THESIS

DESIGN TRADEOFFS OF A RECIPROCATING AUXILIARY POWER UNIT

Submitted by

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In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2013

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ABSTRACT

DESIGN TRADEOFFS OF A RECIPROCATING AUXILIARY POWER UNIT

This thesis presents a comparison of reciprocating auxiliary power units to conventional, gas turbine auxiliary power units. A metric of interest is created to represent the specific auxiliary power system weight including the prime mover, generator, gearbox, and fuel consumed. The metric of interest is used to compare the different auxiliary power unit technologies by incorporating detailed engine simulations, auxiliary power unit system weight modeling, and flight path-realized fuel consumption modeling. Results show that reciprocating auxiliary power units can be competitive with gas turbines in near-term, more-electric aircraft applications.

ACKNOWLEDGEMENTS

Guidance provided by my Advisor; Dr. Thomas H. Bradley, has been critical to the development of every facet of the research presented here, my education, and much more that is not shown in this document.

To my family: Tom, Chris, and Pete, who have supported me through all of my education. Especially to Raili and Matt who have been there for me during my time in Fort Collins.

Finally, I wish to thank my colleagues and friends, especially Morgan Davis, Nicholas Wagner, and Benjamin Geller, who have been there through the years.

Thank you,

Jacob

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1 INTRODUCTION

State of the art commercial aircraft Auxiliary Power Units (APUs) are gas turbines that provide mechanical power to the electrical generation system on board the aircraft and provide pneumatic power to the pneumatic systems of the aircraft. As realized in state of the art commercial aircraft, the APU powers these aircraft loads while the aircraft is on the ground, and is used only as a backup system in the air. [1]

This thesis studies the applicability of reciprocating engine APUs to replacing the gas turbine APUs in commercial aircraft. To qualify the applicability of this technology, this study must compose a multidisciplinary analysis that can qualify the performance of the reciprocating engine, the performance of that engine within the aircraft system, and must come to some understanding of the constraints that the aircraft application applies to APU design. The multidisciplinarity of the scope of this design study is illustrated conceptually in Figure 1 as the overlap between the fields of engine design, aircraft design, and system design.

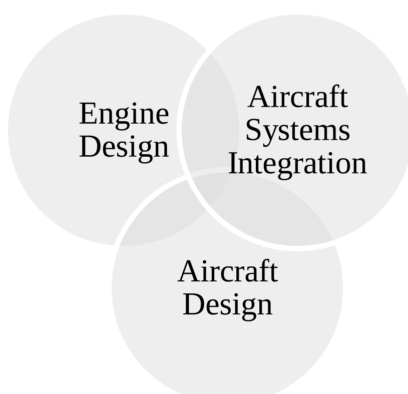

Figure 1. Conceptual relationship between topics of this thesis

There has been extensive research into each of these three areas individually, but no studies have considered the design of each in aircraft APU applications. Current APU design has not been publically researched as thoroughly as other systems within the aircraft. As aircraft design becomes more complex and integrated, there is a need for an integrated approach to aircraft APU design.

1.1 **Aviation Systems** Background

The requirements from advanced APU designs come from the changing requirements of the aviation transportation system. The changing transportation requirements of US and international passengers, and more stringent environmental constraints have enabled a number of significant changes in the architecture and function of the aviation industry [2][3][4]. These changes will come in the form of new aircraft technologies, and new systems for using those aircraft and each will have an effect on the applicability of advanced APU technologies to future aircraft.

For example, various sources show that there will be a significant increase in aviation transportation demand in the near and long term [2][5]. The current system will not be able to handle this growth of commercial traffic, so there needs to be a change in how aircraft operate on the ground and in-flight. NASA's NextGen system is a proposed aircraft control and coordination architectures that can enable the air transportation system to increase its carrying capacity. These benefits are to be realized by creating more automated aircraft control capabilities to reduce ground time, by reducing the separation time between aircraft, and by more accurately predicting the performance of individual aircraft. One impact of NextGen will be reducing the time the aircraft is on the ground between takeoff and landing [5]. Local air pollution and emissions can be reduced by reducing the time the aircraft is on the ground between landing and takeoff. [6] Another major contributor to environmental impacts is emissions during flight [3][4]. New APU technologies will allow aircraft to decrease fuel consumption and environmental impact. Another change to the industry that will affect the design of the APU is the move to More Electric Aircraft (MEAs). In the MEA aircraft architecture, electrical power takes over the powering of systems that are conventionally powered by hydraulic, pneumatic, and mechanical power. In a MEA system, the APU is envisioned to handle these electric loads that are conventionally powered by the main engine, and an MEA would demand more power of the APU than a conventional APU [6][7][8][9].

All of these proposals will increase the requirements of APUs, but APU design has not advanced at the same pace as other aviation systems. Aircraft continue to use simple cycle, high emissions, gas turbines in this application. The requirements of current APUs are based on limitations on cost, weight, and compatibility with existing aircraft architectures. The aviation industry would to be able to consider new APU technologies (such as solid oxide fuel cells [10], and reciprocating engine APUs [11][12]) but evaluating these technologies requires the development of high fidelity engine simulations and a system level understanding of the requirements of this new technology.

At present, APUs are relatively low efficiency with high specific power density [13]. By using alternative power source APUs, we can hope to achieve fuel savings and therefore APU system weight savings. [10] A reciprocating APU is a possible alternative to gas turbine APUs, but the multidisciplinary tradeoffs among the many objectives of APU design complicates a direct comparison. As such, aircraft-integrated APU performance modeling is required to quantify and understand the potential costs and benefits.

1.2 Systems Design Background

Aircraft design is a complex engineering task where, in practice, most new aircraft designs are extrapolations of preexisting technologies. This type of evolutionary design is strategically important because it reduces risk, builds on past performance analyses, and relies on preexisting system configurations to reduce complexity. The disadvantage of evolutionary design is that "revolutionary" performance improvements are not realizable [14]. Aircraft are large and complex technical system, and the design of any aircraft component must consider the integration of that component in the aircraft system. In order to design new APU systems we need to understand the tradeoffs between the requirements for efficiency weight cost and durability within the context of the aircraft as a system.

The design of more efficient and effective aircraft components presently understood to be most effective when component design is informed by the requirements of its integration at a system level. The individual components must be optimized at the system level to ensure an optimal design [15]. The characteristics of the APU that interact at aircraft conceptual design level with the other systems of the aircraft are power, efficiency, energy consumption, weight. Therefore, the conceptual design model of the aircraft APU must output these characteristics to enable a relevant tradeoff for conceptual aircraft design.

In conventional aircraft conceptual design, the APU is most often treated as a linearly scalable component with specific power of 2 lb/hp (kW/kg) and an efficiency of 40% [11]. For example, the entirety of the text regarding APUs in a recent aircraft conceptual design textbook is [16]:

"An auxiliary power unit is of sufficient size to require location in the fuselage as the layout is developed. Location in the extreme rear of the fuselage is common in transport types. It is included as a powerplant installation factor"

These types of highly simplified models are not relevant when we begin to consider the revolutionary changes in aircraft function and topology that are associated with the MEA and

NextGen effort described above. For these new aircraft designs, the APU will be an important component of describing the overall capabilities of the aircraft. Instead of the APU being relatively isolated in terms of its systems interactions, a more active and integrated APU will begin to have system design interactions with other aircraft subsystems including HVAC, avionics, fueling systems, controls, etc. For this problem, systems design is important because optimization of the APU system will have a greater impact with a move towards MEA.

1.3 Engine Modeling and Design Background

There is a large literature basis for modeling of internal combustion engines at various levels of fidelity. Literature exist on all relevant aspects of engine engineering including fundamental thermodynamics [17][18], valve dynamics [19], intake design, [20][21], turbo design [22][23][24], and more. Although many of these studies can consider the details of engine design, integration of a full engine simulation is more complex. There are only a few studies that attempt to model the engine as an engine system inclusive of relevant thermodynamics, dynamics, component selection, and controls [25]. For instance, Taraza et al. describes a MATLAB Simulink based simulation that can define the engine operating conditions as a function of a variety of input variables [26]. In another example, some researchers have used GT power to determine the optimal valve timing for an automobile engine [19].

In none of these cases, has engine design been used to meet system-level design objectives. For instance, in the design objective was to replicate the experimental results for a single engine and three operating conditions. In none of these cases was the engine design simulation incorporated into a multidisciplinary optimization framework.

1.4 Summary of Background

In summary, simulation of the system-level design and function of reciprocating engines is still a nascent research topic. The toolsets used in literature are generally custom constructed for each research project and are validated across only a limited dataset. There are only a few available toolsets that claim to describe the thermodynamic, heat transfer, fluid dynamic and chemical interactions that characterize the types of tradeoffs implicit in ICE design. No such toolsets have been used for design studies in the application of aviation reciprocating APUs.

1.5 Research Questions

On the basis of the literature, we can define two research questions:

1.5.1 Research Question 1

How do the characteristics of conventional and reciprocating APUs compare based on aircraft-integrated metrics of interest? This research question is answered through the completion of three tasks.

Task 1 – Characterize Reciprocating APUs. – In order to answer this research question, we need to develop and validate a model of reciprocating APUs that is relevant to the aircraft APU application.

Task 2 – Define metrics of interest. – These metrics of interest will be derived from analysis that attempts to combine fuel consumption, weight, power, and flight path in a way that is representative of an aircraft-level optimization metric.

Task 3 – Comparison and Synthesis – This study seeks to compare optimized reciprocating APU modeling results to the state of the art in conventional APUs.

1.5.2 Research Question 2

Under what externalities can reciprocating APUs compete with conventional technologies? This research question is answered through the completion of three tasks.

Task 1 – Characterize Conventional APUs. – To answer this research question, we need to determine the characteristics of conventional APUs to which we can equivalently compare the characteristics of reciprocating APUs.

Task 2 – Determine factors that affect reciprocating APUs most predominately. – Once we are able to compare the different APU power sources, we can determine which MoI will most effectively allow reciprocating APUs to compete with conventional APUs.

Task 3 – Comparison and Synthesis. – We can then determine at what point will reciprocating APUs will be able to compete with state of the art conventional APUs.

2 METHODS

2.1 Model Development

Figure 2 shows the modeling framework for translating the performance of APUs into aircraft-specific APU performance metrics of interest (MoI). There are two parallel tracks of analysis. Track 1 models the performance of the reciprocating APU in terms of the MoI. Track 2 models the performance of the gas turbine APUs in terms of MoI.

The first model in Track 1 represents a detailed model of the reciprocating APU modeled in GT-POWER. The engine model is discussed in detail in Section 2.1.1. The second model of Track 1 represents a model of the weight and fuel consumption of the reciprocating APU. This model uses the performance outputs from the GT-POWER model as inputs and is discussed in detail in Section 2.1.2 and 2.1.3. The final model in Track 1 calculates the aircraft specific APU performance MoI as a function of APU weight, power, and fuel consumption. The engine model is discussed in detail in Section 2.1.4.

The first model in Track 2 is a MATLAB model that has performance outputs of a state of the art conventional, gas turbine APU. The second model of Track 2 represents a MATLAB model that translates the performance outputs of the conventional, gas turbine APU into the weight and fuel consumption of the APU. The final model in Track 1 calculates the aircraft specific APU performance MoI as a function of APU weight, power, and fuel consumption.

The comparison between the performance of the gas turbine APU to the reciprocating APU is based on the comparison of each APU's aircraft-specific MoIs.

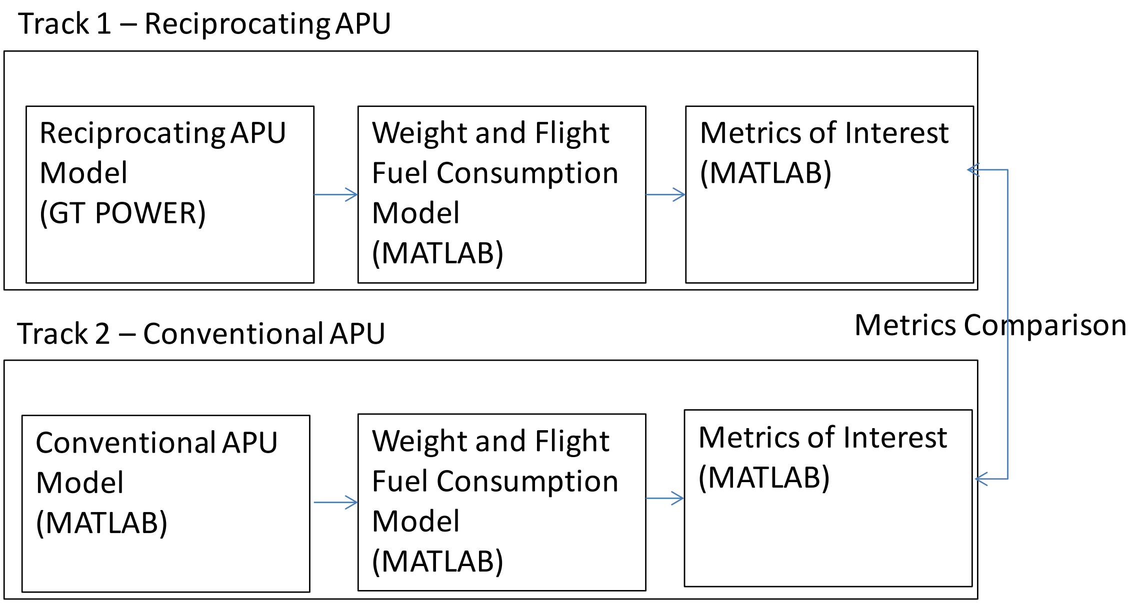

Figure 2. Diagram showing modeling tracks and subcomponent models for this study. Modeling languages in which each code is developed are shown in parenthesis

2.1.1 Engine Model

GT-POWER is an engine simulation tool developed by Gamma Technologies. GT-POWER has the ability to simulate various types of engines, including two-stroke, four-stroke, spark ignition, and compression ignition with various applications. Its built-in functionality allows the user to create complex engine design with ease and quickness. GT-POWER can simulate engine dynamics from power and torque curves to thermal analysis to control system analysis. Built-in functionality allows the user to optimize the different aspects of the engine, such as valve lift profile and timing, control systems, and manifold design and tuning. There are specific tools for turbo matching, acoustics, and emissions controls.

Figure 4 shows the model that was created in GT-Power to simulate performance characteristics of a reciprocating APU. This model allows engine design variables to be changed through the built-in GT-POWER design of experiments (DoE) function. The reciprocating APU model represents a turbocharged, intercooled, eight-cylinder, diesel engine. The objective of this model is to model an optimized reciprocating APU through an integrated DoE in GT-POWER.

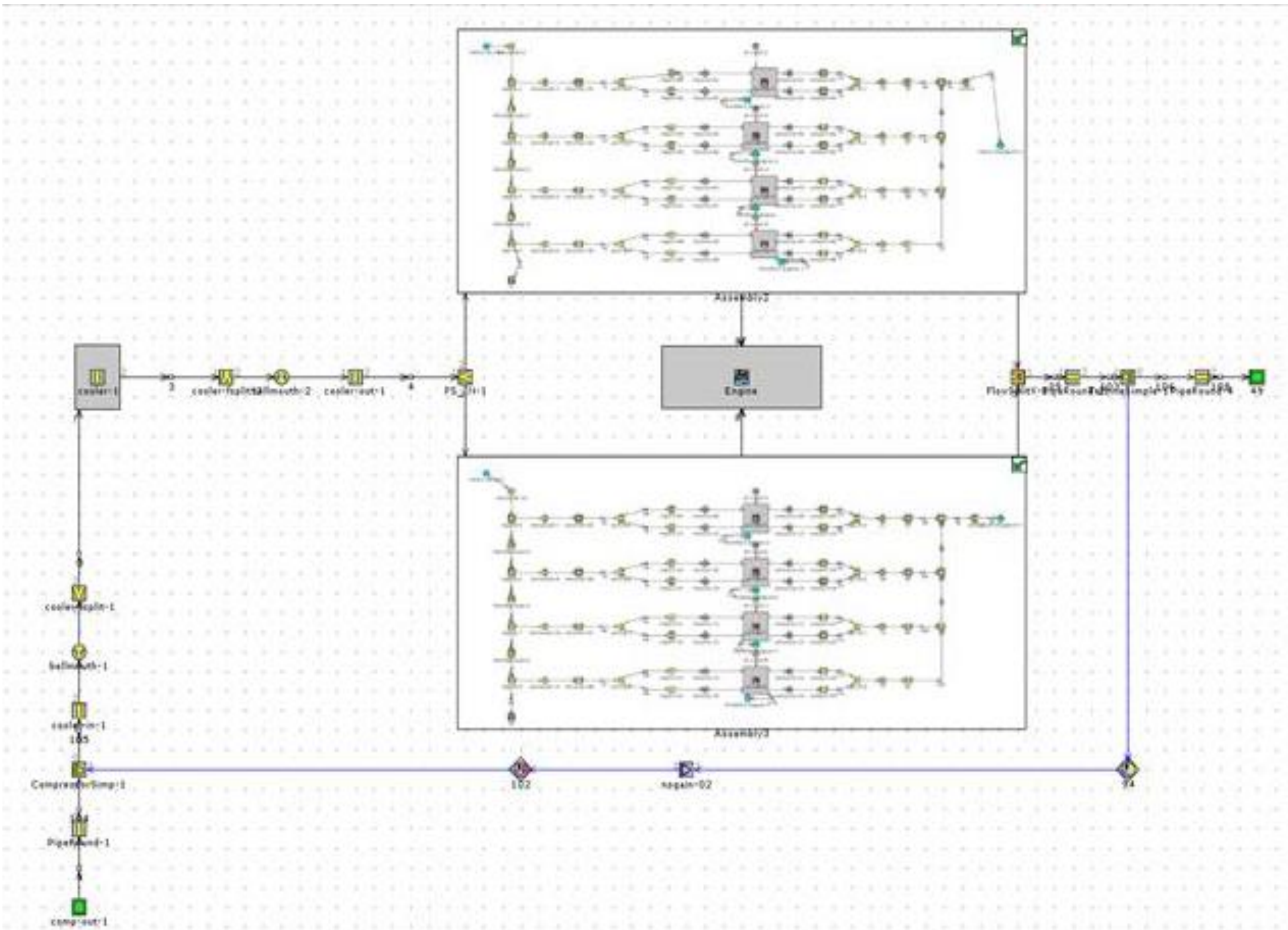

Figure 3. Reciprocating APU model as implemented in GT-POWER

The reciprocating APU is modeled with four valves per cylinder. The valve lift profile, nozzle spray profile, and intercooler are based on a diesel engine GT-POWER sample model of similar size. The cylinder geometry is based on a normal range for a diesel engine of this size [13]. The range of compression ratios is based on fundamental combustion theory to include high power and efficiency regions [13]. The valves' dimensions were initially based on the valves used in the JD4045T, but have been increased in size based on the range of cylinder sizes used in the final design of experiments.

The intake and exhaust manifold design was determined by using a sample model for the geometry and varying the size based on the cylinder dimensions. Detailed manifold design can be very complex [13]. Intake and exhaust geometry design is based on various engine parameters, such as desired peak torque, speed, cylinder geometry, turbocharger design [13]. This study uses the same intake and exhaust manifolds for all experiments run in the DoE for simplicity and transparency.

The A/F ratio is set to a specific number throughout the entire speed range. This is controlled through GT-POWER by setting the injected mass to a mass much larger than the available air. GT- POWER then reduces the mass based on the amount of available air to reach the desired air/fuel ratio.

The turbocharger model is a simplified version of the model built into GT-POWER. This simplification is justified for this study because turbine and compressor matching is computationally expensive and is difficult to perform at the conceptual design stage. For this study, we used thermodynamic relationships with common efficiencies for the turbine and compressor to build the model. This model increases the initial intake and exhaust manifold pressure to the pressure desired out of the compressor. The turbine and compressor work rates are determined in the MATLAB fuel consumption calculation after the GT-POWER simulation is completed.

2.1.2 Weight Modeling

The purpose of the weight model is to describe the mass of a variety of size and types of reciprocating APUs. At the conceptual design stage (of this study), there does not exist enough detailed information to perform weight modeling based on subcomponent modeling (material volumes, mounting structures, etc.). Instead, linear and nonlinear regression is commonly used to do first order synthesis and sizing of aircraft components. To populate a database of reciprocating APUs, I performed a literature search of aviation diesel engine design, and selected 14 engines with comparable size, displacement power, as might be required from a candidate reciprocating APU. Table 1 lists some key characteristics of these engines.

Table 1. Performance of Diesel Aviation Engines

Make	Model	Power (bhp)	Weight (lb)	Displacement (L)
DeltaHawk	DH160A4	160	327	1.6
Austro	E4 AE300	168	408	2
SMA	SR305-230	227	430	4.988
Junkers	Jumo 205	867	1312	16.63
Junkers	Jumo 204	740	1653	28.5
Napier	Nomad	3150	3580	41.1
Charomskiy	Ach-30	1500	2800	61.04
Charomskiy	M-40	1250	2500	61.04
Daimler-Benz	DB 602	1320	4356	88.5
Klockner-Humbolt-Deutz	DZ 710	2700	3197	51.5
Packard	DR-980	240	550	16
Bristol	Phoenix I	380	1067	28.7
Guiberson	A-1020	340	650	16.73
Beardmore	Tornado	650	4733	84.125

The engines used in the weight model are primarily diesel engines for aircraft from the 1930s to the 1950s. These engines were used as input to the weight meta-model because they were designed for the aviation application (with similar metrics of interest as the design of a new reciprocating APU). As such, these engines were designed to be lightweight and provide high power.

Weaknesses of using these engines to populate an engine weight database are based on the differences between these historical engines and the capabilities of more modern diesel engines. These historical engines have either centrifugal or inline cylinder geometry. Newer automotive diesel engines can provide higher efficiencies than these historical engines, but the weights of these engines include accessories that are not needed on aviation APU. Some automotive engines with higher efficiencies are also not designed with the durability needed for an APU. The Audi W12 diesel engine, used in their LeMans racecar, is an aluminum block, with high output power, and high efficiency, but is rebuilt after every race [29]. A candidate reciprocating APU must have a longer life than the current automotive application diesel engines.

Three different means of fitting the characteristics of these engines were explored. The first fit presumed a linear relationship between engine power and engine weight, resulting in an R2 value of 0.40. The second fit presumed a linear relationship between engine displacement and engine weight, resulting in an R2 value of 0.87. The last fit was a multi-variable fit using both engine power and engine displacement to predict weight. The results were not acceptable because of the low sample size used to create the fit. The linear fit of displacement to predict weight was the best option and was chosen as the basis for a meta-model to predict engine weight as a function of engine displacement.

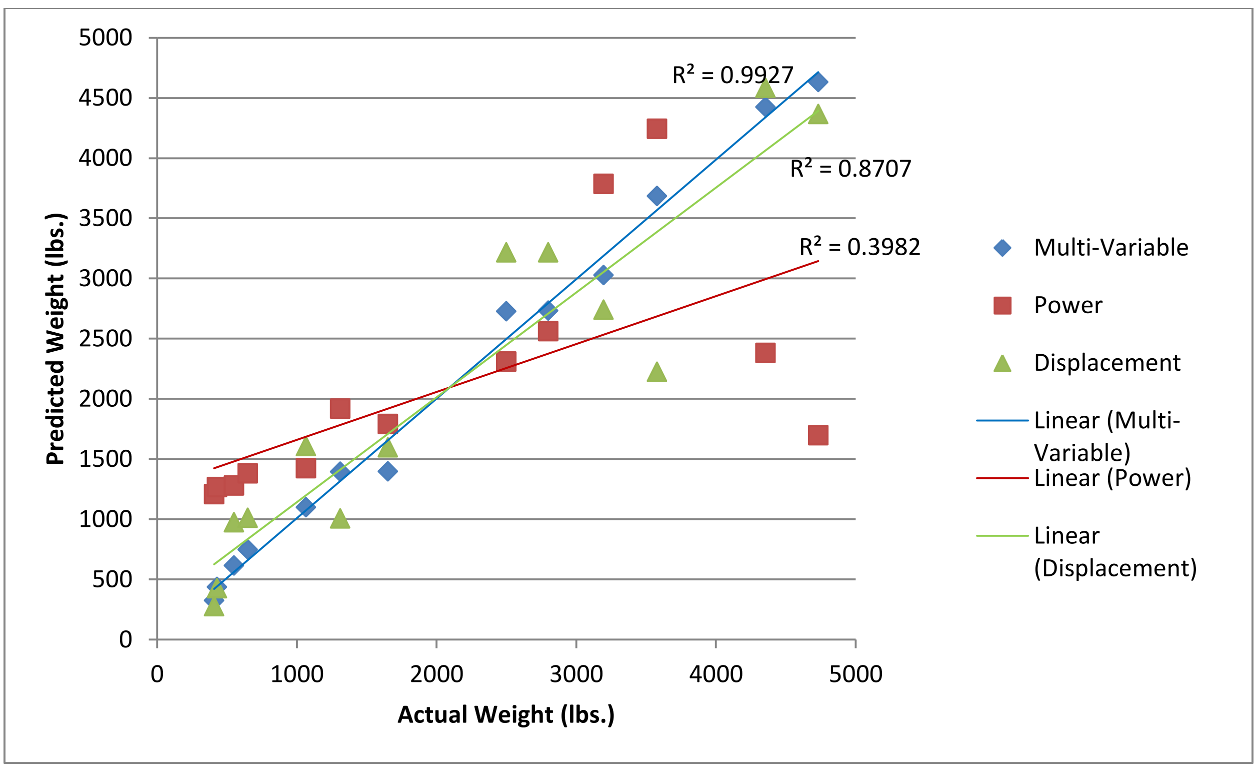

Figure 4. Predicted weight vs. actual weight associated with modeling of the weight of preexisting Diesel aviation engines

2.1.3 Fuel Consumption Model

The fuel consumption model was created to translate the APU efficiency that is the output of the detailed engine modeling into the amount of fuel consumed during a flight. The power and duration the APU needs to produce for each segment of the flight was derived from the findings of [10] and are detailed in Table 2

This model was created to model the APU loads for a solid oxide fuel cell (SOFC) APU designed for a MEA. In a MEA, the APU handles more of the electric load compared to a conventional aircraft, in which the main engine generator would handle the added loads. In fuel consumption model the APU will handle the entire electric load, allowing the main engines to provide only propulsive power.

In this NASA study, the SOFC APU would handle power requirements of the ground operations, main engine start, in-flight environmental control system, wind de-ice, and one-engine-out backup power. The main engine generator power would handle the loads of on-board inert gas generator, fuel tank pump, flight controls, non-essential loads, galley loads, and the electric motor pump. For this study, we assume that in a future MEA, the APU would handle the entire electric load. This change approximately doubles the energy requirement of the APU, but only requires a small increase in maximum APU electrical output power.

There are six main flight segments represented in the fuel consumption model. Traditionally, the APU was only in use during the Ground Operation segment. In the MEA format, the APU run during the entire flight. The cruise segment represents about 70% of the total energy requirement. The power requirement is about 80% of the peak power segment. The peak power requirement occurs during the climb segment.

Two changes to the flight segment model of [10] are made to make the flight segment model more representative of the aircraft of interest for this study. First, the length of the cruise time segment is changed to be more representative of a long-haul flight. The cruise time is largely representative of the length of the flight. The ability to change the length of the flight allows the user to study the sensitivity of the reciprocating to gas turbine APU comparison to flight time. The default flight-segment length of 175 minutes correlates to 1485 miles at 510 mph. Second, the aircraft studied [10] was a 90-passenger regional jet. This study considers an aircraft that will hold up to 215 passengers. To account for the increase in size of the aircraft, the peak power for the flight segment model is increased from 208 kW to 895 kW. The power required in each flight segment was increased by the same percentage to account for the increase in power requirement for a larger aircraft.

The fuel consumption model is a MATLAB model that was run in post-processing after the GT-POWER DoE. The fuel consumed is determined by using the APU engine efficiency, APU mechanical efficiency, and duration of each flight segment to determine the fuel consumed during that segment, and to determine the total fuel consumed over the entire flight.

Table 2. Flight segment power and energy requirements

	Flight Segment	APU Power Required (kW)	Segment Duration (min)	% of Flight Time	APU Energy (kWh)	% Energy
Ground Operations	Gate APU Loading	107.45		0.00%	0	0.00%
	Engine Start	185.31	0.5	0.21%	1.54	0.23%
	Taxi, flap deploy	173.84	10	4.19%	28.97	4.29%
Take-off	Lift-off + climb	186.83	1	0.42%	3.11	0.46%
Climb	Hi-lift + flap stow	208.03	19	7.97%	65.88	9.75%
Cruise	35000 ft	163.96	175	73.38%	478.22	70.77%
Approach	Approach & Landing	190.23	20	8.39%	63.41	9.38%
	Flap deploy	183.67	3	1.26%	9.18	1.36%
Emergency	Go-around again emergency			0.00%	0	0.00%
Ground Operations	Taxi-in	152.26	10	4.19%	25.38	3.76%
	Ground Maintenance			0.00%	0	0.00%
Total			**238.5**		**675.69**	

2.1.4 Development of Performance Metric of Interest

To be able to answer the research questions posed in Section 1.5, this study must compare the different types of APUs using the same metrics of comparison.

The specific performance characteristics I will use to compare APUs are weight, power, BFSC, and fuel consumption. Combining these four characteristics, I am able to compare gas turbine APUs to reciprocating APUs [10]. This MoI represents the specific weight of the APU system.

The combination of the performance characteristics results in:

$$MoI = (W/P)_{APU} + \Sigma(\tau_{fs} \bullet SFC)$$

Where:

W = Weight of APU

P = Peak power requirement

τ_{fs} = Time at each flight segment

SCF – Specific fuel consumption

The weight of the reciprocating APU will be determined by the weight of the engine from the weight model plus the weight of the generator, which is a constant 400 kg. The peak power requirement is 895 kW. The time at each flight is found in the fuel consumption model. For each flight segment, the time and SFC for the corresponding power demanded is used.

For the conventional APU, the power and weight of the gas turbine APU will be based on an estimation of weight per power used for simulation [10]. The peak power requirement will be the same as the reciprocating APU at 895 kW. The time and power demanded will be the same as the reciprocating APU; however, the SFC is determined using a gas turbine efficiency map [30].

2.2 Experimental Procedure

2.2.1 Perform DoE Using Engine Model

As described above, the engine model was constructed in GT POWER. Upon completion, the engine model takes ~45 seconds of CPU time to run. The outputs are saved in text file that is accessible though MATLAB.

A full factorial DoE was performed on the engine model. The design variables that were varied are stoke, bore, injection timing, inlet boost pressure, and compression ratio. Characterizing this design space required 3^5 runs or 243 engines. Below is a table of the design variables and the range over which they were varied.

Table 3. Span of Engine Design of Experiments Input Variables

Parameter	Minimum Value	Maximum Value
Bore (mm)	165	185
Stroke (mm)	165	185
Injection Timing (deg BTDC)	-5	5
Boost (bar)	1	3
Compression ratio	16	20

Each of these engines was then run at 13 different RPMs and 5 different A/F ratios for a total of 12,636 simulations. The outputs of these simulations were saved in text files that are accessible through MATLAB.

2.2.2 Port Outputs of DoE to Fuel Consumption and Weight Models

As described above, the weight model takes the outputs of the GT power simulations and derives a modeled weight for the engine. The outputs of the weight model are saved in text files accessible through MATLAB.

Similar to the weight model, the fuel consumption model also is performed in post-processing in MATLAB. The different engine power outputs desired are met by varying the A/F ratio in GT-POWER. The exact power output needed for the fuel consumptions model is then linearly interpolated between the four AF ratios simulated in GT-POWER. An example of the engine map used to determine power outputs is shown in Figure 5, below.

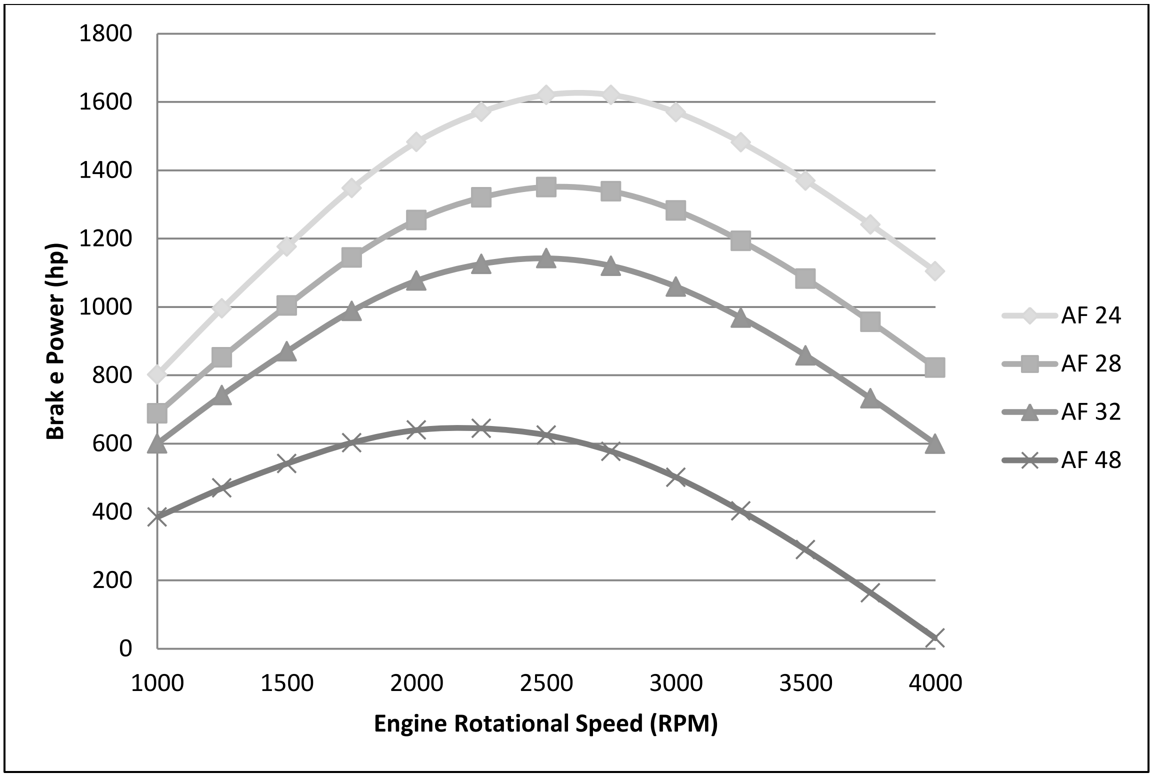

Figure 5: Brake power as a function of engine rotational speed and A/F ratio.

2.3 Model Validation

To determine the degree to which we can design and simulate an engine, I needed to use an existing engine to model in GT-POWER. With this model, we are able to understand the accuracy with which I can trust an engine designed from scratch. I chose the John Deere 4045T (JD4045) to model in GT-POWER. There is extensive data on this engine available publically and Colorado State University has this engine set up on a test stand in the Engine and Energy Conversion Laboratory, making this an ideal engine to model in GT-POWER.

I created a GT-POWER model of the JD4045T using engine parameters found on publically available data sheets. The parameters that were not available were the valve lift profile, intake and exhaust manifold design, nozzle size, spray profile, and turbocharger size. I created the model using designs from a sample engine model of similar size for all of the unknown parameters except the turbocharger design. The turbocharger was modeled by setting the pressure in the inlet of the intake manifold to that of the pressure boost out of the turbocharger of the JD4045. The exhaust backpressure was set to slightly higher than the boost pressure of the turbocharger to account for the efficiency loss through the turbocharger. The GT-POWER representation of the model is shown in Figure 6.

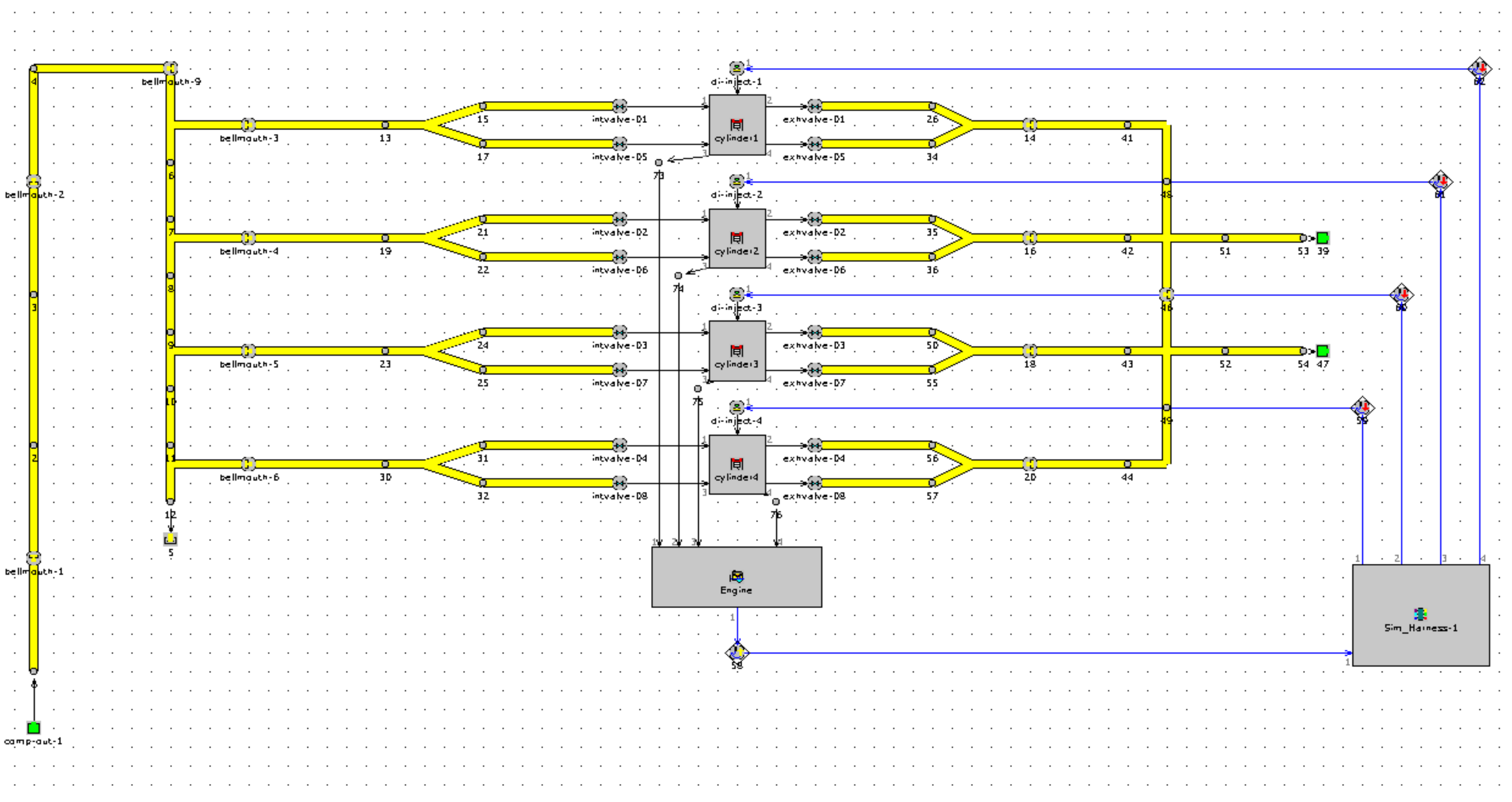

Figure 6. GT Power Model of JD 4045

Performance characteristic of the JD4045 are mostly available at the working point of the engine, 2200 RPM. For this model, the objective was to be able to compare the simulated results of the GT-POWER model to the datasheet performance characteristics. The four results over which validation was performed were torque, power, brake specific fuel consumption (BSFC), and brake mean effective pressure (BMEP). The simulated results for torque, power, BFSC, and BMEP at 2200 RPM were 513 Nm, 118 kW, 207 g/kWh, and 14.3 bar respectively, where the datasheet values for torque, power, BSFC, and BMEP at 2200 RPM were 498 N/m, 115 kW, 221 g/kWh, and 13.9 bar respectively, as shown in Table 4. All of the simulated results were found to predict performance within 8% of the datasheet values.

Table 4. Comparison of Simulation Outputs to Experimental Data for Validation of GT POWER Simulation [31]

Results at 2200 RPM		
	Simulation	JD4045T
Torque (N-m)	513	498
Power (kW)	118	115
BSFC (g/kWh)	207	221
BMEP (bar)	14.3	13.9

The results matched very well at the working point, but the simulation lacked predictive power over the full RPM spectrum. These discrepancies could be caused by numerous confounding variables, e.g. unknown valve lift profile, unknown intake and exhaust manifold design, unknown spray profile, and nozzle size. A comparison of the simulated results and the datasheet figures is shown below in Figure 7, Figure 8, and

Figure 9.

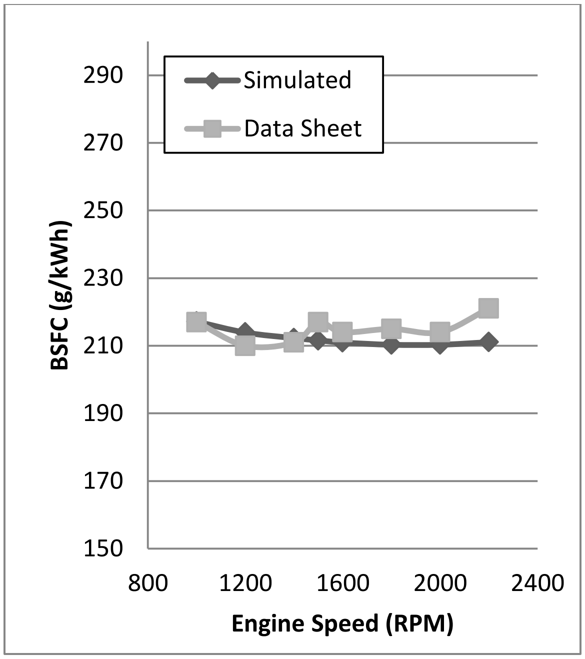

Figure 7. BSFC vs. Engine speed for JD4045. [31]

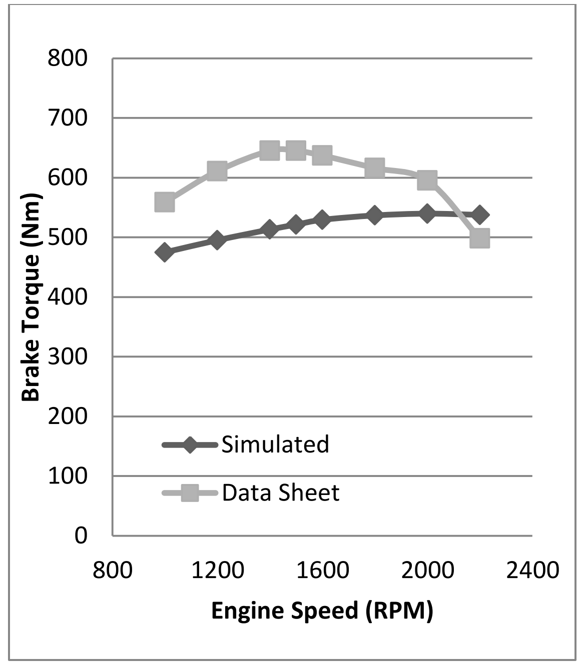

Figure 9: Torque vs. Engine Speed for JD4045. [31]

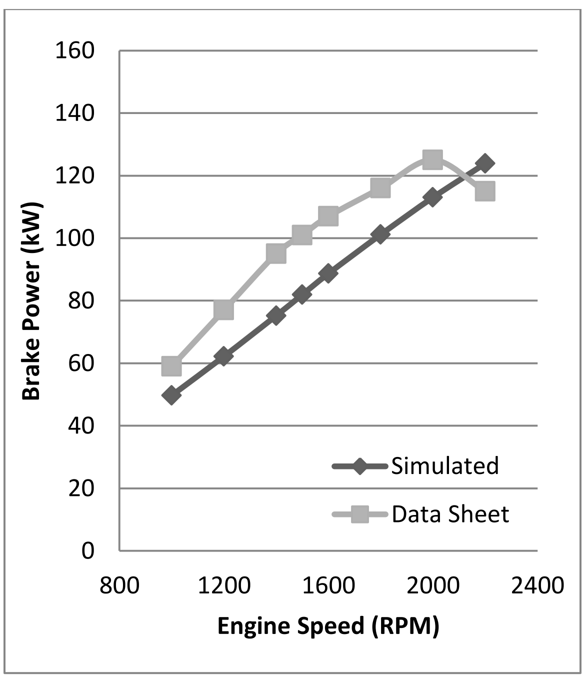

Figure 8. Power vs. Engine Speed for JD4045. [31]

The GT Power model is able to predict the performance of the JD4045 within 10% for the metric of output torque at the working speed. Over the entire speed range, the GT Power model can predict output torque within ±20%. The validity of the model as demonstrated in this validation case is sufficient to be able to make comparisons among engines. Although the absolute accuracy of the model is ±20%, all decision-making comparisons for this study will be made among simulation results, and the utility of the toolset for making design decisions has been validated [32].

2.4 Model Limitations

The modeling performed for this thesis is limited in its applicability to problems outside of those described here, as compromises between the generality of the modeling effort and its complexity had to be negotiated.

For example, GT-POWER only performs 1D flow calculations and then extrapolates to the 3D geometry of the engine. This assumption can cause large error in volumetric efficiency and inducted air values. The DoE is limited to only three or four variations for each parameter. This limits either the accuracy or the scope of the DoE. This study chose to limit the scope of the DoE. To make sure the engines were designed to meet all requirements, the scope of the DoE was trimmed through preliminary design-space exploration studies.

3 RESULTS

In this section, we will present results of the engine simulation DoE and post-processing models including weight model, fuel consumption model and gas turbine model.

3.1 Engine Simulation and DoE Results

This section presents a characterization of the engine design space through the presentation of reciprocating APU engine simulation results. With such a large DoE, it is important to determine whether the results follow the expected results from well-known engine relationships. Below are a few relationships that show that the GT-POWER simulations display the desired relationships among engine design and operation variables.

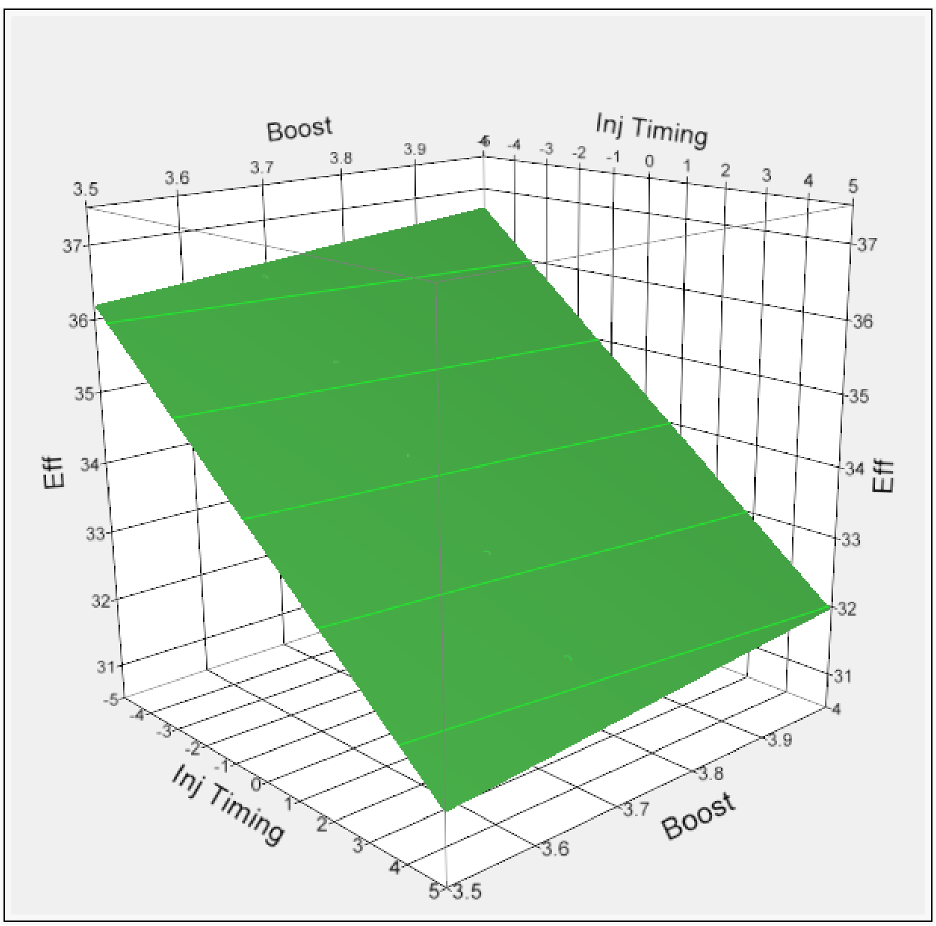

Figure 10. Efficiency vs. Injection Timing, Boost Pressure

Figure 10 shows how intake boost pressure, in absolute bars, and injection timing, in degrees BTDC, affect efficiency. The figure shows that the efficiency is more sensitive injection timing than boost pressure. This follows well-known engine performance relationships [13]. It is understood that increasing boost pressure can increase efficiency, but its effect is relatively minor for the boost pressures considered. In addition, the turbocharger model used for this simulation is a simple model and does not take into account turbine dynamics or airflow dynamics.

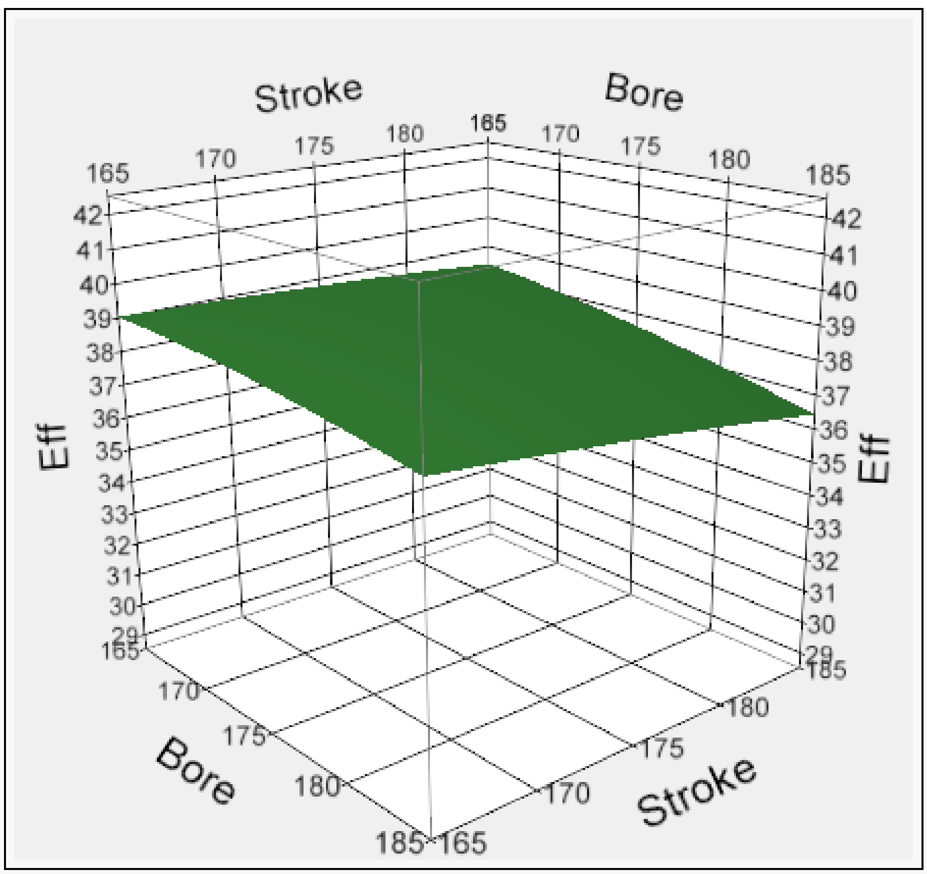

Figure 11. Engine efficiency as a function of bore and stroke

Figure 11 shows the relationships between bore and stroke and efficiency. The figure shows that reducing the size of bore and stroke increases the efficiency. This also shows that keeping the engine as close to a square cylinder as possible also increase the efficiency, further demonstrating well-known engine performance relationships.

3.2 Engine Downselection

From the performance of the From initial examination of the DoE results, engine #64 looks to have a low BSFC and displacement, which, as described previously is proportional to weight. I will use this engine design as an example to show detailed results from GT-POWER. Table XX, gives the unique parameters that define engine #64.

Table 5. Input parameters to engine case #64

Parameter	Value
Stroke (mm)	165
Bore (mm)	165
Boost (Bar, absolute)	4
Compression Ratio	18
Injection Timing (deg BTDC)	-5

As described earlier in this section, theoretical engine relationships would predict a low BSFC for this engine because of the high inlet boost pressure, and low injection timing. Even though the compression ratio is a low indicator for performance within the range selected for this DoE, the compression ratio of this engine is very close to the minimum point to minimize the BSFC and for a specific engine displacement.

Table 6. Engine simulation results from engine case #64

Output	Value
BSFC	213.6 g/kWh
IMEP	27.1 bar
FMEP	2.3 bar
BMEP	24.8 bar
Efficiency	39.2%

Table 6 shows the outputs from engine #64 at 1200 bhp and an air/fuel ratio of 24. As further verification of our model, this table shows the difference in the IMEP, 27.1 bar, and FMEP, 2.3 bar, is the BMEP, 24.8 bar. An efficiency of 39.2% is a high efficiency, but not as high as modern diesel engines have demonstrated (Figure 13 and Figure 14 shows that this engine can achieve higher efficiency at lower rotational speed). To show a better picture of the engine map used to determine the fuel consumption over the flight model, the following figures display a sample of the data collected from simulation of engine case #64.

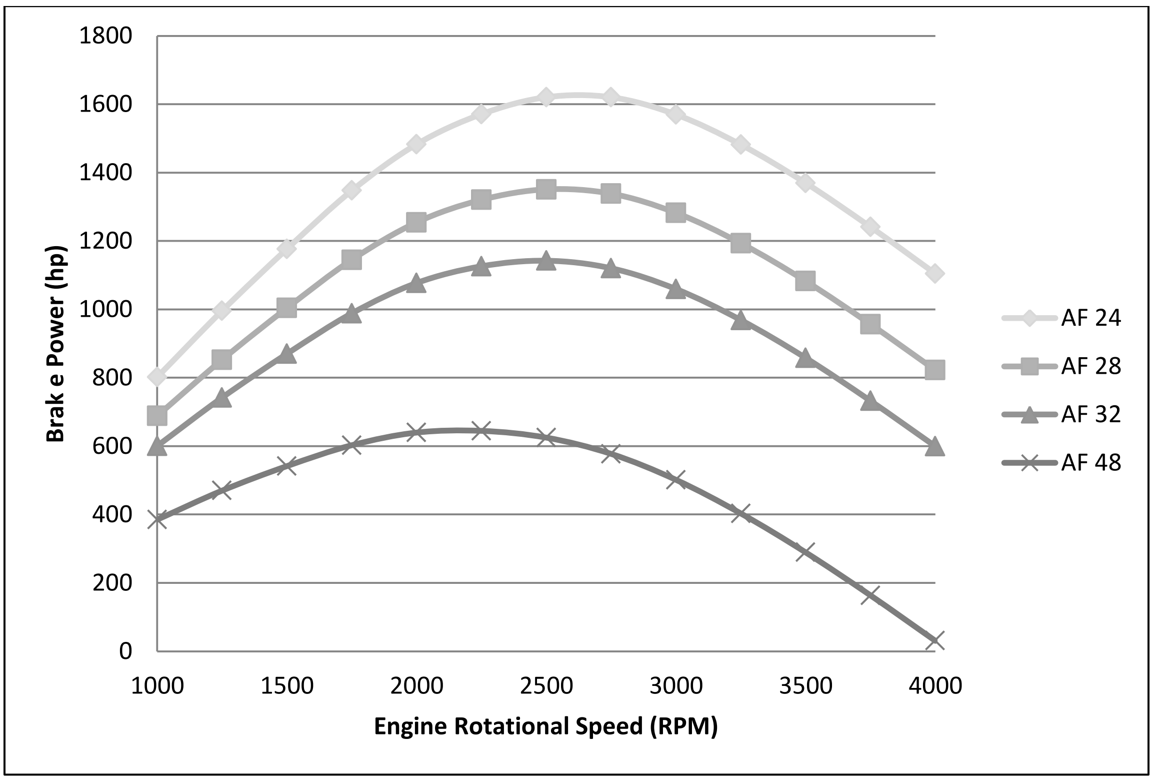

Figure 12. Brake power as a function of engine rotational speed and air fuel ratio, for engine #64

Figure 12 shows the engine brake power as a function of engine rotational speed and A/F ratio for engine #64. Each curve is the same engine design running with A/F ratios of 24, 28, 32, and 48.

This figure shows the way that the data was interpolated to find the operating point corresponding to exactly 1200 bhp. The engine will run at the same RPM for every segment of the flight plan. The working rotational speed is determined for each engine as the rotational speed at which the peak engine torque line produces 1200 bhp. The working rotational speed for engine #64 is 1543 rpm.

To determine the efficiency of the engine at each of the segments of the flight plan, the power required is input to the engine map. The map is interpolated to output the A/F ratio and efficiency that will produce the required power at the working speed, 1534 rpm. Interpolating between Figure 12 and Figure 13, we can calculate that at the working RPM, engine #64 outputs 550 bhp and has a BSFC of 231 g/kWh.

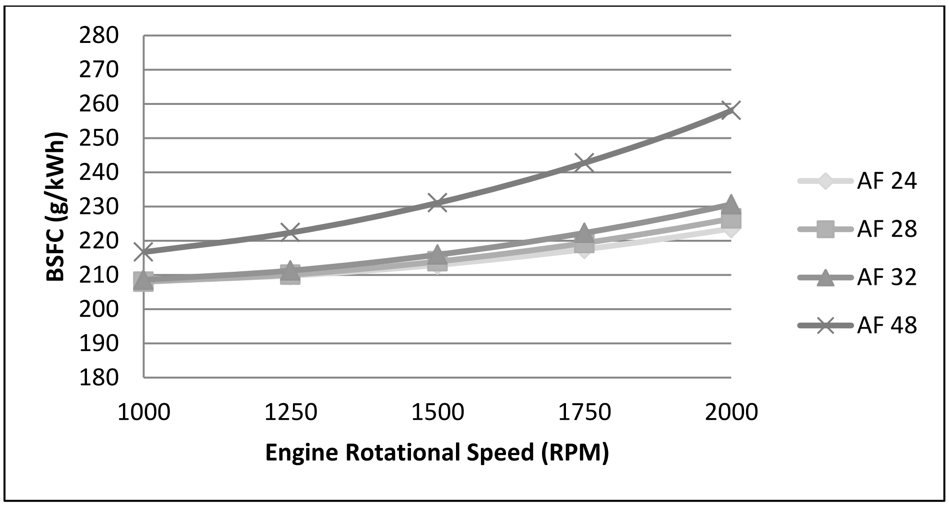

Figure 13. BSFC vs. RPM for engine #64

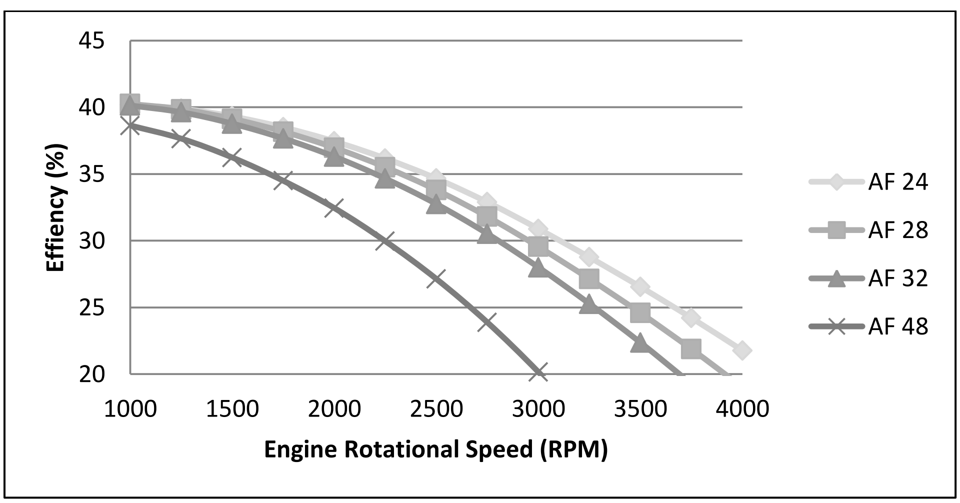

Figure 14. Efficiency as a function of engine rotational speed and air fuel ratio, for engine case #64

Figure 14 shows that at lower RPMs, this engine will run at higher efficiency. At the working point of 1534 RPMs, the engine's efficiency is 39.2%, but can achieve efficiencies of over 40% around 1000 RPM.

3.3 Engine Post-processing Results

This section presents a characterization of the engine design space through the presentation of reciprocating APU weight and MoI modeling.

As shown in Figure 15 and Figure 16, the engine weight and fuel weight are functions of both efficiency and displacement.

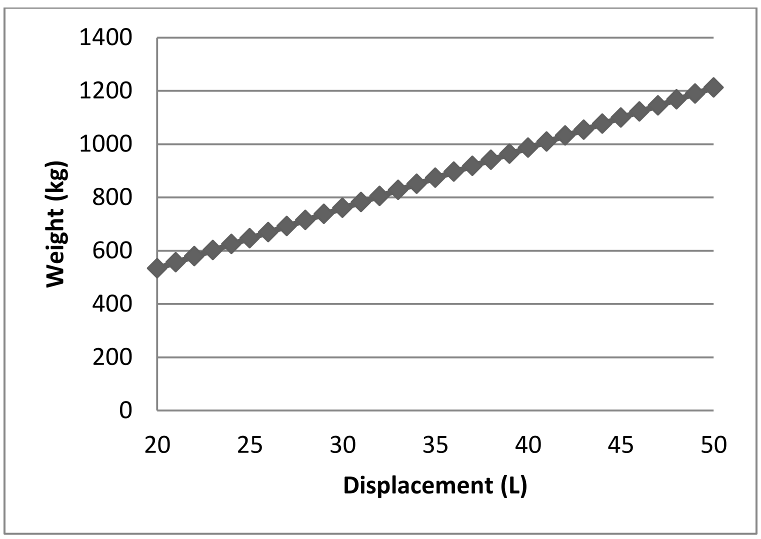

Figure 15. Engine weight as a function of reciprocating APU engine displacement

Figure 15 shows the engine weight vs. displacement for the range of engines modeled. The largest engine is 39.8L and has a corresponding weight of 981 kg. The smallest engine is 28.2L and has a corresponding weight of 719 kg. The resulting difference in weight between the largest and smallest engine is 262 kg, which is a significant increase in weight when using the larger engines.

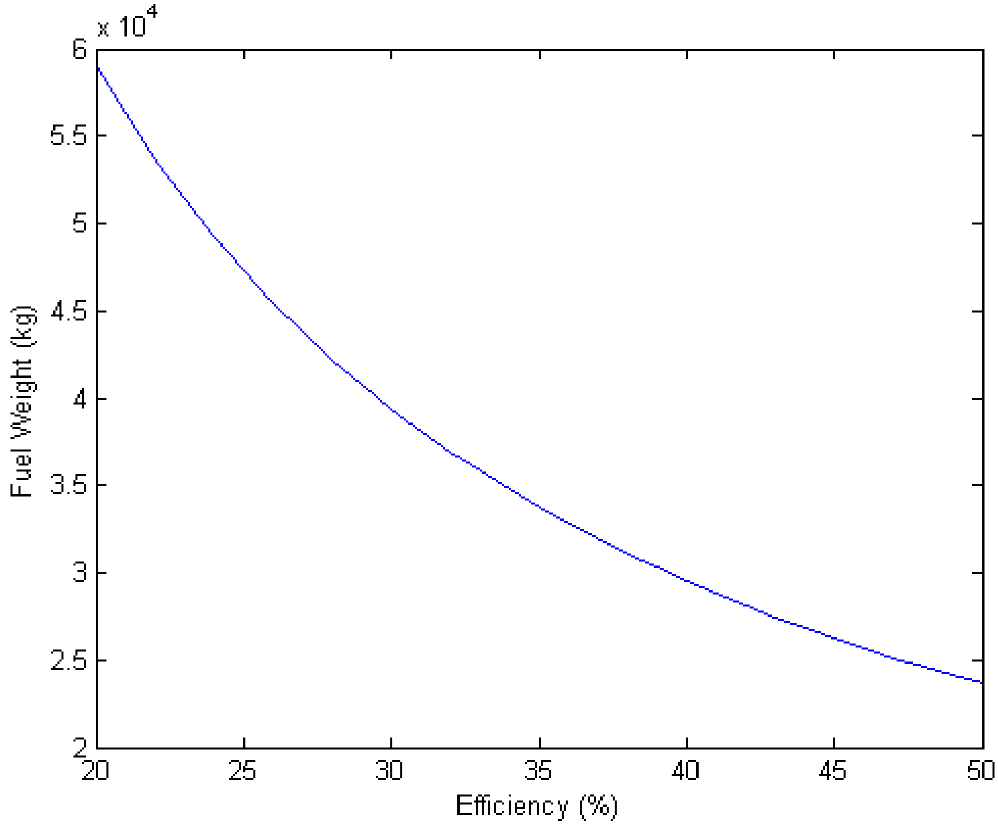

Figure 16. Fuel weight as a function of engine efficiency for modeled flight path

Figure 15 and Figure 16 show how the engine simulation outputs relate to the two parts of the MoI. These plots show that since the BSFC is very close to as good as the best engines of this size are getting, reducing engine weight is the next step to decreasing the MoI of the reciprocating APU. Figure 16 shows the effect efficiency has on fuel weight. Increasing the engine efficiency from 35% to 40% corresponds to a 422 kg reduction in fuel weight. This is larger difference than reducing the engine displacement. Increasing the engine efficiency further would greatly affect the MoI of the reciprocating APU.

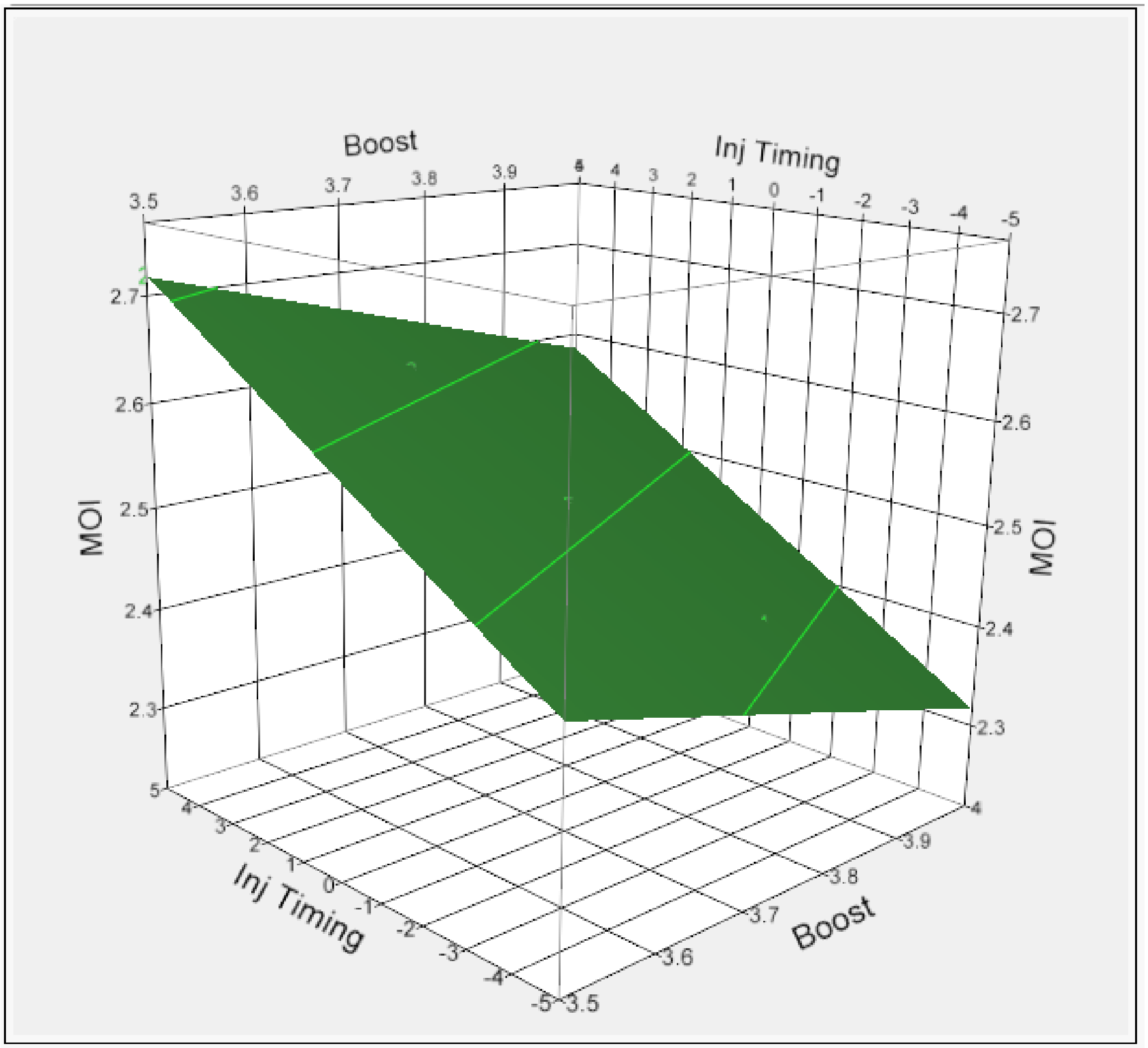

Figure 17. Boost Pressure vs. Injection Timing vs. MoI

Figure 17 shows the response of MoI to two of the largest contributors from the tornado plot.

To quantify the effect of the design variables on the MoI further, I performed a response surface equation (RSE) fit to the design space. The Pareto plot, Figure 18, is a plot of the absolute value of orthogonal estimates showing their composition relative to the sum of the absolute values. The Pareto plot is presented with respect to the unorthogonalized estimates [33]. The Pareto plot characterizes the sensitivity of the MoI to each of the input design variables.

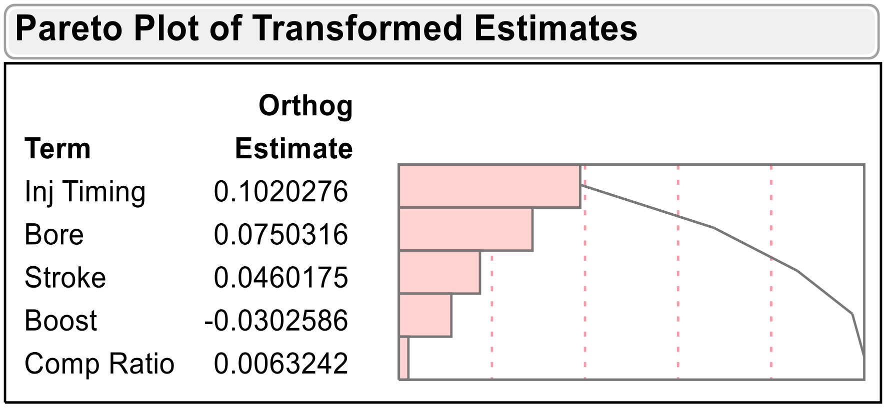

Figure 18. Pareto plot of response surface equation transformed estimates (variables are Injection Timing, Bore, Stroke, Boost, and Compression Ratio)

Figure 18 shows that the MoI is most sensitive to changes in injection timing. Bore, stroke, and boost pressure affect the MoI slightly less, where the compression ratio has very little effect. This means that about 85% of the change in the MoI is affected by only injection timing, bore, and stroke.

To visualize how the engine parameters affect the MoI further, Figure 19 shows a prediction profiler displaying how the five input parameters will either increase or decrease the MoI. The parameters shown in Figure 19 are those of engine #64. In this figure, the blue lines represent the change in MoI if a parameter is changed. For example, the current parameters correspond to a MoI of 2.17 kg/kW. If the injection timing were increased to 0 degrees BTDC, the MoI would be increased to about 2.3 kg/kW.

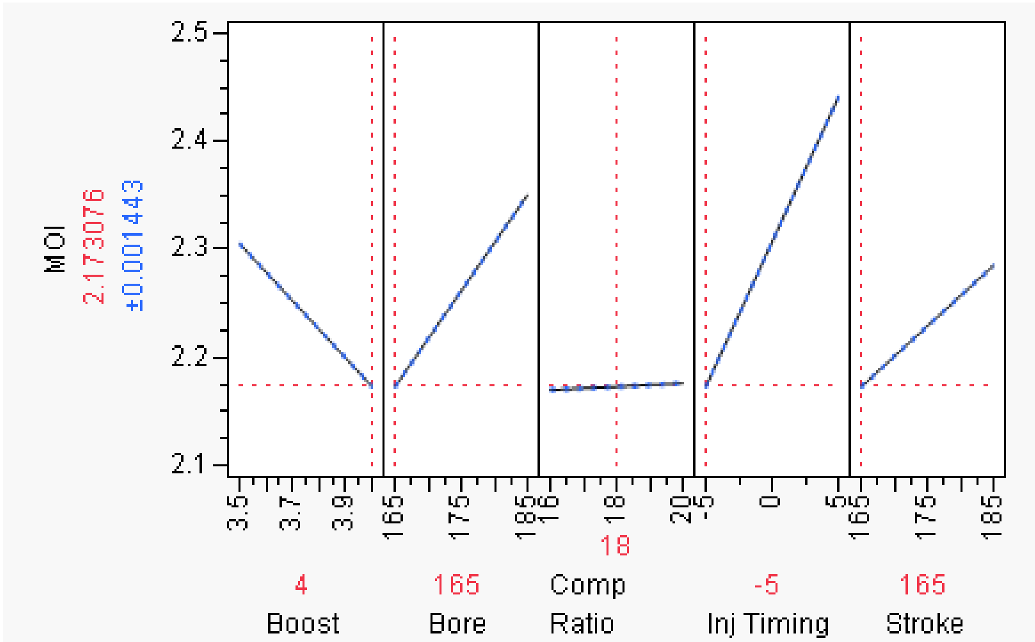

Figure 19. Prediction profiler of MoI as a function of the reciprocating engine modeling input variables.

From Figure 19, the most impactful engine parameters are shown to be the same as those shown in the Pareto plot of Figure 18, i.e. intake boost, bore, stroke, injection timing, and stroke.

As a means to contrast engine efficiency and MoI in terms of the effect of the design variables on each metric, Figure 20 shows a similar prediction profiler plot for efficiency. This plot also includes rotational speed and A/F ratio since they directly affect efficiency, unlike the MoI. This plots shows that rotational speed, A/F ratio, and injection timing are the most impactful engine parameters.

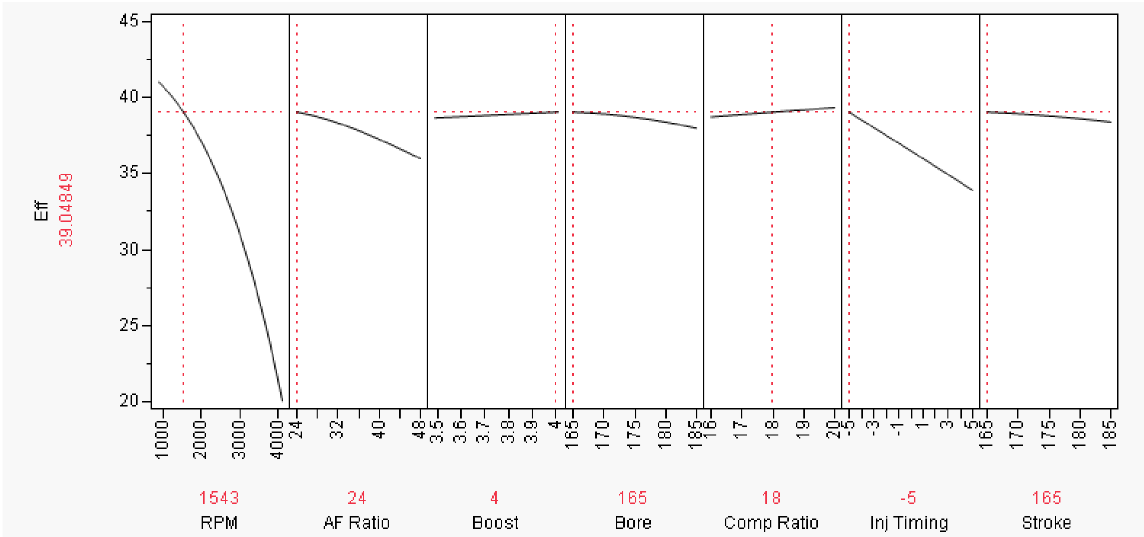

Figure 20. Prediction profiler of efficiency as a function of the reciprocating engine modeling input variables

Of the five engine parameters that effect MoI, only injection timing has a large impact on efficiency. These results can be explained by understanding that MoI includes the weight of the engine. The bore and stroke have a very large impact on the weight of the engine in because the weight model is based directly based on engine displacement.

Figure 21: Efficiency vs. Power/Weight Ratio for all engines and operating points shows the efficiency vs. power/weight ratio of all engines at every operating point. The optimal engine operating points is circled in red. The optimal point at peak power is located where the two red lines cross.

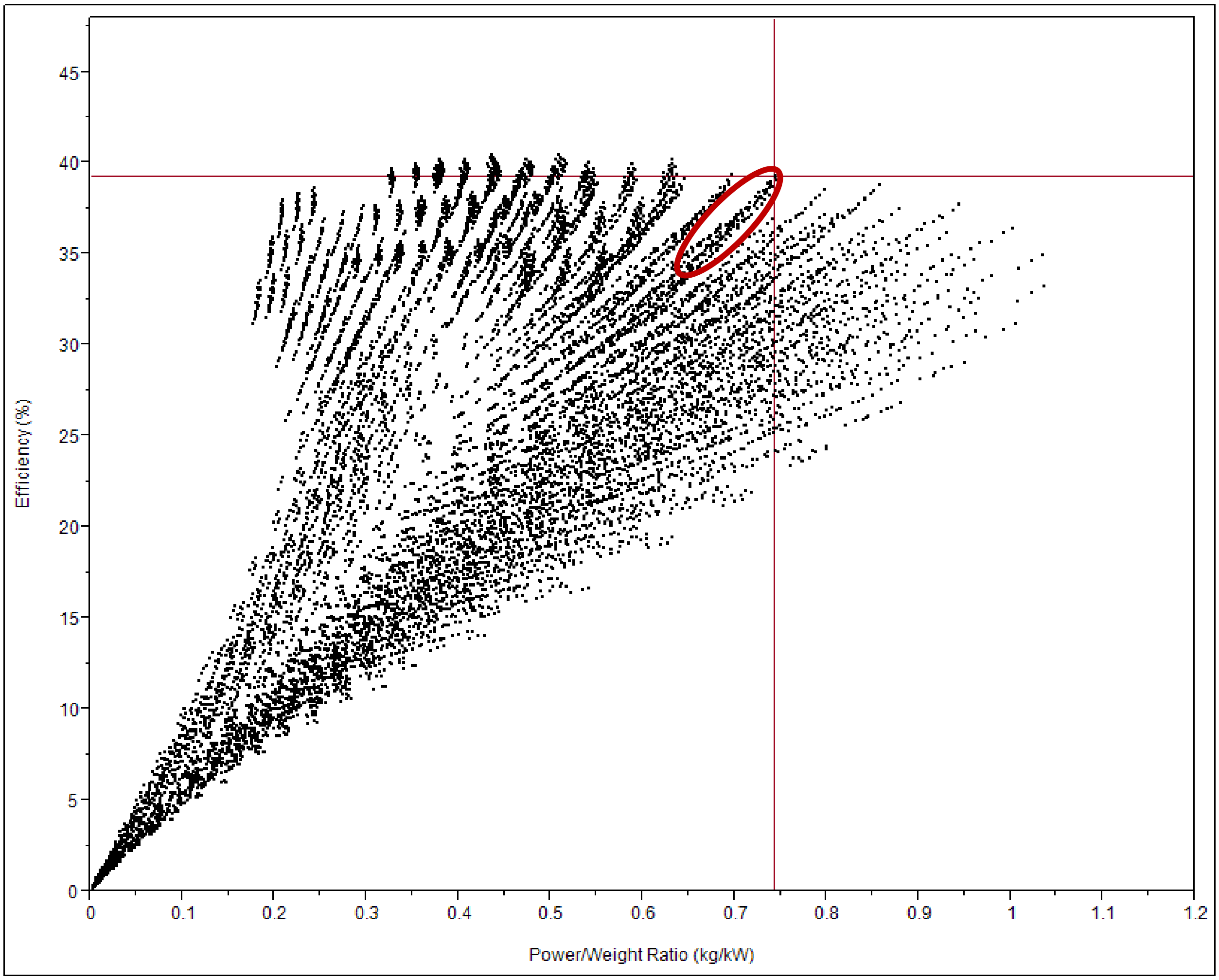

Figure 21: Efficiency vs. Power/Weight Ratio for all engines and operating points

Figure 21 shows that there are many engines with operating points with greater power/weight ratios and with greater efficiencies. The results of designing for the MoI shows that designing for just efficiency or just for power to weight ratio does not result in the optimal engine, and that a systems engineering approach is necessary for designing aircraft APUs.

4 DISCUSSION

Based on these results, we can begin to address the research questions posed in Section 1.5.

4.1 Research Question 1

Research Question 1 seeks to compare the characteristics of conventional and reciprocating APUs based on metrics of interest.

To answer this research question we must first characterize the characteristics of conventional APUs. Table 7 lists the characteristics of a conventional APU as derived from a literature search of academic and industrial publications.

Table 7. Characteristics of conventional and reciprocating APUs

	Conventional APU	**Reciprocating APU**
Minimum BFSC (g/kWh)	319	213
Specific Power (kW/kg)	0.82	1.24
MoI	2.93	2.17

These characteristics can be directly compared to the characteristics of the optimal reciprocating APU as derived from the engine simulation and post processing results presented above. Based on the MoI advanced in this study, the optimal reciprocating APU is case number 64, whose characteristics are summarized in the right column of Table 7.

Comparison of these APUs shows that the reciprocating APU has higher values of MoI. This advantage is primarily driven by the lower BSFC (high efficiency) of the reciprocating APU, and the high power to weight ratio available from modern turbocharged diesel engines.

4.2 Research Question 2

Research Question 1 seeks to understand the externalities under which reciprocating APUs can compete with conventional technologies.

From the MoI proposed for this study, reciprocating APUs will be competitive with conventional APUs in the near-term. Reciprocating APU's have equivalent or better MoI as designed in this study.

Of course, several constraints on APU/aircraft integration limit, near-term, the applicability of reciprocating APUs to conventional aircraft.

Size/Shape – Although a rigorous characterization of the geometric size of the APUs considered for this study is outside of the scope of the current investigation, the size and shape of reciprocating APUs may preclude their installation in conventional aircraft. (Estimate size of conventional and reciprocating APUs), show that the reciprocating APU is bigger or that it is squarer. Because of their size and shape, reciprocating APUs will be difficult to package in the conventional location for conventional aircraft. This does not preclude their acceptance in future or non-conventional aircraft.

Vibrations and Balance – The acoustics of APUs is of great importance to their successful integration into the aircraft. In this study, we considered a V-8 type reciprocating APU, despite the understanding that a reciprocating APU will have balance and vibration characteristics very different from a gas turbine APU. In general, it will take careful design for the aircraft application to match the vibrations and balance characteristics of the reciprocating APU to an aviation application. For instance, a V12 engine may have better acoustic and vibration characteristics due to its having no 1^{st} or 2^{nd} order modes of vibration [34].

Dynamics and Rotational Inertia – the dynamic load of an aircraft power system can lead to electrical and rotational dynamics in the APU/generator system. An increase in electrical load will lead to a decrease in generator speed until the APU control system can compensate. In conventional APUs, the high speed and high inertia of the APU rotor provides inertia to minimize the speed change and corresponding frequency fluctuations under dynamic loading. In reciprocating APUs, the speed of the crankshaft is much lower and the gear ratio between the engine and generator is much lower leading to a much lower equivalent inertia.

Aircraft Systems Architecture – The choice of APU in commercial aircraft design is limited by limitations in the commercial aircraft architectures available. For instance, the wide body aircraft architecture that houses conventional APUs was developed with the development of the 727 in 1963 [35]. This architecture was designed around the conventional APUs and the location and type of APU has not changed since. New commercial aircraft architectures (such as the BWB [36]) will provide the opportunity to consider innovating APUs including the reciprocating APU.

Aircraft Conditions of Use – In this study, reciprocating APUs are characterized as having a lower MoI than conventional gas turbine APUs. The definition of MoI as advanced in this study is dependent on the conditions of use of the aircraft under study. Aircraft with higher or lower APU loads or with differing flight paths will result in different MoIs for both conventional and reciprocating APU cases. For example, a transatlantic flight schedule would have three times the distance and cruise duration than the flight schedule considered for this study. Under this transatlantic case, the reciprocating APU has a MoI of 3.19 and the conventional APU has a MoI of 4.72. This example shows that the efficacy of the reciprocating APU will be a function of the details of the aircraft and flight schedule considered.

Modern Materials in Reciprocating APU – All of the reciprocating APUs considered for this study can be modernized in terms of their materials and design features. For instance, the reciprocating APU weight model for this study is based off engines with a cast-iron block, due to the availability of detailed engine performance data for these engines. Automotive aluminum block CI engines have demonstrated a 30% weight reduction relative to cast-iron block CI engines and similar weight reduction should be available in aviation applications [29] [37]. An aluminum block aviation reciprocating APU with a 30% weight reduction would result in a MoI of 1.65, comparable to the conventional APU's MoI of 2.93. These results show that the development of aviation-specific reciprocating APU technologies, materials and systems will improve the competitiveness of reciprocating APUs in aviation applications.

5 CONCLUSIONS

APU design is becoming more important as aircraft more towards more advanced, more demanding, and more efficient energy systems, including MEA concepts. APUs will soon handle a much higher electric load than current designs. Taking a systems engineering approach to designing the APU for a MEA will ensure the APU will be designed towards a system-level optimum, optimizing the APU for efficiency, fuel weight determined by flight path, and APU system weight instead of just efficiency. There has been much research into optimization of aircraft and is generally used in aircraft design. However, there has been very little research into using a systems engineering approach to designing APUs. The optimization performed in this study has shown that a systems engineering approach to APU design is necessary for future aircraft design.

Two research questions were posed in this study. First, how do conventional and reciprocating APUs compare based on metrics of interest? To answer this question, this study first characterized conventional APUs by running a DoE-based simulation design study of reciprocating diesel engines at APUs. Comparing the optimal reciprocating APU from the DoE to the baseline conventional APU based on the MoI resulted in a 24.6% reduction in the MoI.

The second question, under what externalities can reciprocating APU's compete with conventional technologies, required changing scenarios of flight paths and materials of the reciprocating APU. Results show that increasing the time the aircraft spends at cruise for longer flights increases the MoI reduction percentage over the baseline conventional APU. Results of a material change to a lighter weight material showed a 35% reduction in MoI over the baseline conventional APU.

After answering the two research questions in this study, this study concludes that:

Even in the near term, reciprocating APU’s can compete with conventional APUs on the basis of their performance in the aircraft.

The two engine variables that will affect the MoI most significantly are engine displacement and injection timing. These low-level design variables must be represented in system-level modeling of reciprocating APUs in the aircraft application.

Flight path will be a factor in determining how well the reciprocating APU will compete with a conventional APU.

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