 2240	-140 to 86
		Extended Idling Duration ^b	Average	10	99	5	95	272	-15
			Range	-7 to 31	-68 to 314	1 to 12	22 to 225	-270 to 900	-140 to 37

^aAll stop duration: Annual sum of all hours of the combination of the duration of base engine idle, APU usage and shore-power usage

^bExtended Idling Duration: Annual sum of all hours of the combination of the duration of base engine idle, APU usage and shore-power usage excluding stops shorter than the criterion for extended idling duration, which is 7 hours

^cFor numbers that are italicized, the estimates are based on average exhaust concentrations from measurements below the detection limits of 20 ppm for HC and 200 ppm for CO. For these numbers, there is less confidence in the stability of the mean values.

Table E-3 Avoided Energy Use Attributable to Auxiliary Power Unit and Shore-Power^a

Fleet	APU	Truck No.	Avoided Fuel Use Attributable to APU Operation (gal/yr)		Avoided Fuel Use Attributable to SP Operation (gal/hr)	
			All Stop Duration	Extended Idling Duration	All Stop Duration	Extended Idling Duration
A	APU-A	1	63	44	9	2
		2	278	255	5	1
		3	366	257	8	0
		4	164	137	5	0
		5	298	272	8	1
		Average	234	193	7	1
	APU-B	6	367	252	0	0
		7	416	388	0	0
		8	197	160	0	0
		9	114	96	1	0
10		307	288	2	0	
Average		280	237	1	0	
B	APU-A	11	4	3	0	0
		12	1	1	0	0
		13	1	1	0	0
		14	1	1	3	2
		15	89	75	0	0
		Average	19	16	1	0
	APU-B	16	71	18	0	0
		17	-4	-7	0	0
		18	6	3	0	0
		19	3	3	0	0
20		71	31	0	0	
Average		29	10	0	0	

^aSum of avoided fuel use attributable to APU and SP operation is equal to absolute amount of avoided fuel use reported in Table C-2

Section F. Avoided Energy Use and Emissions for Shore-Power versus Base Engine Scenarios

In order to assess the real world avoided fuel use and emissions for SP versus base engine, the base engine scenario and shore-power scenario are compared. The shore-power scenario is based on the actual scenario but it assumes that the shore-power instead of the APU is used for all APU usage durations. The differences between the base engine scenario and shore-power scenario are avoided fuel use or emissions attributable to the usage of the SP as the only anti-idling techniques in the real world conditions.

The average and range of avoided fuel use and emissions for all stop durations for shore-power versus base engine scenarios are summarized in Tables F-1 and F-2. Table F-1 provides the percentage reduction in fuel use and emissions, and Table F-2 provides the amount of avoided fuel use and emissions. Table F-2 is also shown as Table 2 in the main paper.

Table F-1 Percentage of Avoided Energy Use and Emissions for All Stop Durations and for Shore-Power versus Base Engine Scenarios^a

		Avoided Energy Use (%)	Avoided NO _x Emission (%)	Avoided HC Emission (%) ^b	Avoided CO Emission (%) ^b	Avoided CO ₂ Emission (%)	Avoided PM Emission (%)
Fleet A, APU-A	Average	52	60	60	60	54	52
	Range	17 to 73	20 to 83	<i>20 to 84</i>	<i>20 to 83</i>	18 to 75	18 to 74
Fleet A, APU-B	Average	43	48	<i>49</i>	<i>49</i>	44	43
	Range	18 to 70	19 to 79	<i>19 to 79</i>	<i>19 to 79</i>	18 to 72	18 to 71
Fleet B, APU-A	Average	9	10	<i>10</i>	<i>10</i>	10	9
	Range	0 to 40	1 to 44	<i>1 to 44</i>	<i>1 to 44</i>	0 to 41	0 to 40
Fleet B, APU-B	Average	17	19	<i>19</i>	<i>19</i>	17	17
	Range	4 to 28	5 to 30	<i>5 to 30</i>	<i>5 to 30</i>	4 to 28	4 to 28

^aAll stop durations: Annual sum of all hours of the combination of the duration of base engine idle, APU usage and shore-power usage.

^bFor numbers that are italicized, the estimates are based on average exhaust concentrations from measurements below the detection limits of 20 ppm for HC and 200 ppm for CO. For these numbers, there is less confidence in the stability of the mean values.

Table F-2 Absolute Amount of Avoided Energy Use and Emissions for All Stop Durations for Shore-Power versus Base Engine Scenarios^a

		Avoided Energy Use (gal eq./yr)	Avoided NOx Emission (kg/yr)	Avoided HC Emission (g/yr) ^b	Avoided CO Emission (g/yr) ^b	Avoided CO ₂ Emission (kg/yr)	Avoided PM Emission (g/yr)
Fleet A, APU-A	Average	552	97	<i>3788</i>	<i>18039</i>	5767	1312
	Range	154 to 893	28 to 155	<i>1081 to 6071</i>	<i>5145 to 28919</i>	1617 to 9318	368 to 2124
Fleet A, APU-B	Average	554	95	<i>3718</i>	<i>17714</i>	5769	1318
	Range	208 to 763	34 to 132	<i>1340 to 5143</i>	<i>6390 to 24501</i>	2149 to 7946	495 to 1814
Fleet B, APU-A	Average	53	9	<i>348</i>	<i>1661</i>	548	126
	Range	3 to 230	1 to 38	<i>36 to 1498</i>	<i>171 to 7142</i>	37 to 2381	8 to 547
Fleet B, APU-B	Average	86	15	<i>581</i>	<i>2770</i>	894	204
	Range	10 to 143	2 to 25	<i>72 to 972</i>	<i>344 to 4629</i>	108 to 1486	25 to 341

^aAll stop durations: Annual sum of all hours of the combination of the duration of base engine idle, APU usage and shore-power usage.

^bFor numbers that are italicized, the estimates are based on average exhaust concentrations from measurements below the detection limits of 20 ppm for HC and 200 ppm for CO. For these numbers, there is less confidence in the stability of the mean values.

Section G. Fuel Penalty due to APU Weight and Adjusted Avoided Fuel Use

The purpose of this section is to estimate the incremental fuel use for each truck associated with the additional weight of the APU system. While the additional weight has no effect on fuel use during idling, it will lead to an increase in fuel use when the truck is moving. The magnitude of the incremental increase in fuel use is estimated and compared to the fuel savings associated with usage of the APU instead of the base engine during idling.

The weight of an APU system, which is about 380 lbs, is 0.5% of the weight of a loaded heavy-duty truck, which is typically 75,000 lbs (EPA, 2004b). In a study of dump trucks, an increase in vehicle weight was found to increase fuel consumption. When the vehicle was loaded, the weight was 2.4 times greater than when unloaded, and fuel consumption was 30 to 35% higher (Frey and Kim, 2006). Based on these data and a linear interpolation, a 0.5 percent increase in truck weight would increase truck fuel use by 0.1%.

The average fuel economy for long-haul trucks is estimated to be 5.9 miles/gal (BTS, 2008), which corresponds to an average fuel use rate of 0.17 gal/mile. The fuel penalty due to APU weight is the product of the percentage of fuel use increase due to APU weight, average fuel use per mile traveled for long-haul trucks and annualized total miles traveled.

The estimated fuel penalty due to APU weight is summarized in Table G-1. The estimated annual fuel penalty is approximately 17 to 24 gal/yr for each truck. The average penalty is 8 to 10% of the avoided fuel use for Fleet A when comparing the actual versus base engine scenarios. However, for individual trucks, the weight penalty during non-idle ranges from 5 to 33 percent of the avoided fuel use during idle. Thus, although the weight penalty is not negligible, it does not qualitatively alter the conclusion that there is a net fuel

use savings associated with the APU for Fleet A trucks. The net avoided fuel use for Fleet A trucks ranges from 42 to 394 gallons per year, with an average of approximately 225 gallons per year.

However, the situation for Fleet B is different since the gross amount of avoided fuel use during idle is typically much smaller than for Fleet A. Thus, although the fuel weight penalty is approximately the same as for Fleet A, since the trucks typically are driven a similar number of miles per year (e.g., approximately 115,000 miles per year for Fleet B versus approximately 127,000 miles per year for Fleet A), the Fleet B fuel weight penalty is a much larger percentage of the gross avoided fuel use. For 7 of the 10 Fleet B trucks, the avoided fuel use is less than 10 gallons per year. Thus, the typical fuel use penalty of 19 to 20 gallons per year offsets the avoided fuel use, leading to a net increase in total fuel use. For the three trucks that have a net fuel savings, the weight penalty is 49 to 73 percent of the avoided fuel use during idle. Thus, not surprisingly, for trucks that have low APU utilization levels, the weight penalty associated with the APU can be comparable to or greater than the avoided fuel use savings. This implies, of course, that either APU usage needs to be increased or that APUs are not attractive if they are likely to have low utilization levels.

Table G-1 Fuel Penalty due to APU Weight and Adjusted Avoided Fuel Use

Fleet	APU	Truck No.	Total Elapsed Time Since Truck Started Service (hours)	Total Miles Traveled Since Truck Started Service (miles)	Annualized Miles Traveled (miles/Year)	Fuel Penalty due to APU Weight (gal/yr) ^a	Avoided Fuel Use for All Stop Durations without Considering Fuel Penalty (gal/yr) ^b	Percentage of Fuel Penalty to Avoided Fuel Use without Considering Fuel Penalty (%)	Net Avoided Fuel Use for All Stop Durations Considering Fuel Penalty (gal/yr)
A	APU-A	1	12997	184484	123061	21	63	33	42
		2	12834	204503	138154	23	278	8	254
		3	12815	183022	123822	21	366	6	345
		4	8738	126328	125345	21	164	13	143
		5	12631	209322	143684	24	298	8	273
		Average	12003	181532	130813	22	234	10	212
	APU-B	6	9862	152611	134170	23	367	6	345
		7	8762	112527	111342	22	416	5	394
		8	7151	83685	101464	23	197	11	175
		9	11487	186985	141135	23	114	20	91
		10	11265	174117	134009	22	307	7	284
Average		9705	141985	124424	23	280	8	258	
B	APU-A	11	9511	145305	132458	23	4	506	-18
		12	7176	100885	121897	21	1	1764	-20
		13	7254	90543	108220	18	1	1816	-17
		14	8871	103533	101186	17	1	2040	-16
		15	7309	84821	100622	17	89	19	71
		Average	8024	105017	112877	19	19	100	0
	APU-B	16	9530	114875	104513	18	71	25	53
		17	9348	112154	104019	18	-4	-420	-22
		18	8345	134702	139947	24	6	412	-18
		19	9018	119531	114921	20	3	568	-16
		20	8983	134429	129745	22	71	31	49
Average		9045	123138	118629	20	29	68	9	

^a Average fuel use rate for long-haul trucks is 0.17 gal/mile; APU system increases truck fuel use by 0.1%; (fuel penalty due to APU weight) = (total miles traveled) × 0.17 × 0.1%

^b Based on data summarized in Table E-3

Section H. Sensitivity Analysis for Net Cost Savings per Unit of Energy Use Reduction and Simple Payback Periods

To evaluate the potential economic benefits of APUs, the net cost savings per unit of energy use reduction and simple payback periods are estimated. Furthermore, to evaluate variability and uncertainty in key measures of economic feasibility, a sensitivity analysis is performed taking into account variation in factors such as fuel price, capital cost, and non-fuel operating and maintenance (O&M) cost.

Net cost savings per unit of energy use reduction is estimated based on net cost savings divided by avoided fuel use. Net cost savings is the annual energy cost saving minus annualized cost. Annualized cost is the product of capital cost and a fixed charge factor plus the annual non-fuel O & M cost.

APU lifetime is estimated to be 5 years. The discount rate for calculating the fixed charge factor is assumed to be 10%. Thus, the fixed charge factor is 0.264.

Simple payback periods are used to evaluate the time needed to recover the initial investment. The payback periods for the APU of each truck are evaluated based on the number of years required to recoup the initial costs of the APUs as a result of net annual fuel cost savings. Net annual cost savings of implementing the APUs is the difference between annual fuel costs savings and annual non-fuel operation and maintenance costs. Such estimates are based on a discount rate of zero. Consideration of the discount rates lead to longer payback periods.

Sensitivity analysis for net cost savings per unit of energy use reduction for all stop durations for all trucks are summarized in Table H-1. Diesel fuel price, APU capital cost and

APU non-fuel operation and maintenance cost are the chosen input variables for sensitivity analyses. The ranges of the inputs and the impacts are listed in Table H-1. Fuel penalty due to APU weight is not considered here. The results show that only three trucks have positive net cost savings per unit of energy use reduction in the scenario of the lowest APU capital cost and highest diesel fuel price. Seventeen trucks have no net cost savings per unit of energy use reduction due to low avoided fuel use. Thus, field trucks need to either install fuel-efficient APU or use the APUs more aggressively in order to be get net cost savings.

Sensitivity analysis for the simple payback periods for all stop durations for all trucks are summarized in Table H-2. In general, simple payback periods ranges from 6 years to no payback period because of no net cost saving. The estimated payback periods are significantly longer than literature estimates, which are 1.4 to 4.3 years (Stodolsky et al., 2000). Even based on very high diesel fuel price of \$8 per gallon, the shortest simple payback periods are 3 years. If discount rates and fuel penalty due to APU weight are considered, longer payback periods are expected.

Table H-1 Sensitivity Analysis for Net Cost Savings per Unit of Energy Use Reduction for All Stop Durations for All Trucks

Fleet	APU	Truck No.	APU Annual Fuel Saving (gal/yr)	Net Savings per Unit of Energy Use Reduction (\$/gal)											
				Diesel Fuel Price (\$/gal) 2.56				Diesel Fuel Price (\$/gal) 4.50				Diesel Fuel Price (\$/gal) 8.00			
				APU Capital Cost (\$) 8,500		APU Capital Cost (\$) 12,000		APU Capital Cost (\$) 8,500		APU Capital Cost (\$) 12,000		APU Capital Cost (\$) 8,500		APU Capital Cost (\$) 12,000	
				APU O & M Cost (\$/yr) 400	APU O & M Cost (\$/yr) 600	APU O & M Cost (\$/yr) 400	APU O & M Cost (\$/yr) 600	APU O & M Cost (\$/yr) 400	APU O & M Cost (\$/yr) 600	APU O & M Cost (\$/yr) 400	APU O & M Cost (\$/yr) 600	APU O & M Cost (\$/yr) 400	APU O & M Cost (\$/yr) 600	APU O & M Cost (\$/yr) 400	APU O & M Cost (\$/yr) 600
A	APU-A	1	63	-2483	-2683	-3407	-3607	-2361	-2561	-3285	-3485	-2140	-2340	-3064	-3264
		2	278	-1933	-2133	-2857	-3057	-1393	-1593	-2317	-2517	-421	-621	-1345	-1545
		3	366	-1707	-1907	-2631	-2831	-996	-1196	-1920	-2120	286	86	-638	-838
		4	164	-2224	-2424	-3148	-3348	-1905	-2105	-2829	-3029	-1330	-1530	-2254	-2454
		5	298	-1882	-2082	-2806	-3006	-1304	-1504	-2228	-2428	-262	-462	-1186	-1386
	APU-B	6	367	-1703	-1903	-2627	-2827	-990	-1190	-1914	-2114	296	96	-628	-828
		7	416	-1579	-1779	-2503	-2703	-772	-972	-1696	-1896	684	484	-240	-440
		8	197	-2139	-2339	-3063	-3263	-1757	-1957	-2681	-2881	-1067	-1267	-1991	-2191
		9	114	-2353	-2553	-3277	-3477	-2133	-2333	-3057	-3257	-1736	-1936	-2660	-2860
		10	307	-1859	-2059	-2783	-2983	-1264	-1464	-2188	-2388	-191	-391	-1115	-1315
B	APU-A	11	4	-2633	-2833	-3557	-3757	-2624	-2824	-3548	-3748	-2608	-2808	-3532	-3732
		12	1	-2641	-2841	-3565	-3765	-2639	-2839	-3563	-3763	-2635	-2835	-3559	-3759
		13	1	-2641	-2841	-3565	-3765	-2639	-2839	-3563	-3763	-2636	-2836	-3560	-3760
		14	1	-2642	-2842	-3566	-3766	-2640	-2840	-3564	-3764	-2637	-2837	-3561	-3761
		15	89	-2417	-2617	-3341	-3541	-2245	-2445	-3169	-3369	-1935	-2135	-2859	-3059
	APU-B	16	71	-2462	-2662	-3386	-3586	-2324	-2524	-3248	-3448	-2075	-2275	-2999	-3199
		17	-4	-2655	-2855	-3579	-3779	-2663	-2863	-3587	-3787	-2678	-2878	-3602	-3802
		18	6	-2629	-2829	-3553	-3753	-2618	-2818	-3542	-3742	-2598	-2798	-3522	-3722
		19	3	-2635	-2835	-3559	-3759	-2629	-2829	-3553	-3753	-2616	-2816	-3540	-3740
		20	71	-2462	-2662	-3386	-3586	-2324	-2524	-3248	-3448	-2075	-2275	-2999	-3199

Table H-2 Sensitivity Analysis for Simple Payback Periods for All Stop Durations for All Trucks

Fleet	APU	Truck No.	APU Annual Fuel Saving (gal/yr)	Simple Payback Period (yr) ^a											
				Diesel Fuel Price (\$/gal) 2.56				Diesel Fuel Price (\$/gal) 4.50				Diesel Fuel Price (\$/gal) 8.00			
				APU Capital 8,500		APU Capital 12,000		APU Capital 8,500		APU Capital 12,000		APU Capital 8,500		APU Capital 12,000	
				APU O & M Cost (\$/yr)	APU O & M Cost (\$/yr)	APU O & M Cost (\$/yr)	APU O & M Cost (\$/yr)	APU O & M Cost (\$/yr)	APU O & M Cost (\$/yr)	APU O & M Cost (\$/yr)	APU O & M Cost (\$/yr)	APU O & M Cost (\$/yr)	APU O & M Cost (\$/yr)	APU O & M Cost (\$/yr)	APU O & M Cost (\$/yr)
A	APU-A	1	63	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	82	N/A	116	N/A
		2	278	27	76	39	108	10	13	14	18	5	5	7	7
		3	366	16	25	22	36	7	8	10	11	3	4	5	5
		4	164	416	N/A	587	N/A	25	61	35	86	9	12	13	17
		5	298	23	52	33	74	9	11	13	16	4	5	6	7
	APU-B	6	367	16	25	22	35	7	8	10	11	3	4	5	5
		7	416	13	18	18	26	6	7	8	9	3	3	4	4
		8	197	81	N/A	115	N/A	17	30	25	42	7	9	10	12
		9	114	N/A	N/A	N/A	N/A	77	N/A	108	N/A	17	28	24	39
		10	307	22	46	31	65	9	11	12	15	4	5	6	6
B	APU-A	11	4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		12	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		13	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		14	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		15	89	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	28	78	39	110
	APU-B	16	71	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	50	N/A	71	N/A
		17	-4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		18	6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		19	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		20	71	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	50	N/A	71	N/A

^aN/A means that there is no pay-back period for this truck because there is no net saving; APU O & M cost is non-fuel O & M cost