Advanced Geared Turbofan 30,000lb$_f$ – Electrified (AGTF30-e) Engine Model User Guide v1.1.0

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The Advanced Geared Turbofan 30,000lb$_f$ – Electrified (AGTF30-e) is an open-source software package developed by the National Aeronautics and Space Administration (NASA). The software models an electrified advanced geared turbofan for a single-aisle aircraft and includes a controller. The model is meant to facilitate various research studies, particularly in the area of gas turbine engine electrification. It is envisioned for use with concept exploration, technology impact studies, and dynamic and controls studies. It is not meant to be representative of a real system or to be used for detailed product development. The engine model can be run in various modes of operation including boost and power extraction. It also has options for enabling electric power transfer for low engine power performance benefits, and Turbine Electrified Energy Management (TEEM) for transient operability improvement that alleviates design constraints. These are just some of the highlights of the model. The contents of the user guide provide some basic background about the model and its features. Also provided are instructions for how to use the AGTF30-e model. Readers can expect to come away with the basics they need to run the model and understand its outputs. Information is provided to build the foundation needed to write scripts for performing studies with the model. Some comments are made about making model modifications tailored to one's own research studies.

I. Introduction

The Advanced Geared Turbofan 30,000lb$_f$ – Electrified (AGTF30-e) is a dynamic engine model and controller that leverages the previously developed Advanced Geared Turbofan 30,000lb$_f$ (AGTF30) [1]. The AGTF30 is based upon a NASA N+3 concept with technologies expected to mature around the year 2035. Like the AGT30, the AGTF30-e leverages the Toolbox for Modeling and Analysis of Thermodynamics Systems (T-MATS), which provides a modular and visual coding environment for creating propulsion system models within MATLAB/Simulink®.

NASA has been pursuing research on electrified propulsion systems for many years. Industry and academia have taken a similar interest. The primary goals have been to reduce fuel consumption, emissions, and noise [2]. As the electrified aircraft propulsion has gained traction, the need for modeling tools to support that research has also grown.

There is value in having a generic propulsion system model to use in system studies as well as control studies. The Intelligent Control and Autonomy Branch at the NASA Glenn Research Center (GRC) developed the original AGTF30 model for this purpose. Since its public release in 2016, the AGTF30 has been used in numerous studies. A few of those studies are noted: Ref. [3-17]. Several studies including those in Ref. [5,6,7,9,12,13,14] are electrified aircraft propulsion (EAP) studies that required significant modifications to the engine model. These studies were conducted by NASA but the modifications to the AGTF30 were never released publicly. Publicly releasing an updated electrified version of the AGTF30 in the spirit of NASA's mission to benefit humankind is seen as valuable. Doing so aides the larger aeronautics community to advance the understanding of EAP and its associated technologies. It also provides a tool through which NASA can collaborate with external partners such as universities.

There are a variety of EAP architectures of interest. A summary of the architectures of interest are covered in Ref. [2]. Of particular interest are EAP concepts that include turbomachinery that is interfaced with an electrical power

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system. This typically entails augmenting a turbofan with electric machines (EMs) or using EMs to extract power from the engine to produce thrust elsewhere on the airframe. These architectures feature either significant amounts of power injection to or extraction from the engine shafts. It is desirable to capture the impact of these features in terms of implications of performance, operability, and controls. A generic model that provides a common basis and enables such investigations without significant development time would be valuable.

Mild hybrid propulsion system concepts have garnered attention as well. Mild hybrid concepts offer a quicker time-to-service than significantly electrified parallel hybrid and turboelectric concepts. Turbine Electrified Energy Management (TEEM) is one technology that could be a promising feature in a mild hybrid propulsion system. TEEM has been the topic of several papers including Ref. [5,6,7,9]. TEEM describes a means of using and electrical power system interfaced with a gas turbine to improve engine operability such that engine performance can be positively impacted. Another feature with a good potential for performance improvements is low engine power electric power transfer (EPT). This involves transferring power from the low pressure shaft (LPS) to the high pressure shaft (HPS) at low engine power settings. One key impact of this is it allows the high pressure compressor (HPC) to improve stability and hold an adequate bleed pressure while burning less fuel and reaching a lower thrust level [18]. EPT would be useful during descent and while operating the engine during ground operations.

EAP features such as boost and TEEM call for the use of energy storage and with that comes the challenge of energy management and the potential to charge energy storage devices during flight. Thus, an in-flight charging feature is desired, as it would allow energy management studies to be conducted.

A detail that is often overlooked in EAP studies is the engine-EM integration method and the impact it has on the engine shaft dynamics through modifying the effective inertia of the shafts. Interfacing large EMs with the engine shafts could impact the dynamics and control of the engine. It would be desirable to have a virtual testbed to account for this. In addition, the engine-EM integration method could create new possibilities in power/energy management. While dedicating EMs to a specific engine shaft through its own dedicated gearbox is a straightforward and easily visualized approach, the NASA-proposed Versatile Electrically Augmented Turbine Engine (VEATE) gearbox concept [7] could have potential to deliver benefits. The VEATE gearbox concept describes a gearbox system that interfaces EMs with the engine shafts through a linked mechanical power transmission system. The idea allows electric power injection or extraction to simultaneously influence a power split or power transfer between the engine shafts. Thus, it enables new possibilities in power management that provides the potential for reducing electrical power system size and or to improve failure modes and mitigation strategies and resolve potential integration issues.

The AGTF30-e was developed to include all the features described above so that it could be a fairly comprehensive and versatile tool for conducting research studies. In doing so, it will significantly advance the capabilities of the AGTF30. The remainder of this document will provide the following information: background about the AGTF30, description of the various features that distinguish the AGTF30-e from the AGTF30, information to help users get started with running the AGTF30-e, information to help users modify the engine model for their research purposes, and information about the steps taken to verify the model. Keep in mind that the information presented in this user guide is not comprehensive. It is meant to provide the basis for using the AGTF30-e model. A future conference paper publication is planned to provide a more in-depth example for using the AGTF30-e to conduct EAP research.

II. Significant Updates Since the Last Release

This section will summarize the updates made to the AGTF30-e model from its original release. The updates are presented as bulletized lists.

Version 1.1.0

- Replaced simplistic power system model with one developed using the Electrical Modeling and Thermal Analysis Toolbox (EMTAT). The model leverages EMTAT 1.3.1 and includes a copy of the software within the file structure on GitHub.
- Incorporated power losses in the electrical power system and introduced a convenient user option to run the model with or without electric power system losses.
- Developed a new state of charge controller.
- Modified logic with respect to the determination of "the load" during some use-cases (primarily power extraction mode).
- Updated the VEATE gearbox EPT implementation to achieve the same engine performance with less electrical power system usage.
- Modified logic for determining the nominal coupling EM power command with the VEATE gearbox approach.

- The gearbox parameterizations implemented in the model are consistent with optimization studies performed to achieve weight-efficient designs.
- Updated and cleaned-up model setup functions. This includes the setup of a new power system, updates to gearbox setup script, introduction of the power system loss option to the input files, and modifications to the way controller data is interpolated in the setup code such that the model initialization time is significantly reduced.
- Removed structured inputs from the main simulation setup function for user definition of the gearbox parameters.

III. Summary of the AGTF30

The AGTF30 is a model of a conceptual two-spool geared turbofan engine capable of producing ~30,000 lb_f of thrust at sea level static (SLS) conditions. The engine is representative of technologies thought to be matured in the mid-2030's and applicable to a single-aisle commercial transport. The AGTF30 features a compact gas turbine core and a variable area fan nozzle (VAFN). It was created primarily with the NASA developed T-MATS tool and leverages MATLAB/Simulink®. T-MATS provides the building blocks for creating a component level model of a gas turbine engine. T-MATS modeling and solution methods are based upon and very similar to those used by the Numerical Propulsion System Simulation (NPSS) tool. The components (examples: compressors, burners, turbines) are parameterized and connected in Simulink's visual block diagram coding format. The modeling methods include turbomachinery performance maps, thermodynamic relations, 1st order sensor and actuator models, and more. An iterative solver is used to enforce conservation laws.

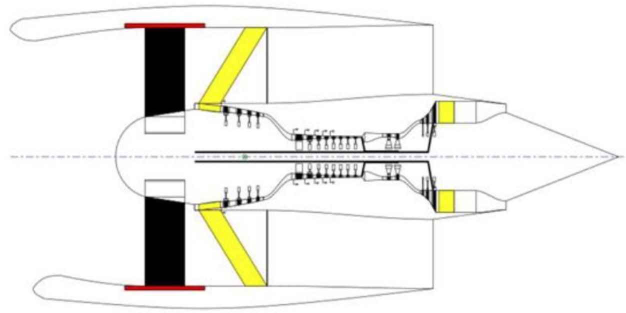

Figure 1. Representation of the AGTF30

Figure 1 is a depiction of the AGTF30 created with NPSS Weight Analysis Turbine Engine (WATE) ++ code [19] for the N+3 reference engine [20] upon which the AGTF30 is based. The AGTF30 model includes a representative full-flight envelope controller. Ref. [1] describes the development of the controller. The controller includes schedules for the variable bleed valve (VBV) and VAFN. A closed-loop proportional integral (PI) controller commands the fuel flow rate required to achieve the desired corrected fan speed. The fuel flow controller has various limit controllers that seek to protect the engine from unsafe or damaging operating conditions such as compressor stall, over-speed, over-temperature, over-pressure, and minimum operating pressure.

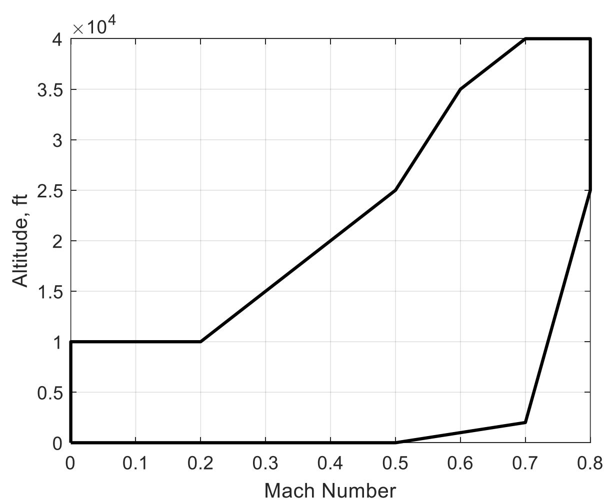

Figure 2. AGTF30 flight envelope.

The AGTF30 flight envelope is shown if Fig. 2. The primary inputs for the AGTF30 include time profiles for the altitude, Mach number, ambient temperature difference from the standard day temperature, and throttle position as prescribed by the power level angle (PLA). The PLA determines the corrected fan speed command and is linearly proportional to the thrust. The PLA is on a range between 40° and 80°. If desired, the user may override the controller and prescribe their own manual inputs for the corrected fan speed, fuel flow rate, VBV, and or VAFN. The engine model is parameterized though running a setup script that calls a variety of setup functions.

IV. Features

The AGTF30-e is built upon the AGTF30 and so it shares many features. However, it also possesses many differences. The following sub-sections will describe each of the key features that differentiate the AGTF30-e. Note that the descriptions are meant to help develop a high-level understanding of the features, not an in-depth comprehensive understanding of how the features are implemented in the model.

A. Operating Envelope and Maps

Given the complexity added in the development of the AGTF30-e, the flight envelope was reduced in size to make the development more practical. Figure 3 shows a plot of the AGTF30-e flight envelope, which can be compared with Fig. 2 for reference. The “x’s” on the plot indicate the points at which steady-state analysis, linearization, control design, and model testing were conducted.

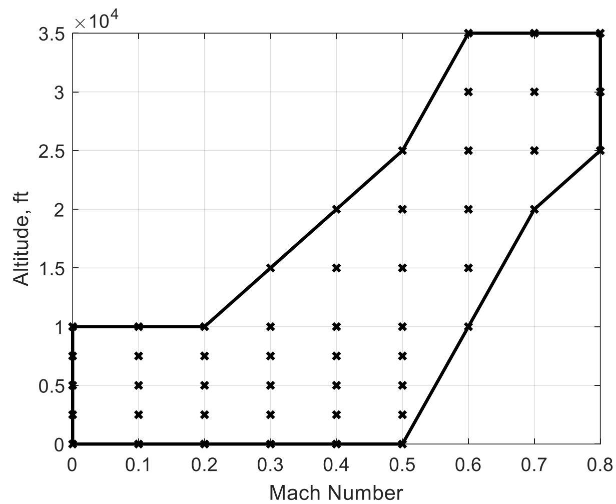

Figure 3. AGTF30-e flight envelope.

The turbomachinery performance maps for the AGTF30-e are shared with the AGTF30. However, the maps were extrapolated to help prevent numerical instabilities during development phase. While the maps are expanded, the operating point on each performance map was constrained to stay within the operating range defined in the original AGTF30 maps.

B. Engine-EM Integration Option

The AGTF30-e has two options for integrating the EMs with the engine shafts. The first is the straight-forward approach of interfacing each EM with an engine shaft through a gearbox with a fixed gear ratio. The method will be referred to as the dedicated EM (DEM) approach. The second options is inspired by the VEATE gearbox concept. It defines a variable speed ratio gearbox design that interfaces the EMs with the engine shafts. It provides a mechanical path for power flow between the shafts and can be leveraged to split power or influence shaft-to-shaft power transfer

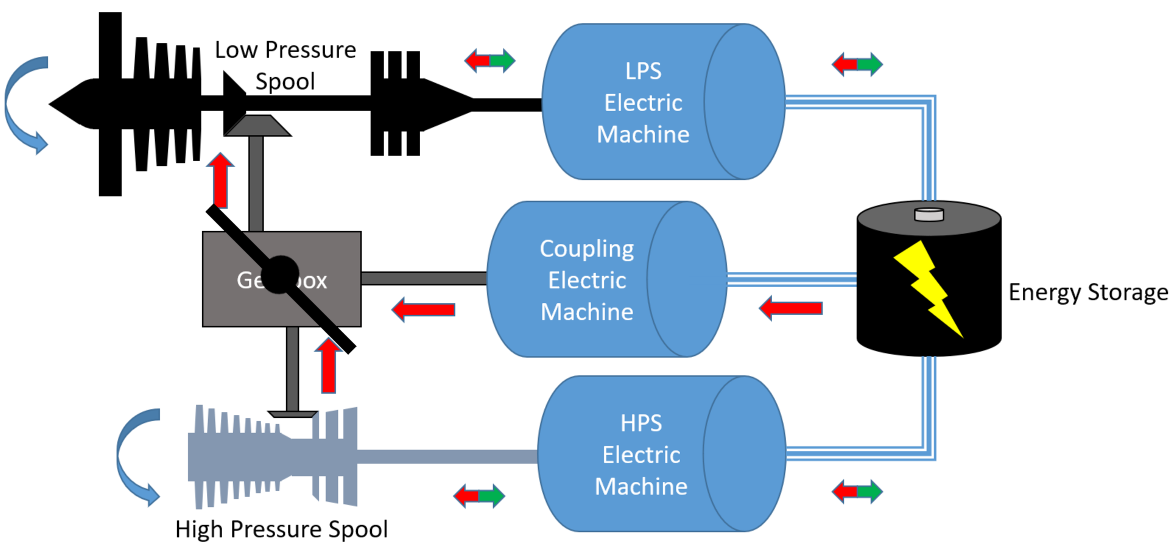

Figure 4. Schematic to describe the VEATE gearbox concept. The gearbox can be thought of as a lever that helps to direct power flow. In the case shown, power sourced from the energy storage and applied through the coupling EM influences power transfer from the HPS to the LPS. Other electric machines can be used to independently impact the shafts for balancing the load.

through us of a coupling EM. Figure 4 is a schematic that will help visualize the concept. One method for how the EMs are interfaced with the engine shafts is through a planetary gearbox (PGB). Figure 5 shows how a PGB could be used to implement the idea. As can be seen, the LPS is interfaced most directly with the carrier, the HPS is interfaced most directly with the sun gear, and a "coupling EM" is interfaced most directly with the ring gear. Applying torque with the coupling component will create a channel for mechanical power flow and will dictate a power split for funneling power with the coupling EM, or it will influence power transfer between the shafts. The relative size of the gearbox sun gear and ring gear, speeds of the engine shafts, and gear ratios created by any intermediate gearbox components will determine the impact of the coupling EM(s). The user can pick which integration method to use. A default design is parameterized for each engine-EM option. It is unlikely that either of the parameterized gearbox models are optimal in the since of metrics such as weight and reliability, but it provides a starting point for optimization studies to ensue. The parameterized model for the PGB option assumes a configuration as shown in Fig. 5. However, the model is capable of working with 2 other configurations. It is noted that 6 configurations are possible. However, the other 3 configuration were not found to produce the desired gearbox effect. The engine-EM integration option is specified by the parameters MWS.In.Options.EngineEMInt and the PGB configuration is set by the parameter MWS.In.Options.PGBConfig.

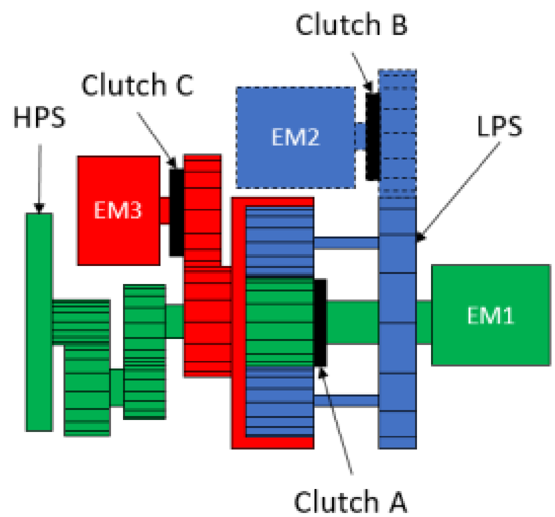

Figure 5. Planetary gearbox implementation of a VEATE gearbox. The HPS and LPS are rigidly

C. Power System Model

The power system model was updated in v1.1.0. The original "super-simplistic" model has been replaced with a model developed using the Electrical Modeling and Thermal Analysis Toolbox (EMTAT) version 1.3.1. In addition, changes to the state of charge control logic and electrical power load determination have made it possible to handle power system losses while maintaining power system equilibrium. While the user still has the option to enable or disable the state of charge controller via the vectorized time dependent 1-D lookup table pair MWS.In.t_Charge and MWS.In.Charge, it is recommended to keep the charging toggle on (set to 1) so that power equilibrium can be achieved. The electrical power system includes the electric machines, inverters/rectifiers, cables, a DC-DC converter and an energy storage device. For the boost application the energy storage device is a battery. For the other applications, a super-capacitor bank is assumed. An option has been introduced to enable quick and convenient switching between enabling and disabling power system losses. This is accomplished through the option MWS.In.Options.EPSLosses. When losses are enabled. various resistances are applied and the motors and inverters/rectifiers/converters are assigned efficiencies of 96% and 98% respectively. In all configurations, power is extracted from the HPS to meet the power demand of the engine and aircraft subsystems. This value is assumed to be 175hp nominally and was assumed in the design of controls. The original AGTF30 used a value of 350hp. The AGTF30-e allows the nominal power extraction to be prescribed a time-varying input that can vary over the course of the simulation.

D. Primary Electrification Options

The AGTF30-e can run in three different modes of operation: (1) a standard/conventional standalone engine that could possess some electrified features such as EPT and TEEM, (2) an engine that can be augmented with EM power to increase thrust (boost), and (3) an engine with dual-spool power extraction that would be used to drive propulsors elsewhere on the airframe. Note that for options (2) and (3), EPT and TEEM are appliable sub-options. The mode of operation is set by the parameters MWS.In.Options.HybridConfig.

1. Standard Engine

This mode of operation is very similar to the original AGTF30 when additional secondary options are disabled. However, there are differences which include the operating range of the engine and the controller. Differences in the controller will be described in a later sub-section. The engine operating limits are defined in the "setup_initialize.m" function. During development, the steady-state model was used to identify the maximum and minimum power operating conditions by attempting to push the engine to the most limiting limit. Generally, the AGTF30-e is able to reach a lower minimum thrust than the original AGTF30.

2. Boost

Boost mode will allow up to 2000hp of power injection to the LPS. A schedule defines how the power injection varies as a function of the engine power level and flight conditions. Boost is envisioned to only be used during certain flight segments. Furthermore, there is variability in when and how boost will be applied due to factors such as pilot preferences / flying style, differences in takeoff altitude and conditions, and energy storage limitations. For these reasons a boost command was introduced as a toggle switch command that could be used to enable and disable the boost feature throughout the simulation. The controller was developed to account for the variation in power injection. When boost is enabled, the boost command will be used by the power system model to determine the load supplied by the energy storage device.

3. Power Extraction

The power extraction (PEx) model calls for up to 1000hp of power extraction from the HPS and up to 750hp of power extraction from the LPS. The 1000hp of extraction from the HPS includes 175hp that is allotted for powering the aircraft and engine systems. The power extraction schedule is a function of the altitude, Mach number, and corrected fan speed. The power extraction schedule defines an overall power extraction and a split in power extraction between the two shafts. When PEx is enabled the power commands will be used by the power system model to determine the energy storage use. The model uses information from the power system model to set the electrical load such that the mechanical power extraction is as prescribed.

E. Secondary Options

Secondary options include EPT, TEEM, and Charging. Each option can be enabled or disabled independently and can be used in combination with any of the primary electrification options.

1. Electric Power Transfer

EPT refers to the transfer of power between the engine shafts at the low end of the engine power range. The benefit explored in this model is the ability to reduce thrust and fuel burn during descent and ground operations while maintaining adequate minimum pressure to support engine bleeds. By default, 250hp of power transfer is prescribed. The EPT feature can be enabled and disabled during simulations through a prescribed time-profile that represents a toggled command that would come from the pilot.

2. Turbine Electrified Energy Management

TEEM can be enabled to leverage the electrical power system during transient to improve operability. This feature is enabled or disabled through the input option MWS.In.Options.TEEM. When it is enabled, additional power will be commanded to the HPS during acceleration transients and power transfer will be commanded during deceleration transients.

3. Charging

Charging is especially relevant when boost or TEEM is enabled and is important for maintaining power equilibrium. While the enabling of this feature it is prescribed as a time-profile and represents a toggle command from the pilot, it is recommended to keep the charge toggle enabled at all times to achieve power equilibrium and to prevent excessive charging or discharging of the energy storage device. Charging is managed by a state-of-charge (SOC) controller that has logic to activate when TEEM and boost are not enabled. The controller has a proportional integral (PI) design with integral windup logic protection logic and saturation limits on both the changing power command and the rate of change in the charging power command.

F. Controller

The controller has several features worth highlighting to provide an overview of how the model operates. While there is some overlap in the general approaches of the AGTF30 and AGTF30-e controllers, the AGTF30-e controller was completely re-designed.

1. Adapt to changes in shaft power injection/extraction

The controller set-points, actuator schedules, and control gain schedules are functions of power injection/extraction on the engine shafts. This allows the controller to be used for a wide range of operating conditions without controller re-design. In theory, the power injection/extraction values and schedules for all electrified features could be modified and the controller could still function without significant effort.

2. Differences in fuel flow controllers

One primary difference between the AGTF30 and AGTF30-e with regard to fuel flow limit logic is that the steady-state limit controllers for the AGTF30-e prescribes to corrected fan speed set-point command, while the AGTF30 prescribes a fuel flow command directly. This change was made so that the schedule-based TEEM control strategy [9], which uses the corrected fan speed error as a scheduling parameter, could be supplied with a consistent and continuous error value.

Another feature of the controller is the option to use a designed ratio unit, *RU*, (fuel flow rate divided by static HPC discharge pressure) schedule for limiting the fuel flow rate during transients, or to implement a generic schedule. The *RU* schedule tends to perform better in terms of operability metrics such as stall margin. However, the *RU* schedules were created assuming a given power schedule. Thus, if the power schedule is modified, the *RU* schedule could become invalid. Changes in the engine operation due to an altered power schedule could make the *RU* schedule too limiting, which could cause the model to "get stuck". Another possibility is that the *RU* schedule could become too aggressive with the changes to the model, which could degrade operability and result in numerical stability issues for the model. The generic limiter option enforces maximum and minimum fuel flow rates at any given instant, and this causes the fuel flow rate to follow a 1st order exponential trajectory toward the absolute minimum or maximum fuel flow rate value. An approximate response time is prescribed as one of the parameters to the generic limiter approach. While the generic limiter option will not perform as well with the "out-of-the-box" AGTF30-e as the *RU* schedule option, it will be a more robust option for users who are making drastic changes to the model such as making significant alterations to the boost and PEx power schedules.

3. Adaptability to shaft inertia changes

The PI controllers for the AGTF30-e were designed for a range of LPS and HPS inertias. The LPS inertia can vary from 17.44 to 26.16 slug-ft^2 and the HPS inertia can vary from 1.86 to 5.58 slug-ft^2. The "setup_Controller.m" function interpolates the gain schedules for the effective shaft inertias which are calculated given the electric machine inertias and the engine-EM integration method. This feature theoretically allows the user to significantly modify the shaft inertias without having to redesign the controller. This feature increases robustness of the model and enables studies that investigate the effects of shaft inertia on dynamics and operability.

4. Boost and PEx Control

When boost is enabled, the boost power command varies with the engine power level as determine by the corrected fan speed. The boost power command is limited when the SOC of the energy storage device approaches its minimum allowed value. The boost command will range from 0 to 2000 hp with the intent of applying all that power to the LPS.

Schedules are defined for PEx that determine the overall power extraction and LPS/HPS power split. The total power extraction allocated for producing thrust varies from 175hp up to 1575hp. The power extraction and power split are functions of the engine power level as determined using the corrected fan speed. The altitude and Mach number are also factors in the determination.

5. Control for secondary options

The EPT controller commands a net zero electrical power transfer using EMs available in the electrical power system. By default, he EPT magnitude is set to achieve a maximum mechanical power transfer on the engine shafts. The desire is for power extraction from the LPS and power injection to the HPS. The EPT command is a function of the PLA that decreases with increasing PLA such that the EPT is only active at the lower end of the engine power range. The EPT command has a rate limit that will assure a smooth and gradual transition.

The TEEM control is implemented with a schedule that relates a power command to the flight condition and corrected fan speed error of the fuel flow rate controller. During accelerations, the controller defines an HPS power injection and lesser LPS power extraction. The magnitudes of these powers are large when the corrected fan speed error is large and tapers to zero as the error approaches zero. During decelerations a power transfer is commanded with a magnitude that is large with large corrected fan speed error and tapers to zero as the error approaches zero. The power transfer will result in the movement of power from the LPS to the HPS. The TEEM control commands are added to the nominal power commands determined through boost, PEx, and EPT logic.

The charging control logic was described in section IV.E.3.

6. *Handling of Control for the VEATE Engine-EM Integration Option*

The VEATE gearbox, implemented as a PGB, introduces a third channel of power injection/extraction/transfer though a coupling component that interfaces with both the HPS and LPS. An EM on this component can be used to influence power transfer between the shafts or inject/extract power to/from the shafts at a set ratio that is determined by the gearbox design and relative component speeds. Given the inertias and relative sizes of the gearbox components, and their relative speeds, the impact of applying torque with the coupling component is known. EMs connected to the gearbox components that are rigidly coupled to the engine shafts will essentially only impact the shafts they are connected to. Knowing the impact that each EM will have, and the goals of the control strategy, the EM power commands can be determined. In general, the power command of the coupling component is calculated first as it brings the benefits to the VEATE concept and should be leveraged as much as possible when it makes sense. Knowing the impact of the coupling component will allow the remaining power needs of the HPS and LPS to be determined. The control logic assumes that the gearbox design results in a specific effect. That is, power injection on the coupling component will result in power extraction from the HPS and power injection on the LPS. The opposite will be true for power extraction. If the gearbox design is changed, it is possible that this condition could no longer be met and the VEATE EM sizing calculation and control approach would no work as intended.

Boost and PEx demand certain power injections or extractions as seen by the engine shafts. The VEATE concept will achieve the desired power injection/extraction and split but will do so using the EMs differently. The controller will use the coupling EM to its full potential until the prescribed maximum nominal coupling EM power is reached. The controller will calculate the impact on the two shafts and will fill in the remainder of the demand with the EMs connected rigidly to the shafts.

The EPT power transfer command will remain unchanged at the engine shafts. However, the EM inputs will change. Power will be extracted with the coupling EM and injected with the EM connected to the HPS geartrain. The magnitude of electric power transfer will be determined using the known effect of the gearbox for the current geartrain component speeds.

Adjustments are made for TEEM as well. For accelerations, the desired power injection on the HPS is known. Power extraction from the coupling component is determined to deliver as much of the additional HPS power as it can. Any additional power is supplied by the EM interfaced most closely with the HPS. The coupling effect should provide the ability to enhance the TEEM impact and or reduce power system size. Here, the power extraction with the coupling EM reduces energy usage and could lead to a reduction in the size of the EM required on the HPS. For decelerations, the power transfer command is consistent with the baseline dedicated EM approach. However, the transfer is done using the coupling EM and the EM interfaced most closely with the HPS. Power is extracted with the coupling EM and injected with the HPS EM. This approach results in additional power transfer that enhances the TEEM impact.

V.Getting Started

A. Download/Installation

The model can be downloaded from the NASA Github repository. The download should include a copy of T-MATS with MATLAB executables (mex-files) already generated. It should also include a copy of EMTAT v1.3.1. Users are advised to use these T-MATS and EMTAT files when using the model. This means that it should be unnecessary for new users to go through the T-MATS and EMTAT installation processes prior to using the model. The model should be ready for execution by following the quick start instruction covered in a later sub-section.

B. Introduction to the different models

There are 5 model files (.slx files) that come with the AGTF30-e download. Each model has its own purpose and will be described below.

- AGTF30_eng.slx: Model of the engine that is referenced by the system models (AGTF30SysSS_PExPIn.slx, AGTF30SysLin_PExPIn.slx, and AGTF30SysDyn_PExPIn.slx). This model file contains the T-MATS representation of the AGTF30 with modifications to allow for electric machine torques to influence the shafts. It also contains the VEATE gearbox model and logic to switch between engine-EM integration methods.

- AGTF30PwrSys.slx: Model of the electrical power system for the AGTF30-e that is referenced by the dynamic (transient) engine model (AGTF30SysDyn_PExPIn.slx).
- AGTF30SysSS_PExPIn.slx: Steady-state model of the AGTF30-e. It has an iterative solver that wraps around the engine model (AGTF30_eng.slx). The solver can be used to drive the model to a variety of states. The model was used during the development phase to identify maximum and minimum operating conditions of the engine for various flight conditions and levels of shaft power injection and extraction. It was also used to define steady-state performance throughout the engine power range. Results were used to define trim points for linearization. The solver settings are defined in the "setup_initialize.m" file. The solver can drive the engine to 32 different targets (corrected fan speed, turbine inlet temperature, thrust, and various engine and turbomachinery map limits). Solver variables for the VBV and VAFN can also be adjusted to switch between goals of riding an actuator limit or achieving a desired operability metric (LPC stall margin, and fan operating line).
- AGTF30SysLin_PExPIn.slx: Linearization model for the AGTF30-e. It will simulate 1 time-step of the model and is meant to apply perturbations to the model from a known trim state. This model was used to linearize the AGTF30-e by perturbing the system and extracting the impact on the states and outputs. The collected data was used to create linear state-space models at each of the trim points. The linear models were used in the creation of controllers for the AGTF30-e.
- AGTF30SysDyn_PExPIn.slx: Dynamic/Transient model of the AGTF30-e. The AGTF30-e incorporates shaft dynamics, allowing for the simulation of transients as a result of engine power level changes and changes in environment. This model includes a controller that provides representative transient performance. This model has a long list of options and capabilities. Its controllers can be overridden by user who may supply manual inputs. Actuator and sensor dynamics are included. In addition, nonlinear aspects of the actuators are included such as saturation limits and rate limits.

The dynamic model (AGTF30SysDyn_PExPIn.slx) is the primary model of the set. It is suspected to be the most useful of the models. It is well suited for studies of dynamics, operability, controls, performance, and more. The steady-state model (AGTF30SysSS_PExPin.slx) could prove useful in studies that focus on performance related to the engine itself or the impact of shaft power injection/extraction. Although, the dynamic model could be used to achieve the same results. The linearization model (AGTF30SysLin_PExPIn.slx) could be useful if the user wants to develop their own controllers using linear control theory, or to create a piece-wise linear model for purposes such as estimation or model-based control.

C. Quick Start Guide to Running the Model

A good first step to using the model after downloading it is to run the model using a sample script "run_AGTF30e_script.m". This will confirm the model runs as intended and will give the user a good starting point to begin familiarizing themselves with the model. This script will clean up the workspace, initialize the workspace, provide a template for modifying the workspace, simulate the model, and plot results. This script can be used as a template for writing code to run the model in a way that is tailored toward the user's purpose. Snippets of code are outlined below.

1. *Initializing the Workspace*

Prior to running the model, the MATLAB workspace must be populated with the data that the model needs to run. This includes the model parameters that define the turbomachinery performance maps, environmental and control input profiles, actuator limits, sensor bandwidths, etc. All this information is consolidated into a MATLAB workspace structure under the variable name MWS. Several data structures that are used within the model must also be populated in the workspace. To get these variables into the workspace, one can run the following set of code from the "AGTF30-e" folder.

```
inputMethod = 2; % use excel spreadsheet
In = []; % empty array for now
filename = 'AGTF30e_Inputs.xlsx'; %file to derive inputs from
Mdl = 1; % dynamic model
SSsolverSP = 2; % doesn't matter, not using steady-state model
```

```
MWS = Setup_Simulation(inputMethod,In,filename,Mdl,SSsolverSP,dem,veate);
```

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	**AGTF30-e INPUTS**												
2													
3	**NOTE: ENTRIES BEYOND 10000 TIME INSTANCES ARE INVALID**												
4													
5	**Definitions:**	EM - Electric Machine											
6		TEEM - Turbine Electrified Energy Management											
7		EPT - Electric Power Transfer											
8		LP - Low Pressure (refers to low pressure shaft along with LPS)											
9		HP - High Pressure (referes to high pressure shaft along with HPS)											
10													
11	**Simulation Options**												
12	**Hybridization Option:**	1	1 - Standard Engine, 2 - Boost, 3 - Power Extraction										
13	**Electric Power System Loss Option:**	1	1 - No Losses (idealistic), 2 - Losses (realistic)										
14	**Engine-EM Integration Option:**	1	1 - Dedicated EM approach, 2 - VEATE Gearbox approach										
15	**VEATE Gearbox Option:**	2	1 - HP Sun/LP Ring, 2 - HP Sun/LP Carrier, 3 - HP Ring/LP Sun, 4 - HP Ring/LP Carrier, 5 - HP Carrier/LP Sun, 6 - HP Carrier/LP Ring (NOTE: o										
16	**Transient Limit Logic Option:**	2	1 - Generic limiter, 2 - Ratio Unit limiter (designed for nominal power schedules defined with the model)										
17	**TEEM Option:**	0	0 - TEEM disable, 1 - TEEM enabled										
18													
19	ENGINE INPUT VARIABLES												
20	Altitude		Ambient Temp. Diff		Mach Number		Aircraft Power Load			Power Lever Angle		Boost Toggle	
21	t_Alt	Alt	t_dTamb	dTamb	t_MN	MN	t_PExAC	PExAC	<-- variable names -->	t_PLA	PLA	t_Boost	Boost
22	Time, s	Value, ft	Time, s	Value, °R	Time, s	Value	Time, s	Value, hp		Time, s	Value, deg	Time, s	Value, 0 or 1
23	0	0	0	0	0	0	0	175		0	40	0	0
24	10	0	10	0	10	0	10	175		10	40	10	0
25										10.015	80		
26										40	80		
27										40.015	40		
28										90	40		
29													

Figure 6. Snippet of the excel spreadsheet used to initialize the AGTF30-e

The model is setup to run by executing the "Setup_Simulation.m" function which will create the MWS structure and make necessary directories visible to MATLAB. This function calls various other functions to prepare the model for execution. The input method specifies that the inputs will be read from the excel spreadsheet 'AGTF30e_Inputs.xlsx'. Figure 6 shows a partial snippet of the excel file. The other input method is to use and input structure 'In', that is loaded into the workspace. This structure must be consistent with what the model expects in terms of is input structure 'MWS.In'. With either method, the inputs define the model settings and simulation scenario and are crucial to properly setting up the rest of the model, including generating sufficient initial conditions. The 'Mdl' variable tells the script to open the dynamic engine model upon the completion of the setup process. 'SSsolverSP' tells the steady-state model which set-point target to use (corrected fan speed, thrust, etc.). Since the example calls for running the dynamic engine model, the input is inconsequential. Execution of the final line of code that runs the "Setup_Simulation.m" command will load the necessary bus data variables and create the MWS structure.

2. Modifying the Workspace

If the input structure defined in the first call of the "Setup_Simulation.m" function is representative of the simulation scenario one plans to run, then modifications are unnecessary. However, if one desires to modify the model settings, they can do so. However, one must be careful to run the appropriate setup functions after the MWS structure is updated. When in doubt, the "Setup_Simulation.m" function should be re-run to completely re-initialized the model. The code below shows an example of making changes to the 'MWS' structure and re-initializing the workspace followed by simulating the model and plotting results. A similar script is provided with the model called run_AGTF30e_script.m. This script can be used as a starting point to setup and run other simulations.

```
% Options
MWS.In.Options.HybridConfig = 2; %1-Standard, 2-Boost, 3-PEx
MWS.In.Options.EPSLosses = 2; %1-No Losses, 2-Losses
```

```
MWS.In.Options.EngineEMInt = 1; %1-DEM, 2-VEATE-PGB
MWS.In.Options.PGBConfig = 2; %1-HP Sun, LP Ring, 2-HP Sun, LP Carrier
                              %3-HP Ring, LP Sun, 4-HP Ring, LP Carrier
                              %5-HP Carrier, LP Sun, 6-HP Carrier, LP Ring
MWS.In.Options.WfTransientLogic = 2; % 1-General Limiter, 2-Ratio Unit Schedule
MWS.In.Options.TEEM = 1; %0-disable TEEM, 1-Enable TEEM

% Environment Inputs
MWS.In.t_Alt = [0 10];
MWS.In.Alt = [0 0];
MWS.In.t_MN = [0 10];
MWS.In.MN = [0 0];
MWS.In.t_dTamb = [0 10];
MWS.In.dTamb = [0 0];

% Control Inputs
MWS.In.t_PLA = [0 20 20.015 50 50.015 120];
MWS.In.PLA = [40 40 80 80 40 40];
MWS.In.t_Boost = [0 3 3.015 70 70.015 120];
MWS.In.Boost = [0 0 1 1 0 0];
MWS.In.t_Charge = [0 95 95.015 120];
MWS.In.Charge = [1 1 1 1];
MWS.In.t_EPT = [0 65 65.015 95 95.015 120];
MWS.In.EPT = [0 0 1 1 0 0];

% Update MWS
inputMethod = 1;
MWS = Setup_Simulation(inputMethod,MWS.In,filename,Mdl,SSsolverSP,dem,veate);
```

The hybrid configuration is changed to boost mode, the engine-EM integration method is set to the DEM option, and the PGB configuration (though inactive) is set to interface the HPS with the sun gear and the LPS with the carrier. The *RU* schedule transient limiter option is selected and TEEM is enabled. In addition, environmental and control inputs are re-defined. Finally, the input method is changed to use the input structure rather than the excel spreadsheet and the "Setup_Simulation.m" function is executed once more.

It could be unnecessary to re-run "Setup_Simulation.m" after modifying the model settings. For instance, one can change the environmental and control input profiles without re-running any setup files as long as the initial starting point and commands do not change. Another example is that the TEEM option and transient fuel flow logic option can be changed without re-running the setup functions. However, a change in the initial starting point would require the initial conditions to be recalculated. Changes in the hybrid configuration and PGB configuration (MWS.In.Options.PGBConfig) could have implications on the power system sizing, engine shaft inertias, and controller definition. For this reason, the setup process should be repeated. It is possible that not all setup functions need to be executed again. One should familiarize themselves with the setup files prior to making and trusting modifications to the MWS structure without doing a full re-initialization.

3. *Running the model*

At this point the model can be executed. This can be done manually from the model file or programmatically in a script as shown below:

```
sim('AGTF30SysDyn_PExPIn.slx');
```

The model has been observed to run faster than real-time on a laptop computer.

4. *Plotting Results*

Basic MATLAB plotting commands are applicable for plotting and analyzing the results of the simulation. The only trick will be understanding the output structures of the model. The output structures will be defined more thoroughly in a later sub-section. Below is an example of code used to plot the corrected fan speed (N_{1c}), thrust (F_n), and thrust specific fuel consumption (TSFC). Figure 7 show the plot that the code produces.

```
% N1c, Thrust, TSFC
figure();
subplot(3,1,1);
plot(out_Dyn.eng.Data.FAN_Data.Nc.Time,out_Dyn.eng.Data.FAN_Data.Nc.Data,'-
k','LineWidth',2)
xlabel('Time,s')
ylabel('N_{1c}, rpm')
grid on;
subplot(3,1,2);
plot(out_Dyn.eng.Perf.Fnet.Time,out_Dyn.eng.Perf.Fnet.Data,'-k','LineWidth',2)
xlabel('Time,s')
ylabel('F_n, lb_f')
grid on;
subplot(3,1,3);
plot(out_Dyn.eng.Perf.Fnet.Time,(out_Dyn.act.Wfact.Data*3600)./out_Dyn.eng.Perf.Fnet.
Data,'-k','LineWidth',2)
xlabel('Time,s')
ylabel('TSFC, (lb_m/hr)/lb_f')
grid on;
```

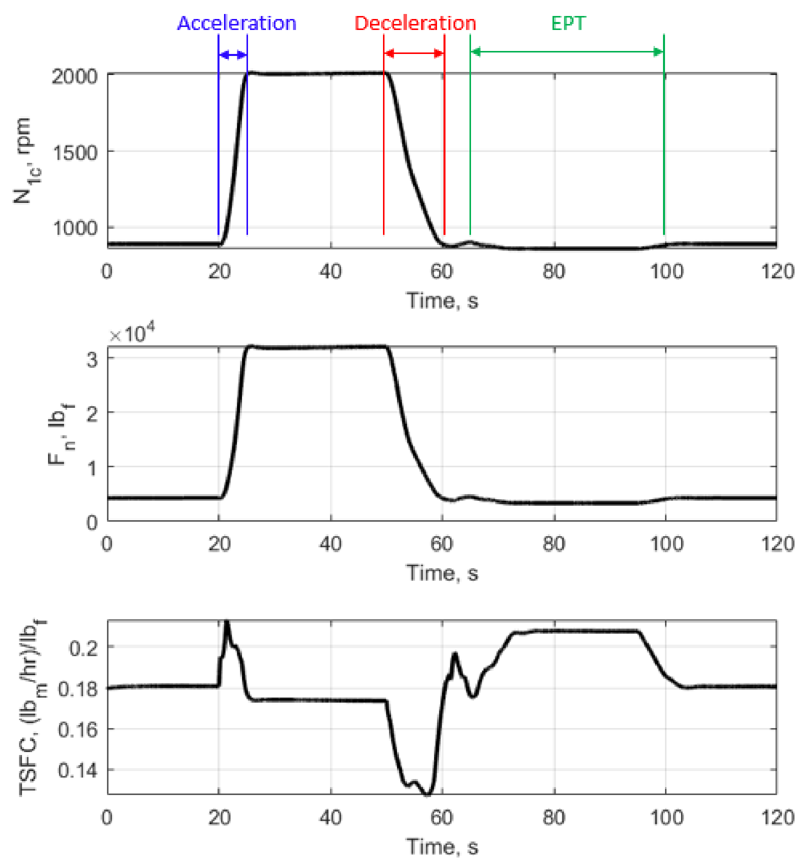

Figure 7. Plot created by the provided code. The code does not generate the blue, red, and green text and lines. Those are added to identify the segments of the simulation scenario. The results are plotted for a simulation ran with the model in boost mode using the DEM engine-EM integration approach with RU transient limiters and TEEM enabled.

The section of code shown next demonstrates how to plot the turbomachinery maps and performance map data. An example of the generated plots is shown in Fig. 8. Note that the user-defined functions “PlotCMap.m” and “PlotTMap.m” are used to plot the compressor and turbine maps respectively. These functions are provided with the download of the AGTF30-e.

```
% Maps
figure();
subplot(2,3,1)
PlotCMap(MWS.FAN.NcVec,MWS.FAN.WcArray,MWS.FAN.PRArray,MWS.FAN.EffArray)
hold on;
plot(out_Dyn.eng.Data.FAN_Data.WcMap.Data,out_Dyn.eng.Data.FAN_Data.PRMap.Data,'-
k','LineWidth',2)
xlabel('W_{c,Map}, lb_m/s')
ylabel('PR_{Map}')
title('Fan Map')
grid on
subplot(2,3,2)
PlotCMap(MWS.LPC.NcVec,MWS.LPC.WcArray,MWS.LPC.PRArray,MWS.LPC.EffArray)
hold on;
plot(out_Dyn.eng.Data.LPC_Data.WcMap.Data,out_Dyn.eng.Data.LPC_Data.PRMap.Data,'-
k','LineWidth',2)
xlabel('W_{c,Map}, lb_m/s')
ylabel('PR_{Map}')
title('LPC Map')
grid on
subplot(2,3,3)
PlotCMap(MWS.HPC.NcVec,MWS.HPC.WcArray,MWS.HPC.PRArray,MWS.HPC.EffArray)
hold on;
plot(out_Dyn.eng.Data.HPC_Data.WcMap.Data,out_Dyn.eng.Data.HPC_Data.PRMap.Data,'-
k','LineWidth',2)
xlabel('W_{c,Map}, lb_m/s')
ylabel('PR_{Map}')
title('HPC Map')
grid on
subplot(2,2,3)
PlotTMap(MWS.HPT.NcVec,MWS.HPT.PRVec,MWS.HPT.WcArray,MWS.HPT.effArray)
hold on;
plot(out_Dyn.eng.Data.HPT_Data.WcMap.Data,out_Dyn.eng.Data.HPT_Data.PRMap.Data,'-
k','LineWidth',2)
xlabel('W_{c,Map}, lb_m/s')
ylabel('PR_{Map}')
title('HPT Map')
grid on
subplot(2,2,4)
PlotTMap(MWS.LPT.NcVec,MWS.LPT.PRVec,MWS.LPT.WcArray,MWS.LPT.effArray)
hold on;
plot(out_Dyn.eng.Data.LPT_Data.WcMap.Data,out_Dyn.eng.Data.LPT_Data.PRMap.Data,'-
k','LineWidth',2)
xlabel('W_{c,Map}, lb_m/s')
ylabel('PR_{Map}')
title('LPT Map')
```

```
grid on
```

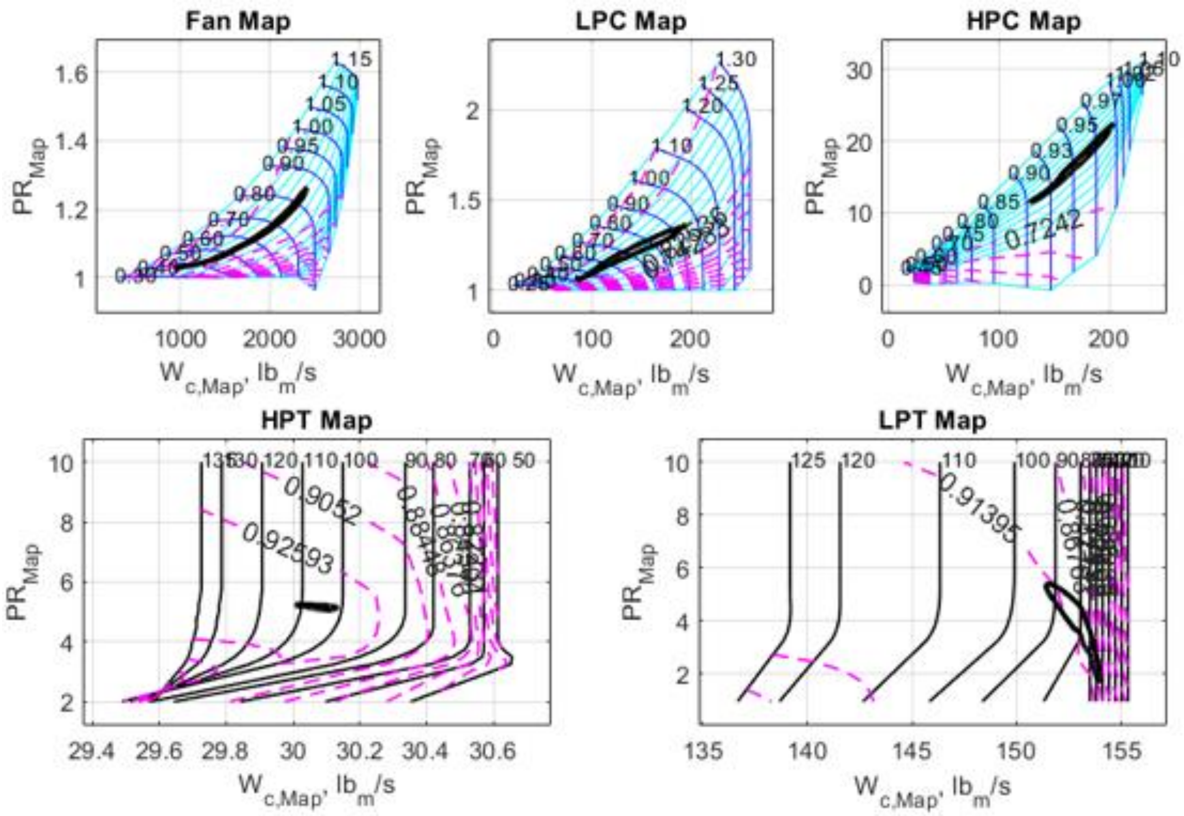

Figure 8. Example of compressor and turbine map plots.

D. Modifying Model Settings

There are 3 ways in which the model settings can be modified. The first is through the model inputs which are listed in Table 1. The inputs can be modified in the excel spreadsheet and read in through execution of the setup files, or it can be modified once it is defined in the MATLAB workspace. In the later case, the user should take caution to assure the model is setup appropriately before running the model. This might require running the setup procedure again, using the new input structure in the initialization. The second way to modify the inputs is the "Setup_Simulation.m" input SSsovlverSP. The SSsolverSP variable is only applicable to the steady-state model and it determines which primary equation/target to use to drive the model. The user can choose from driving the model to a corrected fan speed target, turbine inlet temperature target, thrust target, or various limit targets. The limit targets are listing in Table 1 under the description of "EnLimitStop_Prim". The engine targets and limits are defined in the "setup_intialize.m" function. Of course this method of modifying inputs only provides the ability to set the target variable for the steady-state model, which is rather limited. The final method for adjusting model setting is to modify the setup files. This should be done with caution but could be necessary to accommodate specific studies that require model changes.

Table 1. List of model inputs. All variables are stored in the workspace under the structure MWS.In

Variable Name	Scaler/Vector	Units	Description
Options.HybridConfig	Scaler	N/A	Defines the primary electrification option. The options are: 1 – standard engine, 2 – boost, and 3 - PEx
Options.EPSLosses	Scaler	N/A	Enables or disables power system losses. The options are: 1 – no losses (idealistic), 2 – losses enforced (realistic)

Options.EngineEMInt	Scaler	N/A	Defines the engine-EM integration method. The options are 1 – a dedicated EM approach that places an EM on each shaft, and 2 – a VEATE gearbox approach that utilizes a planetary gearbox design and includes a coupling component that provides a mechanical path for power flow between the two shafts.
Options.PGBConfig	Scaler	N/A	Defines the planetary gearbox configuration that is applicable when MWS.In.Options.EnginEMInt = 2. The options are defined by which component of the gearbox is rigidly interfaced with the engine shafts. The options are: 1 – HPS to sun gear / LPS to ring gear, 2 – HPS to sun gear / LPS to carrier, 3 – HPS to ring gear / LPS to sun gear, 4 – HPS to ring gear / LPS to carrier, 5 – HPS to carrier / LPS to sun gear, and 6 – HPS to carrier / LPS to ring gear. By default, this value should be set to 2. Changing the configuration could require changes in the gearbox design (relative gear sizes and gear ratios) to results in the desired effect and make the EM sizing and control approach valid.
Options.WfTransientLogic	Scaler	N/A	Defines which transient limit logic to use. The options are: 1 – a generic fuel flow limiter that enforces a 1st order fuel flow rate profile with respect to time, and 2 – a ratio unit schedule that was developed for the nominal operation of each hybrid configuration. Option 2 is better when sticking with the operating modes that come with the engine model. If the operating modes are modified the ratio unit schedules may no longer be valid. In that case option 1 could be used to enforce acceleration and deceleration limits.
Options.TEEM	Scaler	N/A	Enables or disables the TEEM feature. The options are 0 – disabled, and 1 – enabled.
t_Alt	Vector	s	Time vector corresponding to the altitude input.
Alt	Vector	ft	Time varying altitude vector.
t_dTamb	Vector	s	Time vector corresponding to the ambient temperature delta input.
dTamb	Vector	°F	Time varying ambient temperature delta vector. The value is the difference of the air temperature from the standard day atmosphere.
t_MN	Vector	s	Time vector corresponding to the Mach number input.
MN	Vector	-	Time varying Mach number vector.
t_PExAC	Vector	s	Time vector corresponding to the aircraft power offtake
PExAC	Vector	hp	Time varying aircraft power offtake vector. A (+) value refers to a power extraction from the engine. The default value is 175hp.
t_PLA	Vector	s	Time vector for the power lever angle .
PLA	Vector	°	Time varying power lever angle. This value defines the throttle position. It ranges from 40° to 80° and linearly scales with thrust.
t_Boost	Vector	s	Time vector for the boost toggle switch.
Boost	Vector	N/A	Time varying boost toggle switch command vector. All entries should either be 0 to disable boost or 1 to enable boost.
t_EPT	Vector	s	Time vector for the EPT toggle switch

EPT	Vector	N/A	Time varying EPT toggle switch command vector. All entries should either be 0 to disable EPT or 1 to enable EPT.
t_Charge	Vector	s	Time vector for the charging toggle switch.
Charge	Vector	N/A	Time varying boost toggle switch command vector. All entries should either be 0 to disable charge or 1 to enable charge.
t_N1cMan	Vector	s	Time vector for the manual corrected fan speed command.
N1cMan	Vector	rpm	Time varying manual corrected fan speed command. When enabled, this value will override the corrected fan speed command from the set-point controller, including limit logic.
t_WfMan	Vector	s	Time vector for the manual fuel flow rate.
WfMan	Vector	lb_m/s	Time varying manual fuel flow rate vector. When enabled, this value will override the fuel flow rate commanded by the controller.
t_VBVMan	Vector	s	Time vector for the manual variable bleed valve.
VBVMan	Vector	frac. open	Time varying manual variable bleed valve vector. When enabled, this value will override the VBV schedule defined in the controller.
t_VAFNMan	Vector	s	Time vector for the manual variable area fan nozzle
VAFNMan	Vector	in^2	Time varying manual variable area fan nozzle vector. When enabled, this value will override the VAFN schedule defined in the controller.
t_PwrInLPNomMan	Vector	s	Time vector for the manual nominal LPS power input
PwrInLPNomMan	Vector	hp	Time varying manual nominal LPS power input. This input is separate from any EM power input. It is useful for the steady-state model or when one does not want to impact the electric power system model of the dynamic engine model.
t_PwrInLPOffNomMan	Vector	s	Time vector for the manual off-nominal LPS power input
PwrInLPOffNomMan	Vector	hp	Time varying manual off-nominal LPS power input. This input is separate from any EM power input. It is useful for the steady-state model or when one does not want to impact the electric power system model of the dynamic engine model.
t_PwrInHPNomMan	Vector	s	Time vector for the manual nominal HPS power input
PwrInHPNomMan	Vector	hp	Time varying manual nominal HPS power input. This input is separate from any EM power input. It is useful for the steady-state model or when one does not want to impact the electric power system model of the dynamic engine model.
t_PwrInHPOffNomMan	Vector	s	Time vector for the manual off-nominal HPS power input
PwrInHPOffNomMan	Vector	hp	Time varying manual off-nominal HPS power input. This input is separate from any EM power input. It is useful for the steady-state model or when one does not want to impact the electric power system model of the dynamic engine model.
t_PwrInLPEMNomMan	Vector	s	Time vector for the manual nominal LPS EM power input.
PwrInLPEMNomMan	Vector	hp	Time varying manual nominal LPS EM power input. When enabled it will replace the base EM power command the includes boost/PEx, EPT, and the aircraft power load.
t_PwrInLPEMOffNomMan	Vector	s	Time vector for the manual off-nominal LPS EM power input.

PwrInLPEMOffNomMan	Vector	hp	Time varying manual off-nominal LPS EM power input. When enabled it will replace the TEEM and changing power commands.
t_PwrInHPEMNomMan	Vector	s	Time vector for the manual nominal HPS EM power input.
PwrInHPEMNomMan	Vector	hp	Time varying manual nominal HPS EM power input. When enabled it will replace the base EM power command the includes boost/PEx, EPT, and the aircraft power load.
t_PwrInHPEMOffNomMan	Vector	s	Time vector for the manual off-nominal HPS EM power input.
PwrInHPEMOffNomMan	Vector	hp	Time varying manual off-nominal HPS EM power input. When enabled it will replace the TEEM and changing power commands.
t_PwrInSEMNomMan	Vector	s	Time vector for the manual nominal sun gear EM power input.
PwrInSEMNomMan	Vector	hp	Time varying manual nominal sun gear EM power input. When enabled it will replace the base EM power command the includes boost/PEx, EPT, and the aircraft power load.
t_PwrInSEMOffNomMan	Vector	s	Time vector for the manual off-nominal sun gear EM power input.
PwrInSEMOffNomMan	Vector	hp	Time varying manual off-nominal sun gear EM power input. When enabled it will replace the TEEM and changing power commands.
t_PwrInREMNomMan	Vector	s	Time vector for the manual nominal ring gear EM power input.
PwrInREMNomMan	Vector	hp	Time varying manual nominal ring gear EM power input. When enabled it will replace the base EM power command the includes boost/PEx, EPT, and the aircraft power load.
t_PwrInREMOffNomMan	Vector	s	Time vector for the manual off-nominal ring gear EM power input.
PwrInREMOffNomMan	Vector	hp	Time varying manual off-nominal ring gear EM power input. When enabled it will replace the TEEM and changing power commands.
t_PwrInCEMNomMan	Vector	s	Time vector for the manual nominal carrier EM power input.
PwrInCEMNomMan	Vector	hp	Time varying manual nominal carrier EM power input. When enabled it will replace the base EM power command the includes boost/PEx, EPT, and the aircraft power load.
t_PwrInCEMOffNomMan	Vector	s	Time vector for the manual off-nominal carrier EM power input.
PwrInCEMOffNomMan	Vector	hp	Time varying manual off-nominal carrier EM power input. When enabled it will replace the TEEM and changing power commands.
t_PwrInPEMNomMan	Vector	s	Time vector for the manual nominal planet gear EM power input.
PwrInPEMNomMan	Vector	hp	Time varying manual nominal planet gear EM power input. When enabled it will replace the base EM power command the includes boost/PEx, EPT, and the aircraft power load. The value is for a single planet gear. This value must be multiplied by the number of planets to get the total power injected to / extracted from the planet gears.

t_PwrInPEMOffNomMan	Vector	s	Time vector for the manual off-nominal planet gear EM power input
PwrInPEMOffNomMan	Vector	hp	Time varying manual off-nominal planet gear EM power input. When enabled it will replace the TEEM and changing power commands. The value is for a single planet gear. This value must be multiplied by the number of planets to get the total power injected to / extracted from the planet gears.
N1cManEn	Scaler	N/A	Enables/disables the manual corrected fan speed command. Options are: 0 – disable, and 1 – enable.
WfManEn	Scaler	N/A	Enables/disables the manual fuel flow rate command. Options are: 0 – disable, and 1 – enable.
VBVManEn	Scaler	N/A	Enables/disables manual VBV command. Options are: 0 – disable, and 1 – enable.
VAFNManEn	Scaler	N/A	Enables/disables the manual VAFN command. Options are: 0 – disable, and 1 – enable.
PwrInLPNomManEn	Scaler	N/A	Enables/disables manual nominal LPS power addition. Options are: 0 – disable, and 1 – enable
PwrInLPOffNomManEn	Scaler	N/A	Enables/disables manual off-nominal LPS power addition. Options are: 0 – disable, and 1 – enable
PwrInHPNomManEn	Scaler	N/A	Enables/disables manual nominal HPS power addition. Options are: 0 – disable, and 1 – enable
PwrInHPOffNomManEn	Scaler	N/A	Enables/disables manual off-nominal HPS power addition. Options are: 0 – disable, and 1 – enable
PwrInLPEMNomManEn	Scaler	N/A	Enables/disables manual nominal LPS EM power addition. Options are: 0 – disable, and 1 – enable
PwrInLPEMOffNomManEn	Scaler	N/A	Enables/disables manual off-nominal LPS EM power addition. Options are: 0 – disable, and 1 – enable
PwrInHPEMNomManEn	Scaler	N/A	Enables/disables manual nominal HPS EM power addition. Options are: 0 – disable, and 1 – enable
PwrInHPEMOffNomManEn	Scaler	N/A	Enables/disables manual off-nominal HPS EM power addition. Options are: 0 – disable, and 1 – enable
PwrInSEMNomManEn	Scaler	N/A	Enables/disables manual nominal sun gear EM power addition. Options are: 0 – disable, and 1 – enable
PwrInSEMOffNomManEn	Scaler	N/A	Enables/disables manual off-nominal sun gear EM power addition. Options are: 0 – disable, and 1 – enable
PwrInREMNomManEn	Scaler	N/A	Enables/disables manual nominal ring gear EM power addition. Options are: 0 – disable, and 1 – enable
PwrInREMOffNomManEn	Scaler	N/A	Enables/disables manual off-nominal ring gear EM power addition. Options are: 0 – disable, and 1 – enable
PwrInCEMNomManEn	Scaler	N/A	Enables/disables manual nominal carrier EM power addition. Options are: 0 – disable, and 1 – enable
PwrInCEMOffNomManEn	Scaler	N/A	Enables/disables manual off-nominal carrier EM power addition. Options are: 0 – disable, and 1 – enable
PwrInPEMNomManEn	Scaler	N/A	Enables/disables manual nominal planet gear EM power addition. Options are: 0 – disable, and 1 – enable
PwrInPEMOffNomManEn	Scaler	N/A	Enables/disables manual off-nominal planet gear EM power addition. Options are: 0 – disable, and 1 – enable
EnLimitStop_Prim	Vector	N/A	29 element vector of 0's and 1's used to disable or enable flags for limit violations of the engine. When enabled, the steady-state model will indicate a violation of the constraint through one of its outputs. The limits are ordered as follows: 1 – maximum HPC exhaust temperature, 2 – maximum turbine inlet temperature, 3 – maximum static HPC discharge temperature, 4 –

			maximum fan speed, 5 – maximum HPS speed, 6 – minimum fuel to air ratio, 7 – minimum fan stall margin, 8 – minimum LPC stall margin, 9 – minimum HPC stall margin, 10 – minimum corrected map fan speed, 11 – maximum corrected map fan speed, 12 – minimum fan r-line, 13 – maximum fan r-line, 14 – minimum corrected map LPC speed, 15 – maximum corrected map LPC speed, 16 – minimum LPC r-line, 17 – maximum LPC r-line, 18 – minimum corrected map HPC speed, 19 – maximum corrected map HPC speed, 20 – minimum HPC r-line, 21 – maximum HPC r-line, 22 – minimum corrected map HPT fan speed, 23 – maximum corrected map HPT fan speed, 24 – minimum map HPT pressure ratio, 25 – maximum map HPT pressure ratio, 26 – minimum corrected map LPT fan speed, 27 – maximum corrected map LPT fan speed, 28 – minimum map LPT pressure ratio, 29 – maximum map LPT pressure ratio
EnLimitStop_VBV	Vector	N/A	2 element vector of 0's and 1's used to disable or enable flags for limit violations of the VBV. The first element corresponds to the minimum VBV value and the second element corresponds to the maximum VBV value. When enabled, the steady-state model will indicate a violation of these constraints through one of its outputs.
EnLimitStop_VAFN	Vector	N/A	2 element vector of 0's and 1's used to disable or enable flags for limit violations of the VAFN. The first element corresponds to the minimum VAFN value and the second element corresponds to the maximum VAFN value. When enabled, the steady-state model will indicate a violation of these constraints through one of its outputs.

E. Outputs and Data Analysis

The outputs of the model are stored within MATLAB time series structures: out_Dyn, out_FANmp, out_LPCmp, out_HPCmp, out_HPTmp, out_LPTmp, out_S0, out_S17, out_S2, out_S21, out_S25, out_S36, out_S4, out_S45, out_S5. These outputs are largely inherited from the original AGTF30 model. The primary output is out_Dyn. Infact, it contains all the information provided by the other outputs. Therefore, this discussion will only focus on out_Dyn to prevent redundancy. Table 2 defines the data contained within the out_Dyn time series structure.

Table 2. Contents of the out_Dyn time series structure

Variable	Units	Description
act.TrqEMC	ft-lb$_f$	Torque applied with the carrier EM. Applicable when MWS.In.Options.EngineEMInt = 2.
act.TrqEMH	ft-lb$_f$	Torque applied with the HPS EM. Applicable when MWS.In.Options.EngineEMInt = 1.
act.TrqEML	ft-lb$_f$	Torque applied with the LPS EM. Applicable when MWS.In.Options.EngineEMInt = 1.
act.TrqEMP	ft-lb$_f$	Torque applied with the planet gear EM. Applicable when MWS.In.Options.EngineEMInt = 2.
act.TrqEMR	ft-lb$_f$	Torque applied with the ring gear EM. Applicable when MWS.In.Options.EngineEMInt = 2.
act.TrqEMS	ft-lb$_f$	Torque applied with the sun gear EM. Applicable when MWS.In.Options.EngineEMInt = 2.
act.VAFNact	in^2	Variable area fan nozzle area.
act.VBVact	frac. open	Variable bleed valve position.

act.Wfact	lb_m/s	Fuel flow rate.
cntrl.Dmd.Wfdmd	lb_m/s	Fuel flow rate command.
cntrl.Dmd.VBVdmd	frac. open	Variable bleed valve command
cntrl.Dmd.VAFNdmd	in^2	Variable area fan nozzle command
cntrl.Dmd.TrqEMLdmd	ft-lb_f	LPS EM torque command
cntrl.Dmd.TrqEMHdmd	ft-lb_f	HPS EM torque command
cntrl.Dmd.TrqEMSdmd	ft-lb_f	Sun gear EM torque command
cntrl.Dmd.TrqEMRdmd	ft-lb_f	Ring gear EM torque command
cntrl.Dmd.TrqEMCdmd	ft-lb_f	Carrier EM torque command
cntrl.Dmd.TrqEMPdmd	ft-lb_f	Planet gear EM torque command
cntrl.Data.N1cMax	rpm	Maximum N1c
cntrl.Data.N1cMin	rpm	Minimum N1c
cntrl.Data.N1cN	unitless	Normalized N1c
cntrl.Data.N1cErr	rpm	N1c error
cntrl.Data.WfMax	lb_m/s	Maximum fuel flow rate
cntrl.Data.WfMin	lb_m/s	Minimum fuel flow rate
cntrl.Data.WfRegNum.N1cSP	-	N1c set-point regulator: 0 – nominal controller, 1 – maximum HPC discharge temperature limiter, 2 – maximum HPT inlet temperature limiter, 3 – maximum inter-turbine temperature limiter, 4 – maximum fan speed limiter, 5 – maximum HPS speed limiter, 6 – maximum static HPC discharge pressure limiter, 7 – minimum static HPC discharge pressure limiter.
cntrl.Data.WfRegNum.Wf	-	Fuel flow regulator: 0 – command from the N1c controller, 1 – maximum fuel flow rate allowed by the acceleration limit logic, 2 – minimum fuel flow rate allowed by the deceleration limit logic, 3 – minimum absolute fuel flow rate.
cntrl.Data.Wf_SP.N1c	rpm	N1c set-point command.
cntrl.Data.Wf_SP.N1cSPLims.T3Max	°R	Maximum HPC discharge temperature limit
cntrl.Data.Wf_SP.N1cSPLims.T4Max	°R	Maximum HPT inlet temperature limit
cntrl.Data.Wf_SP.N1cSPLims.T45Max	°R	Maximum inter-turbine temperature limit
cntrl.Data.Wf_SP.N1cSPLims.N1Max	rpm	Maximum fan speed limit
cntrl.Data.Wf_SP.N1cSPLims.N3Max	rpm	Maximum HPS speed limit
cntrl.Data.Wf_SP.N1cSPLims.Ps3Max	psi	Maximum static HPC discharge pressure limit
cntrl.Data.Wf_SP.N1cSPLims.Ps3Min	psi	Minimum static HPC discharge pressure limit
cntrl.Data.Wf_SP.WfLims.Accel	lb_m/s	Maximum fuel flow rate for accelerations
cntrl.Data.Wf_SP.WfLims.Decel	lb_m/s	Minimum fuel flow rate for decelerations
cntrl.Data.Wf_SP.WfLims.WfMin	lb_m/s	Minimum fuel flow rate
cntrl.Data.EPTsolver.SumPwrErr	hp	An iterative solution method is used to determine the minimum engine power condition for scheduling purposes when EPT is enabled. This is relevant when the VEATE gearbox engine-EM integration method is chosen. This value indicates the sum of the power error from the prior solution to provide a reference point to conclude that a solution has been converged upon.
cntrl.Data.EPTsolver.iter	-	Number of iterations for the EPT solver to converge
cntrl.Data.N1c	rpm	N1c as calculated by the controller based on sensor feedback.
cntrl.Data.Alt	ft	Altitude calculated by the controller based on the ambient pressure.
cntrl.Data.MN	unitless	Mach number inferred by the controller based on the inlet pressure ratio (P2/Pa).

cntrl.Data.PwrInLP	hp	Power input in to the LPS from the EMs at the prior control step.
cntrl.Data.PwrInHP	hp	Power input in to the HPS from the EMs at the prior control step.
eng.Amb	-	Structure with ambient data (Pa – pressure, and Ts – temperature)
eng.S0	-	Structure with flow path data (W-flow rate in lb_m/s, ht-total enthalpy in Btu/lb_m, Tt-total temperature in °R, Pt-total pressure in psi, FAR-fuel to air ratio) at the inlet of the engine
eng.S2	-	Same as eng.S0 except its values are for the fan inlet
eng.S21	-	Same as eng.S0 except its values are for the fan exit
eng.S13	-	Same as eng.S0 except its values are for the fan duct after the splitter
eng.S22	-	Same as eng.S0 except its values are for the core flow after the splitter
eng.S23	-	Same as eng.S0 except its values are for the LPC inlet
eng.S24	-	Same as eng.S0 except its values are for the LPC exit including the VBV
eng.S25	-	Same as eng.S0 except its values are for the exit of a duct downstream of the LPC and VBV
eng.S36	-	Same as eng.S0 except its values are for the HPC exit and it adds to additional parameters: Ps – static pressure (psi), and Ts – static temperature (°R)
eng.S4	-	Same as eng.S0 except its values are for the inlet of the HPT
eng.S45	-	Same as eng.S0 except its values are for the exit of the HPT
eng.S48	-	Same as eng.S0 except its values are for the inlet of the LPT
eng.S5	-	Same as eng.S0 except its values are for the exit of the LPT
eng.S7	-	Same as eng.S0 except its values are for the exit of a duct downstream of the LPT
eng.S17	-	Same as eng.S0 except its values are for the exit of the fan duct upstream of the bypass nozzle.
eng.Shaft.N_Fan	rpm	Fan speed.
eng.Shaft.N_LPC	rpm	LPS speed.
eng.Shaft.N_HPC	rpm	HPS speed.
eng.Shaft.Ndot_LPC	rpm/s	LPS acceleration.
eng.Shaft.Ndot_HPC	rpm/s	HPS acceleration.
eng.SM.SMFan	%	Unscaled stall margin. Same as eng.Data.FAN_Data.SMMap.
eng.SM.SMLPC	%	Unscaled stall margin. Same as eng.Data.LPC_Data.SMMap.
eng.SM.SMHPC	%	Unscaled stall margin. Same as eng.Data.HPC_Data.SMMap.
eng.Perf.Fdrag	lb_f	"Drag" component of the thrust (force due to inlet momentum flux and pressure).
eng.Perf.Fg_Core	lb_f	Gross thrust (force due to exhaust momentum flux and pressure) from the core flow path.
eng.Perf.Fg_Byp	lb_f	Gross thrust from the bypass flow path.
eng.Perf.Fg	lb_f	Total gross thrust.
eng.Perf.Fnet	lb_f	Net thrust (gross – drag)

eng.Perf.TSFC	$(lb_m/hr)/lb_f$	Thrust specific fuel consumption
eng.Data.FAN_Data	-	Data structure with the following information regarding the fan: • SMavail – stall margin with the scaled map (constant flow definition) (%) • s_C_Nc – corrected speed scaler • s_C_Wc – corrected flow rate scaler • s_C_PR – pressure ratio scaler • s_C_Eff – efficiency scaler • Wcin – corrected flow rate at the compressor inlet (lb_m/s) • Nc – corrected rotational speed (rpm) • PR – pressure ratio • NcMap – unscaled corrected rotational speed (rpm) • WcMap – unscaled corrected flow rate (lb_m/s) • PRMap – unscaled pressure ratio • EffMap – unscaled efficiency (%) • SurgePR – stall/surge pressure ratio • Wbleeds – flow rates of any bleeds (lb_m/s) • Pwrb4bleeds – power before the bleeds (hp) • PwrBld – power lost due to the bleeds (hp) • Pwrout – net power on the component by the fluid (hp) • SMMap – stall margin with the unscaled map (constant flow definition) • SPRMap – unscaled stall pressure ratio • Nmech – mechanical rotational speed (rpm) • BlkNm – name of the Simulink block • WHPMod – flow rate modifier • PRHPMod – pressure ratio modifier • EffHPMod – efficiency modifier
eng.Data.LPC_Data	-	Data structure for the LPC. Shares the same structure as eng.Data.FAN_Data.
eng.Data.HPC_Data	-	Data structure for the HPC. Shares the same structure as eng.Data.FAN_Data.
eng.Data.HPT_Data	-	Data structure with the following information regarding the HPT: • s_T_Nc – corrected speed scaler • s_T_Wc – corrected flow rate scaler • s_T_PR – pressure ratio scaler • s_T_Eff – efficiency scaler • Wcin – corrected flow rate at the turbine inlet (lb_m/s) • Wcs1in - corrected flow rate at the turbine inlet but calculated without dividing pressure and temperatures by their respective standard values (lb_m/s) • Nc – corrected rotational speed (rpm) • NcMap – unscaled corrected rotational speed (rpm) • WcMap – unscaled corrected flow rate (lb_m/s) • PRMap – unscaled pressure ratio

		• EffMap – unscaled efficiency (%) • Pwrout – net power on the component by the fluid (hp) • Nmech – mechanical rotational speed (rpm) • BlkNm – name of the Simulink block • WHPMod – flow rate modifier • EffHPMod – efficiency modifier
eng.Data.LPT_Data	-	Data structure for the LPT. Shares the same structure as eng.Data.HPT_Data.
eng.GBData.DEM.N	rpm	Speed of the LPS
eng.GBData.DEM.Nem	rpm	Speed of the HPS
eng.GBData.PGB.Ndot	rpm/s	Acceleration of the planetary gearbox components [sun gear, ring gear, carrier, planet gear].
eng.GBData.PGB.N	rpm	Speeds of the planetary gearbox components [sun gear, ring gear, carrier, planet gear].
eng.GBData.PGB.Nem	rpm	Speeds of the EMs connected to the gearbox components [sun gear, ring gear, carrier, planet gear].
eng.GBData.PGB.Data.fsp	lb_f	Force at each interface of the sun gear and planet gears.
eng.GBData.PGB.Data.fpr	lb_f	Force at each interface of the ring gear and planet gears.
eng.GBData.PGB.Data.fpc	lb_f	Force at each interface of the carrier and planet gear axles.
eng.GBData.PGB.Data.JSeff	slug-ft^2	Effective inertia as seen by the sun gear
eng.GBData.PGB.Data.JReff	slug-ft^2	Effective inertia as seen by the ring gear
eng.GBData.PGB.Data.JCeff	slug-ft^2	Effective inertia as seen by the carrier
eng.GBData.PGB.Data.CTrqSR	unitless	Torque coefficient that relates the impact of torque on the sun gear when 1 unit of torque is applied through the ring gear.
eng.GBData.PGB.Data.CTrqSC	unitless	Torque coefficient that relates the impact of torque on the sun gear when 1 unit of torque is applied through the carrier.
eng.GBData.PGB.Data.CTrqSP	unitless	Torque coefficient that relates the impact of torque on the sun gear when 1 unit of torque is applied through each planet.
eng.GBData.PGB.Data.CTrqRS	unitless	Torque coefficient that relates the impact of torque on the ring gear when 1 unit of torque is applied through the sun gear.
eng.GBData.PGB.Data.CTrqRC	unitless	Torque coefficient that relates the impact of torque on the ring gear when 1 unit of torque is applied through the carrier.
eng.GBData.PGB.Data.CTrqRP	unitless	Torque coefficient that relates the impact of torque on the ring gear when 1 unit of torque is applied through each planet.
eng.GBData.PGB.Data.CTrqCS	unitless	Torque coefficient that relates the impact of torque on the carrier when 1 unit of torque is applied through the sun gear.
eng.GBData.PGB.Data.CTrqCR	unitless	Torque coefficient that relates the impact of torque on the carrier when 1 unit of torque is applied through the ring gear.
eng.GBData.PGB.Data.CTrqCP	unitless	Torque coefficient that relates the impact of torque on the carrier when 1 unit of torque is applied through each planet.
eng.GBData.PGB.Data.NdotErr	rpm/s	Error in the acceleration calculation for the planetary gearbox components using 2 different methods. A small

		error value provides confidence in the validity of the outputs.
in.Alt	ft	Altitude
in.dT	°R	Ambient temperature difference from standard atmosphere
in.MN	unitless	Mach number
in.PExAC	hp	Power extraction for supporting aircraft and engine subsystems. (+ value is a power extraction from the engine)
in.PLA	°	Power lever angle
in.BoostToggle	-	Boost toggle command (0-disable, 1-enable)
in.EPTToggle	-	EPT toggle command (0-disable, 1-enable)
in.ChargingToggle	-	Charging toggle command (0-disable, 1-enable)
in.N1cMan	rpm	Manual fan speed command
in.WfMan	lb_m/s	Manual fuel flow rate command
in.VBVMan	frac. open	Manual variable bleed valve command
in.VAFNMan	in^2	Manual variable area fan nozzle command
in.PwrInLPNomMan	hp	Manual nominal LPS power command
in.PwrInLPOffNomMan	hp	Manual off-nominal LPS power command
in.PwrInHPNomMan	hp	Manual nominal HPS power command
in.PwrInHPOffNomMan	hp	Manual off-nominal HPS power command
in.PwrInLPEMNomMan	hp	Manual nominal LPS EM power command
in.PwrInLPEMOffNomMan	hp	Manual off-nominal LPS EM power command
in.PwrInHPEMNomMan	hp	Manual nominal HPS EM power command
in.PwrInHPEMOffNomMan	hp	Manual off-nominal HPS EM power command
in.PwrInSEMNomMan	hp	Manual nominal sun gear EM power command
in.PwrInSEMOffNomMan	Hp	Manual off-nominal sun gear EM power command
in.PwrInREMNomMan	hp	Manual nominal ring gear EM power command
in.PwrInREMOffNomMan	hp	Manual off-nominal ring gear EM power command
in.PwrInCEMNomMan	hp	Manual nominal carrier EM power command
in.PwrInCEMOffNomMan	hp	Manual off-nominal carrier EM power command
in.PwrInPEMNomMan	hp	Manual nominal planet gear EM power command
in.PwrInPEMOffNomMan	hp	Manual off-nominal planet gear EM power command
sen.P.Pasen	psi	Sensed ambient pressure
sen.P.P2sen	psi	Sensed total pressure at the fan inlet
sen.P.P25sen	psi	Sensed total pressure at the LPC exit
sen.P.Ps3sen	psi	Sensed static pressure at the HPC exit
sen.P.P5sen	psi	Sensed total pressure at the LPT exit
sen.T.T2	°R	Sensed total temperature at the fan inlet
sen.T.T3	°R	Sensed total temperature at the HPC exit
sen.T.T4	°R	Sensed total temperature at the HPT inlet
sen.T.T45	°R	Sensed total temperature at the HPT exit
sen.N.N1sen	rpm	Sensed fan speed
sen.N.N2sen	rpm	Sensed LPC speed
sen.N.N3sen	rpm	Sensed HPC speed
sen.N.NemLsen	rpm	Sensed LPS EM speed
sen.N.NemHsen	rpm	Sensed HPS EM speed
sen.N.NemSsen	rpm	Sensed sun gear EM speed
sen.N.NemRsen	rpm	Sensed ring gear EM speed
sen.N.NemCsen	Rpm	Sensed carrier EM speed
sen.N.NemPsen	rpm	Sensed planet gear EM speed
sen.SOC	%	Sensed state of charge
loop.Solver.Iterations	-	Number of iteration completed by the Newton-Raphsom solver

loop.Solver.Dependents	-	Solver dependents corresponding to the fan, LPC, HPC, HPT, LPT, core nozzle, and bypass nozzle.
loop.Solver.Independents	-	Solver independents [inlet flow rate, HPT pressure ratio, HPC r-line, Fan r-line, BPR, LPC r-line, LPT pressure ratio]
loop.N2int	rpm	LPS speed
loop.N3int	rpm	HPS speed
loop.N2dot	rpm/s	LPS acceleration
loop.N3dot	rpm/s	HPS acceleration
pwrsys.EMLbranch	hp, W, and unitless	5 element vector with the following elements for the LPS EM string: (1) EM mechanical power, hp; (2) EM electrical power, W; (3) inverter/rectifier power, W; (4) EM cable power, W; (5) string efficiency or inverse efficiency (nominally equal to cable power / EM mechanical power), unitless.
pwrsys.EMHbranch	hp, W, and unitless	5 element vector with the following elements for the HPS EM string: (1) EM mechanical power, hp; (2) EM electrical power, W; (3) inverter/rectifier power, W; (4) EM cable power, W; (5) string efficiency or inverse efficiency (nominally equal to cable power / EM mechanical power), unitless.
pwrsys.EMSbranch	hp, W, and unitless	5 element vector with the following elements for the sun gear EM string: (1) EM mechanical power, hp; (2) EM electrical power, W; (3) inverter/rectifier power, W; (4) EM cable power, W; (5) string efficiency or inverse efficiency (nominally equal to cable power / EM mechanical power), unitless.
pwrsys.EMRbranch	hp, W, and unitless	5 element vector with the following elements for the ring gear EM string: (1) EM mechanical power, hp; (2) EM electrical power, W; (3) inverter/rectifier power, W; (4) EM cable power, W; (5) string efficiency or inverse efficiency (nominally equal to cable power / EM mechanical power), unitless.
pwrsys.EMCbranch	hp, W, and unitless	5 element vector with the following elements for the carrier EM string: (1) EM mechanical power, hp; (2) EM electrical power, W; (3) inverter/rectifier power, W; (4) EM cable power, W; (5) string efficiency or inverse efficiency (nominally equal to cable power / EM mechanical power), unitless.
pwrsys.EMPbranch	hp, W, and unitless	5 element vector with the following elements for the planet gear EM string: (1) EM mechanical power, hp; (2) EM electrical power, W; (3) inverter/rectifier power, W; (4) EM cable power, W; (5) string efficiency or inverse efficiency (nominally equal to cable power / EM mechanical power), unitless.
pwrsys.Supplybranch.Bus_Pwr	W	Bus power
pwrsys.Supplybranch.DCDC_Pwr	W	DCDC converter power (energy storage side)
pwrsys.Supplybranch.SuppCable_Pwr	W	Supply cable power (energy storage side)
pwrsys.Supplybranch.ESD_Pwr	W	Energy storage power
pwrsys.Supplybranch.V_Bus	V	Bus voltage
pwrsys.Supplybranch.V_ESD	V	Energy storage device voltage
pwrsys.Supplybranch.I_Bus	A	Bus current
pwrsys.Supplybranch.I_Load	A	Load current
pwrsys.Supplybranch.I_ESD	A	Energy storage device current
pwrsys.SOC	%	State of charge of the energy storage system

VI. Foundations for Advanced Studies

This section seeks to address a few topics that are likely to come up if one is to use the AGTF30-e model extensively for their own research purposes. It will be valuable to start by having an understanding of the model setup process and the setup files. This understanding will help the user to make modification in an appropriate manner. Beyond those basics, several model modification scenarios are foreseen and will be discussed to provide the users with some thoughts to help them begin making those modifications.

A. The Setup Process & Navigating the Setup Files

The "Setup_Simulation.m" function streamlines the model setup process. The function inputs were defined previously in Section IV. Therefore, it is appropriate to move onto the inner workings of the function. To run the function, the user should change the MATLAB working directory to the "AGTF30-e" folder. The "Setup_Simulaiton.m" function is in this folder and the various setup functions and data files it loads is within the structure of the "SimSetup" folder that resides within the "AGTF30-e" folder. When "Setup_Simulation.m" is executed it will add paths to allow MATLAB/Simulink to access files on those paths. The paths include the "Functions" and "SimSetup" folders that reside in the "AGTF30-e" folder. These folders and their subfolders (if applicable) are added to the path. The "Functions" folder includes functions for plotting the compressor and turbine maps. The final directory that is added to the MATLAB path is the "TMATS" folder, which gives MATLAB/Simulink access to all of the T-MATS tools used to construct the model. Once the directories are added, the bus data structure for the model "Eng_Bus.mat" is loaded and assigned into the 'base' workspace. Beyond this, the various setup function found within the "SimSetup" folder are executed to populate the workspace. Lastly the appropriate model file is opened. The entire process is straightforward other than the details of the various setup scripts. Thus, the rest of this sub-section will focus on the setup functions.

The first setup function to be called is "setup_Inputs.m". It's call form is given below.

```
MWS = Setup_Inputs(MWS,inputMethod,In,filename);
```

This function is responsible for assigning the inputs into the structure MWS.In. The inputs include an initialized MWS structure which could be an empty array. The rest of the inputs are shared with the "SetupSimulation.m" function as covered in Section IV.C. The inputs assigned by the function were defined in Table 1. As mentioned prior, there are 2 methods for accomplishing the input value assignment. One can read in the inputs through the excel spreadsheet given by the 'filename' input. The spreadsheet must follow a specific format and an example is given by the file "AGTF30e_Inputs.xlsx". The other method is to load in an input structure 'In', modify it if needed, and feed it into the "Setup_Inputs.m" function. The inputMethod options are 1 for using 'In" and 2 for reading the inputs in through the specified excel file.

The next setup file to be executed is "setup_AllEng.m". This file has the call form shown below.

```
MWS = setup_AllEng(MWS);
```

This function consolidates several of the other setup functions, primarily those that define the parameters of the engine model. A list of the function calls is given below.

```
MWS = setup_FAN(MWS);
MWS = setup_LPC(MWS);
MWS = setup_HPC(MWS);
MWS = setup_HPT(MWS);
MWS = setup_LPT(MWS);
MWS = setup_Duct(MWS);
MWS = setup_Sensor(MWS);
MWS = setup_Actuators(MWS);
MWS = setup_ShaftGB_PwrSys(MWS);
MWS = Setup_EMTAT_EPS(MWS);
```

There is also additional code within the “setup_AllEng.m” file that defines parameters for engine components including the inlet, nozzles, variable bleed valve, fan gearbox, and ducts. It is also where the iDesign setting for the T-MATS model is defined. The iDesign setting should be set to 2 to use the performance map scalers defined in the setup functions. The value can be set to 0 to re-scale the performance maps at a new design point using the steady-state model. The functions “setup_FAN.m”, “setup_LPC.m”, “setup_HPC.m”, setup_HPT.m”, setup_LPT.m” and “setup_Duct.m” add parameters to the workspace for the fan, LPC, HPC, HPT, LPT, and ducts respectively. This includes definition of performance maps, map scalers, pressure losses, and other key parameters. The functions “setup_Sensor.m” and “setup_Actuators.m” define parameters for the sensor and actuator models. This includes parameters that define the sensor and actuator dynamics and limits. The “setup_ShaftGB_PwrSys.m” file consolidates definition of parameters for the engine shafts, gearboxes for the engine-EM integration strategies, and the electrical power system. Important parameters include shaft inertias, gear ratios, and EM and energy storage sizes. These parameters are defined in the same script due to interdependence. Primarily, the gearbox parameters will impact the EM sizing, and both will impact the effective shaft inertias. The “Setup_EMTAT_EPS.m” file will parameterize the EMTAT model of the electrical power system.

Next the controller parameters are added to the workspace through the execution of the “setup_Controller.m” function which has the call form `MWS = setup_Controller(MWS)`. The function defines all control schedules and parameters used by the models control logic. This includes logic for boost, power extraction, EPT, TEEM, charging, the variable bleed valve and variable area fan nozzle, and engine power management. The fuel flow rate control gain schedules are defined to be consistent with the effective shaft inertias determined by the “setup_ShaftGB_PwrSys.m” script.

The final function call is to “setup_initialize.m” which defines the solver settings and initial conditions. It also defines initial conditions needed by the sensor and actuator models as well as the controller and shaft speed integrators. In addition, this file contains the definition of engine limits and steady-state solver targets that were used in the steady-state analysis to define the operating range and steady-state performance of the engine. The function call is shown below.

```
MWS = setup_initialize(MWS,startPt,SSsolverSP);
```

The input ‘startPt’ deterimines how to initialize the mode. A value of 0 will initialize the model for the design point defined in the function file, and any other value will initialize the model using look-up tables created from trim point data. After completing the steady-state analysis, the ‘startPt’ input was hardcoded to 1. The input ‘SSsolverSP’ tells the steady-state model which equation/target to use to drive the model (corrected fan speed, turbine inlet temperature, thrust, etc.).

B. Modifying the Electric Power Inputs and/or EM Size

Theoretically the controller should be robust to changes in the electrical power schedules given that many of the control schedules are functions of shaft power injection/extraction. However, it should be kept in mind that the controller has not been thoroughly tested beyond the power injection/extraction schedules provided with the model. Changes in the power injection/extraction schedules could alter the operating range of the engine and the static operating points along the power range. This would make the RU schedule invalid, and it could be necessary for the user to revert to using the generic acceleration and deceleration logic. Furthermore, it is possible that the engine model could encounter untested scenarios in which the control design could benefit from additional tuning.

C. Modifying the Engine-EM Gearbox Arrangement

When using the VEATE gearbox engine-EM integration option, there could be interest in changing the gearbox design. This could entail changing the relative sizes of the gearbox component, and or the arrangement of the gearbox components relative to the engine shafts. These changes could have implications on the effect of the gearbox through the use of the coupling EM. Given that EM sizing and control logic assumes power injection with the coupling EM will result in added power to the LPS and extracted power form the HPS, this effect should be retained to keep consistency with the control design. In the event that the criteria is not met, the setup function will display a warning. If the condition is not met, a new control strategy, perhaps with new goals, could be required. In addition, the sizing code for the VEATE gearbox EMs may need to be modified.

D. Accounting for Power System and Gearbox Efficiencies

The original AGTF30-e contained a simple model of the electrical power system that enabled the ability to implement non-unity efficiencies. Gearbox efficiencies could also be added fairly easily. However, the original release of the model was not well suited for dealing with losses. Since version 1.1.0, the AGTF30-e can accommodate losses and electrical power system losses have been implemented. However, the model is not guaranteed to work if the power system efficiencies are modified. Therefore, users should keep in mind that modifications to the power system and gearbox efficiencies could require the modifications to the SOC control logic to adequately manage power. It might also be necessary to reassess the sizing of the power system, especially the engine storage device.

E. Changing Control Strategies

If one desires to change the controller, they should take care to understand the implications of removing the control logic that they plan to replace. The user may take advantage of the steady-state model, trim point data (‘data_Trim.mat’), and the linearization model to generate linear models for facilitating control design. It is suggested to run the steady-state model to verify the trim point. Then run the linearization model several times with independent perturbations of the states and inputs in order to form the A, B, C, and D matrices of the linear state-space system.

Changes in the control strategies for the electrified aspects of the propulsion system are largely accounted for in the control schedules. Nominal shaft power injection/extraction. EPT, TEEM, and charge strategies could be modified or replaced. Users are cautioned that power limits for these features should be considered. In other words, there is a limit to home much the EM control inputs can be modified. Regarding the VEATE gearbox engine-EM integration approach, different control strategies could require changes in the model and the setup scripts in order to maintain consistency. This includes consideration of code in the model for implementing the control and code in the “setup_ShaftGB_PwrSys.m” file for sizing the EMs and determining the component inertias.

VII. Verification

The model was verified to provide realistic and trustworthy results in a number of ways. First, it is built upon the AGTF30, which went through its own verification process. The AGTF30-e, without electrification options enabled, and with the same nominal shaft power extraction as the AGTF30, was verified to match the AGTF30 performance at key operating points such as full power sea level static and cruise operating points. Having built confidence that the AGTF30-e matches the performance of the AGTF30 under the same conditions, the focus was turned to verification with the additional features of the AGTF30-e. For the engine model itself, this boiled down to verifying operation with power injection/extraction on the engine shafts with both engine-EM integration options. In addition, the controller was verified to operate as expected. The remainder of this section will discuss some of the steps taken to verify the model so that users can have confidence. This section is not a comprehensive documentation of the verification effort, but instead is aimed at providing enough evidence to promote user trust.

Evidence was acquired through simulation to help verify correct implementation of power injection and extraction. To start, model matching with the AGTF30 for a nominal power extraction from the LPS of 350hp was verified. To expand confidence in the model, a range of power injection and extraction (+/-350hp from nominal) was applied to both shafts for both the AGTF30 and AGTF30-e. Matching was verified. Given that the AGTF30 is a trusted software package that accurately captures this effect through assignment of the shaft power extraction parameters, this

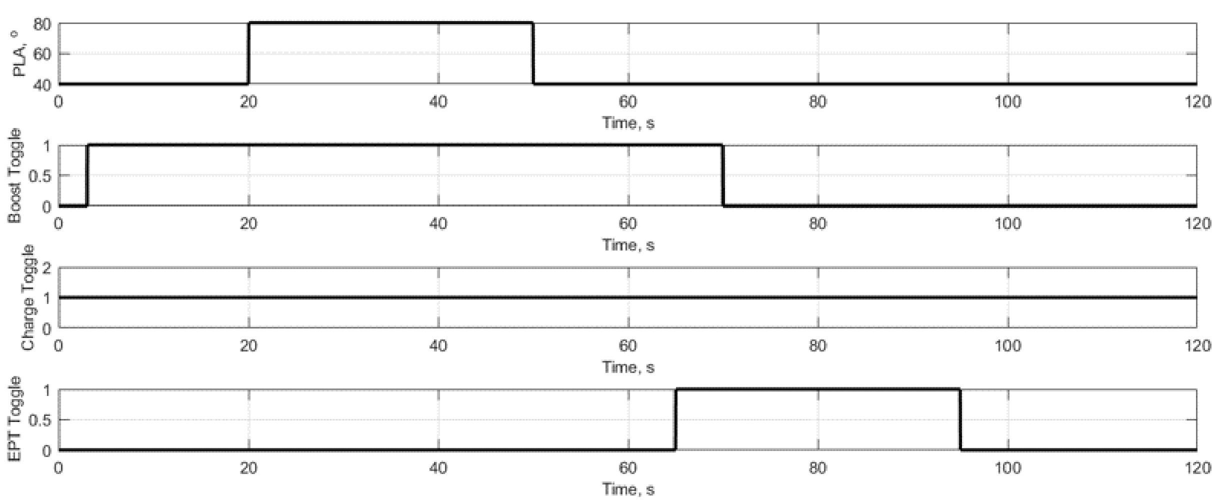

Figure 9. Input profile for test cases

comparison was seen as sufficient to generate confidence in this model feature. Furthermore, the implementation of the power injection/extraction is rather simple and straight-forward, making the possibility of making an error rather small. The additional torque applied to the mechanical component is simply included in the sum of torques used to compute the acceleration of that component.

The DEM engine-EM integration approach was verified by comparing results with power injection/extraction through the EMs with a manual input that goes directly to the shafts. With the DEM method verified, it could then be used to verify the results with the VEATE option. The VEATE option should achieve the same (or very similar) results as the DEM approach, but with different EM inputs. Said another way, the EMs in the VEATE option will be used differently but will result in the same (or very similar) power injection/extraction on the engine shafts, which will result in the same (or very similar) engine performance. Simulation results are shown for a sea level static simulation scenario with the input profiles plotted in Fig. 9. Figure 10-16 shows a set of plots that demonstrate the very different use of EMs for the DEM approach and VEATE approach, and yet the impact on the engine is the same, as predicted. The plots show the following parameters:

- Figure 10: EM torques (τ) and powers (P) (LPS EM and HPS EM have subscripts "L" and "H" respectively)
- Figure 11: EM torques (τ) and powers (P) (subscripts: "S" – sun gear, "R" – ring gear, "C" – carrier, "P" – planet gear)
- Figure 12: fuel flow rate (w_f), variable bleed valve (VBV), variable area fan nozzle area (VAFN)
- Figure 13: corrected fan speed (N_{1c}), thrust (F_n), and thrust specific fuel consumption (TSFC)

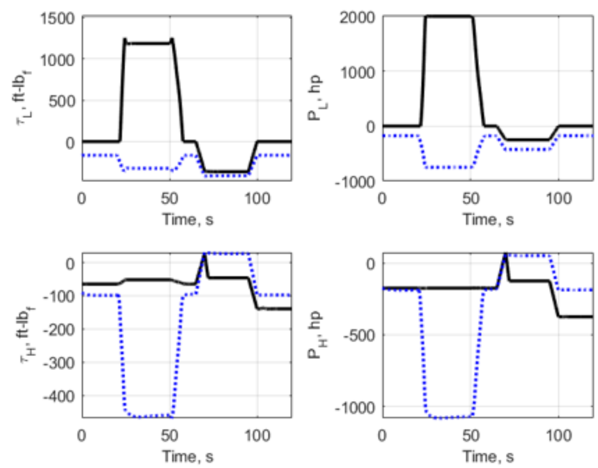

Figure 10. DEM-VEATE matching: DEM EM

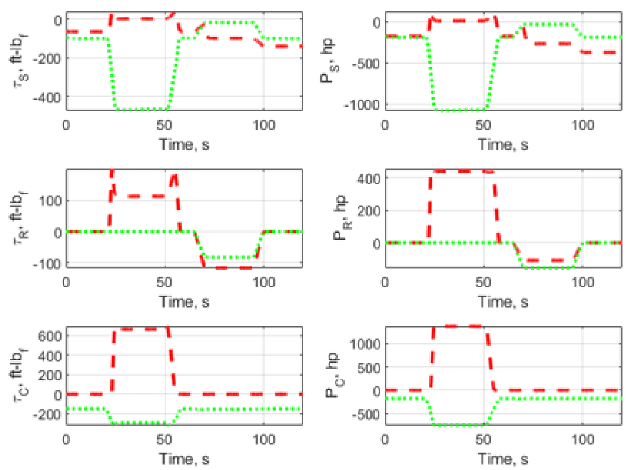

Figure 11. DEM-VEATE matching: VEATE PGB EM

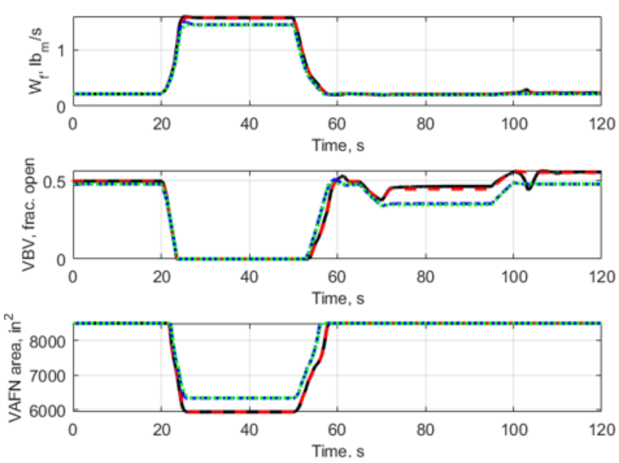

Figure 12. DEM-VEATE matching: Engine actuator inputs.

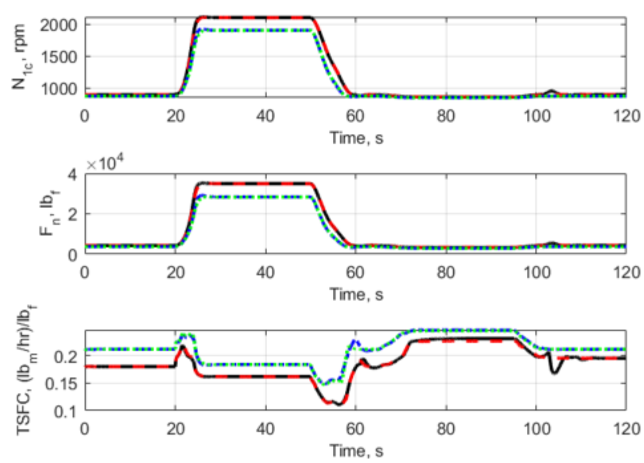

Figure 13. DEM-VEATE matching: corrected fan speed, thrust, and TSFC.

- Figure 14: fan speed (N_1), LPS speed (N_2), and HPS speed (N_3)
- Figure 15: stall margins
- Figure 16: turbomachinery performance maps and running lines

In the plots, the lines are represented as follows:

- Solid black: boost with DEM approach
- Dashed red: boost with VEATE PGB approach
- Dotted blue: PEx with DEM approach
- Dashed-dotted green: PEx with VEATE PGB approach

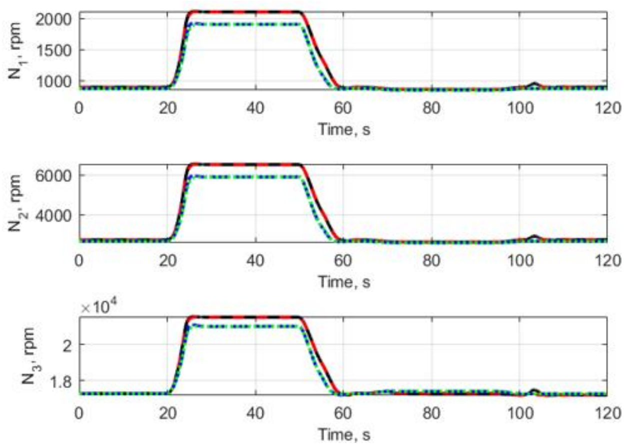

Figure 14. DEM-VEATE matching: engine shaft speeds.

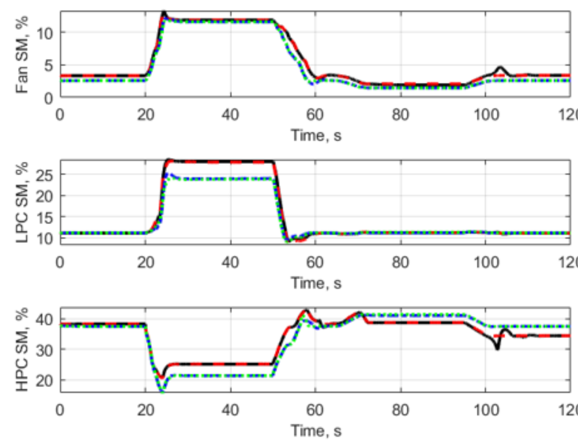

Figure 15. DEM-VEATE matching: stall margins.

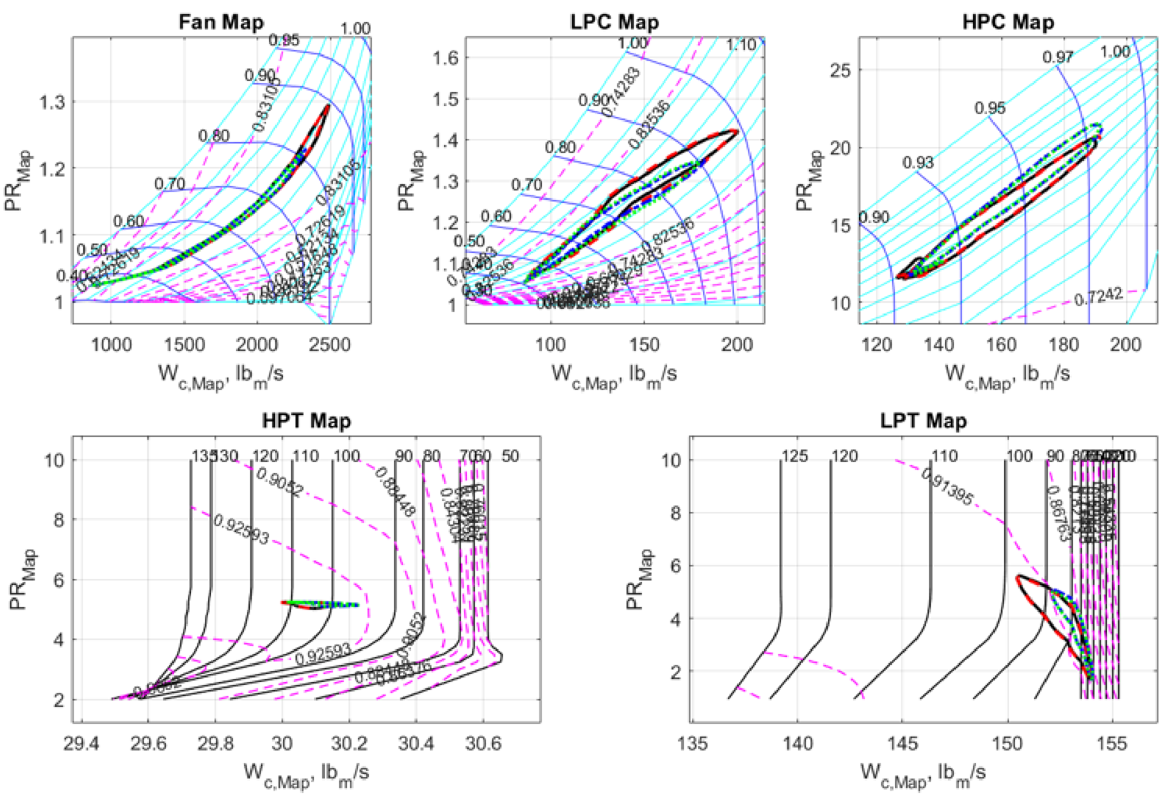

Figure 16. DEM-VEATE matching: turbomachinery performance maps

Power system losses were enabled, TEEM was disabled, and the RU transient limiter option was used to produce this set of results. The results demonstrate essentially the same engine performance for the DEM and VEATE approaches despite the different electric machine inputs. The matching serves as evidence that the effect of the planetary gearbox was modeled correctly and that the effect is understood. By extension, the control approach taken to adapt for the planetary gearbox is verified. Another layer of verification is done at the level of the planetary VEATE gearbox model. The gearbox model performs the calculation of the gearbox component accelerations 2 different ways. The error between the results of those methods is output so that the user can use the results with more confidence. A very low error indicates a low probability of having made a mathematical error in the implementation of the equations used in the calculation.

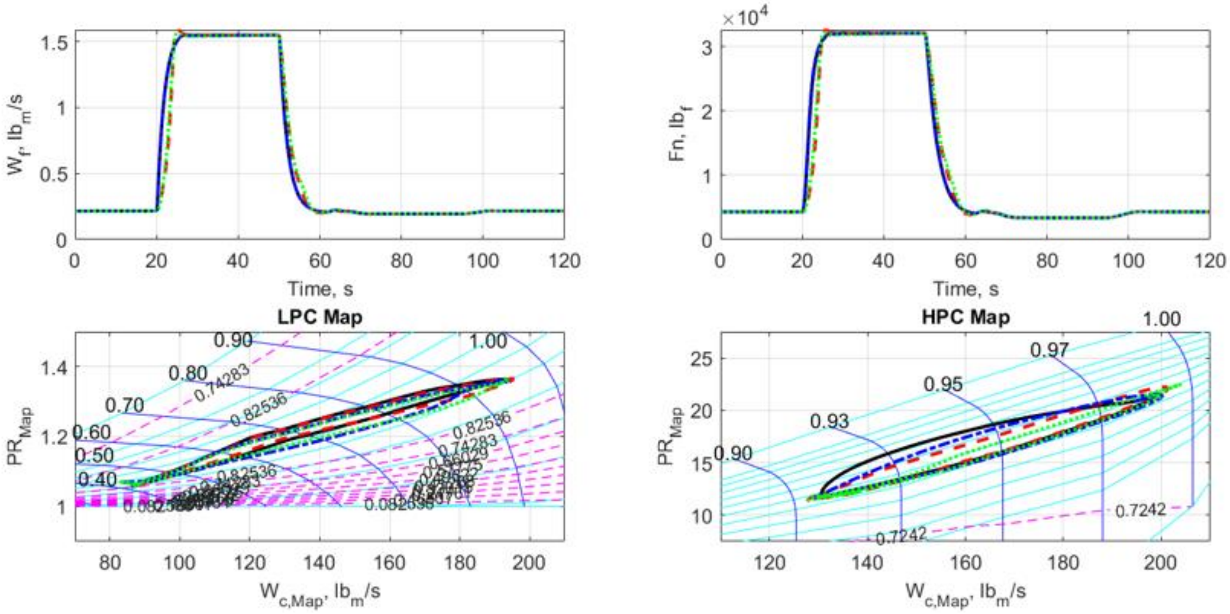

Figure 17. Results with the standard engine and the DEM option

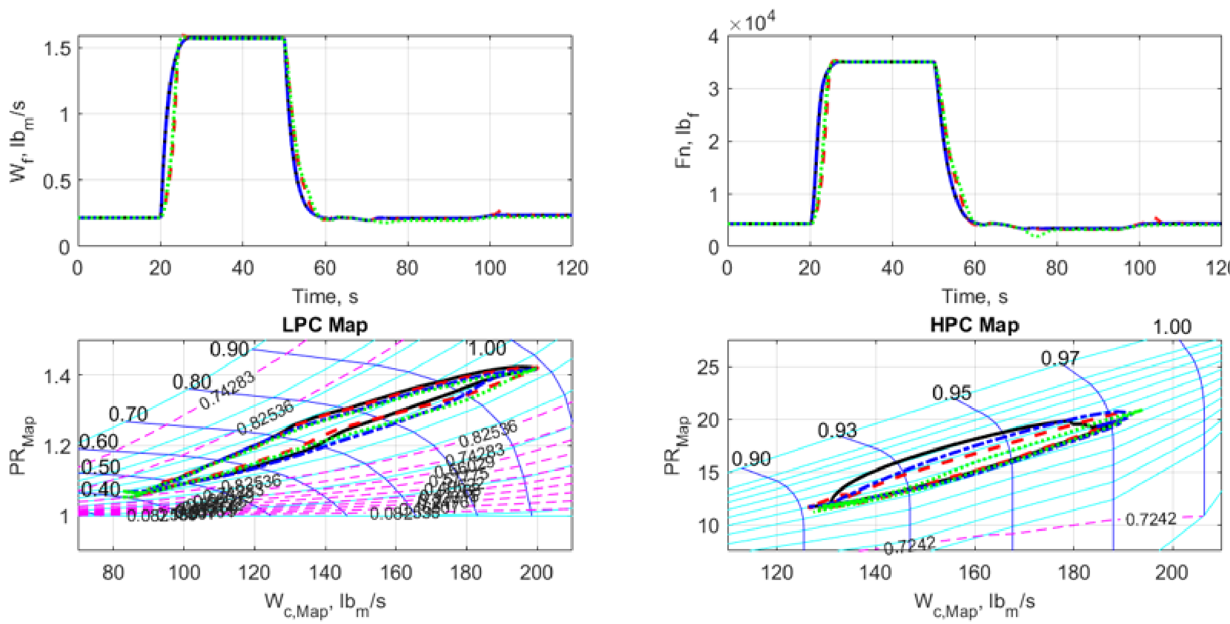

Figure 18. Results with boost and the DEM option

The engine model and controller combinations were verified through testing the model with all combinations of settings with the input profiles shown in Fig. 9. This test scenario exercises the boost, EPT, and charging features as applicable. It also demonstrates steady-state operation at idle and full power. Finally, a rapid acceleration and deceleration demonstrates transient capabilities and operation over the power range. The simulations were repeated for all the altitude and Mach number combinations noted in Fig. 3 with “x’s”. Figure 17 - 19 show examples of the successful operation of the model and controller at sea level static conditions with the DEM engine-EM integration approach. For brevity, only a subset of plots is shown for each case. The plots include the fuel flow rate, thrust, LPC map, and HPC map. Each collection of plots corresponds to each of the 3 primary modes of operation: standard engine, boost, and PEx. Each plot has 4 lines that are represented as follows:

- Solid black: generic transient limit logic without TEEM
- Dashed red: RU schedule without TEEM
- Dotted blue: generic transient limit logic with TEEM
- Dash-dotted green: RU schedule with TEEM

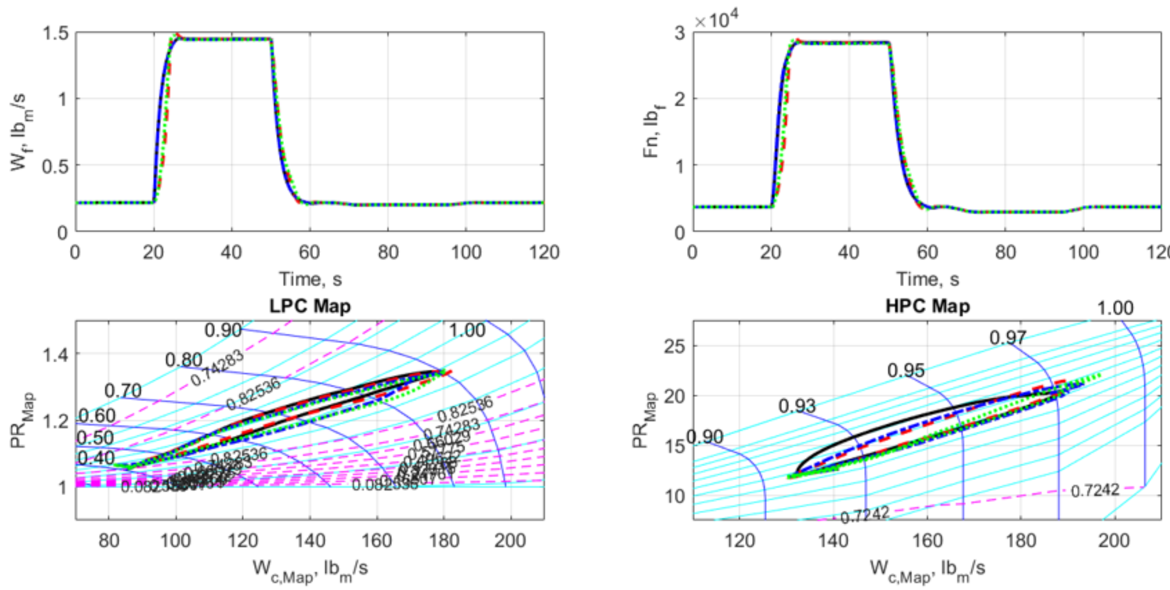

Figure 19. Results with PEx and the DEM option

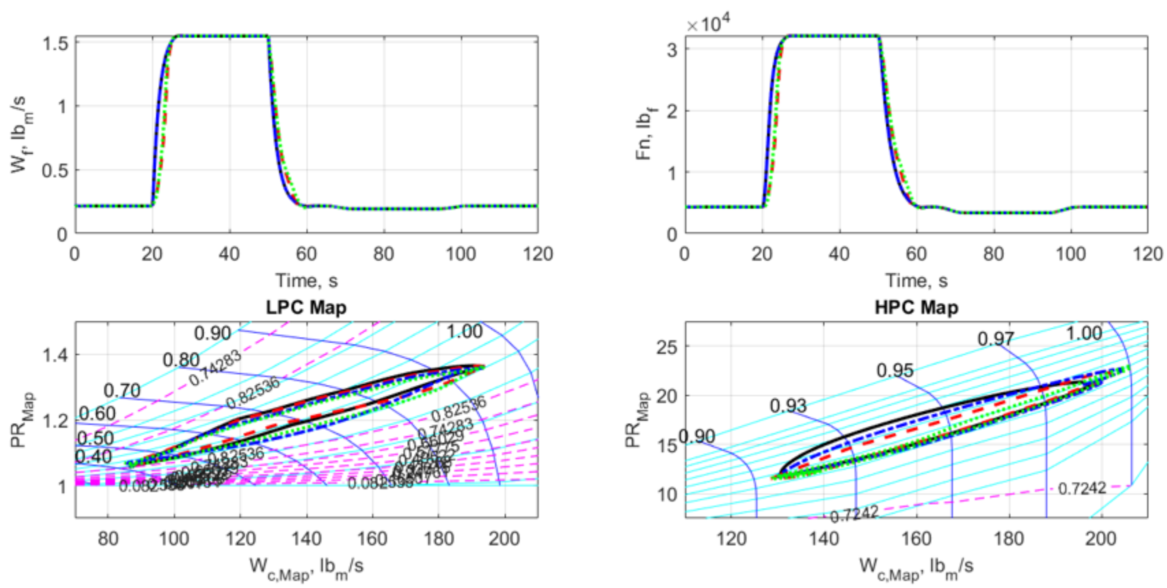

Figure 20. Results with the standard engine and the VEATE option

The same set of plots is shown in Fig 20 - 22 for the VEATE engine-EM integration approach. Similar results can be shown for all other test conditions indicated in Fig. 3. The results demonstrate representative propulsion system performance over a vast range of conditions with a variety of model options.

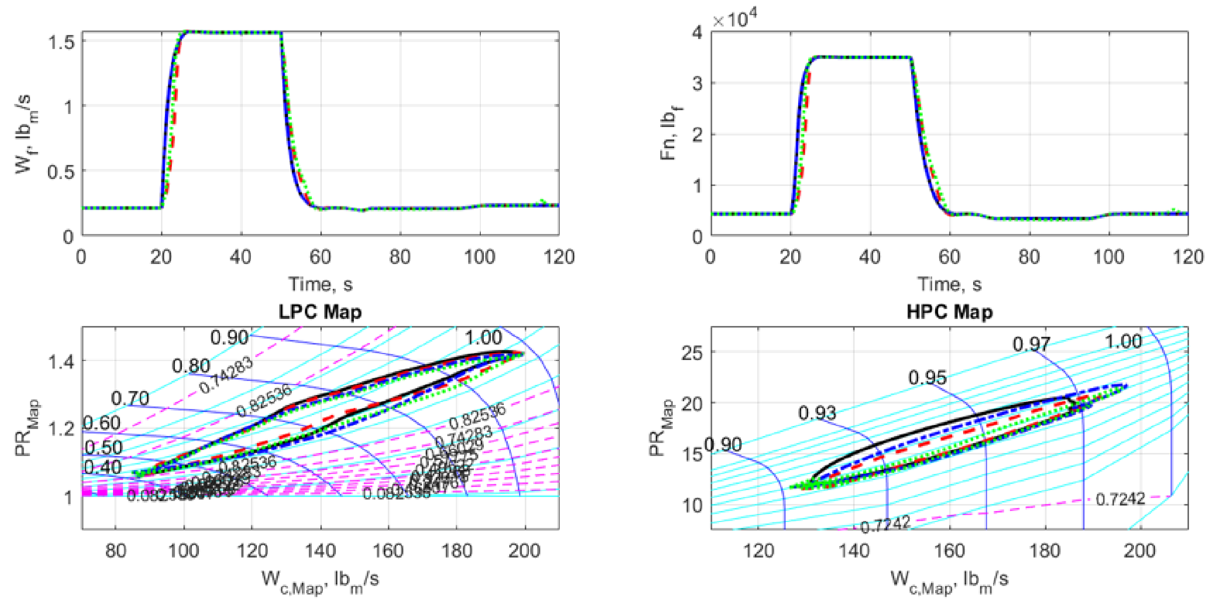

Figure 21. Results with boost and the VEATE option

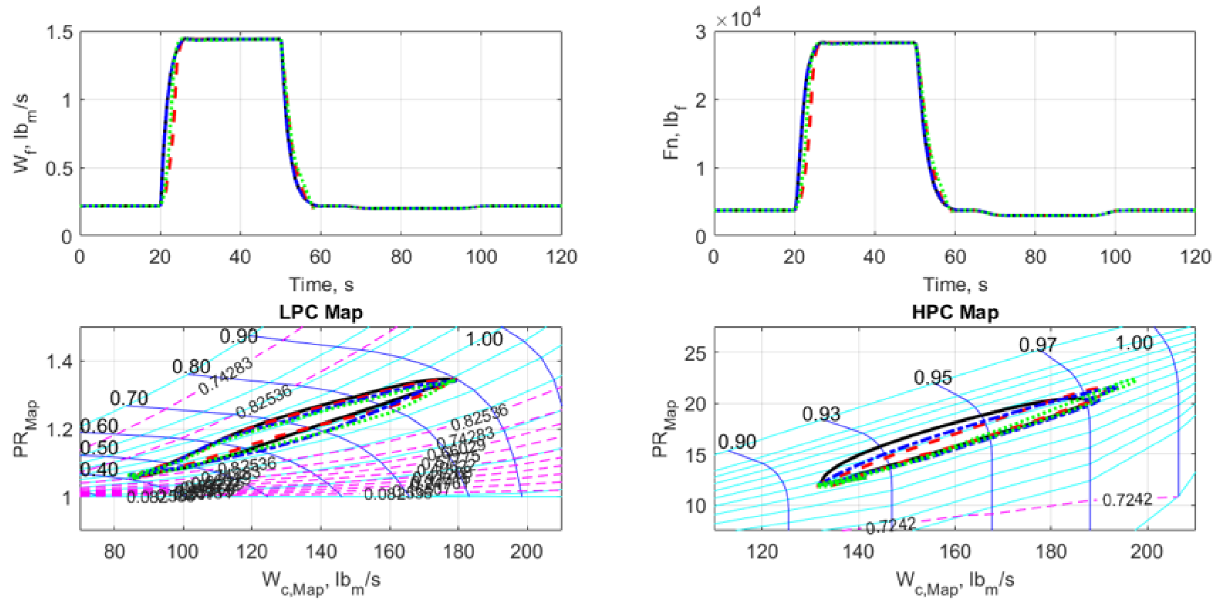

Figure 22. Results with PEx and the VEATE option

Use the results consistent with the test cases shown in Fig. 17, the SOC regulation is demonstrated in Fig 23 to illustrate that the control logic is sufficient to charge the energy storage system and regulate the power such that a desired SOC is maintained. Finally, a closer look is given to the EPT matching. Fig. 24 demonstrates, for standard engine use-case, that the minimum fuel flow rate reached during EPT operation is the same for the DEM (solid black line) and VEATE approach (dashed red line), yet it is noted that the VEATE approach utilizes the EMs substantially less.

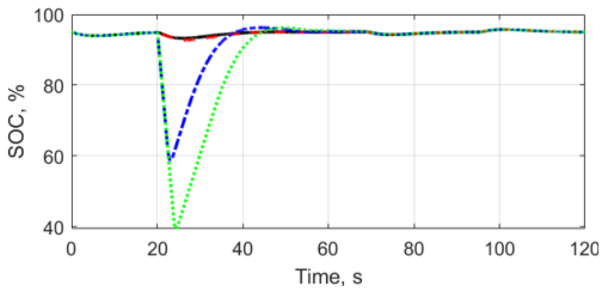

Figure 23. Illustration of SOC regulation with the standard engine.

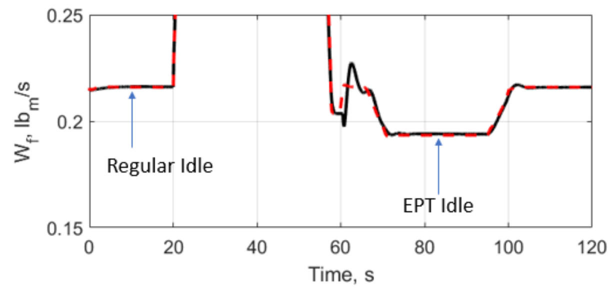

Figure 24. Comparison of the fuel flow rate during EPT operation for the standard engine.

Acknowledgments

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