Effect of Automotive Electrical System Changes on Fuel Consumption Using an Incremental Efficiency Methodology

by

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Bachelor of Science in Mechanical Engineering
University of Pittsburgh, Pittsburgh, PA, April 2002

Submitted to the Engineering Systems Division
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Technology and Policy
at the
Massachusetts Institute of Technology
September 2004

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Abstract

There has been a continuous increase in automotive electric power usage. Future projections show no sign of it decreasing. Therefore, the automotive industry has a need to either improve the current 12 Volt automotive electrical system or move to a higher voltage vehicle electric system. Both of these choices are likely to increase cost of the system. Performance improvements will be needed to justify the increased cost to the Original Equipment Manufacturer. This thesis is investigating the potential for fuel economy improvements and their associated economic advantages for different vehicle electric systems. The objective is to determine the effects on fuel consumption of electrical system choices under a variety of drive and load cycle circumstances. Incremental, or marginal, efficiencies will be used to determine the relationship between loads and fuel consumptions. ADVISOR, a model developed by the National Renewable Energy Lab, has been adapted for use in this application. This included the implementation of industry standard engine performance map and alternator efficiency map data in the ADVISOR model.

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Acknowledgements

I think writing the acknowledgements may be harder than the following 80 pages. LOL! I am awed by the talent here at MIT. The professors, students, and research staff are truly one of a kind. What was viewed once as a simple world will now never be viewed the same through my eyes. Who knew that so much in this world could be questioned – and answered?

I would like to first thank my advisors for putting up with me. I don't know how they did it. They have had patience never before seen. Their guidance and knowledge has turned into a wonderful learning experience for me throughout my two years here. To Rich Roth, Gary DesGroseilliers, Tom Keim, and Frank Field, thank you for all of your time, patience, and constructive feedback. I could never express in words how much they are appreciated.

Before I came to MIT, I thought I was going to be alone and surrounded by students who were smarter than me and rubbed it in. I thought I was in for two isolated years. I guess I basically had all of the worst fears one could have before coming to MIT. Well, all of those fears were put to rest once I arrived in the Technology and Policy Program – except the one where everyone was smarter than me. MIT has truly humbled me. I also couldn't believe the patience from the students when explaining their views to a perplexed audience, or the patience they had when trying to understand my own perplexing thoughts. A brotherhood of sorts was formed with my friends in the Technology and Policy Program. We learned a lot from each other and worked through some tough times. I hope that we can remain friends over the years and continue to help each other out through any tough times ahead.

The Material Systems Lab one was I am very proud to have worked in. The students and staff were truly amazing. I loved all of the conversations about the day to day events in the world and I appreciated the humor with which we could disagree. I suppose I will be remembered as the warmonger of the group but I think that is better than the tree hugger. LOL! Mike Johnson, excuse me, Dr. Johnson, Alex, Colleen, Jennifer, Laetitia, Preston, and Delphine, I wish you the best. And thank you for all of the great conversations and guidance over the years. Joel Clark, thank you for everything you have done for the students. You can be proud of having such a warm and generous heart.

My friends outside of MIT have also been extremely patient and guiding. Jignesh Amin, Victor Anderson, and Kevin Pellerin were very welcoming to me when I first arrived at MIT and Boston. They have been great friends and have gone above the call of friendship duty. I have learned a great deal about friendships through them and I hope to one day be as good and kind-hearted as they were to me through my stay here. I also need to thank Vic for his computer programming advice. A lot of my research results lie in his understanding of what I needed to do but didn't know how to do it.

Last and certainly not least, I need to thank my family. They have been supportive of my decisions and have always been very patient listeners when I had something to complain about. I never could have done it without their support and understanding. I hope you know how important you are to me.

PS MIT is a long way from North Braddock.

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Definitions and Abbreviations:

$\dot{m}_f$ = mass flow rate of fuel
bsfc/BSFC = brake specific fuel consumption
ERPM = engine revolutions per minute
P_b = brake power
η = efficiency
η_{gross} = gross system efficiency
$\eta_{elec.gen.}$ = electrical generation efficiency
$\eta_{Increm.}$ = incremental efficiency
$\eta_{alt.}$ = alternator efficiency
η_{engine} = engine efficiency
$\eta_{incr.\ alt.}$ = incremental alternator efficiency
$\eta_{incr.\ engine}$ = incremental engine efficiency
Q_{LHV} = lower heating value of the fuel
Δ = change in
ω = engine speed
$Torque_{prop}$ = Torque needed for propulsion of the vehicle
$Torque_{alt}$ = Torque supplied to the alternator from the engine shaft
Total Torque = $Torque_{prop}$ + $Torque_{alt}$
∂ = differential change in
P_{alt} = alternator output
CAFE = Corporate Average Fuel Economy
OEM = Original Equipment Manufacturer
AC = Alternating Current
DC = Direct Current
GM = General Motors
ADVISOR = Advanced Vehicle Simulator
IHP = Indicated Horse Power
BHP = Brake Horse Power
NREL = National Renewable Energy Lab
WOT = Wide Open Throttle
NRC = National Research Council

1. Introduction

The automobile has been repeatedly equipped with more electrical and electronic components since its introduction. The increases have been due to the desirability of electrical functions that facilitate low emissions and high fuel economy, and enhance reliability, occupant safety, comfort and convenience [1]. As more increases in vehicle electrical technology take place, the maximum power limit of the system is being reached. This puts the system under strain and leads to inefficiencies. Throughout the years, incremental changes to the systems have occurred but no major shift or overhaul has been done to the system since the 1950s.

In the 1950's a change was implemented from the 6V architecture to the 12V architecture. This transition took place in a three year time period. The need for this transition arose from the high compression spark ignition engine needing a higher voltage ignition system. There were also increases in the growing number of accessories that required more electrical power at that time. Chrysler and GM were the first to introduce the 12V electrical system in their product lines in 1953. More accessories were introduced after Ford developed the AC generator in 1958, replacing the DC generator. During this transition time, the average vehicle's electric load increased from 340 Watts in 1953 to more than 600 Watts in 1963 [1].

The automotive industry is facing a similar situation now as new technologies are increasingly being introduced (e.g. electric power steering, seat heaters, VCR and DVD players, dash mounted navigation systems),and proposed (e.g. electromechanical valves, drive-by-wire technology, and active suspension.) These new technologies will require more electric output in future vehicles. Figure 1-1 shows two possible representations of future vehicle electric requirements. Without more electric output some of these new technologies will be inoperable as the 14V system exceeds its output. Therefore, the automotive industry has a need to either improve the current 14 Volt automotive electrical system or move to a higher voltage vehicle electric system to meet this need. A 42 Volt electrical system has been proposed and accepted as a new automotive electric standard. However, higher costs associated with new electrical systems pose a challenge. The higher costs may be offset by energy efficiency gains and the resulting fuel savings.

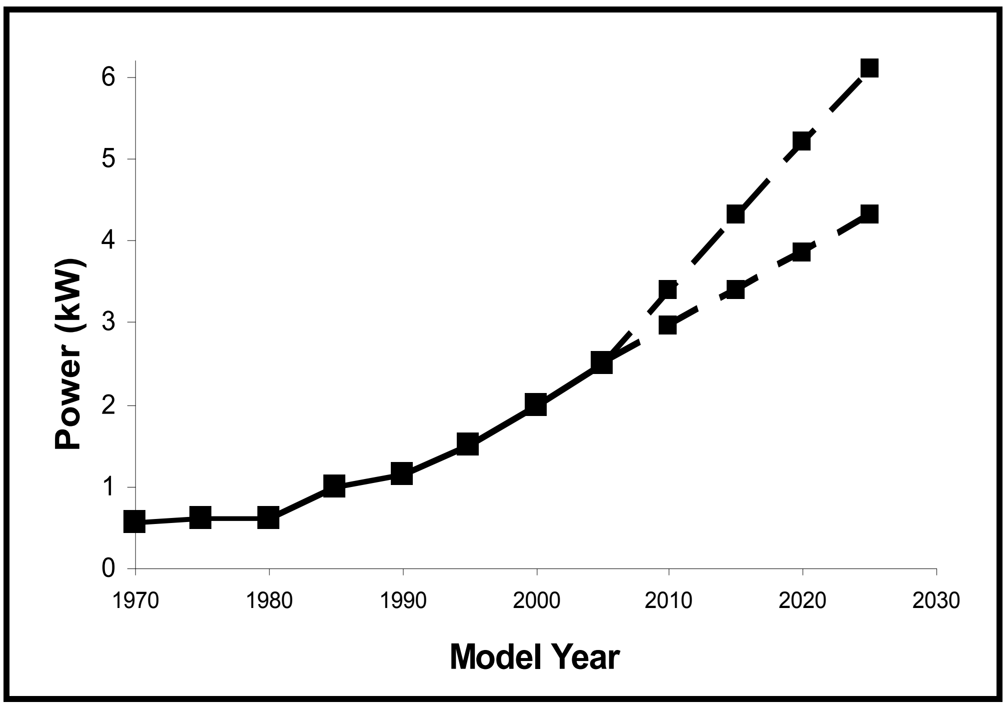


Figure 1-1: Projected Automotive Electric Power Requirements [2]

Only a limited number of vehicles have been introduced to the public, despite a general agreement from the OEMs that a new electrical system is needed. Several vehicles with advanced electrical systems (e.g., Ford Escape Hybrid, Toyota Crown Sedan, GMC Sierra PHT, Saturn VUE, and the GM Silverado Hybrid) have recently been introduced to the public with limited success.

To move to a higher voltage electrical system there are several challenges. Several technical challenges are controlling electric arcing and the possible need for a dual voltage system prior to the higher system. One reason for a dual voltage system when considering a 42 Volt system is that light bulb filaments will become very small and too fragile under a 42V system and may break when the vehicle drives over bumps in the road [3]. Besides some of these technical challenges there are economic challenges as well. There will be a need for a large investment to overhaul the vehicle electric system. The investment comes with high risks because the benefits for new systems do not clearly offset the investment costs. Therefore, no one auto company wants to move alone.

In 1994, a European automobile manufacturer anticipated a higher voltage requirement to support their electrical system in the future. Realizing the need for industry acceptance of a new voltage system, the Massachusetts Institute of Technology was asked to put together the MIT Working Group. Consisting of seven automotive OEMs and suppliers, this group considered issues of safety, reliability, infrastructure and transition costs. The result was a set of recommendations that proposed a 42V system with an engine-off voltage of 36V from an 18-cell lead-acid battery. After spreading the idea throughout Europe and Japan, the working group transformed into the MIT/Industry Consortium on Advanced Automotive Electrical/Electronic Systems [4]. There is also a working group of European OEMs and suppliers that is know as the "Forum Bordnetz". Its work is organized and facilitated by sci-worx GmbH, a German company.

The MIT Consortium, the Forum Bordnetz, the Institute of Electrical and Electronics Engineers (IEEE) and the Society of Automotive Engineers (SAE) work to set standards for new vehicle electric systems to help with any future transition.

Changing to a new electrical system will take an extremely large commitment from the automotive industry costing perhaps millions if not billions of dollars in capital investment [5]. In order to intelligently invest in the new electrical system, the entire life cycle economic cost and benefits must be assessed so that an eventual return on investment, if one exists, can be known [5].

There are industry reports of increased costs due to the transition to a new voltage electrical system. The increase in cost is due to the complexity, increased functionality, device content, and transition uncertainties [6].

There are various benefits that can be used to characterize changes in the vehicle system due to changes in the electrical system. A principal benefit of a higher voltage electrical system is the reduced current required. The lower current means that electrical conductors in the wire harness can be smaller, lighter, and less expensive [7]. The benefits of reduced wire size will probably not be sufficient to overcome the increased costs of the new system. Other benefits include electrically assisted turbochargers, electric power steering, idle start stop systems and many others. No single item seems likely to be able to "pay" for the new system.

A cumulative benefit of these features that may overcome costs is their reduction of fuel use. Reduction in fuel use can also have the positive side effect of reducing emissions. Changes in fuel economy are often used by the auto-industry when evaluating the implementation of new technologies. Fuel economy can be physically measured and has a known value. So, if fuel economy improvement can be gained by changes to the vehicle electric system, a question that arises is, how much?

One method that can be used to estimate fuel economy improvements can be changes in an overall energy balance of the vehicle system. Figure 1-2 below shows an overall energy balance across a sample spark-ignition automobile [8]. Starting at the top of the chart with 100% fuel energy, the chart shows the losses that occur. After combustion of the fuel, 62.4% of the total fuel energy is lost to the ideal 2nd law of thermodynamics and the real inefficiencies of the engine. The remaining 37.6% is called the indicated horsepower (IHP). The IHP is the power that is transmitted to the piston from combustion. Idle friction loss of 17.2% and accessory losses of 2.2% reduce the indicated horsepower to leave the useful work or the brake horsepower (BHP) to 18.2%. Drivetrain, rolling, and aerodynamic losses are further reductions of BHP. The remaining power is then left for acceleration of the vehicle.

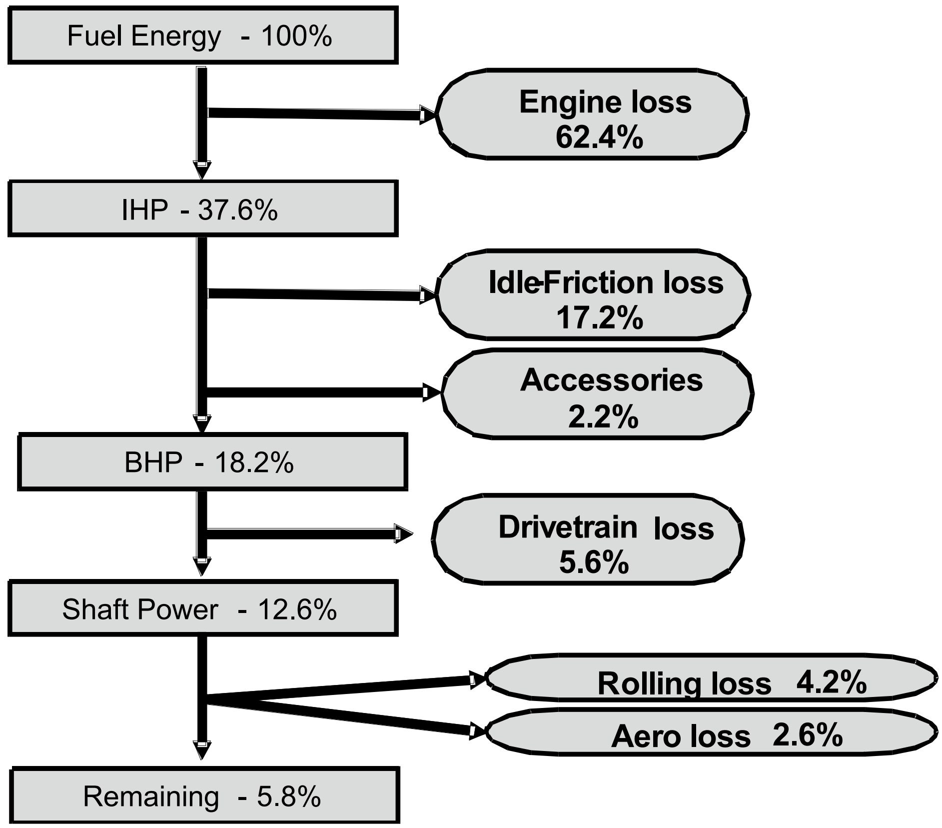


Figure 1-2: Energy Balance of entire automobile [8]

It is generally accepted that the introduction of various electrical technologies will decrease power losses to the engine and drivetrain. Some of the new electrical technologies will replace mechanical components that are presently belt-driven from the crankshaft of the internal combustion engine. Several of the mechanical components that can be decoupled and replaced with electrical components are: electric coolant circulation, electric power steering, and an electric oil pump. The launching of these new electrical accessories can reduce mechanical friction losses in the engine but will increase accessory energy pulled from the alternator. It will be necessary to know the reduction in friction loss and increase in electric accessory power so that an informed decision about overall engine loss can be made prior to installation.

New electrical technologies can also assist in decreasing friction losses due to idling. Cylinder deactivation will shut the engine off while the vehicle is stopped at a red-light or stop sign. This will decrease idle friction loss while the vehicle is stopped.

This high level energy balance is not a sufficient method to determine actual fuel consumption improvements. A high level energy balance misses multiple system interactions that are important when calculating fuel economy benefits. For instance, there will be changes in the engine and alternator system efficiencies that would be missed by the high order energy balance. A high level energy balance method uses average engine efficiency irrespective of engine speed. When in fact at various engine operating conditions the engine efficiency can be quite different. A variation of V-8 engine efficiencies is illustrated in Table 1-1.

Table 1-1: Steady State Engine Efficiency for Various Constant Speed Drive Cycles [9]

Constant Drive Cycle Speed(mph)	Engine Efficiency(%)
30	19.8
40	21.3
50	22.75
60	23
70	22.22
80	23.1

Another factor that discourages a high order energy balance is the fact that the same load has different effects at various operating conditions. This is because the engine efficiency changes at the different operating conditions when an extra mechanical or electrical load is turned on during a drive cycle.

Table 1-2 shows the effect of various electric loads at different operating speeds on engine efficiency.

Table 1-2: Engine Efficiency Changes with Various Electrical Loads Added [9]

Constant Drive Cycle Speed(mph)	Electrical Load (W)	Engine Efficiency No Load (%)	Engine Efficiency with Electric Load (%)
30	502	19.8	19.98
30	999	19.8	20.1
30	1999	19.8	20.53
40	502	21.3	21.5
40	999	21.3	21.57
40	1999	21.3	21.92
50	502	22.75	22.9
50	999	22.75	23
50	1999	22.75	23.25
60	502	23	23
60	999	23	23
60	1999	23	23.2
70	502	22.22	22.35
70	999	22.22	22.5
70	1999	22.22	22.67
80	502	23.1	23.29
80	999	23.1	23.5

There are sources that suggest amounts of possible improvement due to a change in the vehicle electric system. One, the National Research Council (NRC) report on "Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards", suggests that a 1 to 2% increase in fuel economy can be accomplished with the introduction of the 42V technology [10]. The numbers given by the NRC do not reflect all the changes possible with an increased 42 Volt system. In fact, their own report goes on to mention additional savings from features such as electro-mechanical valve trains. This feature has been only demonstrated possible with an advanced electrical system. Furthermore, the numbers do not actually address the specifics of how the new electrical system will be implemented. This makes the industry skeptical of the accuracy of these numbers.

These tools and methods are insufficient to address changes in fuel consumption for the detail needed when considering changes to the electrical system and their effects on fuel economy. Another method is necessary to give more detailed and accurate results. A method that will accurately estimate fuel economy improvements that can be obtained with a higher voltage electrical system or a change in the current electrical system, under a wide variety of operating conditions and drive and load cycles is needed. This report will introduce an efficiency metric that will do just that.

2. Problem Statement

Electrical system efficiencies are becoming more important as the automotive industry moves toward the use of more electrical components. With the increase in vehicle functions for safety, fuel economy, and comfort, future vehicles will consume more electrical power. To efficiently meet this demand, higher voltage systems or improving the efficiency of the existing system are being considered. Higher costs associated with these systems might be offset by energy efficiency gains and the resulting fuel savings.

The overall objective of this project is to determine a value proposition for vehicle electric systems. The focus of the research has been on the development of a metric to help determine a value proposition for changes in vehicle electric systems.

A value proposition for moving to a new vehicle electric system is defined as the benefit for either using the existing electrical system more efficiently or moving to a higher voltage electric system in comparison to their respective cost. New or advanced technologies require a net benefit. Therefore, there should be a balance between cost and performance. There are two positive value scenarios. One is where the new electrical system is at or below the cost of the existing system. Then there would be no need for performance improvements. The second is when the cost of the new system is greater than the current system. In that case, there should be performance improvements to justify the higher cost. Previous research and industry experience agree that the transition to a 42 Volt system, the new voltage standard, will increase cost [6]. A question that arises from this is: "Are there sufficient performance benefits to justify the cost increase of a new electrical system?" The motivation for this work is that the benefits that can be gained from moving to a new electrical system are either not correctly measured or not measured at all. This research will help clarify how benefits, or losses, can be measured.

There are several metrics used to define benefits for a new electrical system. Some are:

- a more powerful car
- the addition of luxury features
- reduction in emissions
- reduction in fuel use

This work will only focus on fuel use, or increased fuel economy, to define electrical system changes or, more desirably, benefits.

Fuel economy is used as the metric to define changes in electrical systems for several reasons. One reason fuel economy is chosen is that the automotive industry evaluates the implementation of new technologies by their effect on fuel economy. This fuel economy effect has a value to automobile manufacturers and purchasers and can therefore be compared with its cost. Another reason is that the fuel economy effect can be easily attributed as benefits or costs to automobile manufacturers and purchasers.

Two important questions arise with regard to influence of the electrical system on fuel economy. The first is, "how much is fuel economy worth?" Several approaches to answering this question have been put forth, such as, lifecycle costing of fuel and cost of meeting regulations such as CAFE [11]. The second question that arises is, "how much fuel economy can be gained by moving to a more advanced vehicle electric system?" The focus of this thesis will be to develop a methodology that can help answer this question. The methodology must be able to measure fuel economy changes caused by moving to a more advanced electrical system.

One way to define the changes in fuel economy due to electrical system changes is to use a traditional engineering metric – efficiency; how much can be gained from what is put in. Some difficulty in measuring changes in engine and alternator arises because these systems are not linear. Also, fuel economy is not a linear function of load due to the complexity of the relationships between mechanical and electrical loads over various drive and load cycles.

Several efficiency metrics were chosen to evaluate which one will lead to the most informative measure of fuel economy changes resulting from electrical system, or alternator, outputs. These efficiency metrics will measure effects on fuel consumption due to changes in electrical system choices under a variety of drive and load cycle circumstances. The term efficiency is a difficult and sometimes confusing term to use. Incremental efficiency was chosen as the metric to use when trying to calculate the efficiency of the next electrical watt of power output from the alternator. This thesis will consider other efficiencies that are sometimes used to express changes in the electrical system. These other efficiencies are the gross system efficiency and the electrical generation efficiency. Each will be clearly defined and their differences pointed out.

A model of engine and alternator performance is needed to identify changes in fuel consumption due to changes in the electrical system. An engine performance map is the automotive standard used to describe an engine's fuel consumption vs. engine speed and torque. The map is a function that outputs brake specific fuel consumption given the inputs of torque and speed. For this work, an engine performance map was developed from industry supplied data.

Alternator efficiency data is also needed to help identify changes in fuel consumption due to changes in the electrical system. The alternator efficiency data were recreated from the Bosch handbook [12].

A computer simulation tool that could incorporate the engine performance map and the electrical energy efficiency data is also needed. The National Renewable Energy Laboratory's **AD**vanced **V**eh**I**cle **S**imulat**OR** (ADVISOR) [13], is used as the primary tool throughout this study to calculate various engine performance parameters with a conventional automotive configuration over chosen drive cycles. A key feature of ADVISOR, relevant to this research, is that it incorporates both engine and alternator efficiencies into its calculations of fuel consumption. ADVISOR is also an open source code that can be changed to suit this research (i.e. no "black box").

A validation of the integration of the efficiency data with ADVISOR is necessary to verify accuracy of the ADVISOR results using the incorporated data. Several of the tests consisted of calculating the results using the engine and alternator tables without ADVISOR and then comparing to ADVISOR results. This is demonstrated in the Appendix on page 78.

Incremental, or marginal, efficiencies may be the most informative way to determine the correlation between loads and fuel consumptions at various operating points at various loads. The incremental efficiency is defined as the efficiency of production of an additional electrical Watt at the engine and/or alternator operating point. Electrical device efficiencies, other than the alternator, are not part of this study.

This thesis focuses on developing and using a tool to measure the fuel consumption implications from changes in vehicle electric systems. In order to do this, the work has focused on measuring incremental efficiencies throughout constant speed drive cycles and varying electric load cycles to identify a load's efficiency. Incremental efficiencies will be compared to the total gross efficiency and the electrical generation efficiency to help explain when incremental efficiency is the correct measure to use when trying to calculate changes in electrical system outputs.

3. Tools & Methods

Fuel economy is described using several metrics. In the United States, the figure of merit is almost always miles per gallon. The rest of the world uses liters of fuel per one-hundred kilometers. In addition to using different units, these two measures bear an inverse relationship to one another. Yet another measure is brake specific fuel consumption (BSFC) with units of pounds of fuel per horsepower hour or grams per megajoule, among other choices. BSFC is an explicit measure of the effectiveness of the engine at converting fuel to mechanical work, without reference to whether that mechanical work is efficiently used.

Closely related to these concepts is that of efficiency. There are many definitions of efficiency. All bear the common characteristic that they comprise a dimensionless ratio. The numerator is some desired output, for example, the net power out of the engine into the driveshaft. The denominator is some measure of input, for example, the net chemical power produced inside the engine cylinders. This example would measure the engine's efficiency.

To measure changes in fuel economy due to changes in the electrical system, the incremental efficiency metric will be used. It will be compared to some of the other efficiency metrics to help clarify its importance as a metric.

In order to calculate incremental efficiency, the fine structure of engine and alternator systems is needed. First the computer simulation model will be described. The following sections of this chapter will cover engine and alternator performance. There is a need for a computer simulation software tool that can integrate both engine and alternator performance data. Without the integration of the engine and alternator data, a clear evaluation of the system cannot be done. ADVISOR, the software tool chosen, will be described. The final section of this chapter will discuss the energy balance scenarios that define the different efficiency performance metrics.

3.1 Computer Simulation Tool – ADVISOR

ADvanced **V**eh**I**cle **S**imulat**OR** (ADVISOR) was created in 1994 by the National Renewable Energy Lab (NREL). It is a set of model, data, and script text files for use with Matlab and Simulink [13]. ADVISOR can be used to calculate fuel economy and emissions data for conventional, hybrid, or electric vehicles.

With this program, fuel economy under different operating conditions can be found for different vehicles through the use of engine performance maps and fairly detailed drivetrain and propulsion resistance models. The electrical system elements of ADVISOR are not well modeled. However, the model is unencrypted, so Matlab scripts for electrical component models can be added. ADVISOR has various built-in drive and load cycle models that can be applied to the vehicle and its defined components. The drive and load cycles can be changed to explore changes in fuel economy under a variety of conditions.

ADVISOR version 2002 has both desirable and undesirable attributes when considering its application for evaluating advanced vehicle electric systems and fuel economy. Two desirable attributes are that it has built-in engine performance models and it is an open-source code. ADVISOR can also be used to estimate fuel economy of vehicles that have not yet been built as well as learn how conventional, hybrid, or electric vehicles use and lose energy throughout their corresponding drivetrains [13]. Output graphs from ADVISOR can show changes in torque, engine speed, engine efficiency, and instantaneous changes in fuel consumption while the vehicle is going through a chosen drive cycle. ADVISOR lets the user define which vehicle components to study. The major thrust of ADVISOR is comparing different, substantially non-standard, powertrain configurations, in comparisons of significant complexity, for example, in operation over one or more drive cycles.

A disadvantage is that documentation for ADVISOR is limited. Another disadvantage of ADVISOR is that it was not designed or created for this specific project. These disadvantages are not necessarily major. It does mean that ADVISOR has significant capabilities that are not applied to this project. However, it could be a disadvantage if these unused capabilities have been obtained at the expense of reduced accuracy or usefulness in modeling those capabilities which will be used. Efforts were taken to determine that this is not the case.

ADVISOR uses the term 'fuel converter'. This is a generalization. In conventional drivetrains like the ones considered, this term refers to the engine. But in many of the ADVISOR graphics the reader will see the term fuel converter.

3.1.1 Defining the Vehicle

The first step in using ADVISOR in this project is to define the vehicle for which tests will pertain. Figure 3-1 is the first screen that is shown in ADVISOR. There are predefined vehicle load files that incorporate various vehicle components across different drivetrain configurations. After careful evaluation, it was decided to define a vehicle and components that were not predefined in ADVISOR. Looking at the top center of Figure 3-1, there is a tab named 'Load File'. There, the vehicle name that was created and saved can be seen, 'LEES_in'. The Drivetrain configuration is chosen to be conventional. Without going into detail, the rest of the vehicle's components are defined below the 'Drivetrain Config' tab in Figure 3-1. The tabs are 'Vehicle', 'Fuel Converter', 'Exhaust Aftertreat', etc. The specific choices for the components are then made from the tabs and are shown to the right of the vehicle component in Figure 3-1.

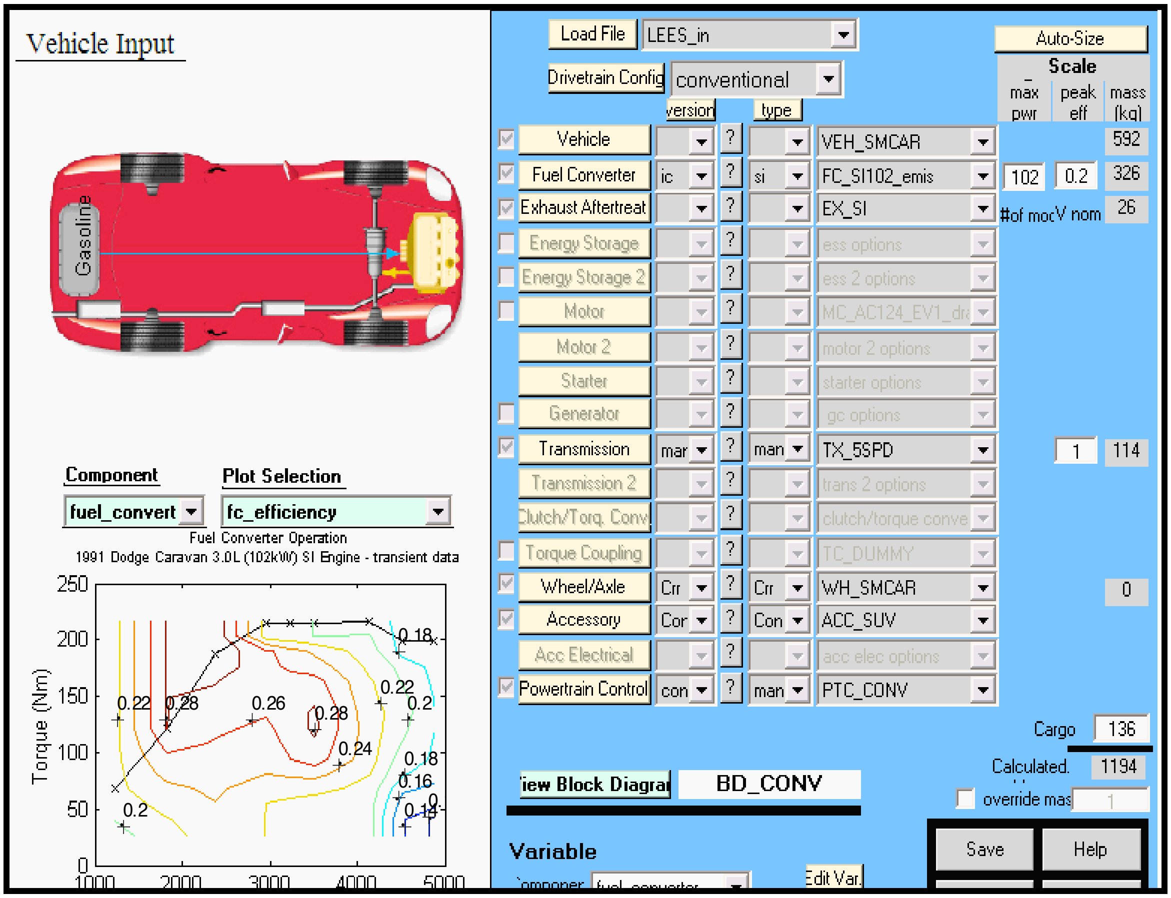


Figure 3-1: First Page in ADVISOR

In the bottom left hand corner of Figure 3-1 there is a picture of the engine performance map chosen with this vehicle configuration. The contours are of constant engine efficiency displayed in a torque-speed plane. The engine is identified above the plot as a '1991 Dodge Caravan 3.0L (102kW) SI Engine'.

ADVISOR also has the ability to define specific accessories. One tab to make note of in Figure 3-1 is the 'Accessory' tab. There are various accessory choices throughout all of the load files. Since most of the focus of this research will be on the accessories and their loads, it is imperative to understand their definitions and how they interact with the rest of ADVISOR.

3.1.2 Drive Cycle, Initial Conditions, and Electrical Auxiliary Loads

Once the vehicle and its components are chosen, ADVISOR then continues to the second screen. In Figure 3-2, the drive cycle, initial conditions and electrical auxiliary loads can be accessed.

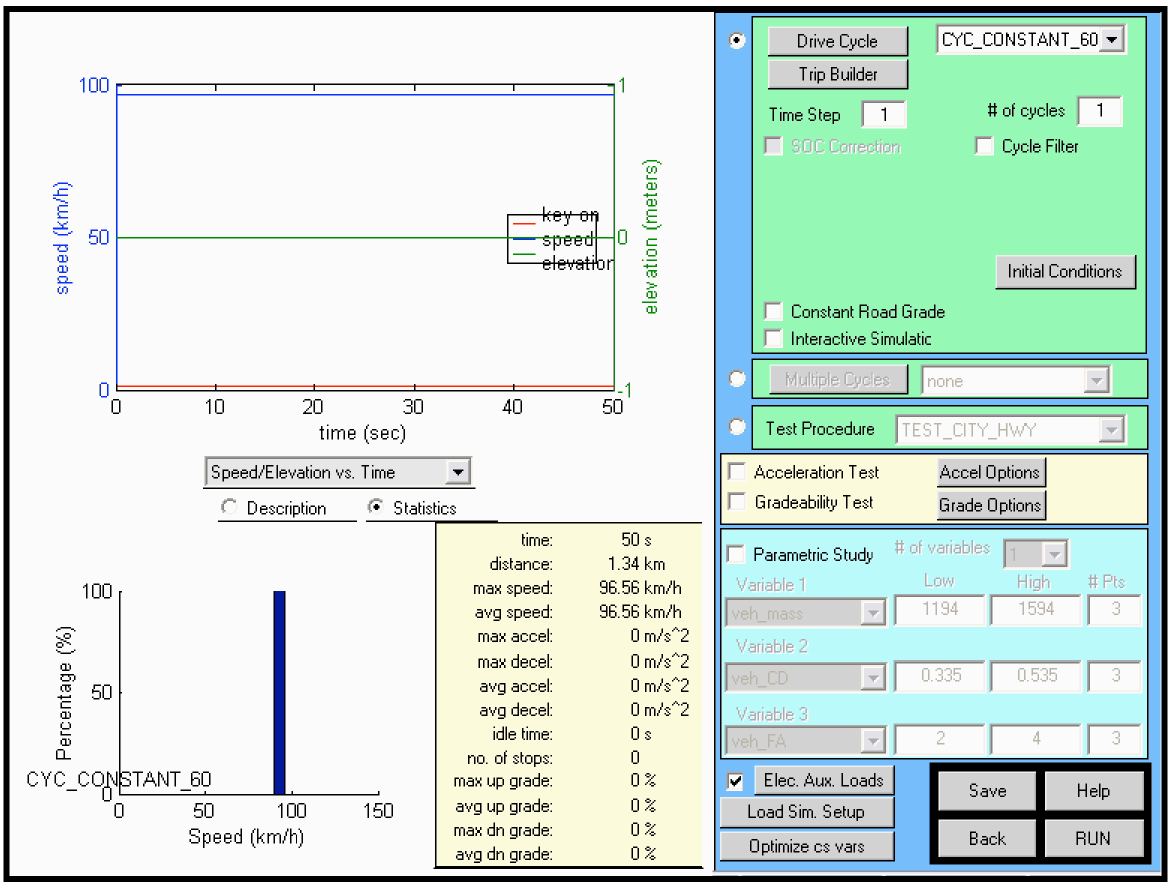


Figure 3-2: Second Page of ADVISOR

The top left hand corner of Figure 3-2 shows the graph of the drive cycle that the vehicle will be tested over. The speed versus time trace that is shown is selected from a pull down menu. The drive cycle chosen for this graphic is a constant 60 mph, or 96.56 km/h, cycle for 50 seconds with zero elevation above sea level. The x-axis of the elevation grid can be seen within the figure at 0 meters. The key-on line is set at one, or the on position, and can also be seen in near the bottom of the graph. Initial temperature conditions can also be set from this screen. The 'Load Hot' conditions were chosen. The engine cylinder, engine interior and exterior, hood temperature, and the exhaust system temperatures have temperature dependent models that are moved to highest initial temperatures in ADVISOR. By choosing the highest temperatures, warm-up effects on fuel consumption and engine efficiency are reduced throughout a drive cycle.

In Figure 3-2 another tab named 'Elec. Aux. Loads' can be seen. Here the user has access to a list of electrical auxiliary loads, as shown in Figure 3-3. By loading a predefined electrical auxiliary file, or creating a special purpose file, different electrical loads can be chosen to be applied during a drive cycle. The example electric auxiliary load shown in Figure 3-3 is one that was predefined by ADVISOR to simulate city summer driving during daytime conditions.

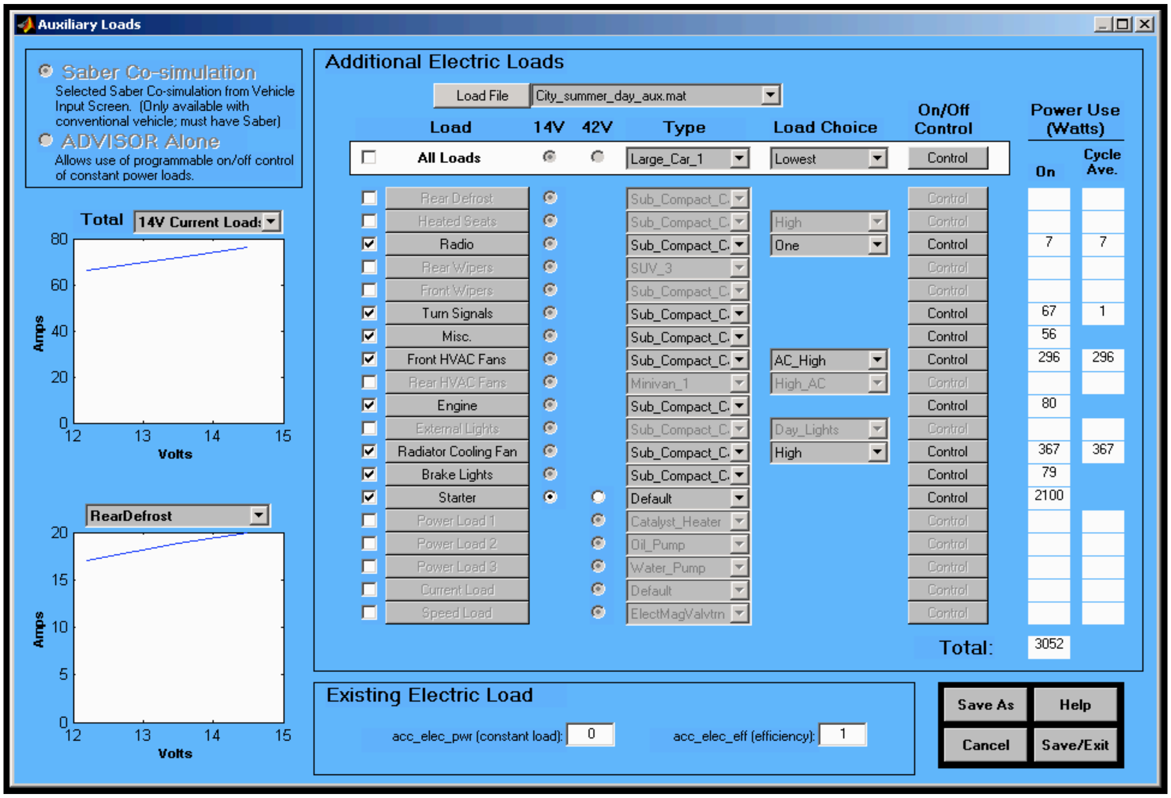


Figure 3-3: Additional Electrical Loads Page in ADVISOR

One of the benefits of these electrical choices is that the user also has control to turn on or off the electrical load throughout the drive cycle. Figure 3-4 shows a front defroster on/off profile. It shows that the defroster is initially on and then is shut off at 200 seconds, turned back on at 300 seconds and then turned back off again at 600 seconds. This gives the user the flexibility to start an electrical load initially off and then turn on the electrical load at any time in the drive cycle to study the loading effects.

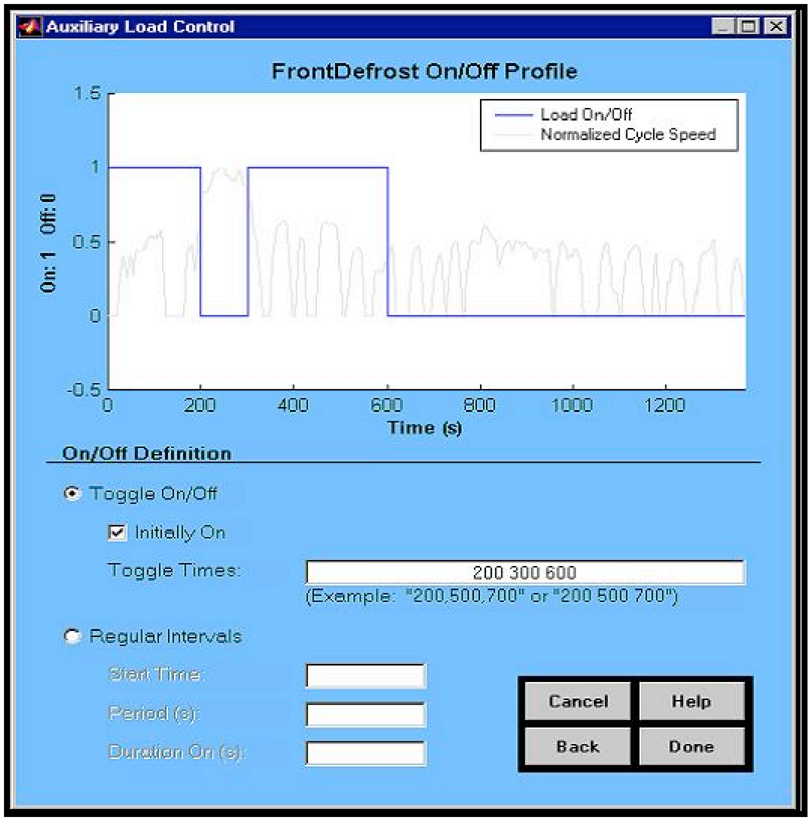


Figure 3-4: Front Defroster On/Off Profile

This software tool is used to assist in finding the fuel economy benefits of changes in the vehicle electrical system. ADVISOR uses the engine performance map and the alternator performance data described above. ADVISOR defines the engine, transmission, auxiliary loads, and the exhaust system among others. Initial temperature conditions can be set for the vehicle's engine, cylinder, hood, and several other front end engine parts. The instantaneous vehicle engine outputs of torque, engine speed, and efficiency will be evaluated using ADVISOR's outputs, during a chosen time within a drive cycle. Alternator efficiency, engine energy efficiencies and changes in fuel consumption can and will be evaluated over different constant speed drive cycles. More closely, the incremental changes in engine efficiency as well as incremental changes in fuel consumption will be studied with the addition of a load to the engine during the drive cycle.

The primary goal of doing a detailed examination of the combined effects of the engine and electrical system is to understand the incremental improvements in efficiency that can be gained using different electrical systems and loads. The first step in this direction is to understand how energy consumption (or efficiency) changes in response to a single electrical load being placed on the system. The results of the tests, conclusions, and future work will be discussed.

3.2 Engine Performance Map

The true details of the engine's fuel efficiency can be captured with an engine performance map, the automotive standard for describing an engine's fuel consumption vs. engine speed and torque. The map is a function that specifies brake specific fuel consumption or engine efficiency for a given input of torque and speed. The function used throughout the research is displayed with engine speed (rad/sec) as the horizontal axis, torque (Nm) as the vertical axis, and engine efficiency contours (%) that correspond to a speed and torque. ADVISOR has pre-installed engine performance maps, consisting of tabulated data and interpolation functions for arguments between data points in the form of Matlab files. The ADVISOR table for a typical engine performance map is sparse. It is in the form of a 9 x 15 matrix covering the approximate range of 900 to 5700 rpms. For this work, a new engine performance map, with a matrix of 20 x 25, was developed from industry supplied data. The industry map was used because it covered a wider range of data points. The industry data gave a denser map with more credible data. The matrix, however, was not a complete 20 by 25 matrix. Linear interpolation was used to fill in the blanks. This raised questions about the credibility of some of the results and a more thorough discussion on this is forthcoming.

The engine performance map in Figure 3-5, used throughout the study, corresponds to a V-8 engine. Therefore, throughout the test runs in ADVISOR, a sport utility vehicle frame was used to simulate a larger automobile.

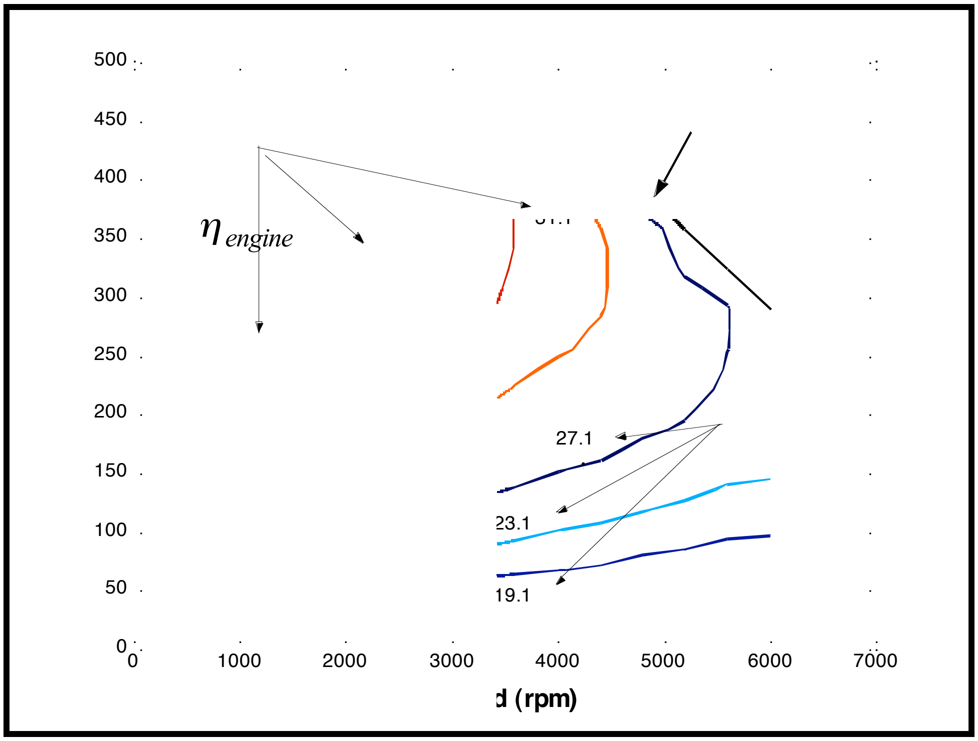


Figure 3-5: Engine Efficiency Map with Contours

The brake specific fuel consumption data points for the 20 by 25 engine map matrix have been converted to efficiency points using Equation 3-1.

$$\eta = \frac{1}{bsfc * Q_{LHV}} \qquad \textbf{Equation 3-1}$$

Bsfc is the brake specific fuel consumption and Q_{LHV} is the lowering heating value of the fuel, in this case gasoline. The efficiency points thus calculated have been used to generate the constant-efficiency contours shown in Figure 3-5. The numbers written next to the contours are the corresponding efficiencies. The solid black line at the top of the graph is not an iso-efficiency line, but is the wide open throttle (WOT) torque-speed function. A sample of the tabular data can be found in Table A-2 in the Appendix. The contour plotting utility used to generate Figure 3-5 is an ADVISOR function. Much of the kinkiness of the curves is attributable to the discrete tabular nature of the raw data.

Brake specific fuel consumption numbers were not supplied for all of the engine rpms and torques. A linear interpolation in bsfc was used to fill the grid where the numbers where absent. It is possible, however, that the behavior of bsfc between the end points of interpolation is not linear. Note from Equation 3-1 that efficiency and bsfc are inversely related. As a result, linear interpolation on bsfc followed by conversion to efficiency produce a different result from linear interpolation in efficiency. A more detailed explanation is found in the Appendix on page 84. All torques and engine speeds fell within the range of brake specific fuel consumption data, therefore, no extrapolation was needed.

3.3 Alternator Efficiency Data

An alternator efficiency map is used to determine how much mechanical input power is needed to produce a given electrical output. Alternator efficiencies vary with the operating conditions of the alternator. A graph of an alternator efficiency map is shown in Figure 3-6.

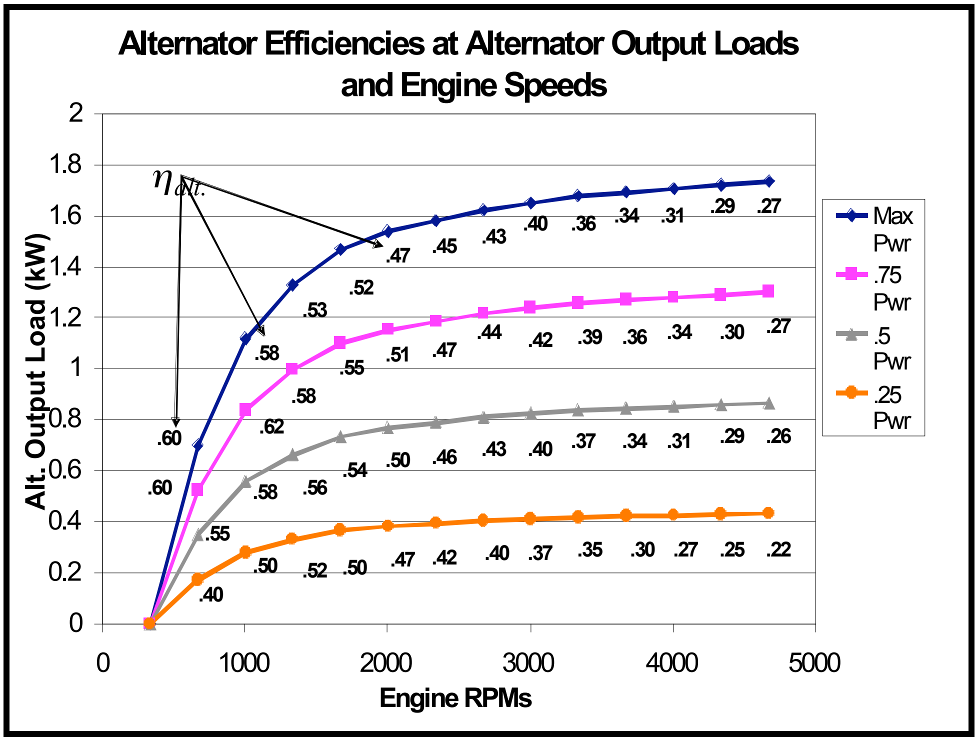


Figure 3-6: Alternator Efficiencies at Alternator Output Loads and Engine Speeds

Figure 3-6 is an approximation of a figure from the Bosch handbook [12]. The figure is used to create a matrix that is used within ADVISOR to find mechanical input from the engine to the alternator at the various alternator output loads and engine speeds. This data replaced an existing alternator file in ADVISOR that was used primarily for large trucks. Figure 3-6 indicates alternator efficiency as a function of engine speed (x-axis) and load (y-axis). The four curves in the graph represent power levels of 25, 50, 75, and 100% of the maximum alternator load. There is also a fifth curve that is not shown on the graph and that is the 0% of maximum load line. This is the x-axis. The two digit number adjacent to each discrete load point is the efficiency at that point. Iso-efficiency contours are not plotted in Figure 3-6. However, the reader can visualize what they may look like from the numbers shown here.

Alternator efficiency is related to mechanical input to the alternator through Equation 3-2:

$$\text{Mechanical Input} = \frac{\text{Alternator Output}}{\text{Alternator Efficiency}}$$ **Equation 3-2**

At zero alternator output the efficiency is zero percent, however, it is important to note that there are still losses, and therefore mechanical loads, at these points. This means at zero alternator output the alternator is still pulling a load from the engine shaft. The alternator losses at zero output correspond to mechanical and iron losses of the alternator and are a function of alternator speed. The alternator losses at zero output were found using information from the Bosch Handbook [12]. Total losses were predicted at the 25% maximum output line and were divided into two parts: the losses due to alternator speed and the losses due to electrical load. The losses due to electric load were extrapolated from a trend-line created in an EXCEL spreadsheet. These loads were subtracted from the losses at 25% maximum outputs. The remaining number was used as the power drawn from the engine shaft by the alternator at zero electrical output at each corresponding alternator speed.

3.4 Methods – Energy Balance and Efficiencies

3.4.1 Energy Balance

To see the details of the engine/alternator system, start with the energy balance deduced from Figure 3-7.

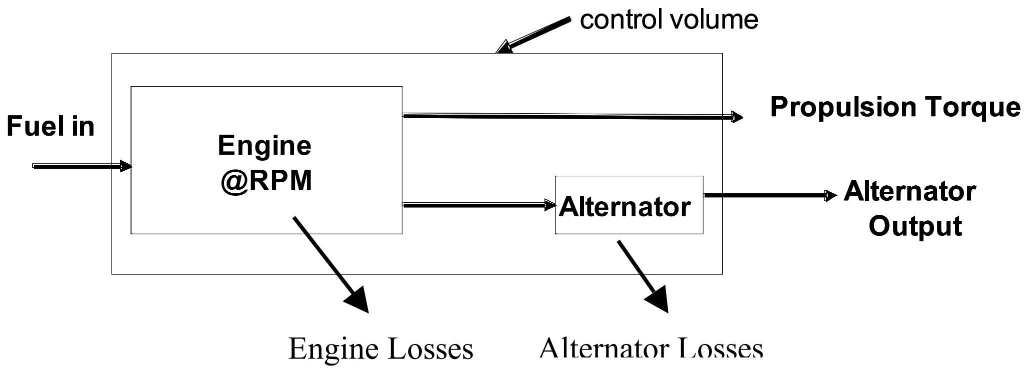


Figure 3-7: Engine Alternator System used for Energy Balance

The control volume above in Figure 3-7 includes the engine and alternator system. For that analysis, assume that losses for any other accessories attached to the engine, except the alternator, are included in engine losses. The engine losses consist of the thermodynamic losses, pumping losses, and the accessory work, other than the alternator, throughout the system. Alternator losses are due to running the alternator fan and bearings, belt slippage, iron losses, copper losses and diode losses. On the left side of the control volume, the fuel enters the system. The fuel and air enter the engine at a rate consistent with the engine speed and throttle conditions and air to fuel ratio. The fuel enters the cylinders and is then combusted with the air. This is a change from chemical to thermal energy. The hot gases push down on the pistons, creating linear mechanical energy. The linear mechanical energy is then converted into rotational mechanical energy via the rods attached on one end to the piston and on the other, the engine shaft. The volume of fuel-air mix influences the downward pressure on the pistons and the corresponding torque. The engine speed and vehicle speed are related by the transmission. In steady driving, the engine torque is just enough to overcome drag and hill climbing loads. If more or less torque is produced, the vehicle accelerates or decelerates. The engine shaft provides torque to the transmission, driveshaft, and ultimately to the drive wheels. The torque out of the engine to the transmission is called propulsion torque.

The alternator is connected to the engine shaft via a belt. In this scenario, when an alternator load is needed, some of the engine torque is used in rotating the alternator shaft to produce electrical energy. In summary, the mechanical torque to the alternator is converted to electrical energy via the alternator at some efficiency. The sum of the propulsion torque and alternator torque multiplied by the engine speed is equal to what is called the "brake power". The brake power is the useful work out of the engine.

It was first decided to look at an energy balance at constant vehicle speed. The results from ADVISOR of fuel flow rate, engine torque, and engine speed were first recorded with zero alternator output. Once the data for the base case is recorded, the alternator output was increased by 100 Watt increments while keeping the vehicle speed constant at 30mph. The change in fuel flow rate and engine torque can then be determined using ADVISOR. The engine speed will stay constant for constant vehicle speed. By multiplying the engine torque and engine speed the brake power can be calculated.

Figure 3-8 shows a representative power balance for an engine/alternator system operating at constant traction power. The y-axis is the fuel power into the engine. The x-axis is the alternator output from 0 to 1200 Watts. The vehicle stays at constant speed of 30 miles per hour throughout the changing of alternator output. One thing to note here is the large thermodynamic losses from the engine. From the representation we can measure efficiencies of the system. From this figure, it is not obvious that the influence of small changes in the sub-systems can be easily seen with this representation.

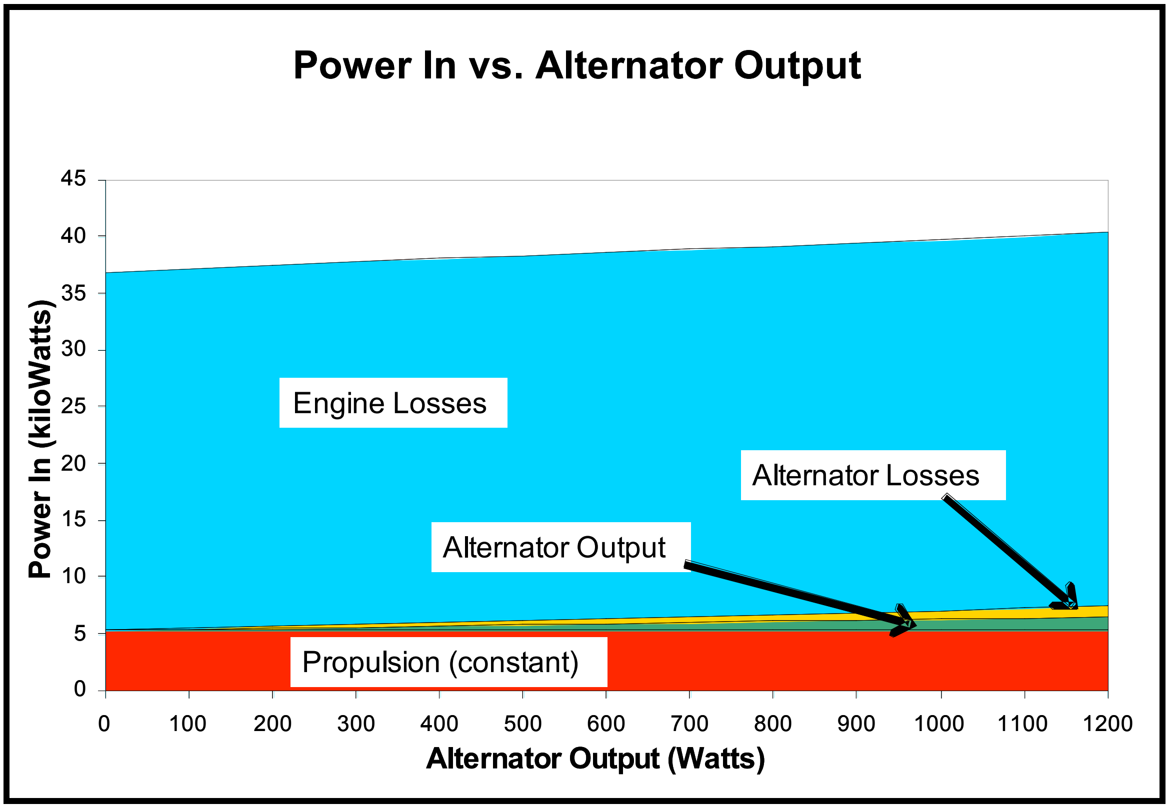


Figure 3-8: Power Balance at 30mph; 0-1200 Alternator Output

Zooming in on Figure 3-8, Figure 3-9 is graphed. It is noted that there is in fact some "fine structure" to the engine performance that suggests that there are some local effects that would influence our perception of how to most efficiently run or design this system. This is most visibly seen at the inflection in alternator losses at 1000 watts in this figure. There are also other local effects that are not easily visible in this graphical representation. The propulsion power is constant by definition. The alternator output is by definition at a 1 to 1 ratio to the corresponding input power. This means that for this graph, for each 100 Watts of power output by the alternator, the corresponding input line is 100 Watts higher. The slope of the alternator output line is constant. The alternator inefficiencies are shown in the alternator losses line, still in mechanical watts. The engine losses line in Figure 3-8 goes up more steeply than any other.

Since the propulsion power is constant, all the changes in engine losses arise from the alternator load.

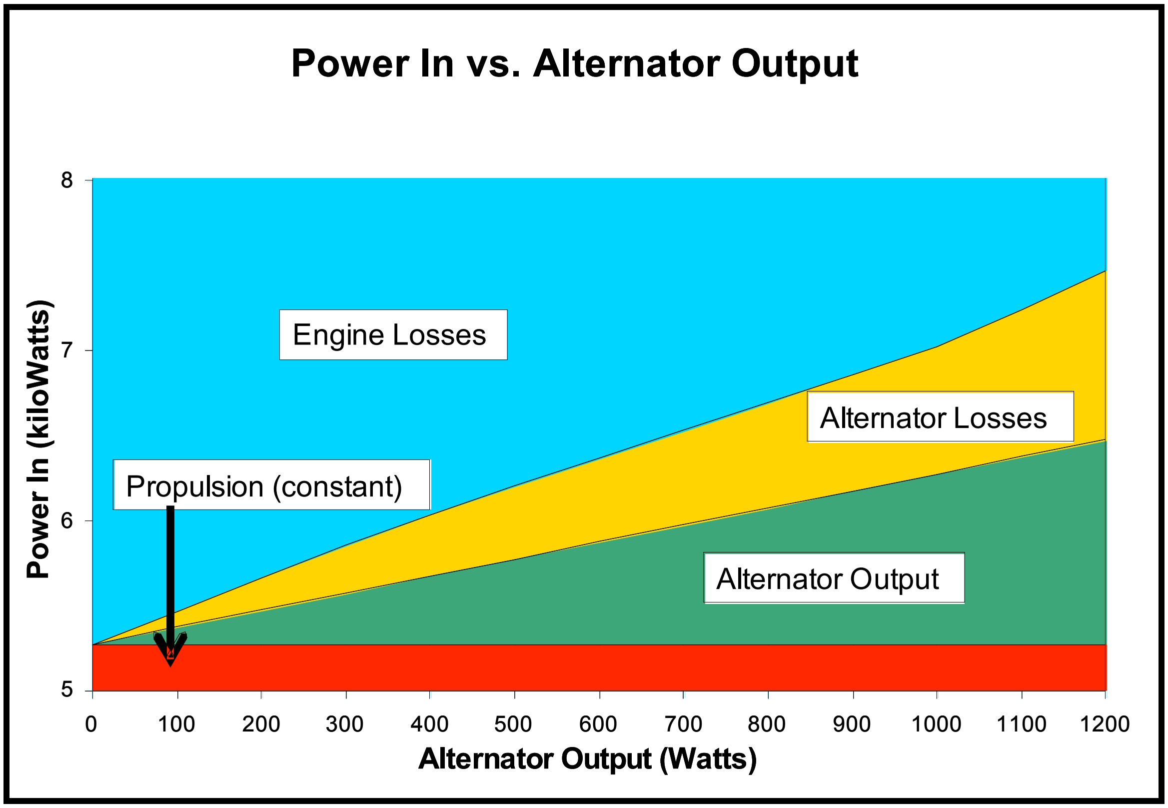


Figure 3-9: Zooming of Figure 3-8's Power Balance at 30 mph

3.4.2 Gross System Efficiency

One possible metric that can be used to characterize performance is gross system efficiency – usable power out divided by fuel power in as given by Equation 3-3.

$$\eta_{gross} = \frac{\text{Power Out}}{\text{Power In}} \qquad \textbf{Equation 3-3}$$

The system consists of the engine/alternator with fuel power into the system. Some of that fuel power is converted into propulsion torque to maintain constant speed at a corresponding engine RPM. The rest of the torque goes to the alternator to produce electrical output. The power to the alternator is transferred to alternator output at the alternator efficiency. The power out to power in ratio then reduces to Equation 3-4.

$$\varsigma_{gross} = \left(\frac{(Torque_{prop.} * \omega + Torque_{alt.} * \omega * \varsigma_{alt.}}{\dot{m}_f * Q_{LHV}} \right)$$ **Equation 3-4**

The torque for propulsion is seen as the dominant torque. Therefore, the gross system efficiency will be dominated by the torque that goes to propulsion. Equation 3-4 will not help in identifying the effects of small changes in the electrical system designs.

The computer simulation model was first validated as described in the Appendix. It then became possible to run simulations of system performance, and to calculate and compare the different indicators of system performance. Figure 3-10 is a gross efficiency bar chart detailing the evaluation of operation at 400 Watts of electrical output with a constant vehicle speed of 30mph.

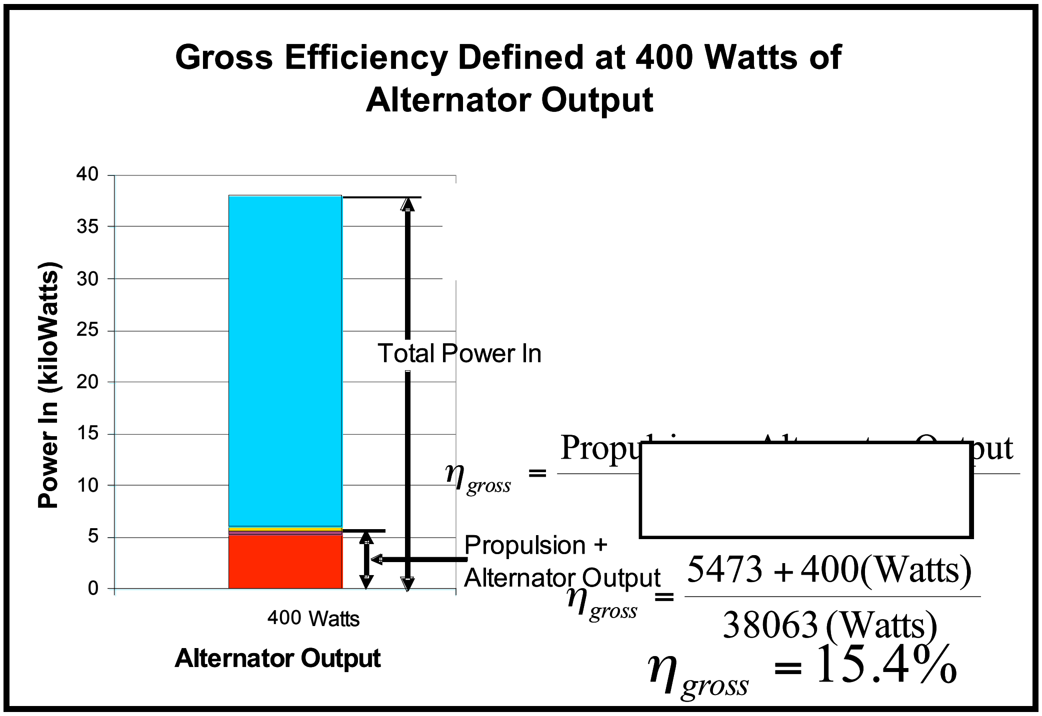


Figure 3-10: Gross Efficiency Example Calculation

This is a slice of the graph from Figure 3-8. This slice was taken at the 400 Watt mark of alternator output. The gross efficiency is defined from Equation 3-4, as the propulsion power plus the alternator output power divided by the total power of the fuel into the engine/alternator system. Adding them up and dividing, an efficiency of 15.4% is found for the gross efficiency of the operating state with 400 Watts of electrical power output from the alternator. As mentioned before we can see that the alternator output of 400 Watts is only a small fraction of the propulsion power. Therefore, this is not a good indicator of the efficiency of the next Watt of electrical output. Figure 3-10 is used as an illustration of this efficiency and why it is described as not useful in determining the efficiencies from changes in the electrical system.

3.4.3 Electrical Generation Efficiency

Using the same system as before, another focus might be upon the efficiency with which electrical energy is generated. The electrical power generated per unit of fuel consumption devoted to electricity generation might be defined by the Equation 3-5. Figure 3-11 and Equation 3-5 describe this efficiency metric. Implicit in this definition is the assumption that the engine produces propulsion power and alternator drive power with exactly the same efficiency. Equivalently, the equation assumes that engine fuel flow can be divided between the propulsion and alternator drive functions in proportion to their respective torques.

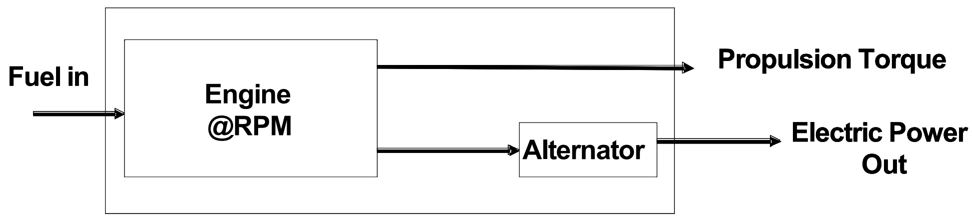


Figure 3-11: Electrical Generation Efficiency Control Volume

$$\eta_{\text{elec.gen.}} = \eta_{\text{engine}} * \eta_{\text{alt.}}$$ **Equation 3-5**

The electrical generation efficiency is defined by the multiplication of the engine and alternator efficiencies. After substitution the Equation 3-5 breaks down to:

Equation 3-6

$$\eta_{\text{elec.gen.}} = \left(\frac{(\text{Torque}_{\text{prop.}} + \text{Torque}_{\text{alt.}}) * \omega}{\dot{m}_f * Q_{LHV}} \right) * \left(\frac{\text{Alternator Output}}{\text{Torque}_{\text{alt.}} * \omega} \right)$$

Rearranging,

Equation 3-7

The ratio of the torques in the denominator provides the same problem as with the gross system efficiency. The torque to the alternator is very, very small compared to the total torque. This is one indication that changes in the electrical system may not be captured with this efficiency metric. Neither the engine nor the alternator act **linearly**. This means that the ratio of torques in the denominator does not accurately describe the engine/alternator system. Other factors such as engine speed and alternator speed will have an effect on the torque ratio even at the same alternator output. The complexities of the engine/alternator power system could mean that this metric is a poor indicator of the consequences of incremental changes in the vehicle power conversion system as well as over a typical drive cycle. When looking at changes to the system, this equation falls apart. We only know the efficiency of the entire engine, not the part that goes to the alternator, which is the part needed to clearly state the efficiency. Figure 3-12 is a demonstration of this issue.

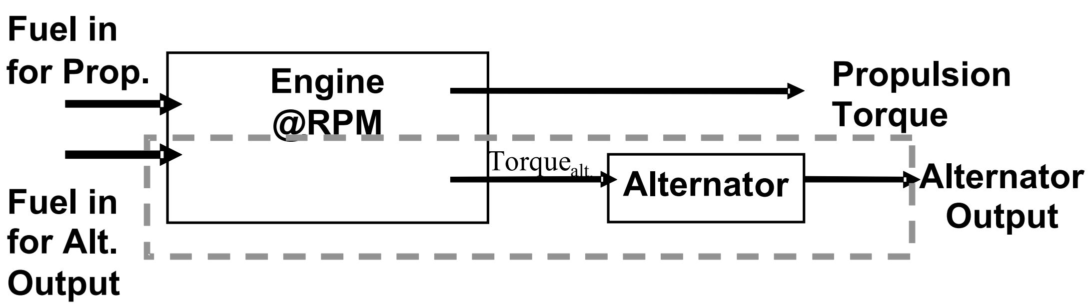


Figure 3-12: Demonstration of What is Needed

The fuel in is thought of as two streams, even though it is only one. The first stream is the amount of fuel used for propulsion while the other stream is fuel input used for alternator output only. In this thought experiment, there are two unknown quantities. There are only arbitrary means of allocating the fuel between these two uses.

Figure 3-13 presents the same bar chart as Figure 3-10. In Figure 3-13, the quantities used to evaluate efficiency from Equation 3-5 are explicitly illustrated. The same slice is used to demonstrate the electrical generation efficiency, seen in Figure 3-13. The electrical generation efficiency is a poor indicator of changes in the electrical system because: 1) the huge heat losses are included in this calculation dominating any changes in electrical output and, 2) the arbitrary assignment of fuel flow into the system is linear.

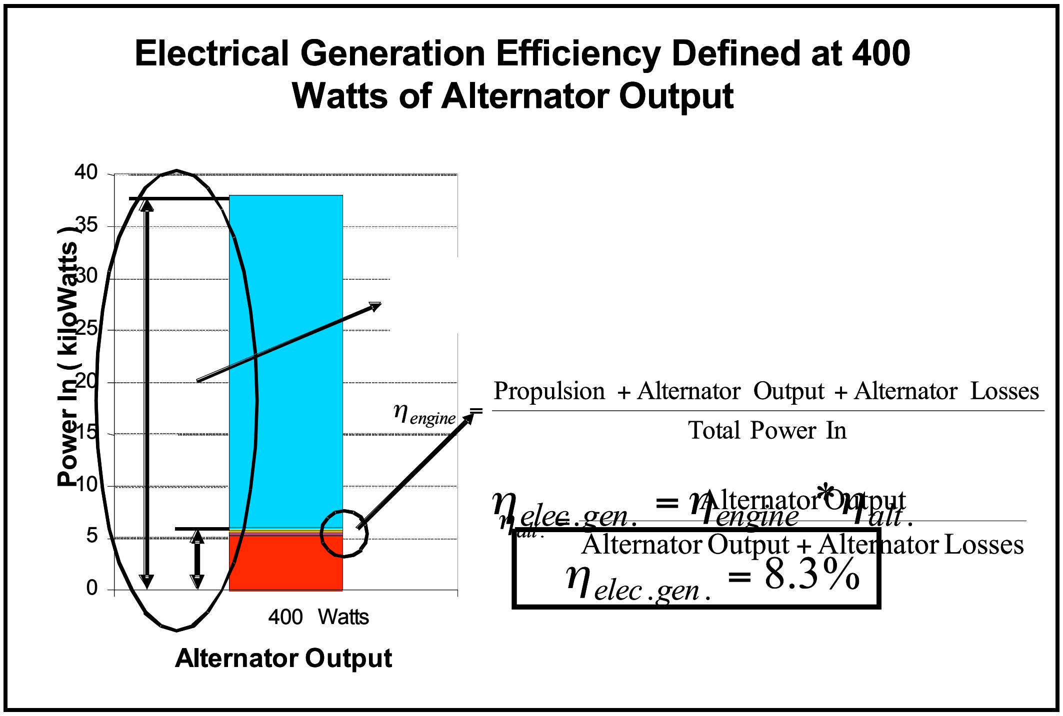


Figure 3-13: Electrical Generation Efficiency Calculation

Therefore, there is a formal need to consider marginal or incremental changes in the system. The desire is to define what the consequences of small changes in engine and alternator loads are. Do local effects have any domination on the system?

3.4.4 Incremental Efficiency

Using the same control volume as before, the incremental efficiency is illustrated in Figure 3-14.

Figure 3-14: Incremental Efficiency Illustration

$$\eta_{Increm.} = \frac{\Delta \text{Alternator Output}}{\Delta \dot{m}_f * Q_{LHV}}$$ **Equation 3-8**

The incremental efficiency is used to demonstrate a change to the electrical system. The incremental efficiency metric cannot be used when the system is in a static state. This metric is useful when comparing changes to the electrical system at a fixed propulsion torque. This metric incorporates the static differences in operation of both the alternator and engine between two points. This is the important factor. One operating point is at one alternator output and vehicle speed and the other is at a different alternator output at the same vehicle speed. The definition in Equation 3-8 can be applied at any difference in alternator output. But the concept is most useful when the difference is small. In the limit,

$$\eta_{Increm.} = \frac{1}{Q_{LHV}} \frac{\partial P_{alt.}}{\partial \dot{m}_f}$$ **Equation 3-9**

where $P_{alt.}$ is the alternator output.

The incremental alternator efficiency can also be expressed as in Equation 3-10,

$$\eta_{incr.\ alt.} = \frac{\text{ÄElectrical Load}}{\text{Engine Speed} * (\Delta \text{Torque})}$$ **Equation 3-10**

The increment of mechanical power is expressed as a change of torque at constant speed because engine speed is determined by the primary function of propelling the vehicle. Therefore, the torque to the alternator will increase according to the alternator efficiency. Rather than use ADVISOR to check the incremental alternator efficiency at every Watt, the incremental alternator efficiencies were evaluated for each additional 100 Watts of electrical power from 0 to 1200 Watts. An average of the previous 100 Watt incremental efficiency and the next 100 Watt incremental efficiency was used to define the incremental efficiency at the 100 Watt electrical load interval.

The incremental mechanical power needed to supply any change in electrical power will be more than the electrical power due to alternator inefficiencies. In order to supply this needed power to the alternator, more fuel will be needed. The incremental efficiency of the engine is defined by Equation 3-11,

$$\eta_{incr.engine} = \frac{\text{Engine Speed} * (\Delta\text{Torque})}{Q_{LHV} * (\Delta\dot{m}_f)}$$ **Equation 3-11**

The engine speed will stay constant. The change in torque will be the same that was used to calculate the alternator incremental efficiency. Q_{LHV} is the lower heating value of the fuel, gasoline. The lower heating value used for the calculations is 42.6MJ/kg. $\Delta\dot{m}_f$ is the change in fuel flow rate that is needed to supply the change in torque that is needed for the alternator to produce the one additional Watt of electric power.

Total incremental efficiency is the product of the engine incremental efficiency and the alternator incremental efficiency.

$$\eta_{\text{Increm.}} = \eta_{\text{incr.engine}} * \varsigma_{\text{incr.alt.}} \qquad \textbf{Equation 3-12}$$

Equation 3-12 reduces to Equation 3-8. By selecting the ΔTorque used to define the incremental engine efficiency to be equal to the ΔTorque resulting from the selected definition of incremental alternator efficiency, the numerator in the first term of Equation 3-11 numerically equals the denominator in Equation 3-10. While this is a convenience, the resulting incremental efficiency would not have been much impacted by a different choice. So long as the numerical increments remain small enough, both incremental engine and alternator efficiencies approximate their differential limit values. The total incremental efficiencies were calculated from 0 to 1200 Watts at different vehicle speeds from 30 to 80 mph, for straight and level steady state.

The graphical representation of incremental efficiency in Figure 3-15 uses two points – 400 and 500 Watt alternator outputs to calculate efficiency. The incremental efficiency is defined as the ratio of the change in alternator output and the change in fuel power in. This clearly shows what we are looking for. The overall incremental efficiency is 36.7% for the case shown in Figure 3-15.

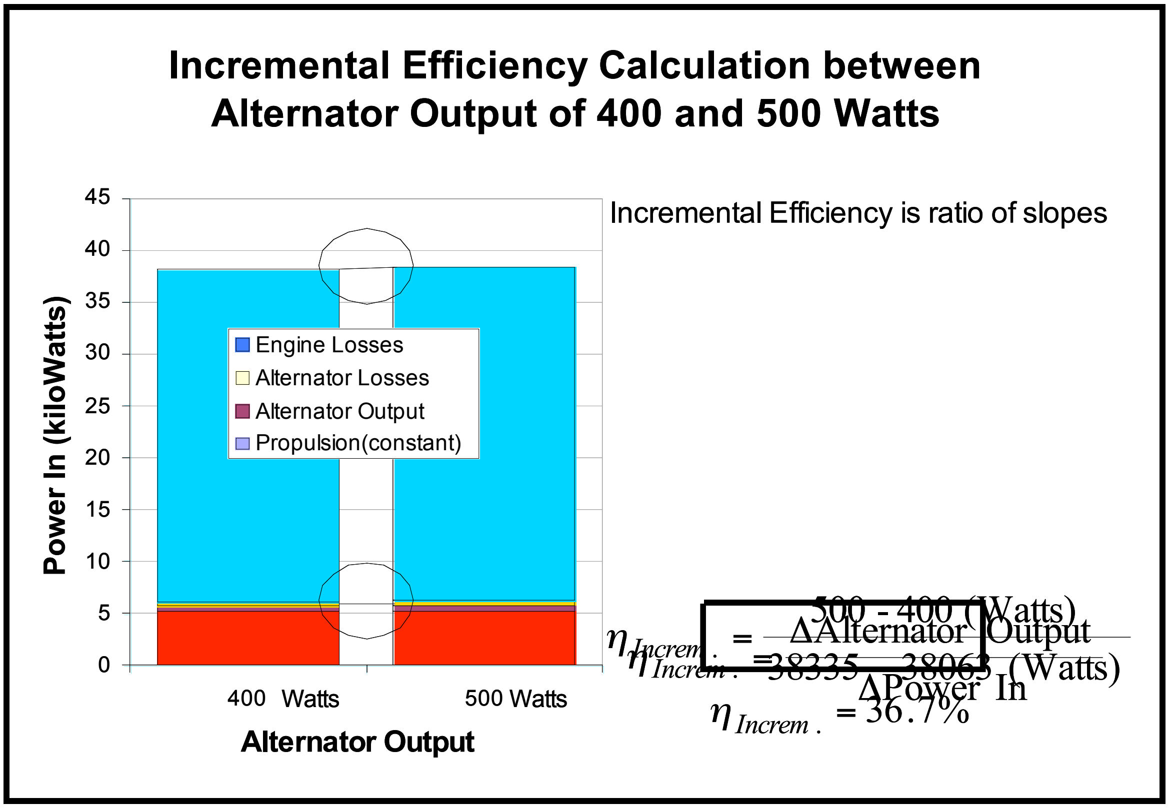


Figure 3-15: Incremental Efficiency Calculation

Incremental efficiencies are the focus of this report because it is believed that conventional thinking often does not take this concept into account when considering the additional power output from the alternator. More electrical power will inevitably need to use more fuel. Incremental efficiencies can be used to determine if there are gains that can be made on the margin when considering the addition of electrical loads. Incremental efficiencies are important because they will represent the most useful way to evaluate contemplated changes in many instances. Incremental efficiencies can help us better understand power management over a drive cycle as well as help us understand transient performance of the engine and alternator simultaneously. This is a meaningful efficiency metric.

4. Cases & Results

The first two cases that are looked at are incremental alternator efficiency and incremental engine efficiency. Then the gross system and electrical generation efficiencies will be detailed as well as the overall incremental efficiency. All test cases will consist of evaluating operation in straight and level, sea-level, steady-state cruising at constant speed. Different operating speeds between 30 to 80 mph in 10 mph increments will be considered. The engine performance map, described in Section 3.2, and the 14 volt alternator performance map, described in Section 3.3, are used in all cases. The reason for looking at the engine and alternator separately first is to see what kind of structure their results have and also to see if any insights or conclusions can be deduced from them.

4.1 Incremental Alternator Efficiency

The incremental alternator efficiency is defined in Equation 4-1.

$$\eta_{\text{incr. alt.}} = \frac{\Delta \text{Electrical Output}}{\text{Engine Speed} * \Delta \text{Torque}} \qquad \textbf{Equation 4-1}$$

To evaluate the incremental alternator efficiency, ΔElectrical Output is chosen to equal 100 Watts. The engine speed does not change for the same vehicle speed and different electrical output because engine speed is determined by the primary function of propelling the vehicle. Therefore, just the torque to the alternator will increase according to the alternator efficiency function. Rather than use ADVISOR to check the incremental alternator efficiency at every Watt, the incremental alternator efficiencies were calculated at 100 Watt intervals of electrical power from 0 to 1200 Watts. A 100 Watt increment was used to calculate the incremental efficiency. For the alternator, the efficiency at each calculation point was calculated as the average of the incremental efficiencies for the 100 Watts immediately lower than and immediately higher than the calculation point. For the engine, the increment in power was that corresponding to 100 Watts electrical output at the calculation point. The engine increments are therefore not all the same value, and in every case greater than 100 Watts. For the engine, the average for the two intervals immediately adjacent to the calculation point was again used.

Figure 4-1 presents the alternator incremental efficiencies at 100 electrical Watt intervals from 0 to 1200 Watts.

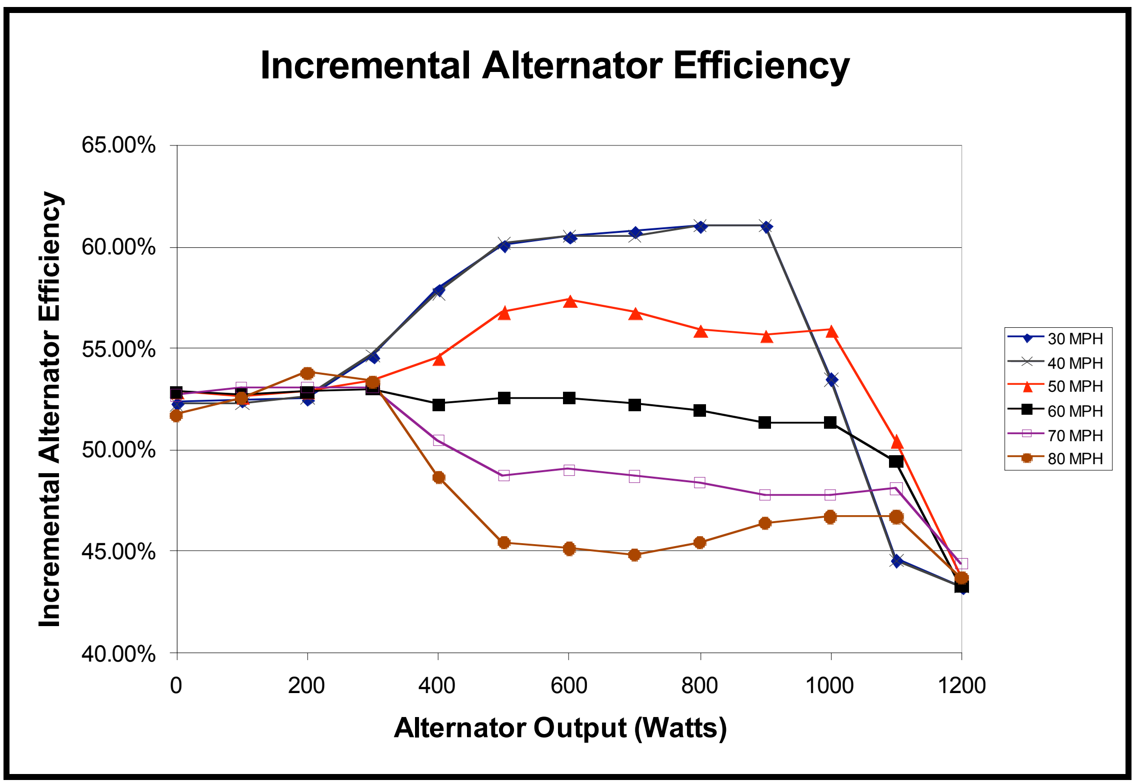


Figure 4-1: Incremental Alternator Efficiency vs. Alternator Output Power in Watts

For example, the first 100 Watts of electric power for each engine speed tested is added at approximately 52% efficiency. They start to deviate at the 300 Watt electrical output and continue their deviation throughout the remaining alternator output. The incremental alternator efficiency at zero is found by using the increment from 0 to 100 Watts alternator output.

The graph also demonstrates that at higher vehicle speeds the incremental alternator efficiency decreases as a function of increasing output after about 300 Watts alternator output. There appears to be an area of higher incremental efficiency that generally occurs between 400 – 900 Watts at 30 to 50mph vehicle speeds. The alternator incremental efficiencies fall sharply with increasing output at high alternator output for all vehicle speeds. The falloff begins at differing alternator output depending on the operation speed. The 30 and 40 mph curves are nearly identical because the engine speeds at the two operating points are almost identical due to a gear shift from 4^{th} to 5^{th} gear (arising from internal ADVISOR-supplied gear selection logic) when moving from 30 to 40 mph.

4.2 Incremental Engine Efficiency

The incremental mechanical power needed to supply one Watt electrical will be more than one Watt due to the alternator efficiency. In order to supply this needed power to the alternator, more fuel will be needed. The incremental efficiency of the engine is defined by Equation 4-2,

$$\eta_{\text{incr. engine}} = \frac{\text{Engine Speed} * \Delta\text{Torque}}{\text{Q}_{\text{LHV}} * \Delta \dot{m}_f} \qquad \textbf{Equation 4-2}$$

The engine speed will stay constant as before. The change in torque will be the same as was used to in the denominator to calculate the alternator incremental efficiency. $\Delta \dot{m}_f$ is the change in fuel flow rate that is needed to supply the change in torque that is needed for the alternator to produce the one additional Watt of electric power.

Figure 4-2 presents the engine incremental efficiencies at 100 Watt electrical intervals from 0 to 1200 electrical Watts. It is important to note that the mechanical power needed to supply 100 electrical Watts is not equal to 100 Watts mechanical power.

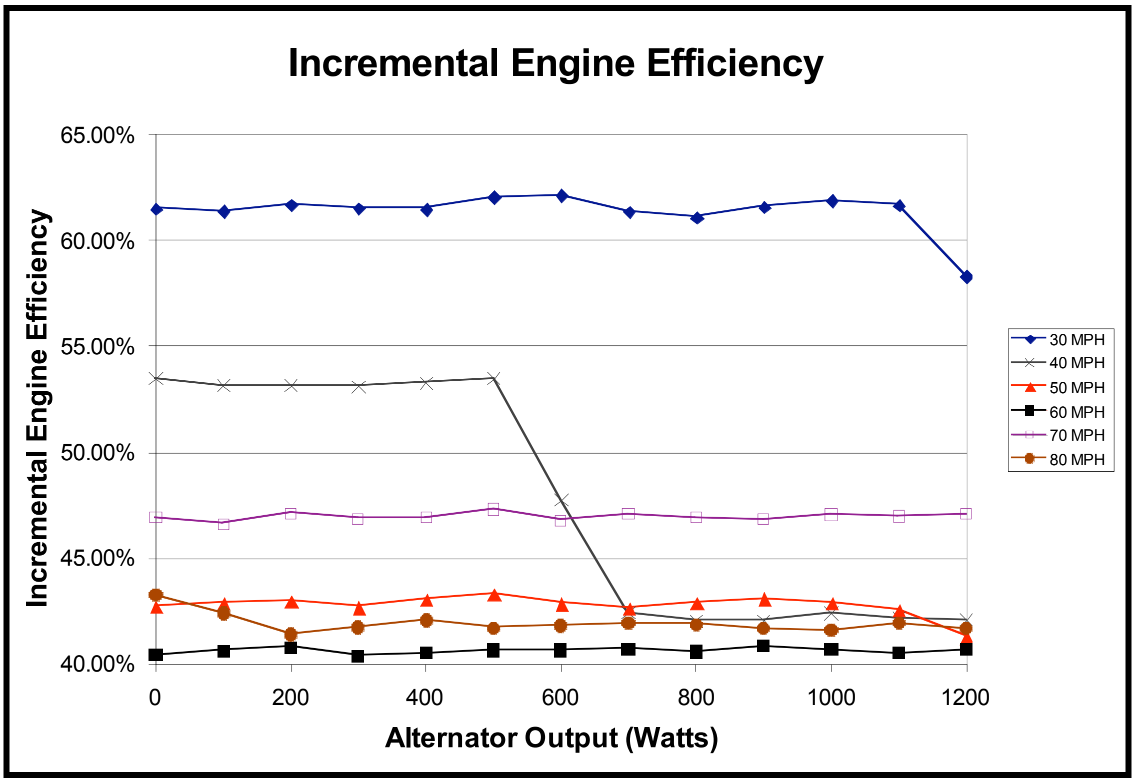


Figure 4-2: Incremental Engine Efficiency vs. Alternator Output Power in Watts

When moving down the figure from the top, the vehicle speed does not follow an order (i.e. lowest vehicle speed to highest vehicle speed). It is important to note that Figure 4-2 demonstrates *incremental* engine efficiencies. Therefore, the idea of better efficiency at higher speeds is not seen in this 'space'. With one exception, the incremental efficiencies are virtually constant with increasing torque at any speed. At this time, there is no totally satisfactory explanation for the big step shown in the 40mph vehicle speed line. It is believed that the result does not represent a calculation or data entry error. It is not completely plausible that the granularity of the engine map could be so large as to cause such a result. However, this remains the most credible explanation. There is also no reason to believe that this is not the true behavior.

4.3 Comparison of Efficiency Metrics

If incremental efficiencies are a good design metric, then some analysis will indicate that a different sort of information can be gained from its development. Each type of efficiency described earlier will be compared to help defend the belief that incremental efficiencies are the right metric to use when trying to determine what happens when changes are made to the electrical system. The test consists of varying vehicle speeds from 30 to 80 mph in 10 mph increments. At each constant vehicle speed alternator output is varied from 0 – 1200 Watts. A valid model for the engine and alternator systems as well as ADVISOR, with the flexibility to help us measure these efficiencies, has been established up to this point. This model is able to capture the "fine structure" of the two power systems of interest: the engine and the alternator. There is no reason to limit future evaluation to these parameters.

4.4 Gross System Efficiency

The first efficiency metric to be graphically demonstrated will be the gross system efficiency metric. The gross system efficiencies were calculated using Equation 4-3.

$$\eta_{\text{gross}} = \frac{\text{Propulsion Power} + \text{Alternator Output Power}}{\text{Total Fuel Power In}} \qquad \textbf{Equation 4-3}$$

This represents the efficiency of producing both propulsion power and electrical power, without discrimination as to the form of the output. It is a measure of the overall power plant in doing the entirety of its job.

Figure 4-3 shows a representation of the gross system efficiencies from 30 to 80 mph with the variation of alternator output from 0 – 1200 Watts. Gross system efficiency is nearly constant at each speed because the alternator output minimally affects the gross efficiency. These efficiency numbers are very close to the value at 0 watts electrical output because the equation is dominated by propulsion power. Only at lower vehicle speeds is there any noticeable effect. This is because the alternator output is a greater percentage of propulsion power and the effect can be seen slightly. The constant speed efficiency lines are in the order expected from reviewing the engine performance map. Moving up the map in relation to engine speed and torque, the efficiency rises. However, this is not a good efficiency metric to use when assessing changes in electrical output for the reasons provided in Section 3.4.2.

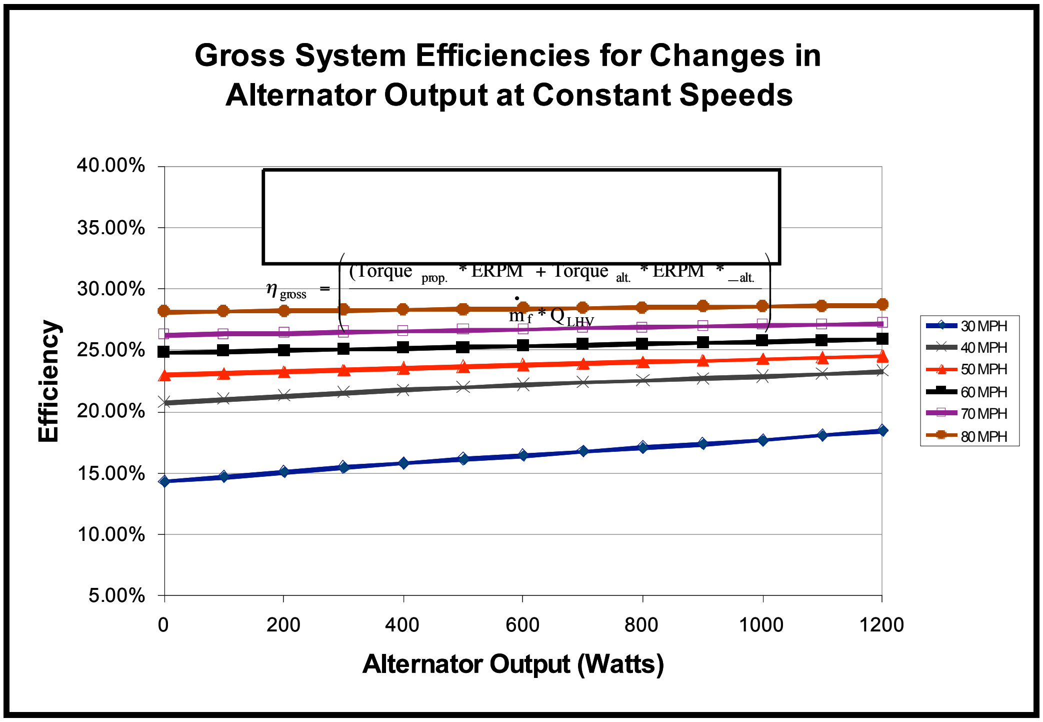


Figure 4-3: Gross System Efficiency Metric

4.5 Electrical Generation Efficiency

The next graphically demonstrated efficiency metric is the electrical generation efficiency. Figure 4-4 is generated by multiplying the non-incremental engine and alternator efficiencies. As shown in section 3.4.3 on page 41, the multiplication of the non-incremental efficiencies rearranges into Equation 4-4.

Equation 4-4

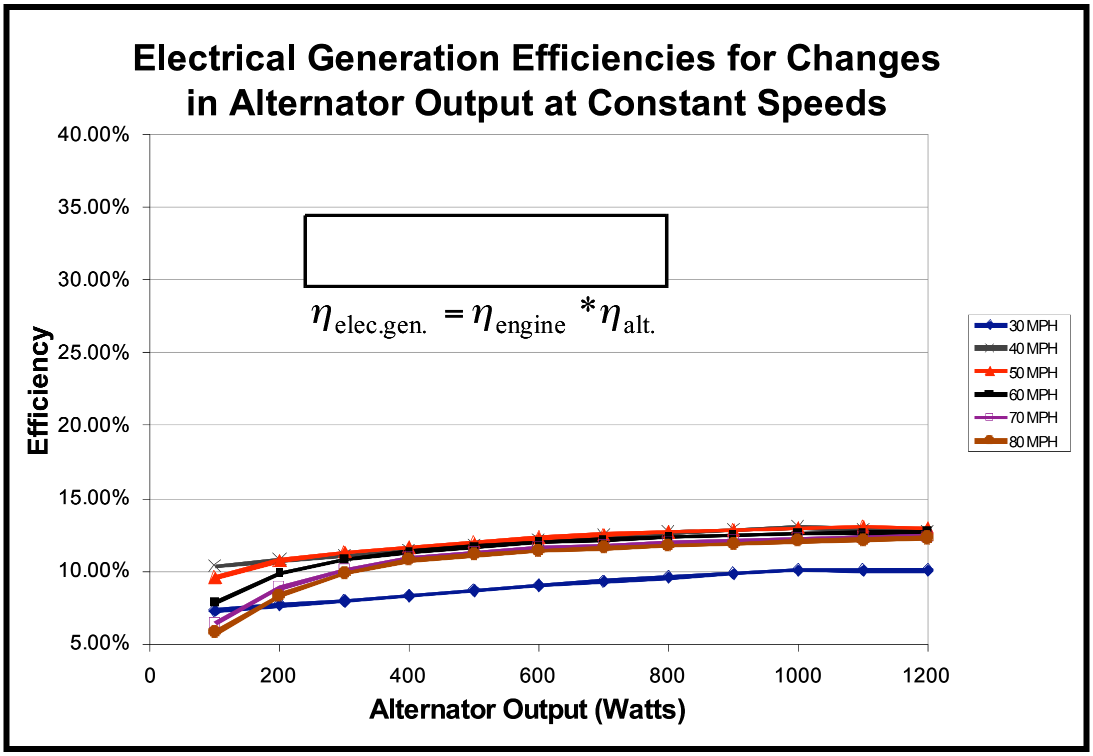


Figure 4-4: Electrical Generation Efficiency Metric

This is not the most revealing convention of thought to find the true electrical efficiency of an additional electric load. However, there is a substantial temptation to use Equation 4-4 to determine the efficiency of electrical production on a car. The two factors (engine efficiency and alternator efficiency) are commonly known as functions of operating conditions, meaning that no analysis is needed to apply Equation 4-4. This efficiency metric has problems of its own. To cite one example, step change in propulsion torque produces a step change in electrical generation efficiency, despite the absence of any change in alternator operation. This is certainly a troubling feature. This efficiency is formally correct if one assigns engine losses to propulsion and to generation in exact proportion to the propulsion and generation torque. While such assignment may appear justified, further consideration provides arguments that the assignment is arbitrary, suggesting that its use needs to be justified by the results it produces. The alternator efficiency is zero at zero alternator output. Therefore, the functions start at 100 Watts alternator output.

4.6 Incremental Efficiency of the Engine/Alternator System

The total incremental efficiency is defined as the incremental change in electric output divided by the incremental change in power from the fuel into the engine as demonstrated in Equation 4-5.

$$\eta_{Increm.} = \frac{\Delta \text{Alternator Output}}{\Delta \dot{m}_f * Q_{LHV}} \qquad \textbf{Equation 4-5}$$

This equation uses the two factors that are of interest when trying to calculate the efficiency of changes to the electrical system (i.e. the change in alternator output and the corresponding change in fuel into the engine). Figure 4-5 is the graphical representation of this data.

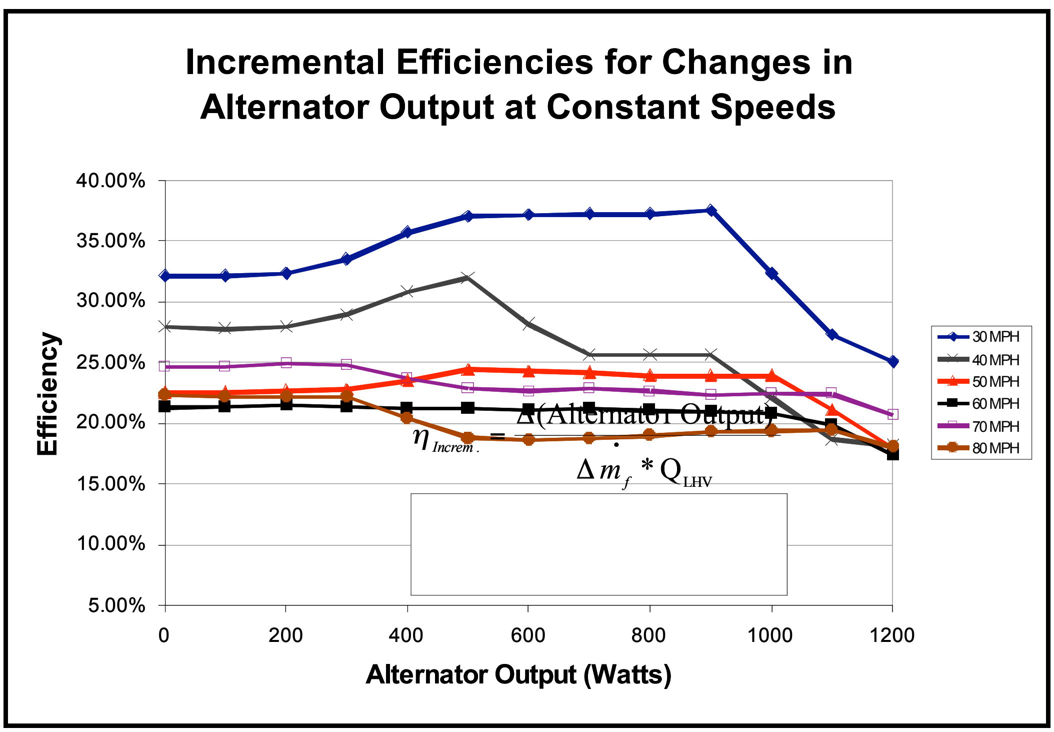


Figure 4-5: Total Incremental Efficiency vs. Alternator Output Power in Watts

Figure 4-5 demonstrates the overall incremental efficiencies for vehicle speeds 30 mph to 80 mph at 100 Watt intervals from 0 to 1200 Watts. The previous three plots are very different. Small local effects from changes in operation of the engine and alternator can be seen in Figure 4-5. This efficiency metric shows what happens and can give insights into how to more effectively use and design electrical systems.

Two important features can be observed from this graph. First, at different constant speeds the same alternator output can be more or less efficient. At some points the incremental efficiency of producing electric power is higher than the highest engine efficiency. This partially counterintuitive result can be understood by realizing that the incremental load in this instance moves the engine to a more efficient operating point. At 30 mph, additional electrical load can be supplied at a very high incremental efficiency. At this speed, the engine is not operating as efficiently – referring to the engine performance map. In these less efficient operating areas, more load, or torque, can be added for less cost in terms of fuel consumption. At higher vehicle speeds the opposite is true. At 80 mph, for example, the engine is already operating at an efficient point. So here when more load, or torque, is added the engine does not give it as efficiently.

Second, at the same constant speed some loads can be produced more efficiently. When moving down the 30 mph line, it can be seen that after 200 Watts the efficiency increases to approximately 37%. After 900 Watts the incremental efficiency begins to drop dramatically.

The alternator efficiencies play a large role throughout this graph. Noting that Figure 4-4 demonstrates virtually constant incremental engine efficiencies, the variances in this graph will follow the incremental alternator efficiencies. At 30, 40, 50, and 60 mph vehicle speeds the alternator efficiency at 900 Watts and beyond is decreasing with increasing alternator load. At 70 and 80 mph the alternator efficiencies are operating at their higher efficiency points. The step in the engine incremental efficiency curve at the vehicle speed of 40 mph from Figure 4-4 is reflected in this graph as well.

5. Policy

5.1 Policy Measure: Increasing Fuel Economy Standards

Increasing fuel economy standards is one regulatory strategy that has been devised to reduce the United States dependence on oil consumption and reduce greenhouse gas emissions. This thesis has devised a methodology that can be used to determine if the implementation of more efficient or higher voltage vehicle electric systems will assist the manufacturer in meeting any possible reductions in fuel consumption standards that may lie ahead. To use the language of this thesis, the value proposition for fuel economy standards depends upon the benefits that accrue to the stakeholders influenced. Is there value for the consumer in reduced costs of fuel if the fuel economy standards are raised? Is there also value for the auto manufacturers to increase fuel economy standards beyond the regulated amount? The value to each will be defined in this section in hopes of reducing the resistance to increased fuel economy standards.

5.2 Why Increase Fuel Economy Standards

Excluding inflation, gasoline prices are at their highest levels ever. As of May 3, 2004 the average price for a gallon of gasoline in the United States was $1.84 [14]. The average price one year earlier in the US was $1.51 - this is over a $.30 increase. The cost of crude oil per barrel of $37.31 on May 3, 2004 is an increase of $11.57 from a year earlier [14].

Currently, 55% of the United States' oil consumption is from imported sources. Ninety-five percent of the total energy used for transportation comes from the US oil supply – imported and domestic. The Transportation sector consumes 2/3 of the total US petroleum requirements [14].

One reason to increase fuel economy standards is that, as more developing countries increase their oil consumption, the prices of oil will rise even higher. Higher prices raise the possibility of damaging the nation's economic stability. As of May 2004, OPEC is very near their maximum output capacity [14]. As more oil is demanded, the prices may rise uncontrollably.

A related reason to start reducing fuel economy is that oil is a limited resource. There are various estimates for oil reserves - *Oil and Gas Journal* says there are 1,212,881 million barrels in total world reserve. The average number of barrels used per year world-wide is approximately 28,100 million. Thus, if everything stays the same, the world oil consumption will deplete the reserves in 43 years. Again, when the supply starts to decrease, oil prices will rise.

To reduce US transportation energy demand, the United States should become a leader in increasing automotive fuel efficiency. A policy that is aimed at improving the fuel economy of vehicles can be met by using different vehicle technologies, one of which is an advanced vehicle electric system. Policy measures could include: raising fuel economy standards, gas guzzler taxes, rebates or incentives to purchase advanced technology vehicles and fuel taxes.

The United States should use a combination of higher fuel economy standards with incentives for consumers to purchase advanced technology vehicles. Higher fuel economy standards may increase fuel efficiency on their own, but if the incentives for the purchase of advanced technological vehicles increase, the manufacturers will produce more fuel efficient vehicles, thus further reducing US oil consumption. If advanced vehicle electric systems offer a cost effective means of meeting an increase in fuel economy standards, then it will happen. This policy chapter will first outline the regulatory system in which the United States operates to increase fuel economy standards then outline several means of cost-effectiveness that advanced vehicle electrical systems can add.

5.3 Fuel Economy Standards

CAFE, or Corporate Average Fuel Economy, stems from the Energy Policy and Conservation Act of 1975 that the US Congress passed in response to the oil crisis in 1973. The goal of this Act was to reduce the country's dependence on foreign oil. This Act established the CAFE program for manufacturer's vehicle fleets. CAFE's purpose is to limit the fleet's weighted average fuel economy. The CAFE standard for the manufacturer's entire fleet of passenger cars was last set by Congress in 1986 at 27.5 miles per gallon (mpg) or 8.55 liter per 100 kilometers. If a manufacturer does not meet the standard, it is liable for a civil penalty of $5.00 for each 0.1 mpg its fleet falls below the standard, multiplied by the number of vehicles it produces. A manufacturer's CAFE is calculated by Equation 5-1.

$$CAFE = \frac{total\#of\ cars}{\sum_i^n \frac{\#\ of\ cars_i}{(mpg_i)}} \qquad \textbf{Equation 5-1}$$

The total number of cars is the total number of passenger cars or light trucks SOLD (not made), within the year the calculation is done. There is a distinction between domestic and foreign fleets. Vehicles with 75 percent or more US/Canadian content are considered to be domestics. Vehicles with less than that are considered to be imports. If a manufacturer has both domestic and import fleets, each fleet must comply separately with the CAFE standard [15]. The total number of cars is then divided by the sum of each model, $cars_i$, divided by the fuel economy for that model, mpg_i, from i to n number of models, as indicated by Equation 5-1. A similar standard, with an average fuel economy of 20.7 mpg, is applied to light trucks.

According to an NRC report, the CAFE program has clearly contributed to improved fuel economy [10]. When CAFE was first implemented, the automotive industry reduced vehicle weight to meet the new fuel economy standards. When gas prices fell in the early 1980s, the increased fuel economy standards contributed to keeping fuel economy levels higher than they would have been without CAFE [10]. A reduction in fuel economy reduced emissions and the dependence on imported oil.

The regulatory system of CAFE has also brought about technological changes that have improved fuel economy to meet the change required. Some of those changes include basic improvement of the engine, drive train, and vehicle aerodynamics [16]. New technologies such as fuel injection and sophisticated electronic controls have also raised gas mileage [16]. However, not all of these changes have been used to improve fuel economy.

The automobile makers have a wide range of choices in what they elect to do with a more efficient engine/drivetrain. They can elect to improve fuel efficiency, but they can also elect to improve acceleration, occupant safety, and add features that offset the energy efficiency of the engine. A more efficient engine gives the automobile makers a bigger design space within which to play. <u>Fuel economy is a design choice!</u>

CAFE standards have previously created an environment for innovation with the introduction of fuel injection and electronic controls. Table 5-1 lists some new electrical technologies which can be implemented with a new electric system that will reduce fuel economy. Some of these technologies represented in the table arguably depend on or benefit from 42 volt technology [10]. These efficiencies cannot be added to evaluate the total benefit. Some of the technology benefits overlap and some cannot be applied at the same time.

Therefore, there is an opportunity to use the incremental efficiency metric to evaluate the benefit of such a system.

Table 5-1: List of Advanced Vehicle Electric Technologies and Their Estimated Fuel Economy Improvement [10]

	MIN	MAX
Production -Intent Engine Technology		
Variable Valve Timing	1.0%	1.0%
Variable Valve Lift & Timing	3.0%	3.0%
Cylinder Deactivation	3.0%	3.0%
Engine Accessory Improvement	1.0%	1.0%
Continuously Variable Transmission	4.0%	4.0%
Automatic Transmission w/ Aggressive Shift Logic	1.0%	1.0%
Camless Valve Activation	5.0%	10.0%
Automatic Shift Manual Transmission (AST/AMT)	3.0%	5.0%
Advanced CVTs (Allows High Torque)	0.0%	2.0%
Integrated Starter/Generator	4.0%	7.0%
Electric Power Steering	1.5%	2.5%

5.4 Value of FE Improvements to Vehicle Owner

There is value in fuel economy improvement both for the vehicle owner and the automobile maker. This value can be used to offset the cost of the advanced electric technologies. If the auto maker's costs increase, the price of the vehicles will increase or the profit margin will fall. One way for the vehicle owner to offset their increased costs is to measure their lifetime cost of fuel savings from fuel economy improvements. With increased fuel economy standards, the vehicle owner will purchase less fuel. By purchasing less fuel, the owner can save money over the life of the vehicle. A vehicle owner's annual cost savings can be determined through the following three equations:

$$COST_{initial} = \frac{\#miles/year}{(miles/gallon)_i} * fuel\ price$$ **Equation 5-2**

$$COST_{final} = \frac{\#miles/year}{(miles/gallon)_f} * fuel\ price$$ **Equation 5-3**

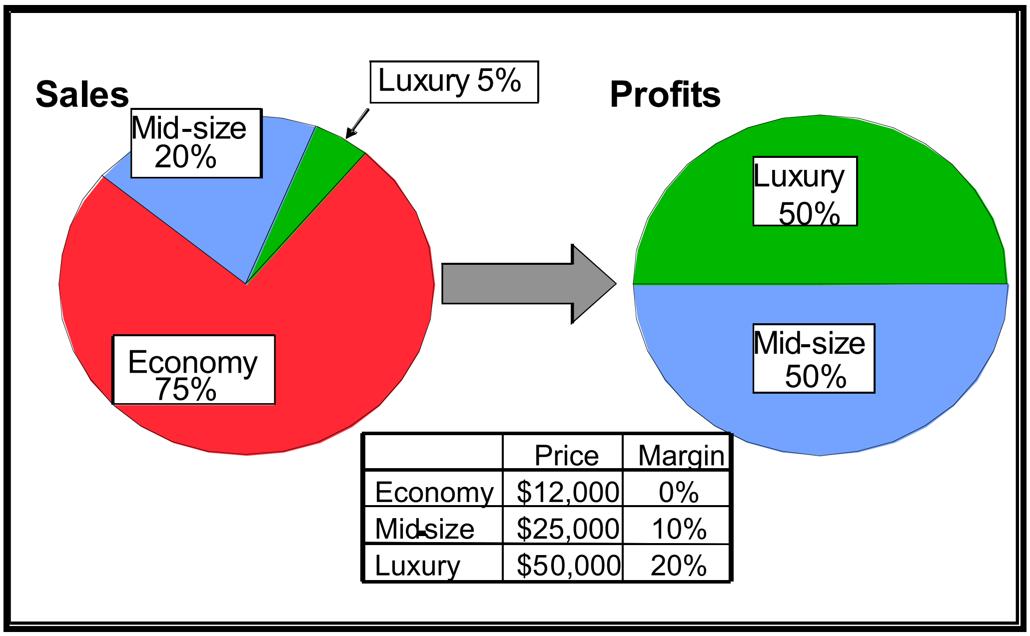
$$Annual\ Cost\ Savings = COST_{initial} - COST_{final}$$ **Equation 5-4**

Savings in future years should be discounted so that the net present value of future savings can be appropriately compared to the initial increase of the new technology. The discounted annual cost savings can then be added to determine total savings.

5.5 Value of FE Improvement to Manufacturers

Manufacturers sell various classes of vehicles including economy, mid-size and large/luxury vehicles. They make a variety of types of cars in each class with various profit margins and fuel economies. CAFE is an industry driver for fleet sales, not production. In the US market, the automakers make profits on popular cars which are generally not fuel efficient. Thus, the automaker has to figure out how to sell unpopular cars that are more fuel efficient or in the alternative, make fuel efficient cars popular. The automaker needs to do some kind of fleet balancing. A demonstration is given below.

Figure 5-1 below shows an example of hypothetical fleet sales and associated profits that would be generated from the sales. The sales and profits pie charts do not resemble each other. Note that in this hypothetical fleet, 50% of the total profit comes from 5% of the vehicle sales in the luxury class vehicle. The other 50% profit comes from the 20% of vehicle sales of the midsize class vehicle. Sales of the economy vehicles, which represent 75% of vehicle sales, do not contribute any profits. Why? A possible explanation could be that individual manufacturers meet the required CAFE standard by adjusting the pricing structure of different vehicle classes. This would allow the manufacturer to use the price of the vehicles as a tool to meet the CAFE standard. A key point to understand with this explanation is that automakers would sometimes attempt to increase sales of unpopular fuel efficient vehicles by selling them at or below cost to raise their CAFE number.



	Price	Margin
Economy	$12,000	0%
Mid-size	$25,000	10%
Luxury	$50,000	20%

Figure 5-1: Cost of Regulatory Compliance [11]

The opportunity cost for the manufacturer in meeting the regulatory compliance is determined by the reduction in sale price of the economy cars when attempting to increase sales of the economy cars. The increased sales in economy cars are necessary to maintain a CAFE number at or above 27.5 mpg. Therefore, the manufacturer must have a delicate balance between classes of cars sold and its fleet fuel economy. Table 5-2 and Table 5-3 demonstrate, with hypothetical fleet numbers, why manufacturers would like to achieve better fuel economy in their vehicle fleet.

This example uses approximate numbers for the fuel economy, sales, and profit margins. This example is used as a demonstration only to help understand the methodology behind how manufacturers can be driven by CAFE standards. In Table 5-2 and Table 5-3 the average profit per vehicle is found by dividing the total profit by the number of total revenue from sales for that vehicle class. The fleet fuel economy for this hypothetical fleet meets the CAFE standard at 27.5 mpg.

Table 5-2: Hypothetical Fleet Calculation [11, 17]

Error! Objects cannot be created from editing field codes.

Fleet Fuel Economy	27.5 mpg
Total Profit	$1,000 million
Total Sales	1,000,000
Average Profit/Vehicle	$1,000

In Table 5-3, assume that the auto manufacturer raises the fuel economy for each vehicle by 1%. With this increase, fewer economy cars need to be sold and more mid-size and luxury cars can be sold while still meeting the CAFE standard. This change in fleet distribution can increase the average profit per vehicle by $50. This example assumes that the price of the vehicles stays constant and that there are buyers willing to purchase more mid-size and luxury vehicles.

Table 5-3: Hypothetical Fleet Calculation with increased fuel economy of 1% [11, 17]

	Fuel Economy	Sales	Profits
Economy	31.3	727,500 (-1.5%)	$0
Mid-size	22.3	218,000 (+4%)	$520 million
Luxury	16.5	54,500 (+6%)	$530 million

Fleet F.E.	27.5 mpg
Total Profit	$1,050 million
Total Sales	1,000,000

A $50 increase in average profit per vehicle with an increase in fuel economy of just 1% can clearly establish a motivation for manufacturers to be interested in increasing fuel economy. This same exercise demonstrates that there is a limited value of improved fuel economy to the manufacturer. In this simple example, at a manufacturer's cost of $50 per vehicle (including the acquisition and warranty costs of the new technology), the manufacturer becomes indifferent to whether he uses the technology or not.

5.6 Opposition to Increasing FE Standards

The Energy Policy Act of 2003, passed by the house in November of 2003, will do little to encourage automakers to produce more fuel-efficient vehicles [18]. Automakers strongly opposed and lobbied against new fuel economy requirements because they claimed it would force them to downsize their vehicles. They argue that downsizing vehicles will decrease vehicle safety. The automakers also argue that the consumer demand is for big, powerful cars and trucks [10, 18]. The backlash of raising fuel economy, the automakers argue, could also lead to major job losses [10, 18]. The United Auto Workers also lobbied against increasing fuel economy standards for the same fear of losing jobs.

There are also arguments that there are certain aspects of the CAFE program that have not worked as expected. In order to appease some opponents, several of these will need to be "fixed." One of which is the extra credit provision for multi-fueled vehicles. This has not succeeded as planned [10]. These vehicles rarely use anything other than gasoline, yet enable the manufacturer to produce less fuel efficient vehicles. Another argument is the failure between the distinction of the passenger car and light truck. When CAFE was first introduced in the 1970's most "light trucks" were not used for everyday driving. But, today, many "light trucks" are now used daily for personal transportation. Therefore, the split between the passenger car and light truck structure that was originally used to make a distinction between personal use and a truck for work will need to be adjusted to meet today's consumer choices. Note: this is not an exhaustive list of the arguments against the CAFE program.

5.7 Conclusion

Improving fuel economy is important for the economic stability and security of the United States. So far, market forces are not encouraging change in fuel economy standards. Therefore, the US government should intervene by increasing the CAFE standard as well as address some of the arguments of the CAFE program's failures. By increasing fuel standards, the US will be less oil dependent, more secure, and give an opportunity to put money back into the pockets of the consumer and the auto manufacturer.

The MIT/Industry Consortium has been working to set standards for vehicle electric systems in hopes to achieve technical advances in the electric system architecture that will lead to changes in improved fuel consumption. The introduction of advanced vehicle electric systems may allow the manufacturers to keep the vehicle size constant and at the same time reduce fuel consumption. The introduction of advanced vehicle electric systems must be cost-effective in order for the manufacturer to implement. An independent study should be done to determine if the implementation of advanced vehicle electric systems will lead to major job losses. The automotive industry is a large contributor to America's economy and it will be important to demonstrate that advanced vehicle electric systems will not lead to job losses. The current CAFE system is not perfect. With a few adjustments, some opposition to the inconsistency of the program can be cleared.

This thesis introduced the incremental efficiency metric that the auto manufacturers can use to help determine the cost-effectiveness of improving fuel economy through advanced electric architectures. If there is a fuel economy increase then the auto manufacturer and owner can calculate their savings as demonstrated in this discussion.

6. Summary

The major contribution of this work lies in defining an efficiency metric that can be used to identify changes in a vehicle's electric system. Due to the ever increasing electrical load requirements, auto manufacturers are making changes to the 14 Volt electrical system or changing to a new system. Making changes to the electrical system will increase its cost.

Several efficiency metrics were compared to try to resolve the value proposition of changes to the electrical system. The incremental efficiency was compared to the gross system and electrical generation efficiencies. The gross system and electrical generation efficiency metrics are sometimes used within the industry to define changes in the vehicle's electric system. However, through the studies shown in this thesis, the gross efficiency and the electrical generation efficiency metrics do not accurately measure changes in fuel consumption and electrical load.

The incremental efficiency can be used to place a value on the changes to the electrical system. Reductions in fuel use are used as a benefit to offset the increased cost. The auto manufacturer should be aware of how the changes they make to the system will affect overall fuel economy of the vehicle. If one of the other efficiency metrics is used, the true value will not be acquired.

There are several benefits that the industry and consumer can gain with the decrease in fuel use. Benefits to industry can arise from the increased profits either through assisting manufacturers in meeting regulatory compliance or by allowing the addition of new luxury features to the automobile. The vehicle owner can benefit from the increase in fuel economy with the introduction of electrical technologies through the lowering of the life-time cost of fuel.

This thesis thoroughly validated the use of ADVISOR and its contribution to this research was immense. ADVISOR offers several benefits. One is that it is an open source code. Meaning the details of all of the calculations done within ADVISOR can be seen, checked, or changed. Another benefit that ADVISOR had to offer was that it integrated the engine performance and alternator efficiency data.

The engine performance data was supplied by an industry source and the alternator efficiency data was recreated from an industry source. The thorough testing of ADVISOR with the integration of the engine and alternator data was necessary so that the results would be more realistic. A simplification of how the incremental efficiency can be measured is shown in Figure 6-1 .

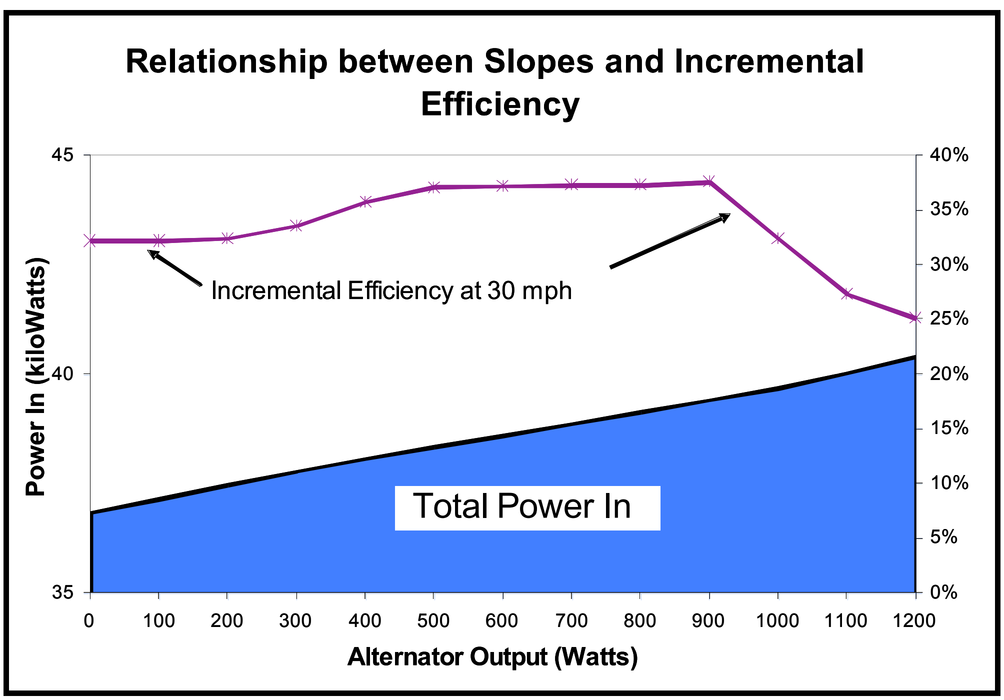


Figure 6-1: Simplification of Calculating the Incremental Efficiency at 30 mph

Figure 6-1 represents the top portion of Figure 3-8 with the incremental efficiency line super-imposed. When working within the scope of the power balance graphs, the incremental efficiency can be calculated by taking the ratio of the slopes of alternator output and the total power in. The alternator output slope is equal to one in this space. Therefore, the incremental efficiency reduces to the inverse of the slope of the total power in curve. The changes in slope in the total power curve are discernible (but barely) in Figure 6.1. A reader viewing the total power curve without thought of incremental efficiency could not reasonably be expected to deduce the significance of these features.

Incremental efficiency can and should be used when the industry is deciding to make changes to their current electrical system. The incremental efficiency focuses on the changes in fuel use for changes in the electrical system. It demonstrated that the change in fuel use included the changes from the engine and electrical system.

7. Future Applications/Work

A more thorough study is needed to evaluate when, whether, and how changes to an electrical system create benefits in fuel economy. There are several areas where the incremental efficiency metric can be used to demonstrate changes in fuel economy for changes in the electrical system.

The results from the incremental efficiency data show that there are speeds and loads where the engine alternator system is more efficient than others. One area where incremental efficiency can be used is with the time-shifting of loads. If a load can be time-shifted during a drive cycle so that more electricity is produced when it is more efficient to do so, the total vehicle electric needs could be produced with decreased fuel consumption. This can be demonstrated by changing the electrical load cycles to the most incrementally efficient points during its drive cycle. Changing the load cycle for recharging the battery is one time shift change where fuel economy benefits may be gained. The engine speeds, torques and fuel use in each drive cycle time step can be recorded from ADVISOR. By changing the timing of loads throughout the drive cycle and comparing the input energy at corresponding times, the incremental efficiencies can be calculated.

Another area of interest that should be considered is one of a constant alternator speed throughout all drive cycles [19]. The incremental results suggest that perhaps the industry should look into operating the alternator at an efficient constant speed so that the fuel economy benefits can be realized over a larger range of alternator loads and drive cycles. However, this would incur a substantial cost and additionally will require a redesign of the electric machine.

The incremental efficiency metric has not been used to demonstrate changes in fuel economy due to the decoupling of mechanical loads from the shaft and converting them to electrical architectures. However, this was one of the prime reasons for the use of incremental efficiencies. Some mechanical loads that can be decoupled include electric power steering, electric water pumps, electric oil pump, and electro-mechanical valves.

The incremental efficiency metric can also be used to demonstrate changes in a 42 Volt system. In order to do so, accurate alternator and electric architectures are needed. There may be an opportunity within the co-simulation package of ADVISOR to research this topic. ADVISOR offers co-simulation packages with Saber [20] and Ansoft Simplorer that more completely model a vehicle's electric system than the standard ADVISOR model.

The ultimate goal of demonstrating the overall fuel economy benefits has yet to be completed. But the value of understanding the results from these tests within the thesis cannot be underestimated. This thesis will hopefully open up the door to other future studies.

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Appendix

ADVISOR VALIDATION

Considering the complexity of the software and the tools, (i.e. engine performance map, alternator performance data), validation of the tools and the software were required. The torque and speed requirements of a known load calculated from first principles should match the torque and speed forecast by ADVISOR. The following is an explanation of how the model was validated.

Since this research is focused on accessories and their loads, it is necessary to understand their definitions in ADVISOR and how they interact with the engine performance map and alternator data. ADVISOR has many options and features that are of no immediate use to this research. It must be established that these features do not interfere with the models studied throughout this research. At least initially the interest was in the steady-state behavior of the systems studied. Solution of differential equations to find the steady state, starting from non-final-state initial conditions is computationally wasteful and time consuming. It will nevertheless be done for a few simple cases, for reassurance of the inner workings of ADVISOR. Once confidence in ADVISOR was established more complex conditions can be studied.

Basic Test

One way to check ADVISOR is to choose a vehicle and a constant speed drive cycle. Once the constant speed is reached during the drive cycle, an accessory load can be chosen and controlled to turn on at a known time. The changes in torque and engine speed at that time during the drive cycle can be recorded from ADVISOR. The test is used to check that the accessory power added to the engine/alternator system at the constant vehicle speed matches the forecast output from the alternator. A constant speed drive cycle with hot initial conditions will allow the vehicle to reach a near steady state condition quickly, providing reassurance that any change in engine torque or speed after the load is turned on is due to the change in additional power extracted and not due to any warm-up effect. Once the constant speed is reached during the drive cycle, a known electrical load is applied to the alternator at a known time. The change in torque and the engine speed at that time will be compared to the actual power, brake torque multiplied by engine speed, used by the accessory load. The load change found in the ADVISOR output should be equal to the additional load divided by its efficiency, as shown in Equation A-1.

$$\frac{\text{accessory load}}{\text{accessory load eff.}} = \Delta\text{Torque} * \text{ERPM} \qquad \textbf{Equation A-1}$$

A summary of the vehicle and drive cycle is shown below:

- 3-Liter, 6-Cylinder Internal Combustion Spark Ignition Engine
- Constant speed 60 mph drive cycle
- 5-spd manual transmission
- Hot initial conditions loaded

An electrical load of 1000W was drawn from the alternator. A constant alternator efficiency can be preset in ADVISOR. It was set to 100% efficiency. The 1000W load was set to initially be off and then to turn on at the 45 second mark of the 50 second cycle. Figure A-1 shows the “Results figure” screen from ADVISOR.

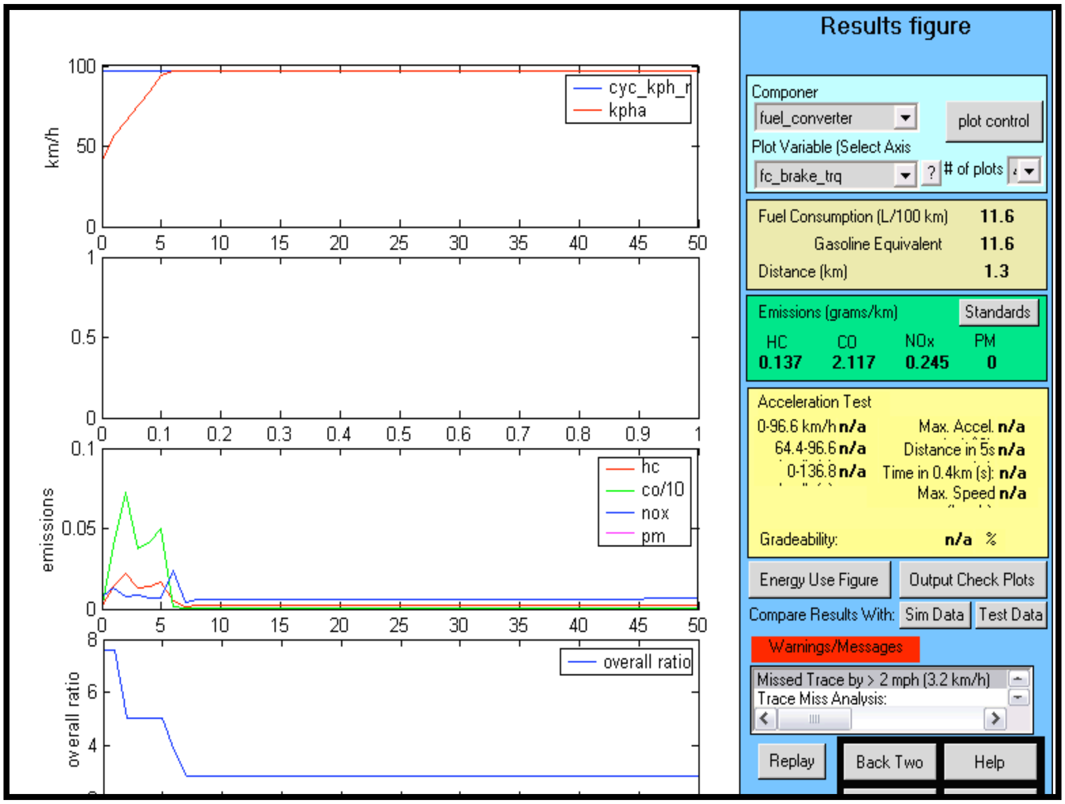

Figure A-1: Output Results Page from ADVISOR

The fuel consumption over the cycle, the distance traveled and emissions data are all found on the right side of Figure A-1. To the left various graphs are found. From top to bottom the graphs show the kilometers per hour achieved compared with the kilometers per hour required by the drive cycle; an empty graph not used in this analysis; vehicle emissions throughout the drive cycle; and the overall drive-train ratio. Two pertinent graphical choices are the engine brake torque versus time and the engine speed versus time, Figure A-2 and Figure A-3, respectively.

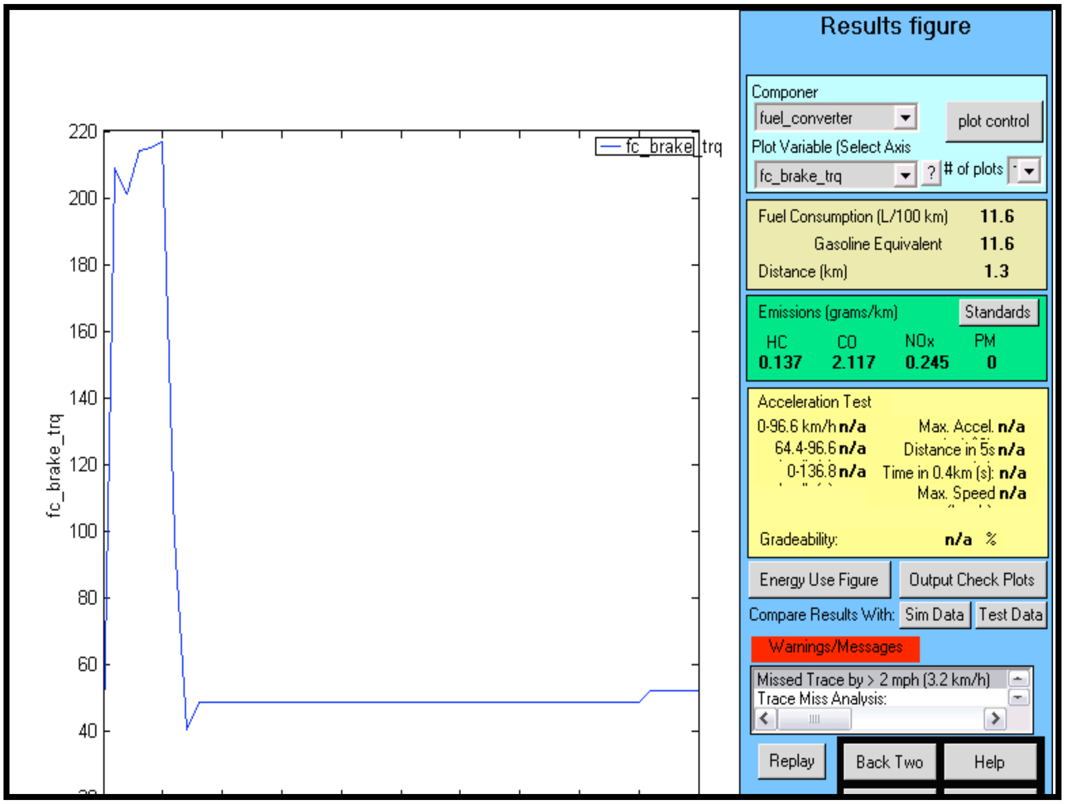

Figure A-2: Engine Brake Torque vs. Time

By examining the graph of brake torque vs. time it can be seen that for approximately the first 7 seconds there is a great demand for torque needed to move the vehicle to 60 mph. Once it reaches 60 mph the torque levels off. At the 45 second mark there is a jump in torque due to the turning on of the 1000W electrical load. It is this jump, or change in torque that needs to be measured. The change in torque can then be multiplied by the engine speed to calculate the power out of the engine. NOTE: In order for there to be a change in torque, more fuel must be added and burned inside the engine.

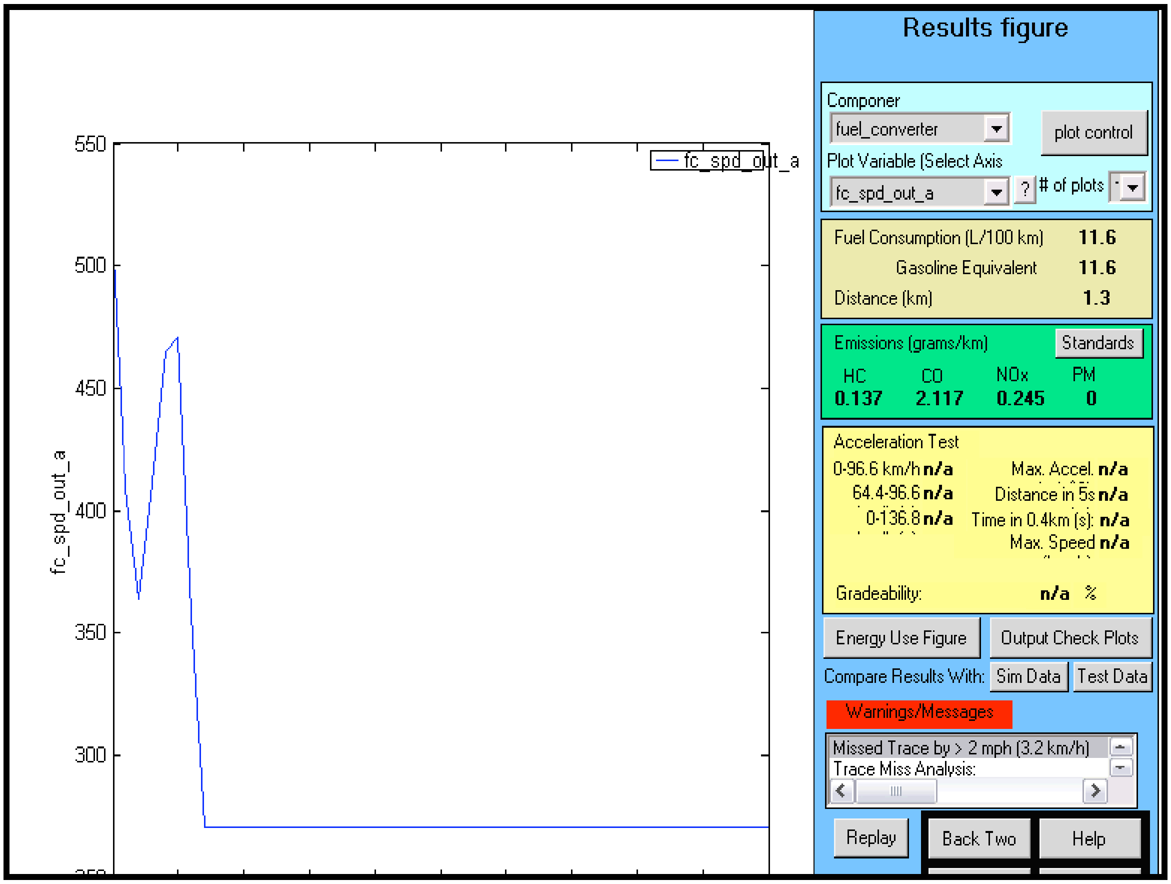

Figure A-3: Engine Speed (rad/sec) vs. Time

The same can be said for engine speed vs. time graph for the first seven seconds as well. However, it can be seen that the engine speed does not change when the additional electrical load is turned on. The addition of the electrical load is done once the engine shaft has reached the speed it needs to maintain constant 60 mph. The alternator will only get additional torque from the engine shaft. Therefore, looking at an engine performance map at this point in time, a slight rise in torque will be seen at this constant engine speed.

The torque trace was viewed with an expanded scale in the vicinity of time at which the 1000W load was drawn, so that the difference in torques before and after the load was turned on can be recorded accurately. The approximate load change in ADVISOR can be calculated by multiplying the change in torque with the engine speed at the appropriate time. It should be compared to the actual accessory load divided by its efficiency, Equation A-1.

Next, the same drive cycle was analyzed but with a 1000W load added at the 45 second mark. With 100% alternator efficiency the load was translated into an engine load also of 1000W. Other alternator efficiencies can be applied to determine corresponding engine loads. Tests were run at loads of 100, 500, 1000, and 2000 Watts and efficiencies of 25, 50, 75, and 100%. In all cases the multiplication of the changes in torques with engine speed found in the resultant graphs of ADVISOR produced exactly the same power loads that were added to the engine at the 45 second mark of the drive cycles.

The conclusion of these tests was expected but was also important to provide confidence that ADVISOR correctly interprets engine efficiency data. With this result, the research could move forward with more complex simulations and have confidence in the ADVISOR results.

A similar test of the ADVISOR-supplied class 8 truck alternator model did not initially produce agreement. Simple cases were chosen and known loads were applied at known times. ADVISOR reported engine torque changes were initially greater than expected. Eventually rectifier efficiency was found to be applied separately from the alternator efficiency. Setting this efficiency to unity allowed the results to be reconciled. So these simple tests can lead to improved understanding of the system model.

Unexpected Incremental Results

A curious result was noticed during the testing stages of the new engine performance map. There were unexpected results that did not seem consistent with the engine and alternator efficiency data provided. A review of the ADVISOR source code together with numerous trial model runs indicated that results significantly deviate from expected values only in regions of the engine performance map with large gradients in efficiency. Further investigation revealed that a 2-dimensional linear interpolation scheme used by ADVISOR in conjunction with the engine performance map was the cause of the unexpected results. ADVISOR converts the brake specific fuel consumption matrix in the engine performance map to fuel flow rates before running a simulation. It then uses the fuel flow rate number throughout. For operating points between tabulated values, linear interpolation is performed on the fuel flow rate table. Equation A-2 was used to calculate brake specific fuel consumption from the ADVISOR output numbers of engine speed, torque and fuel flow rate.

$$bsfc = \frac{\dot{m}_f}{P_b}$$ **Equation A-2**

The mass flow rate of fuel is defined as $\dot{m}_f$. P_b is the brake power. The brake power is calculated using Equation A-3.

$$P_b = \text{Brake Torque} * \omega$$ **Equation A-3**

ω is the engine speed and is measured in radians/second. So, when comparing the bsfc number to the one interpolated using the bsfc matrix, the numbers did not match, especially at lower engine speeds. Table A-1 below shows these results.

Table A-1: Comparison of Two bsfc Calculations for Selected Points

Vehicle Speed (MPH)	Engine Speed (rad/sec)	Torque (N*m)	Fuel Flow Rate (g/s)	bsfc from Equation 2 & ADVISOR results (g/(kW*hr))	bsfc Interpolated (g/(kW*hr))
20	130.8	23.065	0.7058	842	937
30	147.7	35.7	0.865	591	597
40	148.27	60.66	1.0172	407	412
50	185.5	73.1	1.388	368	370
60	222.75	88	1.86	342	342
70	260	107.4	2.5	322	323
80	297.63	134.8	3.355	301	301

At each of the engine speeds and torques, ADVISOR outputs a fuel flow rate. Bsfc is calculated using Equation A-2. The bsfc interpolated number uses the engine performance map directly. These numbers are found by linear interpolation using the engine speeds and torques at the various operating points. There is a large difference at the lower operating speeds.

It was discovered that the discrepancy arises from the difference between interpolation on a fuel flow rate map and interpolation on the bsfc map. The number found by interpolating on a fuel flow rate map and then converting to bsfc is not the same as if the interpolation would have been done on the bsfc map. There is a large discrepancy when comparing the two results at the first operating point in Table A-1. In general, differences in interpolation method can be expected to be large near the lower edges of the bsfc table because there are bigger differences between adjacent bsfc entries in these regions. The difference is less than 1% for the other points in Table A-1.

Note that there is no basis for determining that one of the bsfc columns in Table A-1 is correct and that the other is not. Both represent reasonable approximations for a circumstance where a continuous 3-dimensional function is known exactly only at the discrete points. But the differences are indicative of the magnitude of calculation errors which can arise from the discrete nature of the data. A strategy can be developed to identify unreliable areas of the engine performance map using differences between interpolating on the bsfc matrix and the fuel flow rates matrix. The ADVISOR results will continue to be used for drive cycle analysis but results which rely heavily on calculations from the unreliable portion of the map will be discounted.

ADVISOR will extrapolate if the engine speeds and/or torques lie outside the engine performance map. It will use the last two points of the map and linearly extrapolate. Any results that rely significantly on extrapolation will also be discounted.

Several alternative remedies exist for this problem. They include the use of a more detailed engine performance data and/or alternative interpolation methods. For this work, none of these approaches are necessary since the model results had only very limited deviations from predicted values.

Table A-2: Bsfc Tabulated vs. Engine Speed and Torque

(rad/sec)/Torque(Nm)	16.73	33.84	50.94	68.05	85.16	102.27	119.37	136.48
62.83	1095	611	469	400	357	325	308	296
83.78	1086	611	459	386	352	321	305	290
104.72	1034	605	450	379	347	316	302	289
125.66	1078	562	441	375	344	318	302	289
136.14	1213	609	449	379	345	320	301	288
146.61	1279	616	455	380	344	320	299	287
167.55	1306	602	450	382	345	322	301	289
188.5	1355	617	451	381	344	322	301	289
209.44	1372	629	456	382	343	320	297	287
230.38	1421	636	459	386	347	324	302	291
251.33	1393	632	461	387	349	328	307	294
293.22	1378	660	471	398	358	336	313	299
335.1	1476	688	490	411	366	344	321	305