Argonne NATIONAL LABORATORY

ANL-15/04

Stop and Restart Effects on Modern Vehicle Starting System Components

Longevity and Economic Factors

Energy Systems Division

ANL-15/04

Stop and Restart Effects on Modern Vehicle Starting System Components

Longevity and Economic Factors

by
Paul R. Windover, Russell J. Owens, Terry M. Levinson, and Michael D. Laughlin
Energetics Incorporated for Energy Systems Division, Argonne National Laboratory

April 2015

Contents

Figures

Table

1. Abstract

Many drivers of personal and commercial vehicles believe that turning the vehicle off and on frequently instead of idling will cause premature wear of the starter system (starter motor and starter battery). As a result, they are concerned that the replacement cost of the starter motor and/or battery due to increased manual engine cycling would be more than the cumulative cost of the fuel saved by not idling unnecessarily. A number of variables play a role in addressing this complex concern, including the number of starting cycles per day, the time between starting cycles, the intended design life of the starting system, the amount of fuel used to restart an engine, and the cumulative cost of the saved fuel. Qualitative and quantitative information from a variety of sources was used to develop a life-cycle economic model to evaluate the cost and quantify the realistic factors that are related to the permissible frequency of starter motor cycles for the average vehicle to economically minimize engine idle time. Annual cost savings can be calculated depending on shutdown duration and the number of shutdown cycles per day. Analysis shows that cost savings are realized by eliminating idling exceeding one minute by shutting down the engine and restarting it. For a typical motorist, the damage to starting system components resulting from additional daily start cycles will be negligible. Overall, it was found that starter life is mostly dependent on the total number of start cycles, while battery life is more dependent on ensuring a full charge between start events.

2. Introduction

2.1 Overview of Idling

Vehicle idling has both local and national impacts, incurs additional costs, and results in additional emissions that could be avoided. Many drivers idle their vehicles unnecessarily, despite the knowledge that idling wastes fuel and results in increased fuel costs. Unnecessary idling also produces exhaust emissions of carbon monoxide, carbon dioxide, nitrogen oxide, and particulate matter that can cause health issues for sensitive populations. Another problem associated with unnecessary idling is that the fuel being wasted affects the energy security of this country. Unnecessary idling in the United States wastes approximately six billion gallons of fuel annually, costing the country around $21 billion.

Drivers idle their vehicles for many reasons. For example, drivers of personal vehicles may idle while conducting business at a drive-through restaurant or bank, while waiting for a drawbridge to open or close, or while waiting for a freight train to pass. Drivers may run their heating or air conditioning systems to maintain comfortable temperatures while they wait in the vehicle. Technical solutions are available to address the driver's needs for heat, air conditioning, and electric power in many of these situations; however, this is not the subject of this report. Driver education is often a way to reduce unnecessary idling without the addition of any hardware on the vehicle itself. To further encourage drivers to shut down when stationary, there are laws in many states and municipalities that limit unnecessary idling and impose fines on drivers who exceed time, temperature, location, and exemption limits.

As part of the U.S. Department of Energy's (DOE's) mission to achieve energy security, Argonne National Laboratory has been a leader in the area of idling reduction research, analysis, and outreach for many years. Argonne has supported the DOE Clean Cities program to educate its Coalition Coordinators and their stakeholders on the technical, environmental, and cost impacts of vehicle idling. For this, Argonne created a modular, electronic toolkit for Coordinators called "IdleBox" (http://www1.eere.energy.gov/cleancities/toolbox/idlebox.html) and a compendium of nationwide idling-reduction regulations called

"IdleBase" (http://cleancities.energy.gov/idlebase). These outreach tools and the technical analyses that supported their development address all aspects of educating both laypersons and technical experts on vehicle idling.

2.2 Statement of the Problem

In the course of driver education activities, Clean Cities has encountered a significant concern that many drivers have about idling reduction. These drivers (covering both personal and commercial vehicles) believe that turning the vehicle off and on frequently will cause premature wear of the starter system (starter motor and starter battery). As a result, they are concerned that the replacement cost of the starter motor and/or battery due to increased manual engine cycling during short-cycle idling would be more than the cumulative cost of the fuel saved by not idling unnecessarily. A number of variables play a role in addressing this complex concern, including the number of starting cycles per day, the time between starting cycles, the intended design life of the starting system, the amount of fuel used to restart an engine, and the cumulative cost of the saved fuel.

To improve its technical outreach to Clean Cities Coalition fleets and the broader driving public, the Clean Cities program was interested in evaluating the practice of frequent engine starting cycles in more detail. For this, Argonne and Energetics Incorporated (the Project Team) were tasked with performing a detailed analysis of the effects that frequent starting cycles have on engine starting systems. The purpose of this analysis was to gather information on modern vehicle engine starter systems and to evaluate the short- and long-term effects of increased engine start cycles on the various components. The economic merit of shutting the engine down for short idling periods was also quantified for various engine sizes. The three primary questions to be answered by this report include:

1. Does increased starter cycle frequency shorten the expected life of the starter and, if so, to what extent?
2. Does increased starter cycle frequency shorten the expected life of the battery and, if so, to what extent?
3. Do the fuel cost savings of shutting down the engine counteract any potential component wear cost?

To answer these questions, the team collaborated with technical staff from another DOE national laboratory on this work (see Appendix). Industry technical experts from the Society of Automotive Engineers and the Alliance of Automobile Manufacturers also advised the team (see Appendix). A comprehensive literature search was conducted to identify any prior work in the area and build upon pre-existing knowledge. In addition, the team gathered information, through surveys and technical research, from additional sources. These sources requested to remain anonymous because of the confidential nature of the information provided. Telephone interviews were conducted to acquire information sources, including:

1. Technical staff representing two domestic light-duty automobile manufacturers,
2. Technical staff of three medium- and heavy-duty truck and truck engine manufacturers, and
3. Technical staff of a Tier 1 starter motor supplier and a battery component supplier.

This report examines the impacts on starter system longevity of the additional stop-start cycles associated with idling-reduction efforts. The report also uses information synthesized from the background research to present general recommendations about appropriate idling-reduction behavior that can help minimize the vehicle owner's costs. The team's intent is that the results found in this report will be added to the Clean Cities idling reduction toolkit to expand outreach to the Clean Cities coalitions and the general population.

3. System Information

Modern engine starting systems must rotate the crankshaft of an internal combustion engine (ICE) at a sufficiently high rate of speed to initiate combustion to start the engine. All conventional light-, medium-, and heavy-duty vehicles employ a similar starter system configuration. Diesel engines used in medium- and heavy-duty trucks have similarly configured systems, but they are significantly more robust than those in light-duty cars because these engines require higher torque as a result of the high engine compression ratios and heavy rotating assemblies (e.g., crankshafts, pistons). Hybrid-electric vehicles, and some vehicles equipped with engine stop-start systems, use different system configurations to start the ICE.

Modern engine-starting systems include several components: (1) the ignition switch, (2) a battery, (3) the starter motor, and (4) the alternator. A basic component layout is shown in Figure 1. A high-level description of the starting system operation is presented here. More detailed discussions of each subsystem are in the following sections.

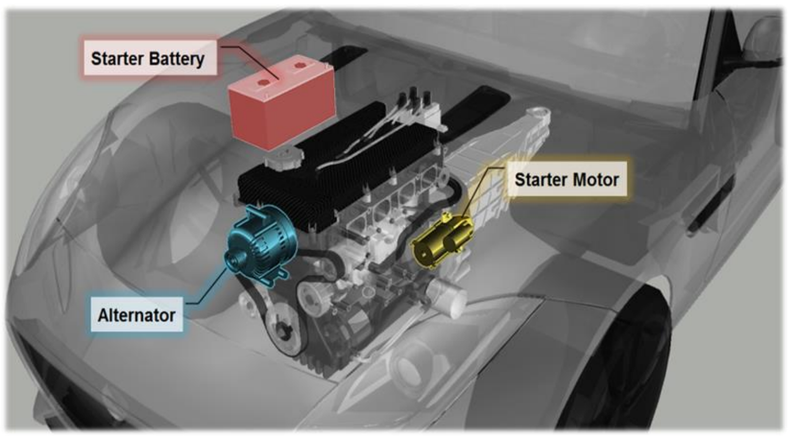

Figure 1: Typical Vehicle ICE Starting System Diagram

The driver-operated ignition switch controls the flow of electricity to control the operation of the starting system. The battery stores energy generated by the alternator when the engine is running. When engine starting is needed, the battery provides the large electrical power to the starter motor required to turn the engine's heavy rotating assemblies to start the engine. The starter motor is a small, but powerful, permanent magnet direct current electric motor with an electric solenoid switch (similar to a heavy-duty relay) mounted on it. When the ignition switch is activated, the electric solenoid is energized and pushes the starter drive gear out to activate the starter motor. As the drive gear is pushed out, it meshes with the large ring gear on the engine's flywheel and spins the engine rotating assemblies. Once electrical power to the solenoid is interrupted by releasing the ignition key, the drive gear retracts into the starter, and the engine runs on its own.

The alternator does not play a role during the engine starting procedure. Rather, its role in the starting system is limited to recharging the battery once the engine is running. The amount of electrical energy needed to recharge the battery after a starting event is very low, as a start event on a modern vehicle is very short.

3.1 Starter Battery

A vehicle starting system typically utilizes a flooded lead-acid battery to store electrical energy generated by the engine's alternator. The stored energy is used for engine-starting events and for operating other electrical devices when the engine is off (e.g., fuel pump, electronic control units, and the instrument panel). The battery provides extremely high levels of power (typically 200–1,200 amps) for a very short period (less than one second) to start the engine. It also provides an electrical energy buffer while the engine is running for powering electrical accessories, such as the radio, lights, and computers. (As a result, this type of battery is typically referred to as a starting, lighting, and ignition battery.) This type of battery is designed to meet the numerous key on-off cycles and engine-starting cycles original equipment manufacturers (OEM) expect as part of the typical customer drive cycle usage. Unlike a "deep-cycle" battery, a starting, lighting, and ignition battery is not designed for significant depth-of-discharge operation and achieves the longest useful life when it is maintained at a fully charged state. The alternator (described later) supplies the necessary electricity to run the electrical loads and surplus energy to recharge the battery. If the engine is turned off and the driver continues to use accessory loads for long times, the battery will be drained and damage could occur as a result of this practice, if done frequently. The depth of discharge reached during an engine-off period varies depending on duration, accessories used (radio, lights, and fans), vehicle make/model, ambient conditions, and many other parameters. However, engine-off periods of up to 5–7 minutes should not damage battery integrity (assuming it is fully recharged between events). Alternatively, a 10–20-minute key-off cycle with many accessories operating (with a high cumulative power demand) will drain the battery considerably and shorten its life (according to information gathered from conversations with major vehicle OEMs).

The most important factor to bolster battery health is to ensure that a full charge is maintained whenever possible and that the battery is returned to full charge between start events. The amount of driving time required to fully recharge the battery can vary considerably, depending on the initial depth of discharge, the health of the battery, battery temperature, and accessory use. Overall, frequent stop-start cycles (start engine, drive 2–3 miles, then shut engine off to restart soon after) will degrade the battery. Less-frequent stop-start cycles (start engine, drive more than about six miles, then shut engine off) will maintain the life of the battery as the state of charge will be maintained at a higher level. To recharge the battery, the vehicle should be driven, rather than idled, because the alternator is less efficient at idle speed. Using accessories while the engine idles could still result in a net drain on the battery.

Battery design is achieved by applying performance standards. Many vehicle OEMs provide a three-year or 36,000-mile warranty on their batteries, but they do not experience a significant number of battery replacements. Increased rates of failure occur in areas with more extreme weather, especially in the American Southwest, because the high ambient temperatures cause the batteries to fail earlier there than in other regions of the country. The performance standard targets a battery life of at least five years, so the expectation is that the battery will need to be replaced before the vehicle's end-of-life. The average starter battery in the field matches the design expectation and lasts an average of around five years. Frequent stop-start cycles (those involving an engine start, a 2–3-mile drive, then shutting the engine off, and restarting it soon after) will degrade the battery because the battery will not be recharged properly. In these cases, frequent engine off-on cycles will damage the battery.

The battery replacement cost varies depending on the quality, battery manufacturer, vehicle manufacturer, warranty, and type of battery desired. Because flooded lead-acid batteries are sold in a limited number of common sizes and energy capacities for use in many vehicle applications, the component cost is less related to vehicle make/model and more dependent on battery brand and options. The battery installation costs are also quite low, as this is considered a wear item and the vehicle OEMs intend them to be easily replaced. Replacement starter batteries typically retail for between $100 and $300. Installation labor is often free with purchase, but it can cost up to $100, depending on the vehicle type and the repair facilities that are used.

3.2 Starter Motor

The starter motor converts the electrical energy from the battery to mechanical energy to spin the crankshaft of the engine. The primary components of a modern electric starter include a starter solenoid, direct current electric motor, reduction gears, and a pinion gear to engage the engine's flywheel. An exploded view of a typical electric starter is shown in Figure 2, with each primary component labeled. Once the ignition key is turned to initiate an engine start event, electric power from the battery is applied to the starter motor terminals to activate the starter solenoid and to energize the direct current motor. When activated, the starter solenoid pushes the plunger and forces the pinion gear to mesh with the teeth on the flywheel. Once the engine is running, the starter is de-energized and the pinion gear retracts into the starter.

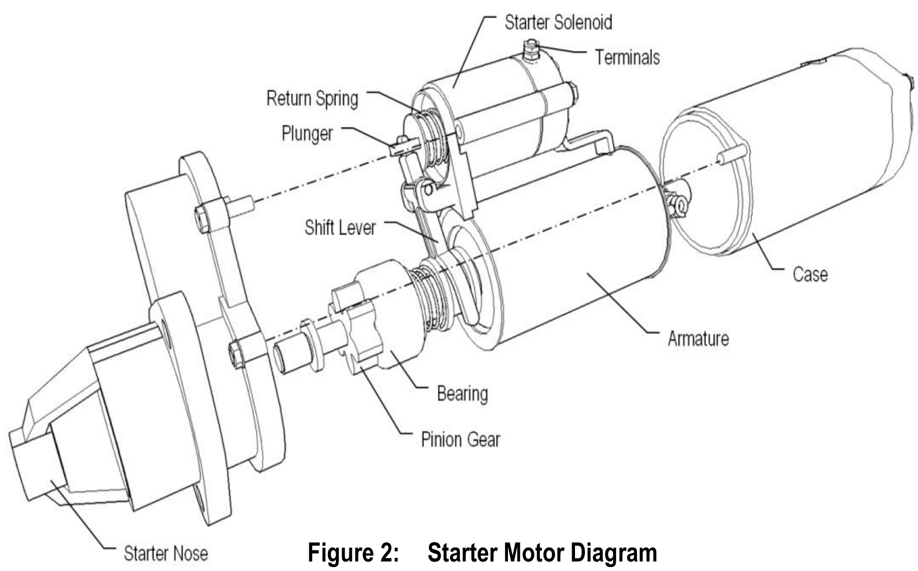

Figure 2: Starter Motor Diagram

Every time the starter is cycled, it is subject to wear resulting from metal-on-metal contact on the gears (especially the pinion gear) and heat buildup within the electronics. Extreme environmental conditions can have a very significant impact on the starter system's lifetime. The starter is exposed to engine heat as well as reflected heat from the road, and excessive heat exposure can lead to rapid life degradation. Specific wear components include the armature bearings, reduction gears, pinion gear, plunger, commutator, and motor brushes. According to information gathered from technical experts consulted for this report, starter motors are designed to last for over 30,000 cycles (estimated to correspond to 10 years or 100,000 miles of use). The useful life varies depending on a number of factors, including ambient conditions, engine condition (crank time required), and the time between starts (heat buildup). The upper bound of starter life was estimated to be approximately 60,000 cycles; most starters will experience failure before this point. The most common reasons for failure include excessive brush wear, armature bearing failure, and pinion gear wear. Failures related to corrosion and electric shorts can also occur, but are not common.

As with any other vehicle component, the purchase price and labor associated with the replacement of a starter motor varies widely, depending on vehicle make, model, and overall difficulty in replacing the component. While the starter motor is not exactly considered a wear item by most OEMs, it is conceivable that it may need to be replaced within the life of the vehicle, so replacing it is typically not a significant undertaking. Thus, starter replacement is typically not expensive; however, it can be costly for expensive, high-end vehicles. The estimated total cost for a starter motor replacement, including parts and labor, is shown in Figure 3 for an assortment of vehicles, ranging from compact cars to pickup trucks.[1] A summary of these data is shown on the right of Figure 3 for each type of vehicle. This information is estimated and is only provided to provide a sense of the cost of these systems and variability by vehicle. Actual costs may vary by location.

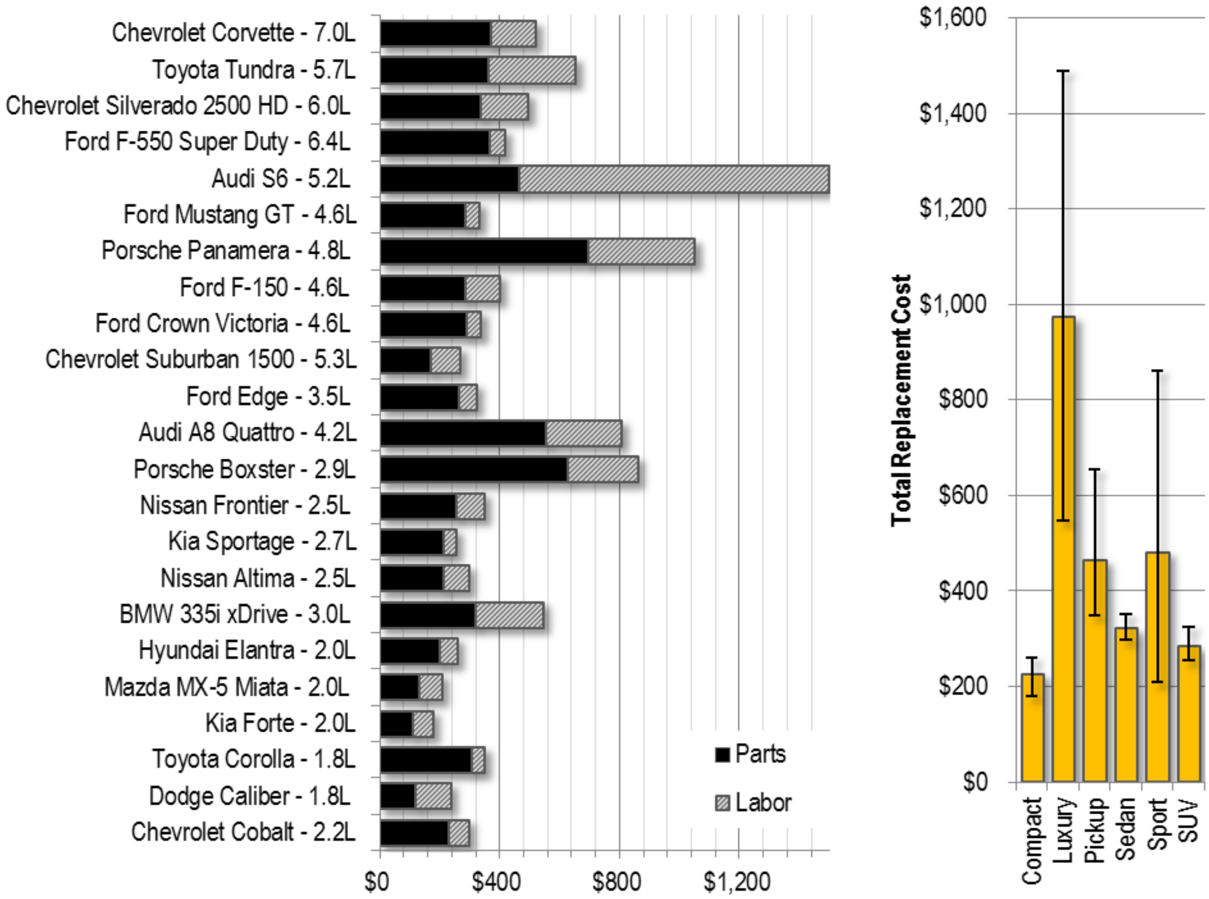

Figure 3: Estimated Starter Replacement Costs

Additional Components

There are a number of other vehicle starting system components, including the ignition switch, alternator, flywheel, and various electrical components (e.g., wiring, relays, controls, solenoids). While these systems do not see significant wear from increased starting cycles, they do interact with the primary system components described above.

The alternator generates electrical power to charge the power ignition system and onboard accessories. A cutaway view of a typical alternator is shown in Figure 4. The alternator is typically powered by a serpentine belt system that is rotated by a pulley mounted directly on the engine’s crankshaft. While the increase in starter system cycling would require a slight increase in average alternator output power, the impact on the alternator life would be minimal. Discussions with the industry experts described earlier revealed that this power level falls well within the OEM design standards and will not contribute to premature failure, regardless of the required minimal additional load.

The engine flywheel, specifically the gear teeth on its perimeter where the starter meshes, is a sometimes-overlooked area of wear. Because of the compression characteristics of an ICE, once shut off, an engine will tend to stop when the cylinders are in the middle of their stroke (resulting in the lowest overall compression). This causes the pistons to stop rotating at specific locations throughout their rotation. As a result, the starter motor pinion gear teeth initially engage on the same flywheel gear teeth at every start. These teeth (on the flywheel and starter motor) therefore are subjected to much higher wear and, over time, can break. However, failure typically occurs only under extreme conditions and is not an issue for light-duty vehicles. (Failure examples were noted by OEM experts regarding heavy-duty-cycle commercial applications.)

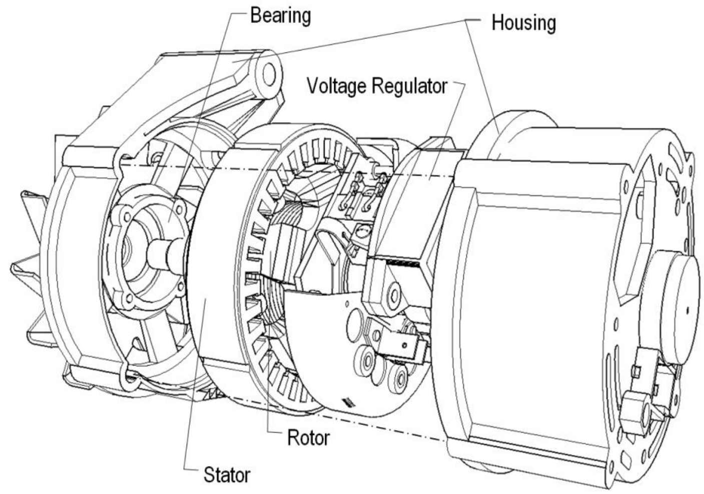

Figure 4: Alternator Exploded View

OEM Start-Stop Systems

OEM start-stop systems are not the focus of this study; however, describing the difference between conventional engine starting systems and start-stop engine starting systems is useful for highlighting the weaknesses of using conventional-engine starting systems for very frequent engine stop-starting. Some early vehicles that offered start-stop functionality were solely equipped with conventional geared starters that engage the flywheel (in the same way conventional systems operate). Most currently available start-stop systems, however, are beginning to utilize a combination starter/alternator design to eliminate any issue with broken teeth on the flywheel or the starter pinion gear. This starter/alternator configuration uses a reinforced serpentine belt system to both power the alternator and rotate the crankshaft of the engine for engine starting events. The configuration is similar to a conventional alternator system.

OEMs use absorbed glass-mat (also referred to as valve-regulated) lead-acid battery designs (rather than flooded lead-acid) for the frequent cycles of a stop-start system because of their performance and tolerance of deep discharges without harming the battery. The deep cycle capabilities are needed to operate electrically powered accessories (e.g., radio, instrument panel electronics, and heating/air-conditioning systems) while the engine is off, to provide the energy needed to restart the engine, and to be recharged without decreasing battery life. Absorbed glass-mat batteries are commercially available for conventional vehicles, but they are often marketed as a "performance" battery upgrade. However, they are more costly than a standard flooded lead-acid battery and may not offer any noticeable life or performance benefits for a typical daily-driven vehicle.

3.3 Exhaust Emissions

The fuel use and exhaust emission rate during (and right after) an engine cold start for legacy vehicles with low compression ratios, non-heated oxygen sensors, carburetors, and rudimentary fuel injection systems were much higher than if the engine were idled. For reasons similar to those discussed for fuel consumption, start-up exhaust emissions have also been significantly reduced. Exhaust catalyst cooling when the engine is off can lead to increased emissions once the engine is restarted because of low catalyst activity at subsequent start-ups. However, a recent Argonne National Laboratory study found that exhaust system catalyst temperatures remained high enough during short stops (up to six minutes) that no loss of emission-control efficiency occurred.[2]

4. Starter System Evaluation

The Project Team gathered qualitative and quantitative information from the industry experts described earlier to address the questions posed in the *Statement of the Problem* section. These data were analyzed and then used to develop a life-cycle economic model to quantify the permissible frequency of the starter motor cycle for an average U.S. passenger vehicle to economically minimize unnecessary engine idling. The developed model calculates the potential for starter motor and battery failure related to the number of incremental starts per day above typical vehicle operation.

4.1 Battery Life Factors

The research revealed that the expected life span of a conventional flooded lead-acid starter battery is impacted minimally from the number of starting events. Rather, battery life is mostly impacted by limited charge times between frequent engine start events and from excessive discharge during engine-off events from accessory loads. The length of and the cumulative accessory power draw during each engine shutdown event has a direct and strong effect on battery longevity because of the depth of discharge. If the battery is returned to a full charge between engine starts, the effect on battery life is negligible or nonexistent. Conversely, the battery will fail significantly more quickly if a full charge is never reached. This is true independent of the number of engine start cycles. Also, idling has been determined to not be an effective way to recharge the battery because of low alternator power output; driving is best.

There are an infinite number of combinations of engine start frequencies, accessory loads during engine-off events, and driving distances between engine starts. Therefore, for the purpose of this evaluation, it was assumed that no accessory loads were active while the engine was off. The distance that a vehicle must be driven to fully recharge the battery between start cycles depends on a variety of factors. But with the assumption of no accessory use during engine-off events, it was estimated that approximately six miles of driving was needed to recharge the battery. Battery failure modes are not abrupt; rather, battery performance slowly degrades until it can no longer reliably start the engine. For the purpose of this study, a definite “failure point” was defined to quantify the potential influences of increased start cycles for evaluating the economic merit of more frequent engine shutdowns. A decaying exponential function curve fit is shown in Figure 5 (assumes that six miles of driving is sufficient to provide a full charge after a start). This type of curve was used because it appropriately characterizes the potential reduction in battery life and best fits the data set provided by industry experts.

This curve is an assumed average and could vary, depending on battery condition, accessories used during driving, alternator output, and a variety of other factors. The anticipated life of the battery can be calculated from data on these variables by dividing the baseline battery life (five years on the basis of discussions with industry) by one plus the battery life reduction value from the Figure 5 graph. Note that the distance between start cycles is an average and not based on a single event (for example, if a vehicle travels 20 miles a day and stops four times, the average distance between stops is five miles). For example, at an average of three miles between stops, the result is:

$$\frac{5\ years}{1 + 0.09} = 4.6\ years$$

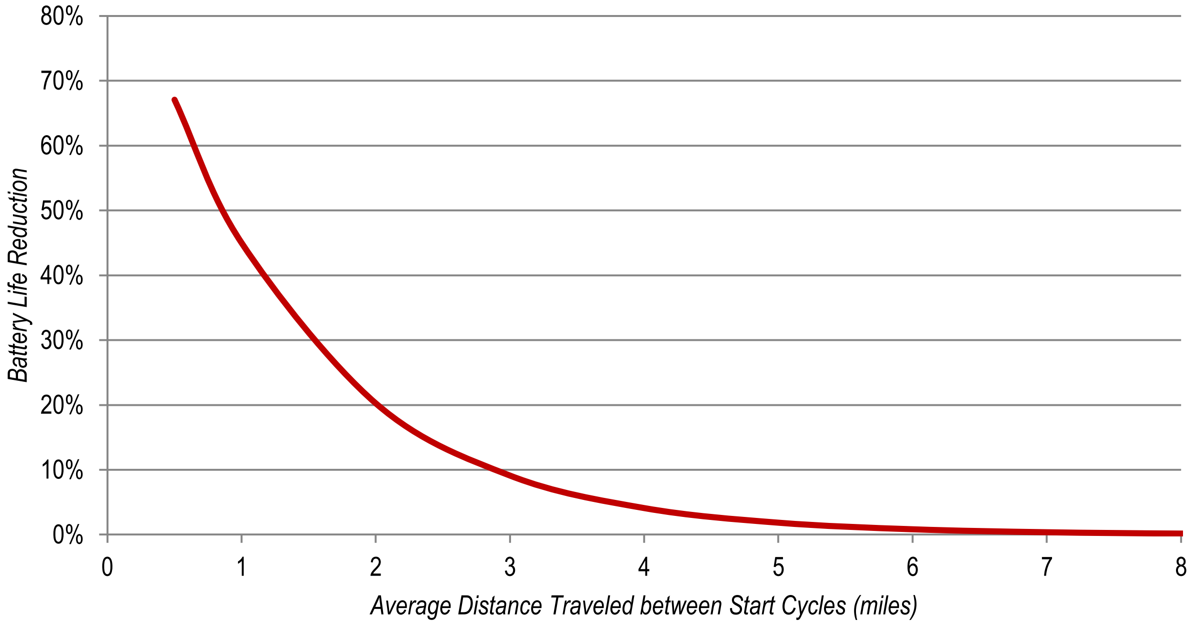

Figure 5: Battery Life Factors Quantification

4.2 Factors Affecting Starter Motor Life

The starter motor of a modern vehicle is an extremely robust component that is designed to last the useful life of the vehicle, as defined below. The information gathered shows that starters will typically fail between 30,000 and 60,000 cycles. Starter motors, however, do fail for a number of reasons related to operating environment, duty cycle, manufacturing quality, and wear from normal operation. As a result, starter motor life is not directly correlated solely to starting event frequency, or to the total number of engine starts. On the basis of the information gathered from OEMs, component manufacturers, and other industry experts consulted for the project, the primary cause for early failures is elevated starter-motor temperature levels. High starter-motor temperatures are caused by several reasons, including (1) high engine temperatures (conducted to the starter through the engine block or convected within the hot engine compartment), (2) high roadway temperatures (radiated and convected from the road surface), (3) high ambient temperatures, (4) limited cool-down time between uses, (5) frequent use, and (6) long-duration cranking. Other premature failures result from corrosion and manufacturing defects.

For the purpose of this study, however, only the incremental starter failure potential due to increased starts is considered. The average potential for this incremental starter failure was estimated by using a Weibull cumulative distribution function (Figure 6) based on starter-motor expected lifetime information provided by the organizations and individuals interviewed for this study. The Weibull distribution function is widely used in reliability engineering for survival/failure analysis and provides an appropriate relation to this application. This calculation also assumes that the majority of starters will fail by the mean of these two extremes (45,000 cycles). This estimates the average starter failures for the typical motorist.

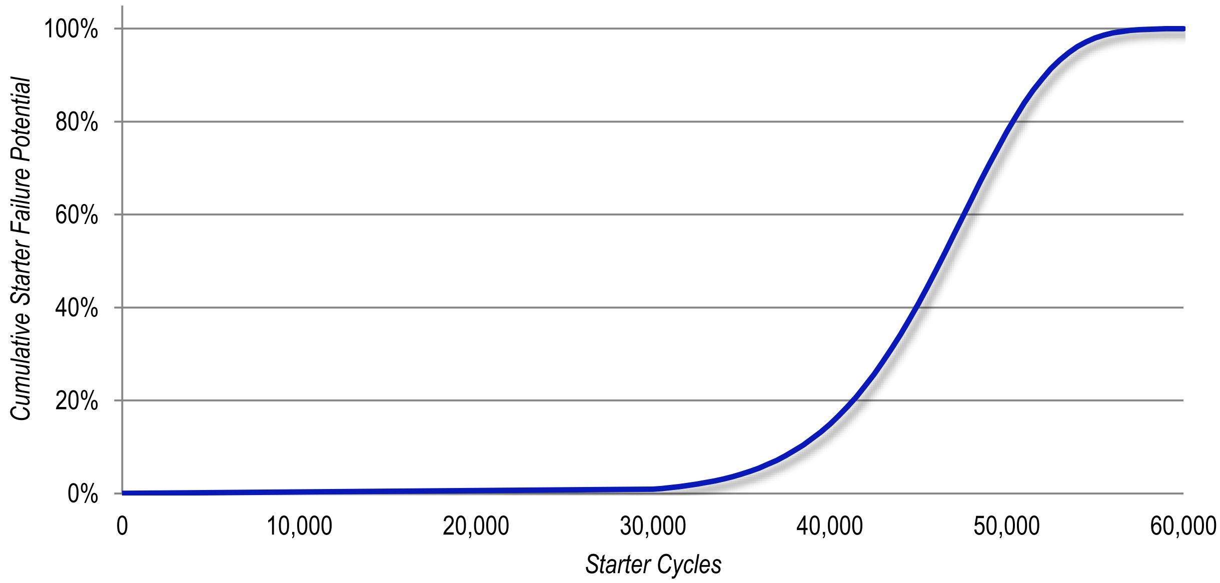

Figure 6: Starter Motor Failure Potential Quantification

4.3 Vehicle Operation Model

Information on battery life reduction and starter motor failure enabled the quantification of the incremental component replacement requirements on the basis of additional start cycles per day. The calculation for replacement potential differed slightly for starters and batteries, but it required that similar assumptions be made to allow the life cycles to be evaluated. (The calculation methodologies are described in the following sections.) The operational assumptions include:

- **10-Year Useful Vehicle Life** – Required for calculating the total lifetime starting events. This follows the U.S. Environmental Protection Agency light-duty vehicle useful life of 120,000 miles/10 years that pertains to emission control systems.
- **11,600 Miles Traveled per Year** – Required to calculate the distance traveled between starts. Value based on information from U.S. Census Bureau, Statistical Abstract of the United States: 2012, Table 1101. Motor Vehicle Distance Traveled by Type of Vehicle: 1970 to 2009 (http://www.census.gov/history/pdf/12s1101.pdf). This value also closely correlates with the U.S. Environmental Protection Agency light-duty vehicle useful life of 120,000 miles/10 years (i.e., 12,000 miles per year).
- **365 Days Operated per Year** – Assumes vehicle is used every day; used to calculate miles traveled per day
- **32 Miles per Day** – Required for battery life calculations, based on miles per year and operational days per year (i.e., 11,600 miles per year divided by 365 days per year)
- **Baseline of Three Starts per Day** – Assumed average baseline number for a typical motorist not employing additional engine stops for idle reduction
- **Baseline Battery Life of Five Years** – Based on industry expert interviews

Battery Model

The decrease in battery life due to increased engine stop-start events is evaluated independent of vehicle life (as it is essentially ensured that the battery will need to be replaced at least once in the 10-year period). The results are based on the average distance traveled between engine start events (i.e., miles per day/increased number of starts per day). As noted earlier, this estimation assumes that no electrical accessories are used while the engine is off. The estimated battery life (in years) is shown in Figure 7. This graphic includes information for various vehicle use durations, ranging from 5 to 200 miles per day. However, for the purpose of this study, 32 miles per day was assumed (based on the information outlined above). While it is obviously impossible to fractionally replace a battery, the curve presents the overall average trend of the impact that increased engine start cycle frequency, above the baseline starts, will have on battery replacement. The additional starts per day are assumed to be the running average over the vehicle life. Thus, restarting a vehicle several times within a short period will not immediately destroy the battery, assuming this is not a common event. However, an increase in average start cycles (and the corresponding decrease in distance traveled between starts) will decrease battery life expectancy.

For example, if the average daily distance traveled is increased to simulate commercial applications (taxicabs in New York City average 190 miles per day[3]), while the number of start cycles remains constant, battery life is not significantly decreased.

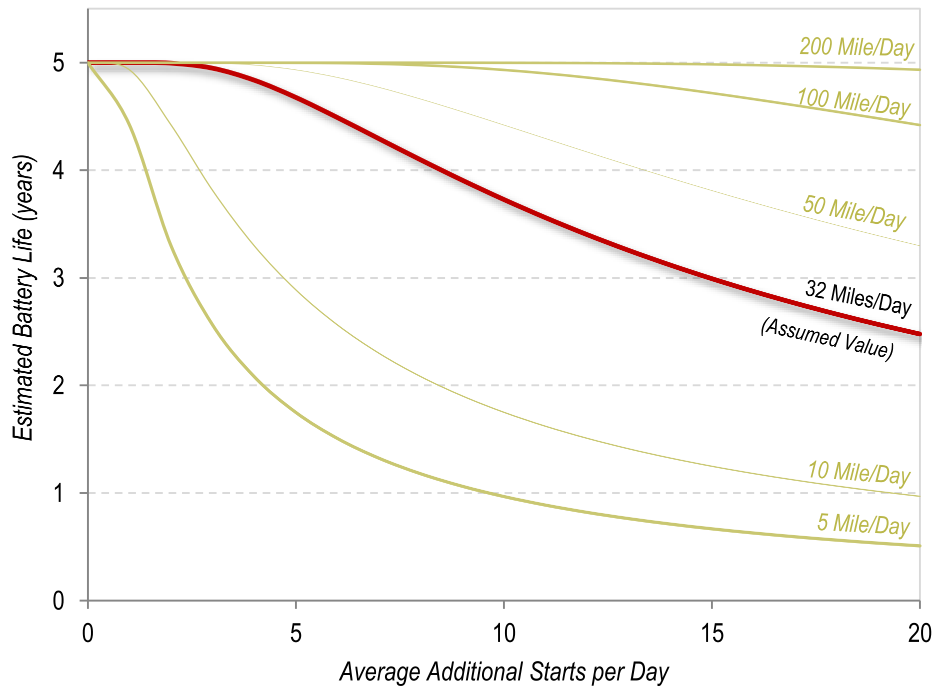

Figure 7: Battery Life Factors per Additional Starts per Day

Starter Motor Model

This model applies the starter-motor failure potential presented above to a typical vehicle operational cycle. The starter-motor failure model estimates the potential for starter motor failure for each additional start per day (above the baseline) for vehicles within a timeframe of 10 years. The increased potential for starter motor failure versus additional starts per day is shown in Figure 8. This model accounts for the potential that, in extreme cases, a starter may need to be replaced twice in a vehicle's life (resulting in a second "S curve" above 100% increased failure potential). The information displayed is the incremental potential for failure due to the increased number of daily start events, not the total potential for failure.

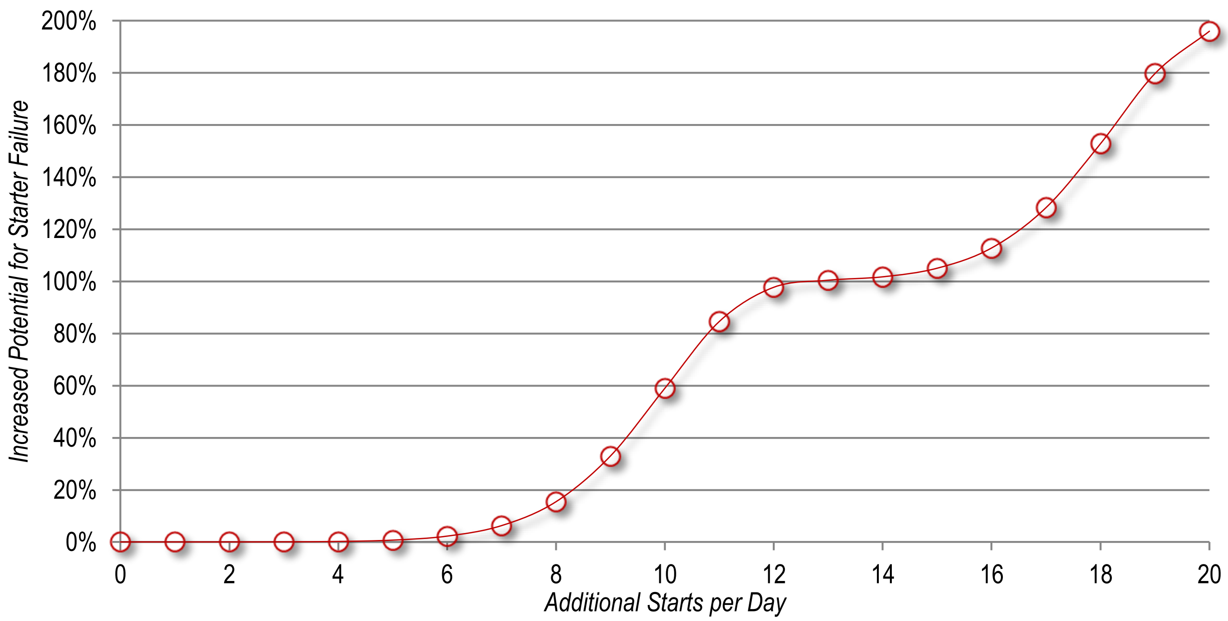

Figure 8: Incremental Starter Failure Potential per Additional Starts per Day over 10-Year Vehicle Useful Life

5. Economic Model

5.1 Overview of Economic Model

The economic model combines the battery and starter-motor replacement models with operating (fuel use and fuel cost) and component replacement cost data to provide end users with information to make an educated decision on whether manually shutting down their engines is economically sound. This model assumes the same 10-year vehicle assessment period. Vehicles typically last longer than 10 years, but after this point numerous and significant component failures typically occur and replacements are needed that cannot be quantified here. Additional inputs required for these calculations included the data provided in Table 1. Each assumption is described below the table.

Table 1: Economic Analysis Assumptions

Engine Displacement (liters)	2	3	4	5
Starter Replacement Price	$256	$463	$566	$648
Battery Replacement Price	$175	$175	$175	$175
Fuel Price (per gallon)	$3.58	$3.58	$3.58	$3.58
Idle Fuel Rate (gallons per hour)	0.25	0.34	0.44	0.53
Additional Fuel Used per Start (gallons)	0.0007	0.0010	0.0012	0.0015

- **Starter Replacement Price** – Estimated for each engine size (specific cost data discussed in Section 3.2);[1] assumed approximately scalable with engine displacement
- **Battery Replacement Price** – Averaged across a wide range of vehicles; not scalable with engine displacement (cost data are included in Section 3.1)[1]
- **Fuel Price** – Average 2013 fuel cost (U.S. $ per gallon) for 87 octane gasoline[4]

- **Idle Fuel Rate** – Related to engine displacement (see Section 5.2 for information)[5]
- **Startup Fuel Consumption** – Fuel quantity required to start the engine (see Section 5.2 for information)[2]

5.2 Economic Factors

An economic analysis was completed for engine displacements of 2, 3, 4, and 5 liters. The results show the total estimated lifetime cost savings of various shutdown durations and additional starts per day. The model includes three specific factors: fuel costs, starter wear cost, and battery wear cost. The model calculates and subtracts the baseline costs for starter and battery wear so the model outputs the incremental savings that are attributed to the increased number of starts.

Fuel Cost Factors

The average idle fuel consumption for light-duty passenger vehicles (passenger cars and light trucks) varies, depending on vehicle model, engine configuration, ambient conditions, accessory loads, and other factors. Argonne National Laboratory provides idle fuel consumption data for a limited number of engines (includes air-conditioning and accessories on and off).[5] To estimate the fuel rate for other engine displacements, a simple linear curve fit was applied to the engine idle fuel rate versus engine displacement (Figure 9). While specific vehicles will deviate from this estimation slightly, the relationship between engine displacement and idle fuel rate is quite consistent. This is because modern engines have similar volumetric efficiency and tightly control their air-fuel ratios at idle by using heated oxygen sensors and other sensors (which enable closed loop operation). The idle fuel rate data from Argonne National Laboratory, and the corresponding curve fit, are shown in Figure 9 (includes data for air conditioning and accessories, on and off).

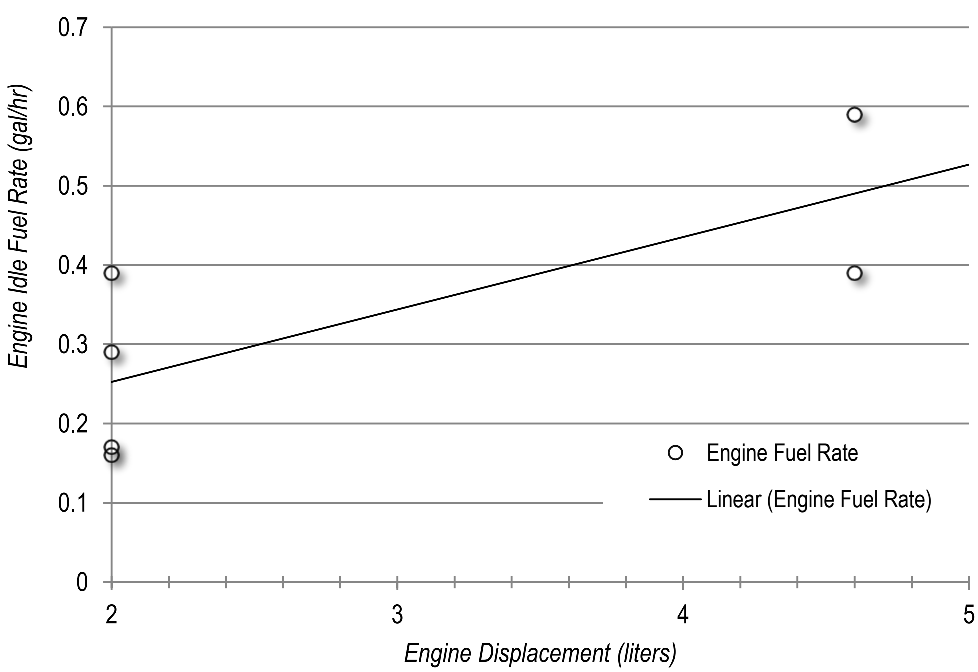

Figure 9: Engine Idle Fuel Rate Estimation

There has been a longstanding belief that starting an engine consumes more fuel than idling for a short duration. This point of view has persisted based on engine technology from decades ago, when low compression ratios, non-heated oxygen sensors, carburetors, and rudimentary fuel-injection systems required over-richening the air-fuel mixture to produce consistent engine restarts. These fuel systems had to inject large amounts of fuel into the cylinders to ensure the initial combustion event occurred to start the engine. This resulted in excessively rich operation for several minutes after each engine start. Modern engines, however, have high compression ratios, sophisticated fuel injection systems, and heated oxygen sensors that, in combination, allow for superior fuel control and enhanced combustion, which allow engine starting at near stoichiometric conditions. The combined impact of these technologies reduces the amount of extra fuel used for each start to approximately 10 seconds worth of idling fuel consumption (Figure 10).[2] More recent developments with direct fuel injection technology, which injects fuel directly in the combustion chamber at extremely high pressures, have further reduced this incremental fuel consumption.

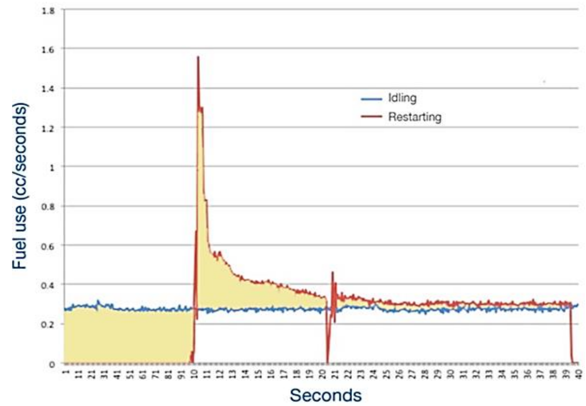

Figure 10: Fuel Flow for Idling versus Restart

Starter Motor Cost Factors

The starter motor wear cost is calculated by multiplying the starter motor replacement cost by the incremental probability of failure caused by increased engine starts over the 10-year useful life period. This component of the economic analysis is shown in Figure 11.

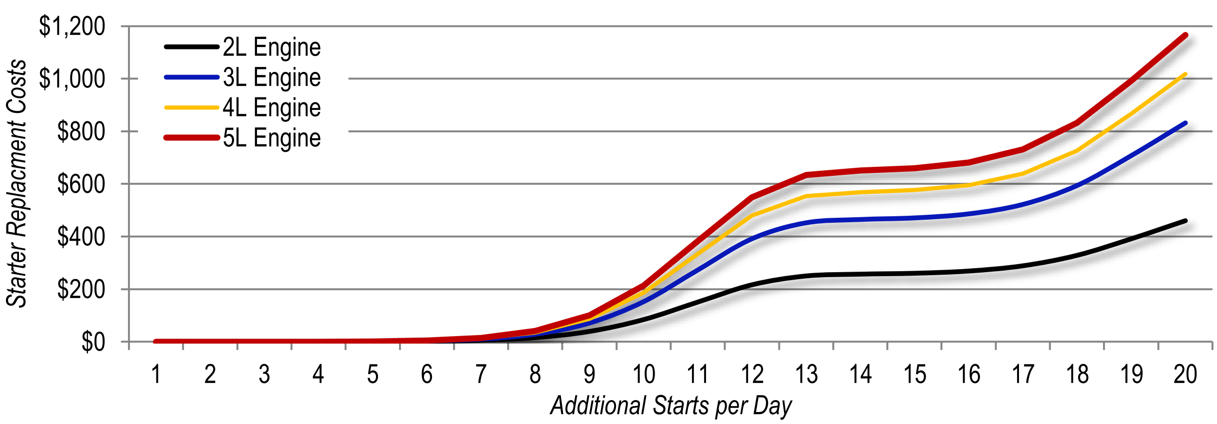

Figure 11: Starter Replacement Cost Factors

Battery Cost Factors

Battery wear cost is the cost of incremental battery replacements throughout the vehicle life. It is calculated from battery replacement cost and the battery life modeling results. Figure 12 shows the average of the expected replacement costs due to increased start cycles. This graph includes fractional replacement costs to account for the average over a wide range of engine starting frequencies.

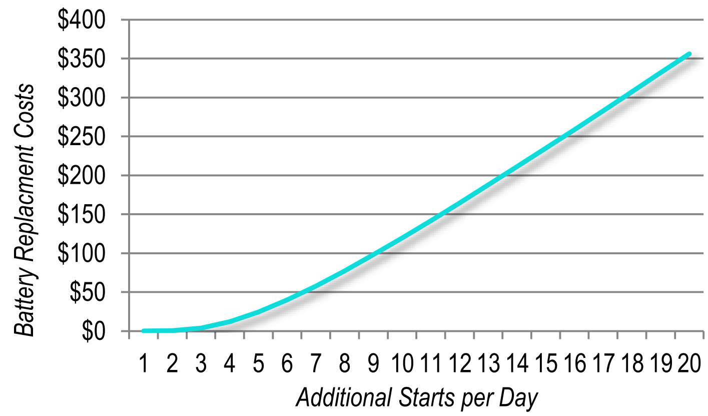

Figure 12: Battery Replacement Cost Factors

Overall Economic Feasibility

The economic viability of short-duration engine shutdowns to reduce idling depends on shutdown frequency, shutdown duration, and engine displacement. The following formula was used to determine the overall cost savings (or loss) for each average incremental start per day and shutdown duration.

$$S_{Total} = F_{savings} - F_{starting} - SM_{wear} - B_{wear} - BL$$

- S_{Total} – The total economic savings throughout the assumed life of the vehicle (10 years) due to the incremental engine shutdowns
- $F_{savings}$ – The fuel cost savings due to the engine-off periods. This is calculated by dividing the idle fuel rate (gallons per hour) by 60 (minutes per hour) and multiplying by the shutdown duration (minutes).
- $F_{starting}$ – The incremental fuel used to start the engine
- SM_{wear} – The starter motor wear costs. This value is the product of the starter motor probability of failure (for a specific incremental cycle increase) and the replacement starter price (for the particular engine displacement).
- B_{wear} – The battery wear cost. This value is the estimated number of battery replacements throughout the life of the vehicle (vehicle life divided by battery life) multiplied by the replacement battery price.
- **BL** – The baseline starting fuel costs, starter motor wear costs, and battery wear costs. This value assumes three starts per day and ignores shutdown duration, as these cycles are assumed to be necessary and not to reduce idling (e.g., at home and work). This factor is included to ensure the economic cases presented are incremental to a typical motorist.

The “Average Shutdown Duration” versus “Additional Starts per Day” results were plotted. Because the data are three dimensional, contour curves divide areas of the graph that represent different savings values (ranging from positive to negative) in discrete increments in a similar manner to engine efficiency maps. Graphs for each of the four engines displacements evaluated, ranging from 2 to 5 liters, are shown in Figure 13, Figure 14, Figure 15, and Figure 16. The contour plot lines show savings in

U.S. dollars over the vehicle useful life. For all engine sizes, the worst possible outcome (negative savings/cost increase) occurs in the lower right corner of the plots. This represents many, short duration, engine-off events per day. The highest cost savings occur near the top of the plot (with longer shutdown periods offsetting more idling). The curves vary in incremental starts per day due to the S-shaped curve that represents the potential starter-motor failure status. From these graphs, it can be seen that the areas of economic feasibility are quite similar among engine sizes. However, the scaling differs significantly due to fuel costs and starter replacement costs between the engine sizes. This translates into similar “break even” points, but with larger cost differences for larger-displacement engines as shutdown duration and/or additional starts per day are varied. The fuel price ($/gallon) has a significant impact on the potential economic savings. Decreased fuel costs shift the contour profile curves down and to the right (resulting in less savings, or increased cost). Conversely, increased fuel costs shift the curves up and to the left (resulting in higher savings). These plots show that (at the $3.58/gallon fuel price) a minimum shutdown duration of approximately one minute for six or fewer additional starts per day results in economic savings due to a reduction in idling fuel cost.

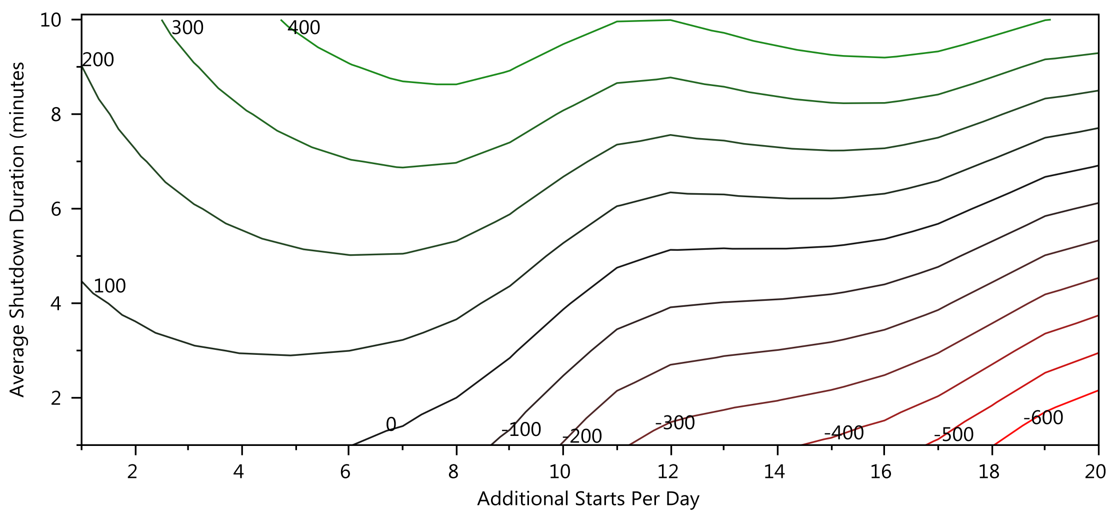

Figure 13: Two-Liter Engine Economic Model Results

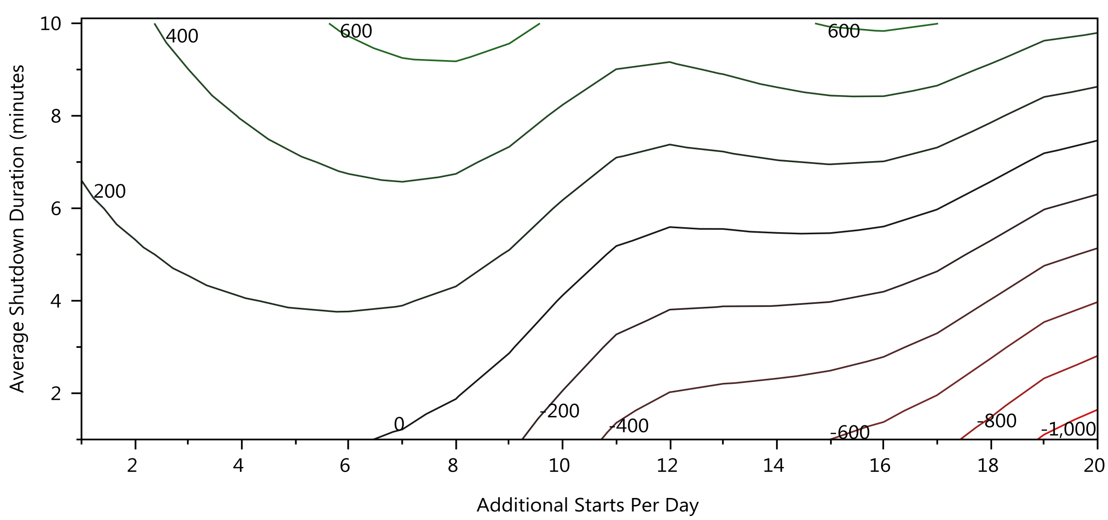

Figure 14: Three-Liter Engine Economic Model Results

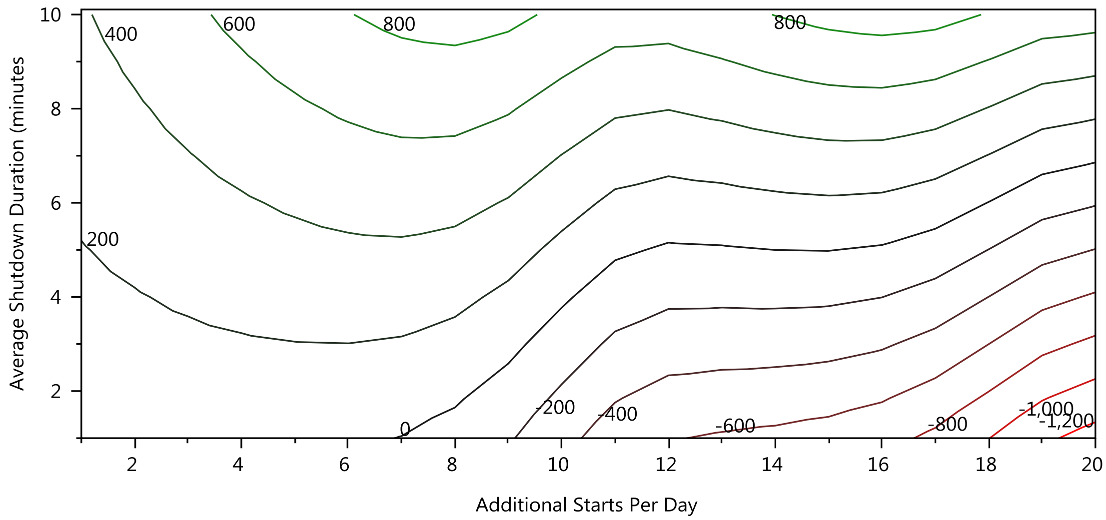

Figure 15: Four-Liter Engine Economic Model Results

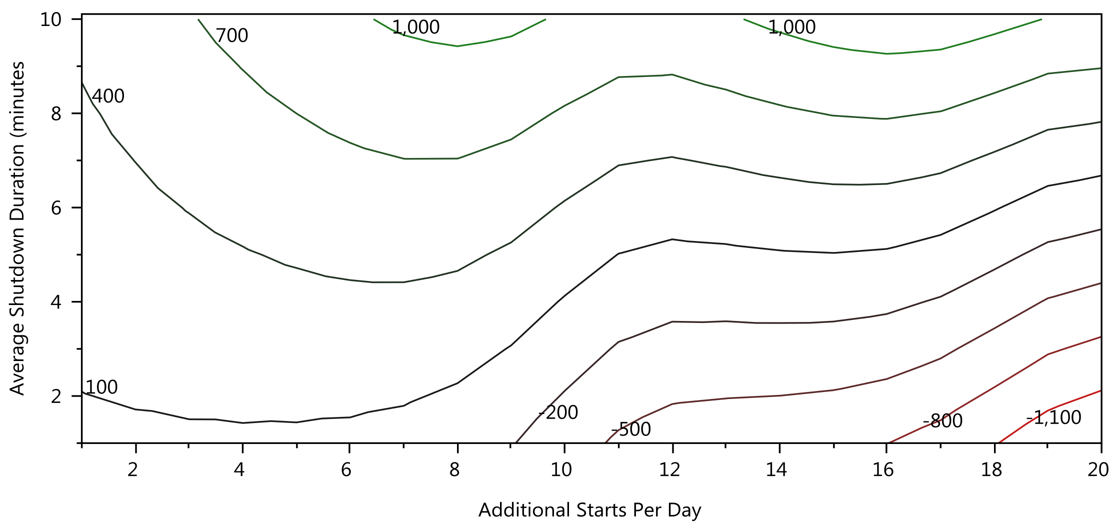

Figure 16: Five-Liter Engine Economic Model Results

6. Conclusion

6.1 Issues with Start Cycles

While aggressive start cycles (>20 cycles per day) could lead to premature failure in the starter system of light- to medium-duty commercial fleet vehicles, modern fuel injection and engine control systems have eliminated any issues associated with drivers of typical light-duty vehicles turning the engine off while stationary for short periods and restarting the vehicles for <10 start events per day. The information provided by industry experts regarding the primary engine starter-system components and the effects of increased engine-start-cycle frequency is summarized in Figure 17.

Starter Battery

- 5-year average life
- Designed for high-power, low-duration use
- Increased start cycles have minimal impact on life
- Accessory use with engine off shortens life
- Full charge must be maintained for maximum life
- $100–300 replacement cost

Starter Motor

- Designed for >30,000 cycles
- 10-year/100,000-mile life (at normal duty cycles)
- Increased start cycles have limited impact on life unless extreme (>20 cycle per day)
- High temperatures accelerate failure
- Often outlasts the life of vehicle
- $200–1,500 replacement cost

Alternator

- Recharges battery between starts
- Increased start cycles have no impact on life unless battery is excessively discharged between starts

Figure 17: Starter System Points of Interest

6.2 Best Practices

Because of the various contributing factors including the differences in vehicle uses, vehicle types, environments, and other factors, the decision to idle the engine for a short period, or to shut the engine off and restart it, is not a simple one. Even so, this study concluded that the majority of drivers of light-duty vehicles could improve their fuel efficiency and reduce fuel costs with minimal, if any, noticeable reduction in the life of starter system components by eliminating some short-duration idling throughout the day. To optimize fuel consumption and reduce the potential for component damage, typical drivers should adhere to the following guidelines:

- Limit engine start cycles to approximately 10 total cycles per day, on average. Occasionally cycling the starter system more than this will not cause damage unless it becomes a long-term trend.
- Assuming seven additional cycles per day are not exceeded (assumed ten total cycles per day), any shutdown with a duration in excess of one minute will result in overall cost savings.
- Limit electric accessory use during shutdowns, particularly during longer shutdown periods.
- Drive more than five miles between start cycles to ensure the battery is fully charged.

The overall conclusion is that cost savings can be realized by eliminating short-duration idling, assuming the average number of engine starts per day remains below 10. It was determined that, for a typical driver of a noncommercial light-duty vehicle, this level of additional daily start cycles will not likely result in additional replacements of starting system components compared to normal use. However, extremely aggressive start cycles, such as could be seen by commercial applications, could lead to premature component failure. It was also found that battery life cannot be tied directly to the total number of start cycles and that the distance traveled between start cycles is the controlling factor for battery life. Because of this, even aggressive duty cycles, as long as the vehicle is driven more than five miles between starts, may not pose a significant risk for a starter battery. Commercial drivers may drive far enough between starts to avoid battery damage, even with more than 10 starts per day (see Figure 7).

An approximate scale showing the effects on the starter system based on total engine start cycles per day is shown in Figure 18. This figure was developed on the basis of the information and analysis developed in this study. The figure provides an approximation, and so it should be used only for estimating the impact of increased stop-start cycles. The figure pertains to typical motorists; extreme cases (such as commercial applications with high daily mileage and usage hours) may see different results.

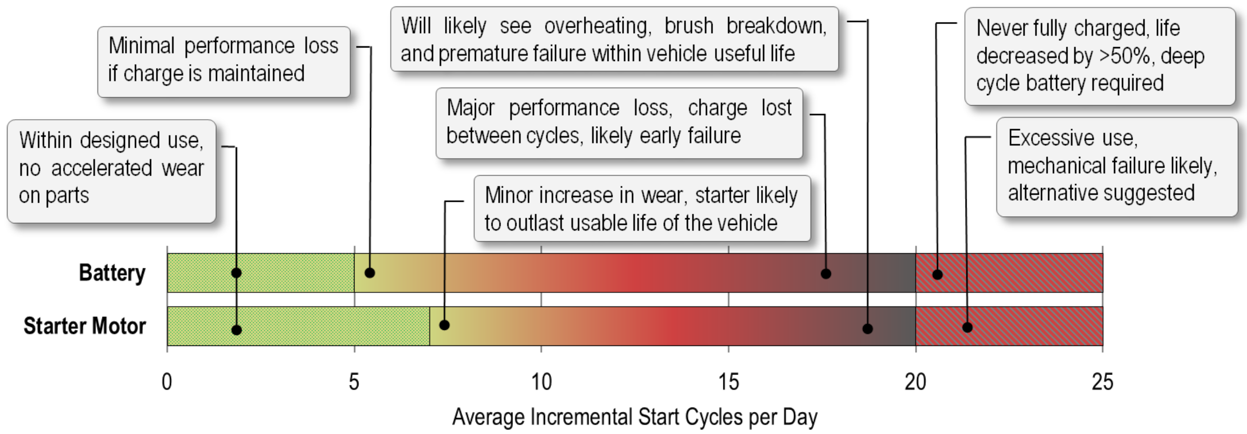

Figure 18: Start Cycles per Day versus Starter System Longevity for Average Short-Range Driving

7. References

1. “Estimate Costs.” *automd.com*. n.p. n.d. Web. 4 Mar. 2015. <https://www.automd.com/repaircost/>.

2. Gaines, Linda, et al. “Which is Greener: Idle, or Stop and Restart?” *energy.gov*. Office of Energy Efficiency & Renewable Energy, 17 Oct. 2012. Web. 4 Mar. 2015. <http://energy.gov/sites/prod/files/2014/03/f8/p-09_gaines.pdf>.

3. New York City Taxi & Limousine Commission. “2014 Taxicab Factbook.” *nyc.gov*. New York City Taxi & Limousine Commission. 2014. Web. 5 Mar. 2015. <http://www.nyc.gov/html/tlc/downloads/pdf/2014_taxicab_fact_book.pdf>.

4. U.S. Energy Information Administration. “Weekly Retail Gasoline and Diesel Prices.” *eia.gov*. U.S. Department of Energy, 2 Mar. 2015. Web. 4 Mar. 2015. <http://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_a.htm>.

5. Argonne National Laboratory. “Vehicle Idle Reduction Worksheet.” *anl.gov*. Argonne National Laboratory, n.d. Web. 4 Mar. 2015. <http://www.anl.gov/energy-systems/downloads/vehicle-idle-reduction-worksheet>.

Appendix: Industry Experts Consulted

Sector	Company
Automobile manufacturers	Chrysler/FCA
	Ford
	GM
Battery manufacturer	Johnson Controls
Heavy-duty manufacturer	Daimler
	Navistar
	Volvo
National laboratory	Oak Ridge National Laboratory
Professional association	SAE
Starter-motor manufacturer	Denso
Trade association	Alliance of Automobile Manufacturers
USPS vehicle repair	Wheeler Brothers

Energy Systems Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4854

www.anl.gov

Argonne National Laboratory is a U.S. Department of Energy
laboratory managed by UChicago Argonne, LLC