

I. Vehicle Systems Efficiency Improvements

I.1.A. Cummins MD&HD Accessory Hybridization CRADA (Task 1000349.00)

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I.1.A.1. Abstract

Objectives:

- Analytically verify novel heavy truck accessory hybridization and electrification approaches, and experimentally validate prototype hardware utilizing the ORNL Vehicle Systems Integration (VSI) Laboratory's component test cell and Cummins' test vehicle.
- Develop and validate medium/heavy duty accessory models by means of data collection on a test vehicle and extraction from Cummins' preexisting models.
- Using the project's generated models and market research, choose and develop an electric or hybrid architecture and controls for one or more accessories depending on fuel consumption reduction and perceived market acceptability.
- Integrate the conventional system and chosen prototype architecture in the component lab for system testing and controls development. This culmination, allows for good comparison of the two systems utilizing the repeatability of the lab environment.
- Add finished system to one of Cummins test vehicles for a proof of concept test.

Accomplishments:

- Typical vehicle level models use a "lumped" mechanical and electrical accessory structure that is not detailed enough to represent dynamic accessory behavior. ORNL has integrated Cummins' accessory models into Autonomie's vehicle architecture to capture these behaviors at a vehicle level.
- Using test vehicle data the power steering model has been validated within the acceptable system assumptions.
- Exercised three different vehicles to determine which vehicle application would have the most impact of fuel consumption: a MD pickup/delivery truck, an HD class 8 bus, and an HD class 8 line haul sleeper cab.
- Validated the class 8 line haul sleeper cab to be accurate within 5% of a chassis tested vehicle.
- Using results from the simulation study as well as data from literature reviews, the CRADA team was able to determine that while line haul sleeper cabs made the smallest impact with hybrid accessories

for driving when compared to MD, P&D, or HD bus, they made the biggest impact when looking into idle mitigation and overnight hotel loads.

- Based on the findings from the literature review and simulation study ORNL proposed and designed a hybrid Auxiliary Power Unit (h-APU) architecture that would allow for hybridization for the air conditioning, electrification of the condenser fans, and energy storage for other electrical hotel loads. This allows for the truck to eliminate or greatly reduce all over night idling by providing hotel loads from a battery pack that utilizes regenerative braking for charging.
- The baseline controls and system architecture have been designed and implemented in Autonomie for further testing and controls development.
- Two possible architectures were chosen and designed for driving the A/C compressor. One is a hybrid system which continues to utilize the existing compressor and the other being a fully electric compressor system.
- Two out of the three lab testing setups have been completed; the conventional and hybrid systems.
- Providing NREL with the proper resources, they have developed a baseline CoolSim Quasi-Transient air conditioning model that can be used with both the simulation portion of the project as well as the Hardware-In-the-Loop (HIL) portion of the project. This will provide a much needed high fidelity model for use in future simulation studies as well as controls development.

Future Achievements:

- Using the data generated in ORNL's VSI Laboratory NREL will improve and validate their baseline model to provide even better accuracy for future use.
- ORNL will test the second compressor architecture that will allow Cummins to make a more educated test if the prototype system were to be chosen for commercialization.
- Cummins is currently testing the proposed h-APU system, providing a proof of concept for all of the work done by simulation and in the component test cell.

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I.1.A.2. Technical Discussion

Background

Medium and heavy duty trucks are a growing market and integral part of our society. From the home delivery of goods by medium duty trucks to the freight hauling of heavy duty line haul trucks, they are the main source of material and goods transport. Due to these trends, there is an overwhelming need to quickly address key problems with excess fuel usage and emissions production of these diesel vehicles.

Modern trucks have become much more advanced in terms of engine, aftertreatment, and transmission technologies which greatly reduced both fuel consumption and emissions. Due to these improvements, focus of truck OEMs has shifted to start looking at what other aspects of MD and HD trucks can be impacted by advanced technologies.

Introduction

There are many areas of MD and HD vehicles that can be improved by new technologies and optimized control strategies. Component optimization and idle reduction need to be addressed, this is best done by a two part approach that includes selecting the best component technology, and/or architecture, and optimized controls that are vehicle focused. While this is a common focus in the light duty industry it has been gaining momentum in the MD and HD market as the market gets more competitive and the regulations become more stringent.

When looking into systems optimization and idle reduction technologies, affected vehicle systems must first be considered, and if possible included in the new architecture to get the most benefit out of these new

capabilities. Typically, when looking into idle reduction or component optimization for MD/HD, the vehicle's accessories become a prime candidate for electrification or hybridization. While this has already been studied on light duty vehicles (especially on hybrids and electric vehicles) it has not made any head way or market penetration in most MD and HD applications. If hybrids and electric MD and HD vehicles begin to break into the market this would be a necessary step into the ability to make those vehicles successful by allowing for independent, optimized operation separate from the engine.

Approach

ORNL and Cummins began this project by discussing which approach would be most successful in reducing fuel consumption, but also which approach would gain acceptance by the market to enable this technology to penetrate the market more quickly. A two phased approach was selected due to ORNL's test cell capabilities and Cummins market resources and access to a test vehicle for data and proof of concept test.

The first phase is a modeling/simulation/data collection and market study phase that is focused on determining, which accessories would be feasible to hybridized/electrify, what accessories have fuel consumption benefits if hybridized/electrify, the ideal vehicle application which would benefit most from these new technologies, and what architecture on the selected vehicle type would have the most impact on fuel consumption.

Phase one of the project started by collecting all of the data and resources ORNL and Cummins had to begin the modeling and simulation. Cummins was able to supply base models for the four major accessories that the project would be addressing: the engine's cooling fan, the vehicle air conditioning system, the power steering system, and the vehicle's air compressor and air brake system. ORNL opted to use Argonne National Laboratory's Autonomie as the platform for simulation work on a vehicle level.

The first change to model was to switch the Autonomie accessory model structure from a "lumped" accessory structure (Figure 1) to a separated accessory structure (Figure 2) in order to capture all of the dynamic behaviors of each accessory and how those behaviors change based on vehicle type and drive cycle variability.

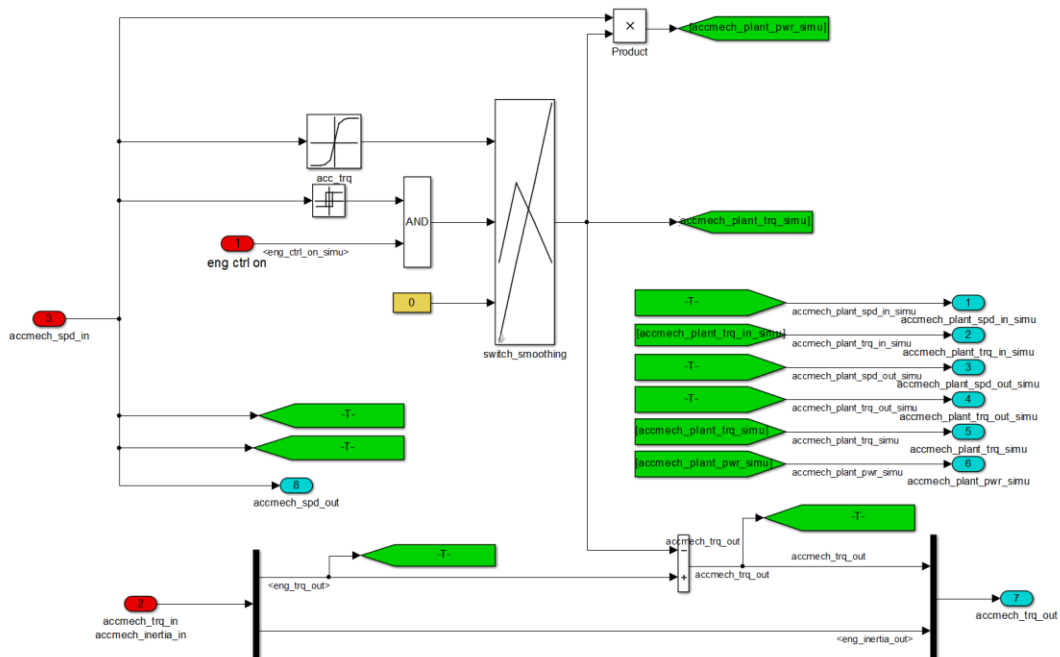


Figure I-1: Original Autonomie "lumped" mechanical accessory model.

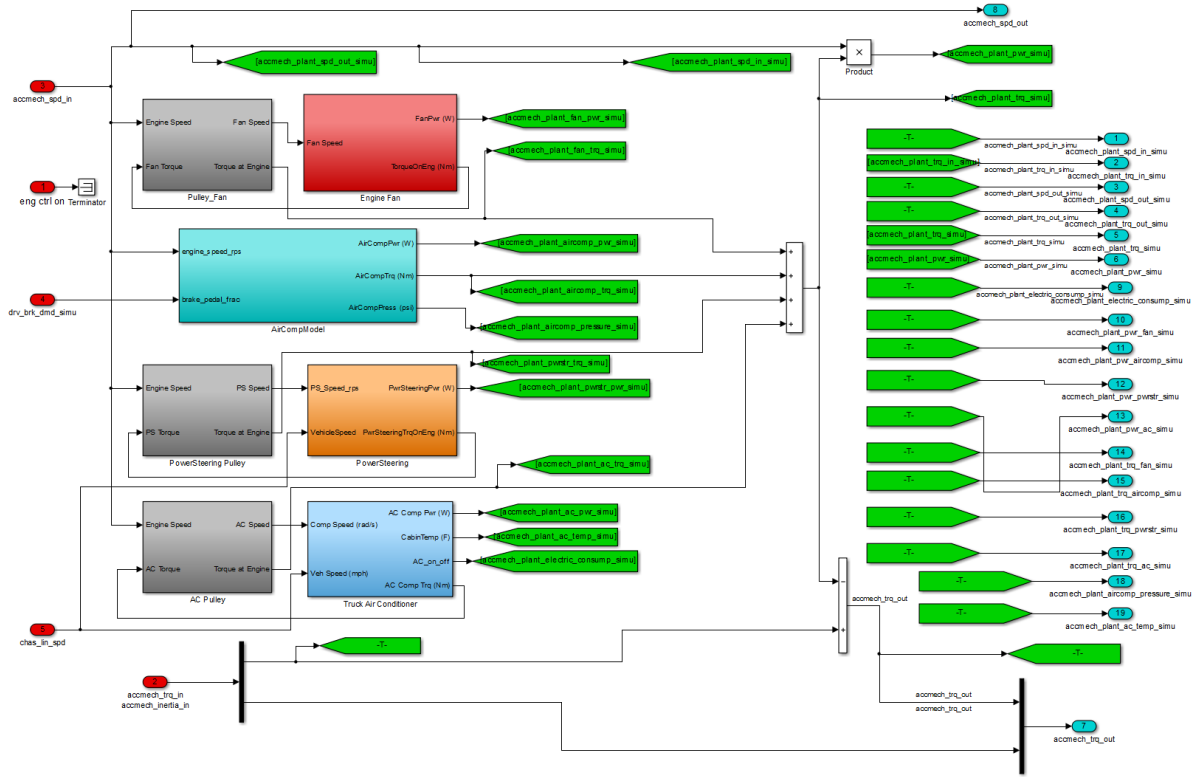


Figure I-2: Separated accessory models. (cooling fan, air compressor, power steering, air conditioning, and electrical accessories)

Several vehicle types were considered but ultimately class 8 line haul (LH) sleeper cabin trucks were chosen as the project's focus. This vehicle was assessed due to its overwhelming market size and total amount of fuel consumed per year compared to the other two vehicles. Additionally, sleeper cabs spend a large amount of time idling, especially during the driver's overnight hoteling in the warm months of the year. ORNL had access to parameters and data on this vehicle type. The engine and transmission for this vehicle has been tested in ORNL's VSI lab as well as had access to vehicle parameters for a Kenworth T700 to further increase the fidelity of this vehicle model (Figure 3).

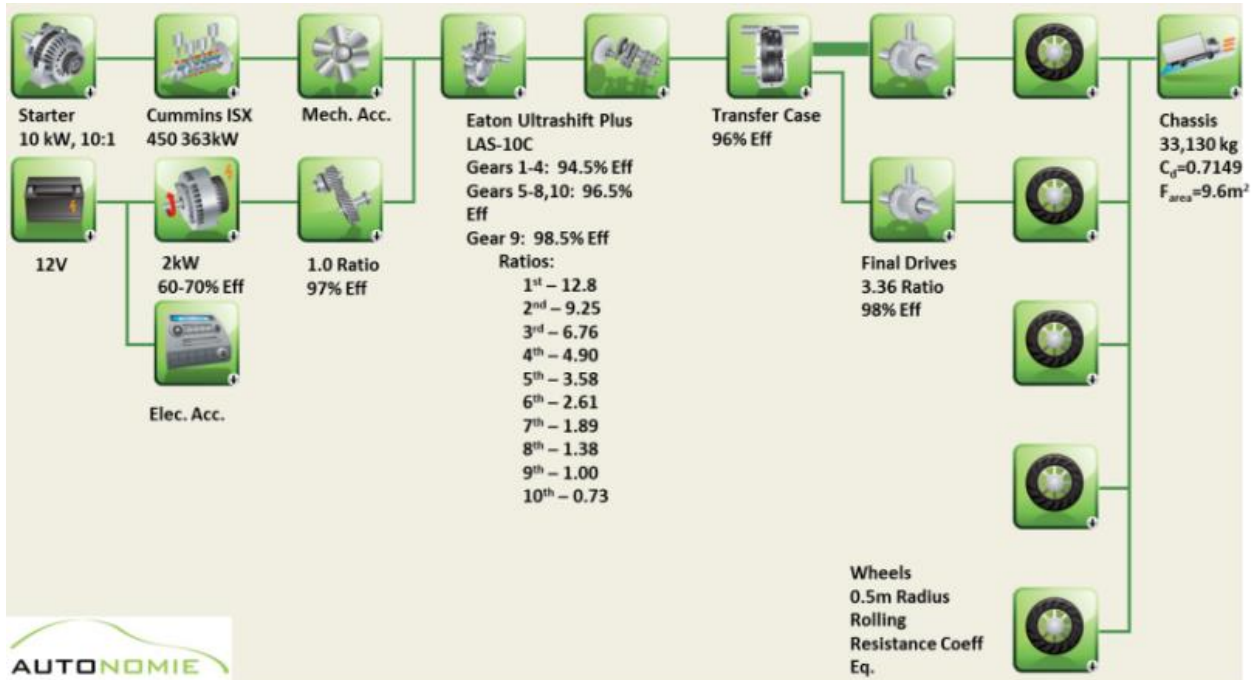


Figure I-3: HD class 8 line haul sleeper cab based on a chassis tested Kenworth T700.

The second phase of the project is prototype development and component/vehicle testing phase which will be used to: validate the developed component and vehicle models, develop and build a prototype system based on simulation findings, create and test prototype controls in ORNL's VSI component test cell using HIL practices, and test the finished system in Cummins test vehicle for a final system proof of concept.

In order further develop and validate the accessory and vehicle models, Cummins was able to leverage a test vehicle from another project in order to instrument the accessories and get real world data from most of the accessories. After analyzing the data and making the HVAC system, the main focus of this project the team decided that testing the components of that system in a test cell would both help NREL further develop their CoolSim model, but also allows to more accurately compare the two different compressors chosen for the h-APU architecture. The first setup (figure 4) tested is the conventional setup in the truck with the condenser changed to a remote setup allowing the fan to be electrified.

• **Instrumentation**

- 1-4: Pressure and Temperature
- 5: Mass Flow of Refrigerant
- 6: Delta Pressure and Temperature
- 7-8: Speed and Airflow from HVAC Boxes

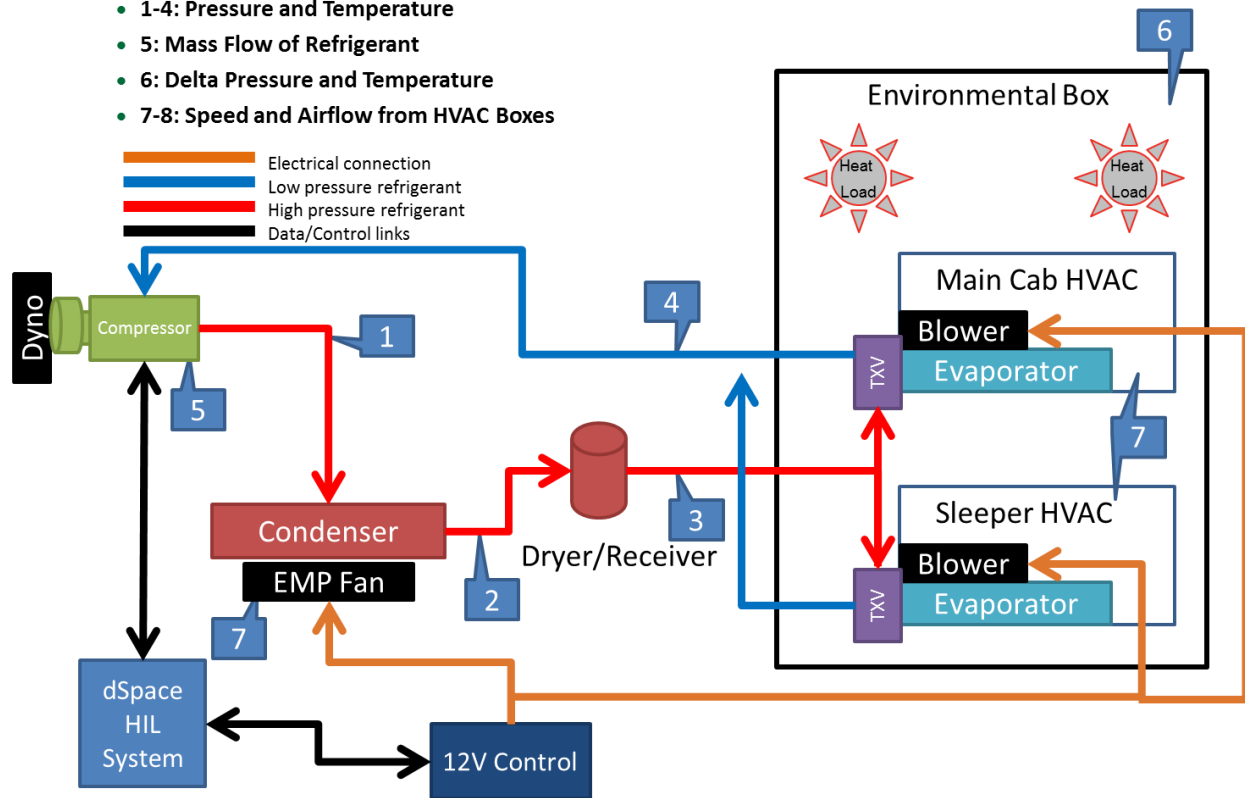


Figure I-4: First component test cell setup. Conventional sleeper cab setup with electrified condenser fan.

The second setup (figure 5) looks at replacing the conventional A/C compressor with an electrified unit that was supplied by Masterflux. It was essential to achieve the same cooling capacity as the conventional system at certain operating points, so the electric compressor is sized to achieve those selected points. Using two Hioki power analyzers we can characterize both the mechanical and electrical power/efficiency differences between the two systems. This will allow the team to make a choice of which setup best serves the finalized h-APU prototype.

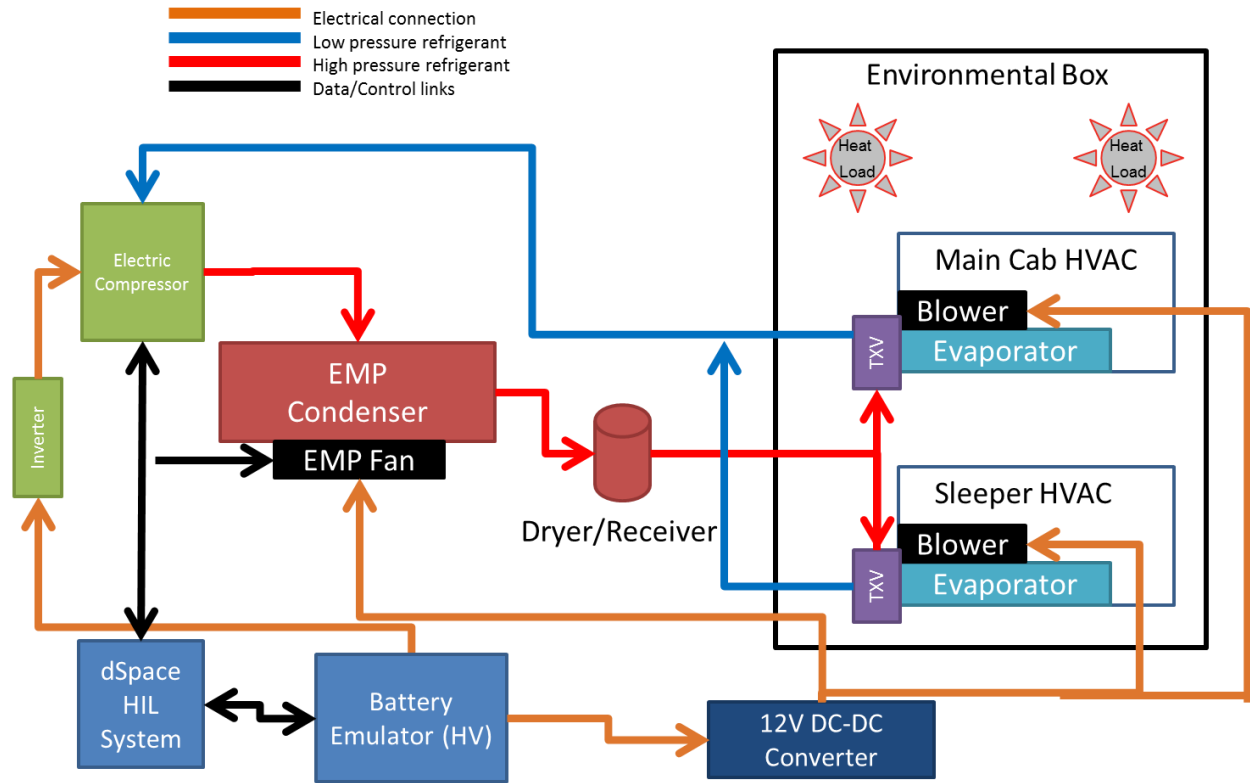


Figure I-5: Second component test cell setup. Electrified compressor with electrified condenser fan.

While phase two is mostly complete, the specifics of the prototype h-APU architecture, its other components, and results are protected under the CRADA agreement.

Results

The on road portion of the vehicle utilization is only one factor that has to be taken into account when looking at accessory hybridization or electrification. When examining the amount of fuel burned during overnight hoteling in a sleeper cab, researchers found that the amount of fuel consumed was larger than any other application for saving during the on road entitlement studies.

An idling line haul truck consumes between 0.4-0.88 gallons an hour. Required driver rest period is at least 10 hours which translates into 4-9 gallons consumed during idling not including idling that might incur during freight drop-off and pick up, an extended period of time at distribution hubs could also be a factor. Cummins and ORNL have chosen and developed an architecture which allows for idle reduction or elimination during these distribution hub times as well as overnight idling.

Table I-1: Accessory entitlements for the Cummins Proprietary Cycle (HD class 8 line haul sleeper cabin)

Fuel Consumption Entitlements	
Data	Fuel Consumption % Decrease
A/C	0.123
Power Steering	0.438
Brake Air Compressor	0.282
Cooling Fan	0.344

With the A/C and hotel loads being the focus for idle reduction, a full mockup of a typical class 8 sleeper cabs HVAC system was installed into ORNL's VSI Component Laboratory (figure 6). This lab is equipped to be able to control temperature up to 105° F and has an E-Storage emulator that can both supply power to electric test components, but also emulate the types of energy storages that the system may use.



Figure I-6: ORNL's VSI Component test cell. Open configuration.

Two setups were used to test the different components. One setup with all of the A/C components was open to the ambient air of the test cell and the other used an insulated box to isolate the evaporator boxes from the ambient temperature of the test cell (figure 7). During the first setup we are able to simulate pull down conditions within the truck; this was performed at the temperature set points of 105°F, 90° F, and 75°F. Regarding the second set of tests (using the insulated box) the focus was on finding the maximum cooling capacity of each system setup, and to test temperature regulation controls to find which strategy was the most efficient. In order to test the cooling capacity of the system at different operating points the ambient temperature was set to either 105°F or 90°F and the system is set to maintain 70°F inside the insulated box. A set of fans with known volumetric flows introduces hot ambient air into the box until the system is just able to maintain the desired 70° F, this allows for the calculation of how much heat load is being introduced into the system providing the cooling capacity at that operating point.



Figure I-7: ORNL's VSI Component test cell with insulated environmental box.

With the conventional system and remote condenser systems tested ORNL was able to provide NREL with all of the HVAC components geometries, volumes, and other specs to build a baseline system in their CoolSim model. As more data is provided to NREL they will continue to validate and adapt the model to be used in both future simulations as well as providing us an Autonomie compatible model that is to be used in our HIL testing (figure 8). This baseline model being developed with this project will be available for public use once a few proprietary parameters are removed and generic ones take their place. Ultimately the CoolSim model will be an invaluable tool once validated to perform offline simulations of the h-APU system engine controls on our selected and validated system.

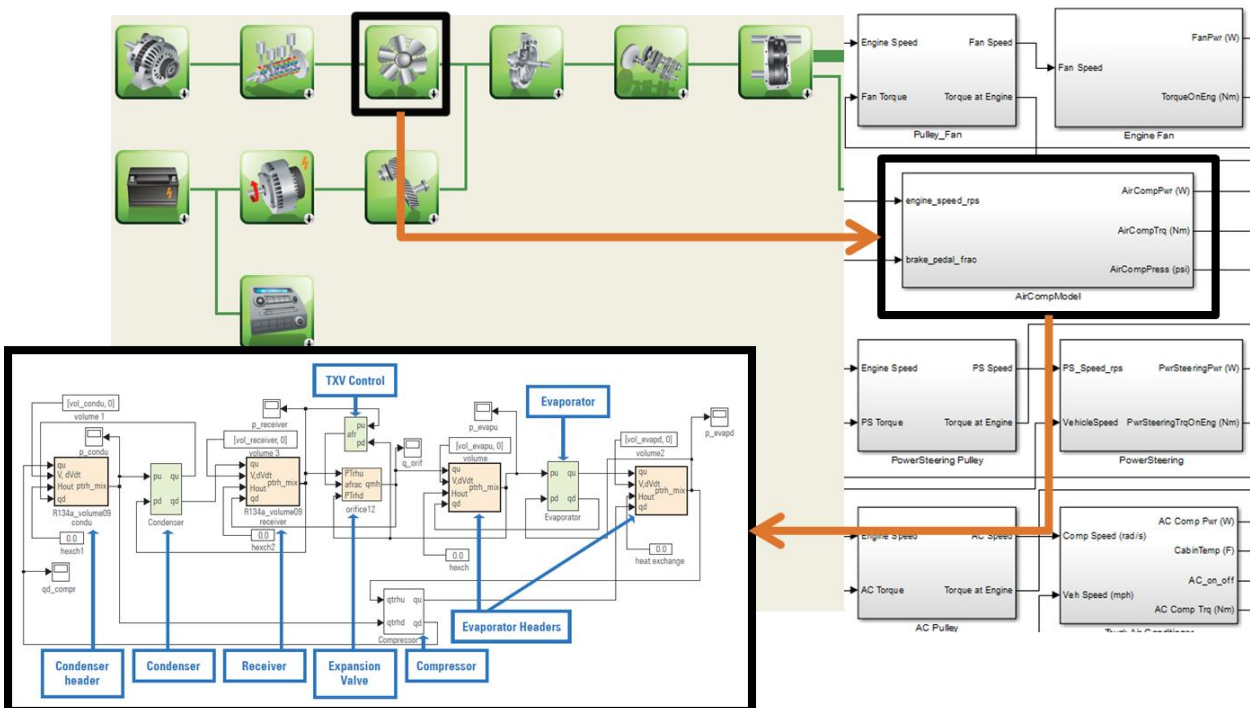


Figure I-8: NREL's CoolSim model and the structure it will take inside our Autonomie model when validated.

Conclusions

Phase one of the project is largely completed. As more data from Cummins test vehicle, ORNL's test cell, and NREL's CoolSim model becomes available the models will continually be updated to provide more realistic results as well as continue to improve ORNL, NREL and Cummins' model libraries for future projects. Phase one has allowed Cummins and ORNL to create tools to evaluate future accessory technologies as well as discover the current landscape in accessory technologies and idle reduction devices.

Phase two is nearing completion. ORNL is concluding testing on the electric compressor system along with the temperate control strategies, and Cummins is finishing integration of the finished h-APU system into the test truck for the proof of concept demonstration. Phase two has also allowed NREL to build a baseline class 8 heavy duty sleeper cab CoolSim model that will be validated and available for public consumption minus a few propriety parameters from this project.

After reviewing the results of the study, Cummins and ORNL determined that an accessory architecture is the best solution for maximized potential in reducing emissions and fuel consumption; this method will either reduce or eliminate the need for idling in HD class 8 trucks. Choosing the accessory architecture best allows the project to address issues of idling for extended periods while accessory loads are still essential, as in overnight hoteling and idling while in queue at distribution hubs. The architecture for this has been chosen and developed based on the findings and testing done on this project, but is protected under the CRADA agreement.

I.1.A.3. Products

Presentations/Publications/Patents

1. Invention Disclosure: 201503581
 - a. DOE S-Number: S-138,217
2. Invention Disclosure: 201503582
 - a. DOE S-Number: S-138,218
3. Invention Disclosure: 201503589
 - a. DOE S-Number: S-138,226