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IMPLEMENTATION AND ANALYSIS OF A 1.4L TURBO LIQUID COOLED CAC AND AC CONDENSER SYSTEM

by

Mitchell Zajac

A thesis submitted to the Graduate College
in partial fulfillment of the requirements
for the degree of Master of Science in Engineering
Mechanical Engineering
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December 2013

Thesis Committee:

Dr. Hosung Lee
Dr. Christopher Cho
Dr. Timothy Scott

IMPLEMENTATION AND ANALYSIS OF A 1.4L TURBO LIQUID COOLED CAC AND AC CONDENSER SYSTEM

Mitchell Zajac, M.S.E.

Western Michigan University, 2013

This project report serves as a continuation and finalization of an overall experience with the design process including working on the development of system components, working with automotive industry leaders, suppliers and dealing with the aspects of business and production feasibility. The development of a dual level cooling concept to apply Centro Richerche Fiat established components on a Chrysler Group vehicle application was the foundation of the design project completed in December 2012 by Matt Cutler and Mitch Zajac. The development of this system aimed to decrease overall vehicle power consumption, minimize overall system packaging space, and to increase vehicle performance and fuel economy. This project builds on that design and development work by way of component implementation, experimental testing, and system feasibility analysis. Through collaborative work with Chrysler Group and their facilities, this project exemplifies an engineer's ability to design, implement, test, and complete analysis for success on an industry applicable system. This is done through start-to-finish, proof-of-concept design and delivery of the new dual level cooling powertrain thermal management system.

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Acknowledgements

I would like to thank all of the individuals that have aided in the completion of the project. These parties include employees at Chrysler Group, namely Dan Hornback (industrial mentor/thesis committee member) and Kevin Laboe (project supervisor/thesis committee member), each who provided support throughout the duration of the project. Thanks are also needed for Bob Lee and John Nigro, who aided in the project selection and coordination between Chrysler and WMU resources. Special thanks to Dr. HoSung Lee (faculty mentor/thesis committee chair), Dr. Christopher Cho (thesis committee member), and Dr. Koorosh Naghshineh (WMU Graduate Advisor) for all of their support and advice throughout the duration of the project. Because of his efforts in the development project that served as our undergraduate thesis, I would also like to thank Matt Cutler for many hours of support and dedication to the groundwork of this project. Lastly I would like to thank my family and friends; without their support this many of my life achievements could have never been accomplished. Without support from each party this project would not have reached its final stage.

Mitchell Zajac

Disclaimer

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Introduction/Description

During the 21st century, a nationwide initiative has been established in order to achieve a greener planet by reducing the “carbon footprint” of our society. Actions have been taken by numerous companies including appliance manufactures, home builders, and companies within the automotive industry. All actions are aimed to meet standards set by governmental agencies, namely the Department of Energy (DOE). The aim of companies around the nation is to produce more efficient products, thus, reducing the amount of energy needed to operate each product. Also, with the onset of heightened energy costs, consumers are looking to purchase products which will cost them less to operate. This also makes producing more energy efficient products attractive to manufactures.

In the automotive industry, the energy needed to operate a given vehicle can be measured by the fuel economy of the vehicle while driven through standardized drive cycles. This requires vehicle components and systems (engines, transmissions, cooling systems, electrical systems, etc.) to be optimizing the trade-off between maximum vehicle performance and overall vehicle fuel consumption. Many innovative concepts and designs have arisen over the past 15 years to reach fuel economy standards set by the DOE. Examples of these concepts include flex-fuel vehicles that can run on ethanol and gasoline, hybrid-electric vehicles which supply drivetrain power from a combination of gasoline and electricity, and increasing existing vehicle through the application of performance add-on products such as exhaust systems, turbochargers, and cold-air intake systems. However, another area of focus for auto manufactures is the powertrain thermal management system; managing the heat generated by drivetrain and cabin cooling components. This system is known to consume roughly one-third of the available power delivered from the fuel while another one-third is used to transition into actual vehicle movement (Kashyap 2007).

This report investigates the re-design of the powertrain thermal management system (TMS) for the Dodge® Dart. With the recent merge of Chrysler and Fiat, Chrysler has begun to investigate many of the creative concepts that Fiat has used to increase the fuel economy of their vehicles. Of these concepts available for investigation is a system known as Dual Level Cooling. This project involves the implementation, including a validated simulation model, of a 1.4L Turbo powertrain with a liquid cooled charge air cooler and AC condenser in place of the conventional cooling components. Working in conjunction with Chrysler, a dual level powertrain cooling system was designed and analyzed for reduction in fuel economy and decreased packaging space.

Completed Work

Below is a summary of the work completed by the author on this project. The work described in this report involves numerical analysis along with a large portion of entire project management, coordination, and application of existing technology on current production hardware.

Project Management/Coordination is outlined in the facilities and Personnel sections as well as Software, Flowmaster, AVL Cruise, Inca, Intecrio, MiniTab 16, Teamcenter/NX, Baseline Instrumentation Dual Cooling Instrumentation, Testing, and ETS. In order for this project to be successful, it was vital to learn the ins-and-outs of each of the above stated software. Each is described in its respective section. Without the coordination of use of resources in different facilities as well as personnel, this project would have been at a standstill. Because of this, these two categories were important parts of the thesis work.

Application of existing technology is outlined and included in the areas of System Comparison, Charged Air Cooler, Condenser, and Front Cooling Module.

Finally, numerical and statistical analysis' were completed in Baseline Testing Validation: Comparison with production testing results and Statistical Analysis, Dual Level Cooling Results, Dual Level Cooling Testing Validation: Statistical Analysis, System Comparison, Experimental Results Comparison, Effectiveness Study, Simulation Results ComparisonPackaging Study, Charged Air Cooler, Condenser, Front Cooling Module, and Volume and Weight Improvements. In each section, the details of the work cannot be disclosed, however, at the end of each section there exists a table of equations that were used including a brief description of the way in which those equations were used. See each individual section for details about the analysis and mathematical solutions applied.

Heat transfer and heat rejection calculations were completed using the general heat transfer equation as well as the convection heat transfer equation where the convection heat transfer coefficient was calculated at the design point load condition for the charge air cooler and at the maximum AC heat rejection condition for the AC condenser in order to achieve optimized results during the standardized AC system tests (6525i, CD25i, and USCTY.)

System pressure drops were analyzed, as a contribution of each component to the overall system pressure drop in order to verify and size the system pump; this was completed after system sizing as described above in the Design Process. This was done using assumptions for line lengths and bends as well as supplier information about each heat exchanger. The purpose of this was to ensure the 100W system pump was adequate and was done using an 1-D analysis similar to that utilized in the Flowmaster model.

Simulation work was completed using Flowmaster and AVL Cruise. These simulations were preliminary to estimate the FE and performance benefits of the system based on a calculated effect on time to boost using the decreased intake line air volume. These simulation programs require understanding of multiple degrees of freedom. Flowmaster is 1D and requires understanding of system input parameters as well as system pressure drops and performance curves. AVL Cruise requires understanding of how the entire vehicle powertrain interacts…relying on powertrain component performance maps and system efficiencies.

The entire vehicle was wired by the author. This included analysis of electrical system resistance, loading, and understanding instrumentation, signal conversion, and data management. This portion of the project alone required 80+ hours of labor in the physical wiring and an additional 40 hours of time spent familiarizing with the Chrysler instrumentation. Specific additional training was required in order to operate the data acquisition system effectively and, because of such training, the author was then able to teach other members of the authors group how to operate the same system.

Statistical analysis of results was completed using MiniTab16 using basic F and 2-T-Sample tests as well as Monte Carlo simulations for multi-vehicle performances under the same mean and standard deviation as obtained from the experimental test data.

The control scheme was defined and realized by the author. It utilizes a new scheme and overall simplification of controlling system components using ETAS hardware and Intecrio rapid prototyping software. The logic for the control scheme is as follow:

<u>ELECTRIC WATER PUMP</u>

– **Feed-Forward**$_{\mathbf{LCAC}}$

– Using preferred final ACT, back solve for $\mathbf{m}_{\mathbf{dot}}$

– **Feed-Back**$_{\mathbf{LCAC}}$

– Read current ACT, solve for difference in HT and apply change in $\mathbf{m}_{\mathbf{dot}}$

– **Feed-Forward**$_{\mathbf{LCOND}}$

– Using linear regression equation for HT with ideal compressor discharge pressure, back solve for $\mathbf{m}_{\mathbf{dot}}$

– **Feed-Back**$_{\mathbf{LCOND}}$

– Read current compressor discharge pressure, solve for difference in HT and apply change in $\mathbf{m}_{\mathbf{dot}}$

<u>CAC FLOW CONTROL</u>

– **Feed-Forward**$_{\mathbf{LCAC}}$ – Using preferred final ACT, back solve for $\mathbf{m}_{\mathbf{dot}}$

– **Feed-Back**$_{\mathbf{LCAC}}$ – Read current ACT, solve for difference in HT and apply change n $\mathbf{m}_{\mathbf{dot}}$

<u>LTR BYPASS VALVE</u>

– **Feed-Forward$_{LTR}$**

– Using preferred final LCAC inlet coolant temp and LTR inlet temp, back solve for $\mathbf{m}_{dot}$

– **Feed-Back$_{LTR}$**

– Read current LCAC inlet coolant temp and LTR inlet temp, solve for difference in HT and apply change in $\mathbf{m}_{dot}$

<u>PWM COOLING FAN CONTROL</u>

– **Standard ECU Control** + **Additional RP Software**

– Intecrio software chooses maximum requested value for fan speed set point. The system chooses if the ECU is commanding a higher fan set point based on ECT, EOT, TOT, and Trans Vapor Setpoint OR if the LT coolant temperature is requesting the fan to turn on.

<u>AGS CONTROL</u>

– **Standard ECU Control** + **Additional RP Software**

– Intecrio software chooses maximum requested value for AGS set point. The system chooses if the ECU is commanding a higher fan set point based on ECT, EOT, TOT, and Trans Vapor Setpoint OR if the LT coolant temperature is requesting the AGS to open. This logic occurs before the fan turns on in order to limit power consumption.

In validating the control scheme, a 150 DOE was generated to test system pressure drops and flow rates at various valve and pump flow rate conditions. These pressures and flows were used to validate system performance maps and to utilize error based gains in controlling system feedback within the drivers in this system.

Project Resources

Facilities

The following facilities will be utilized for the duration of this project in the capacity for which they are respectively described:

Chrysler Technical Center (CTC)
Auburn Hills, MI

CTC will be the location of the majority of our senior design project. Here, an internship position will be held and access will be had to all necessary labs and vehicles. Chrysler simulation software, like Flowmaster, a one-dimensional system used to evaluate system operating parameters, Chrysler labs, and Chrysler computer systems will be accessible at CTC. Climate testing and experimental data analysis will take place at CTC as well.

Chrysler Amrhein Road Center (Livonia)
Livonia, MI

Livonia will be the primary location used for vehicle instrumentation for both baseline and prototype configurations.

Chrysler Proving Grounds (CPG)
Chelsea, MI

CPG will be the primary location for vehicle fuel economy and performance testing for both baseline and prototype runs.

Western Michigan University (WMU)
College of Engineering & Applied Sciences (CEAS)
Kalamazoo, MI

CEAS will be utilized for data compilation, analysis, and report building.

Personnel

The following personnel will be utilized for the duration of this project in the capacity for which they are respectively described:

Mitch Zajac
WMU Student/Chrysler Engineer
Lead Design

Dr. Ho Sung Lee
WMU Professor of Mechanical Engineering
Heat Transfer
Faculty Mentor

Dan Hornback
Chrysler Engineer
Powertrain Thermal Management
Industry Mentor

Kevin Laboe
Chrysler Engineer
Powertrain Thermal Management
Project Supervisor

Matt Cutler
Stryker
Resource

Harry Chen
Chrysler Engineer
Powertrain Thermal Management
Simulation Specialist

Sudhi Uppuluri
Contract Employee
Simulation Specialist

Timothy Scott
University of Virginia
Professor of Mechanical Engineering
Heat Exchangers
Consultant

Ethan Bayer
Chrysler Engineer
Advanced Controls

Sangeeta Theru
Chrysler Engineer
Advanced Controls

Danny Nakhle
Chrysler Engineer
Advanced Controls

Carloandrea Malvicino
CRF Project Management
CRF component and technology consultant

Daniela Magnetto
CRF Project Management
Responsible for dual cooling project at CRF

Jeff Foor
Chrysler FE, Coast down, & Performance Testing
Supervisor responsible for vehicle testing at CPG

Curt Potvin
Chrysler FE, Coast down, & Performance Testing
Test Engineer - CPG

Ron Lasovage
Chrysler Shop Foreman at CPG
Vehicle build-up

John Green
Chrysler Shop Foreman at Livonia
Vehicle build-up

David Schmidt
Chrysler Chief Engineer 1.4L FIRE
FIRE Components and Parameters

Mike Rinaldi
Chrysler HVAC Manager

Rick Amaral
Chrysler HVAC Engineer
Climate Testing

Brad Szkrybalo
Chrysler HVAC Engineer
Climate Testing

John Nigro
Chrysler VP Systems and Components
Career Mentor

Software

Software programs are important parts of all engineering programs, particularly when implementing new technology into existing vehicle systems. In order to successfully complete this thesis project, more than 50 hours were spent developing the skills necessary in order to be able to effectively use the below mentioned software programs. Beyond those 50 hours of learning how to use these programs, more than 400 hours were actually spent using the programs in order to successfully develop, test and analyze the Dual Level Cooling vehicle system.

Flowmaster

Flowmaster is a platform for developing one-dimensional calculations and models that represent actual vehicle hydraulic circuits. To do this, elements of the Flowmaster model are comprised of multiple libraries, including performance maps, of components that make up the overall vehicle hydraulic circuits. In the case of the 1.4L Turbo PF model, some of these important components are mechanical and electric pumps, all heat exchangers (i.e. Radiators, Condensers, Charge Air Coolers, etc.), hoses, valves, and system control components. **Figure 1** shows a basic layout of the baseline Flowmaster Model.

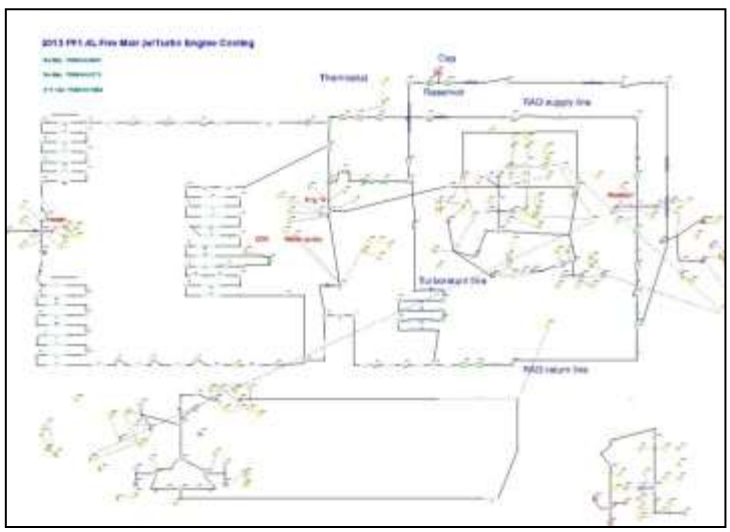


Figure 1 - Flowmaster Flow Layout Schematic

Using the theories of conservation of mass and energy to solve temperature and pressure calculations, the characteristics of each component is based on its specific performance map. In terms of pressure specifically, pressure losses are derived from a standard loss coefficient as calculated from those specific performance maps. The maps that are used in these models have information relating the flow rate of both side fluids, temperature gradients based on the dominant cooling fluid, they give heat rejection characteristics, and pressures at various flow rates. While the data in these performance maps are characterized based on steady state conditions, Flowmaster allows for transient situations to be calculated by imposing changing boundary conditions for the components, and entire system, versus time. These types of imposed boundary conditions include flows, temperatures, and heat addition.

In terms of setting up the vehicle thermal model for the engine, there is an assumption that is made to ensure ease of calculation in the model. This assumption says that there are three sources of heat in the engine; the Block, Crank, and the Sump. The Block is cooled by the coolant and contains all of the passages. Because of this, the temperature of the coolant coming out of the block is said to be the average block temperature. The Crank is considered to contain the crankshaft, pistons, connecting rods, main bearings, and supporting structure. The Sump is the oil reservoir and oil pan. In a similar fashion to the way in which individual thermal circuit components are modeled, so too are the heat exchanging and pumping components of the engine. Because of this, the pressure loss and thermal characteristics can be individually modeled using supplier component maps. The interactions of the different fluids are modeled by Flowmaster using implemented equations for convection and conduction heat transfer based on the coefficients provided by supplier data.

The engine model takes into consideration various boundary conditions like velocity, engine torque, and engine speed versus time. Generally, these conditions versus time datasets are traces for time for particular vehicle drive cycles. For example, the instantaneous combustion heat, frictional heat, coolant and oil flow rates are found using engine RPM and torque by the engine thermal model. These are also used to calculate the temperatures in various sub-systems. The key outputs of the model are the transient temperatures of the coolant, engine oil and transmission oil in addition to the thermal performance of individual components such as the radiator, engine oil cooler, etc.

AVL Cruise

AVL Cruise is a vehicle and driveline system analysis software used for evaluating vehicle powertrain, fuel economy, and performance. AVL Cruise is combined with the vehicle Flowmaster model as part of a larger vehicle energy balance model (VehEbalance) as the main source of data that are explained in the simulation results portion of this report. The AVL Cruise

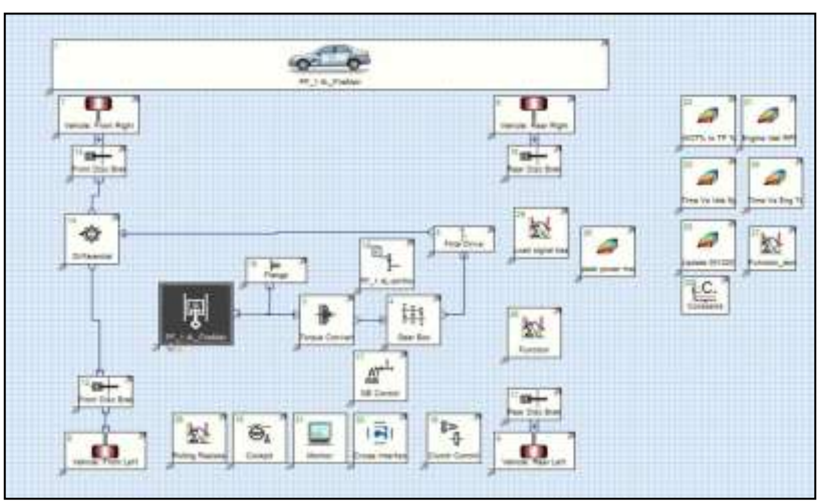


Figure 2 - AVL Cruise Environment

is shown in **Figure 2** below.

As seen in the figure above, and much like the Flowmaster scheme, AVL Cruise incorporates the idea of deriving a one dimensional equation from multi-degree-of-freedom component performance maps. These maps are connected in such a way that the successive maps reference those in which they interact physically with in real automobiles.

To run these tests, certain specific configurations are required beyond the compilation of specific component data. For the purpose of this test vehicle, the model of powertrain was already created in order to match previous, unique vehicle tests. The vehicle test configuration for this project included the use of transient fuel economy and performance tests. To configure the fuel economy tests, it was necessary to input a specific speed, rpm, and torque trace for the simulation model vehicle. Doing this allowed accurate modeling for each specific test by ensuring exact alignment between the model and vehicle dynamics. The performance tests require manipulation of the model transmission and vehicle starting speeds in order to ensure symmetry between the vehicle model performance and actual vehicle performance. This was not completed as a part of this project because of the requirement of in-depth understanding and manipulation of the vehicle AVL Cruise model.

The outputs of this simulation model include heat rejections, warm-up times, and other physical characteristics about the vehicle powertrain. The most important piece of information for the purpose of this project is the fuel economy data. In the results portion of this report, specific data is discussed as well as the creation of the model calibration coefficients for each test, in order to validate Dual Level Cooling fuel economy results.

Inca

INCA MDA

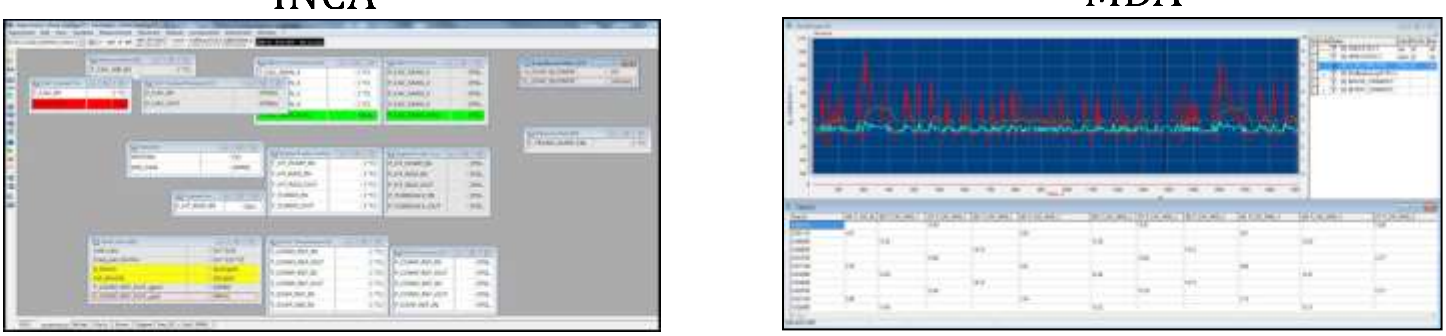


Figure 3 - ETAS System

INCA is a data acquisition system that is created by ETAS. In **Figure 3** shown above, INCA and MDA (Measure Data Analyzer) combine to make a system that allows for readily accessible, real time vehicle data information. These two paired with the unique approach to instrumentation of this vehicle, as described later in this report, combine to make data acquisition efficient and readily accessible. INCA allows for ETAS equipment to be attached by Ethernet to a laptop and to connect the laptop to the engine controller by used of an ETK. The ETK is, in a sense, a parasitic element that attaches directly to the ecu control board and allows INCA to spy on the controller as well as, real-time, modify all engine calibrations contained on the controller. The left portion of the figure below shows a shot of the INCA system where each channel is written on the screen. The right portion shows MDA with a graph and table for specific read channels.

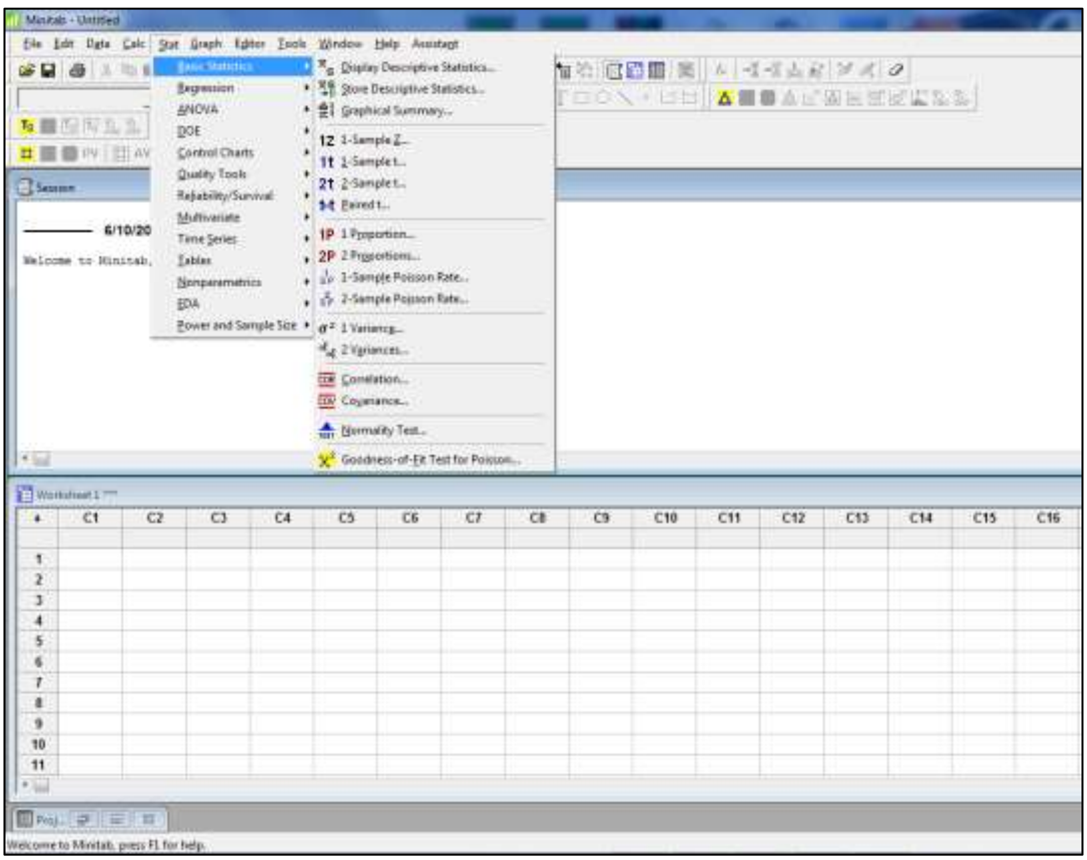


Figure 4 - Minitab 16

Intecrio

Intecrio is another system created by ETAS used to add additional controls to an existing engine controller. Rather than having to modify base engine code, Intecrio provides either supplemental control to parameters not currently on the base engine controller OR adds additional logic to existing vehicle components. Intecrio requires additional hardware (ES 910 and 930) for control of any new devices, as well as prototype code that delivers logic to new devices or adds to existing controller logic.

MiniTab 16

MiniTab 16 is a software used for completing the statistical data analysis on a given set of data. Functioning much like excel, it is possible for the standard statistical comparisons, such as mean, median, mode, variance, and standard deviation. This tool also has capability to easily plot box plot comparison data to evaluate the improvement of one set of data over another. With these box plots, the program also allows for more advanced statistical analysis like linear and polynomial regression, one- and two-sample “t” tests, “z” tests, and more.

This is an important program because it allows for the engineer to clean up the samples of data and compare non sequential test runs. This clean-up is an important part of data acquisition process because much of the data is comprised of points creating higher standard deviations based on test cell, driver, and environmental inconsistencies. **Figure 4**, shown above, is the environment of the Minitab 16 statistical analysis software program.

Teamcenter/NX

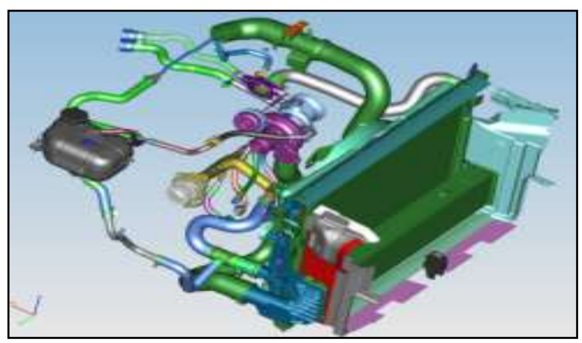


Figure 5 - Teamcenter

Teamcenter is the system used for viewing vehicle CAD models. Using this software, it is possible for dimension and weight analysis. The other important aspect of this software, aside from showing the location of components in space, is the fact that this program allows for viewing ONLY the components, in space, which are desired. This allows for visual understanding of system packaging, shown in **Figure 5**. Beyond the ease of understanding for the engineer, a major part of this thesis project is the development of the “Powertrain Thermal Management Instrumentation ‘Best Practice’ build document.” This document is explained later in this report. It is important to note, however, that by use of Teamcenter, the engineer is able to explicitly demonstrate the location of desired instrumentation and vehicle configuration changes.

ETS

ETS is short of “Emissions Test Systems” and is an environment used for developing and reviewing vehicle test requests. The test request development process requires that the engineer have a profound understanding of not only the specific vehicle tests that are being requested, but also a deep understanding and appreciation for the vehicle configuration and the way in which each vehicle must be input into the testing system. These appreciations are important because without accurately inputting vehicles into the testing system and aligning the right test configurations for each vehicle and test, testing itself will not accurately conclude with the desired results. The system also allows for vehicle tracking and vehicle test results review, along with the test procedure development itself. **Figure 6** shows the multiple screens of ETS for vehicle test request creation, test review, and vehicle tracking.

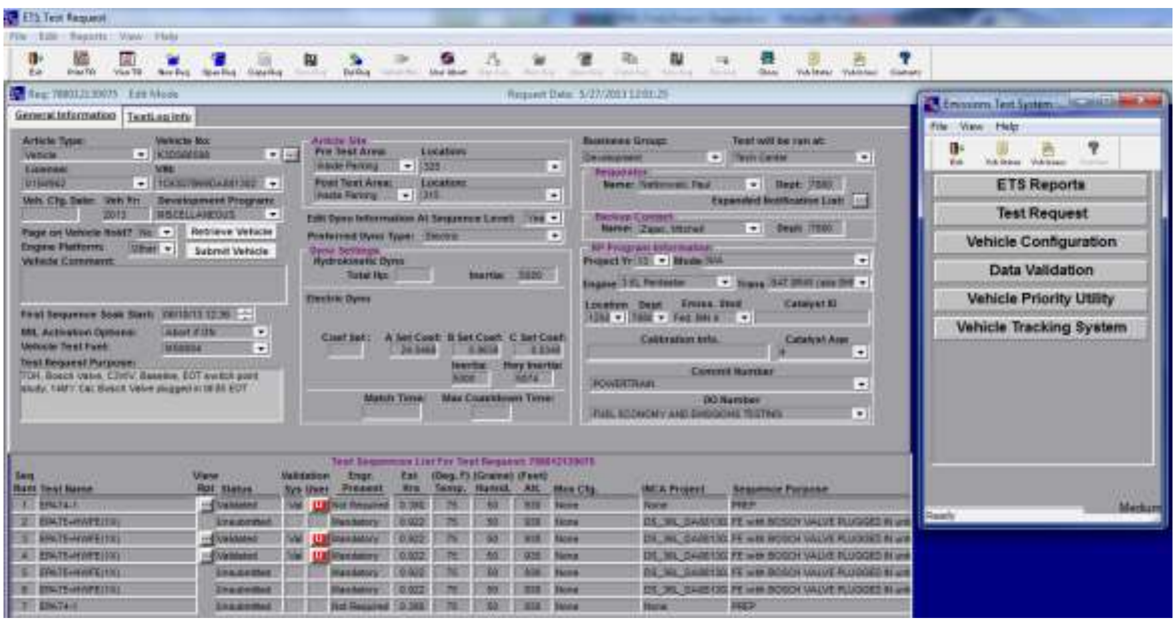


Figure 6 - ETS (Emissions Test Systems)

Powertrain Thermal Management System (TMS) Background

In any transportation unit (car, truck, bus, ATV, etc.) that is powered by an internal combustion engine (ICE), high temperatures from the combustion of fuel are produced within the engine and exhaust systems. High temperatures within the transmission are also present due to the contact between each of the gears during vehicle movement. These high temperatures can hinder the performance of the vehicles powertrain for a number of reasons and could even result in complete failure of powertrain components (engine and transmission). To control the high temperatures experienced by the powertrain, a powertrain cooling system must be integrated as a part of the powertrain. Along with servicing the extreme temperatures within the engine, the

The cooling system of an automobile plays a vital role in the operation of the engine. As the engine begins to output power to the transmission, heat is generated due to the inefficiency of the engine. After a period of time, this heat will lead to increased engine temperatures which further restrict the efficiency of the engine. To maintain the engine block at optimal temperatures, the cooling system is required to remove the excess heat. This is achieved by pumping coolant through the engine block, where heat is transferred to the coolant causing an increase in coolant temperature while decreasing the temperature of the engine. As the coolant is exits the engine block it continues to what is known as the high temperature radiator (HTR) where, by forced convection via a fan and vehicle ram air, the coolant is cooled and the heat gain experience from within the engine block is dissipated to the ambient environment. A conventional engine cooling system can be found in **Figure 7**. This also shows some of the main components found in a conventional engine cooling system. The temperature distribution at different points within the system, shown in blue versus red, represent the cool to warm temperature gradient experienced across the system.

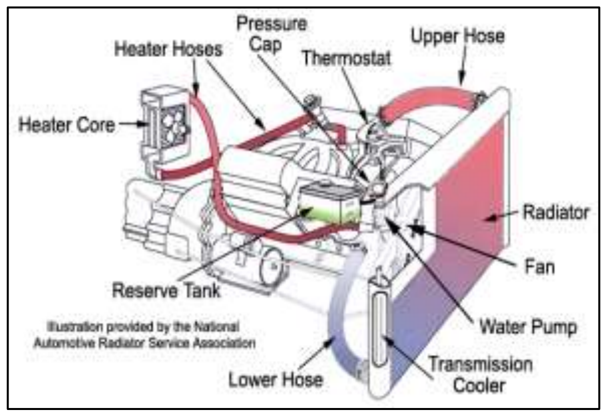


Figure 7 - Conventional automotive cooling system
Source: **sundevilauto.com**

Components

Due to the complexity of today's automobiles, the list of thermal management system components has become very extensive to satisfy the needs for all of the vehicles sub-system cooling requirements. The components within a system also vary depending on engine and transmission type, powertrain add-ons, vehicle cabin size, and more. In a standard vehicle thermal management system, cooling power must be supplied to the engine, transmission, and air-conditioning systems, while heat is provided to the cabin heater core as a part of the cabin heating system. However, with the addition of performance parts, such as a turbo charger, additional components need to be incorporated into the structure due to the cooling demand of these added performance parts.

Each of the components within the cooling system varies in size and specific purpose, but many of the components are similar in the fashion that they serve as a certain type of heat exchanger. A heat exchanger is a device that transfers heat from one fluid medium to another. This report focuses on heat exchangers for fluid mediums; common for automotive applications. **Figure 8** shows how heat is transferred from one fluid to another within this type of device.

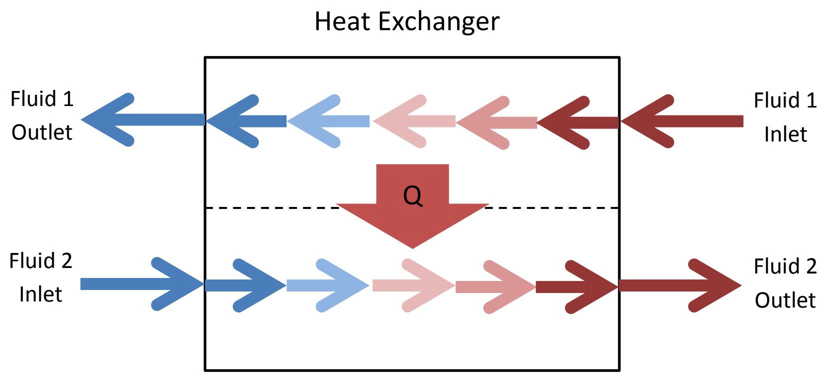


Figure 8 - The process of a heat exchanger (blue are cool temperatures; red are hot temperatures)

The amount of heat transferred from one fluid to another in heat exchangers for fluid mediums can be calculated by the relationship found in Error! Reference source not found.. In an automotive hermal management system, understanding this process is essential to effectively design for the heat rejection demands of the system.

$$Q = \dot{m}c_p\Delta T \qquad \textbf{Equation 1}$$

Where:

Q	:=	Heat transfer
$\dot{m}$	:=	Fluid mass flow rate
c_p	:=	Fluid heat transfer coefficient
ΔT	:=	Temperature difference between two fluids

In the following sections, each of the main components and modes of heat transfer comprising an automotive thermal management system will be described. These components and modes will include those that are needed for proper operation of a vehicle which uses a turbocharger for fuel economy purposes.

Radiator

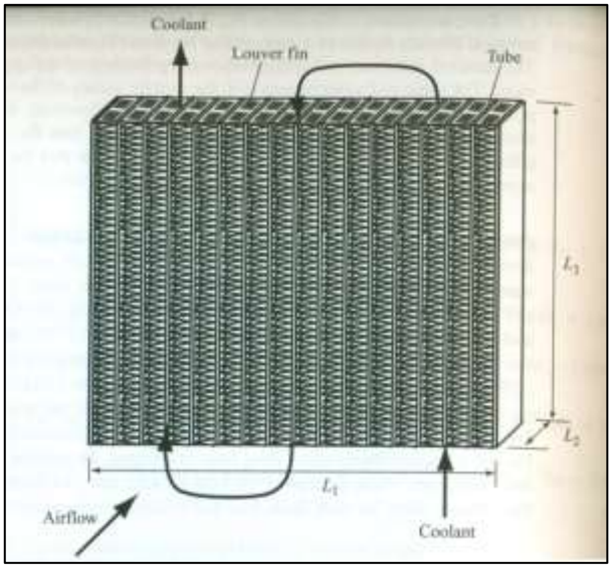


Figure 9 - Louver fin type plate-fin heat exchanger (Lee 2010)

The radiator is an example of a commonly known automotive heat exchanger. Coolant within the radiator travels from the radiator where it is at a relatively cool temperature and flows through the engine, where it gains heat. After the engine is warmed up to operable temperatures, this coolant will flow back to the radiator. At the radiator the coolant (fluid 1) flows through tubes that are traversed by ram air flow and fan forced convection (fluid 2) from the vehicles forward movement and a certain Pulse Width Modulated (PWM) signal sent to the fan based on thermal conditions. . Forced convection by the radiator fan allows for heat to be dissipated at the back side of the radiator; capitalizing on the full component geometry and optimum temperature difference between the two heat exchanging fluids. This type of convection is preferred to natural convection because of the amount of heat that is required to be removed from the system. Forced convection allows for a much more rapid heat exchange between the two fluids. Radiator design uses a heat exchanger concept of the louver fin type plate-fin to pass coolant through vertical tubes that are cooled by forced airflow over the louver fins in the direction traversing the tubes. The louver fin type plate-fin exchanger is shown in **Figure 9**. This component is often referred to as the radiator or radiator core. It can either be arranged in the orientation shown or oriented so that the coolant tubes are horizontal in nature. For the radiator core to provide sufficient heat dissipation, air is forced over the louver fins by means of forced convection as described above. Small openings at the front of the radiator in the car body allow a passage for airflow to the radiator. When needed, the fan is either powered by the engine, through a belt driven power transmission, or by means of electrical power; a common practice today with manufacturers.

Water Pump

The coolant that is supplied throughout the system requires a volumetric flow rate that is proportional to the amount of engine block cooling required. A centrifugal water pump is installed between the output line of the radiator and the engine block. This pump obtains its pumping power from the engine; a belt drive is connected between the crankshaft and pump. The pumping must be sufficient enough to overcome the total amount of head losses created by each of the cooling system components.

Valves

Valves play an important role in the amount of cooling power that is delivered to each component after coolant leaves the radiator. A three way valve is a device that has one input port and two output port locations. The valve can direct a percentage of the input flow to the desired output branch and is done so to provide cooling to certain cooling components constructed in either branch. The percentage of opening in the valve is controlled by a control system which calculates the components that are in need of more cooling power.

Thermostat

The amount of coolant flow from the radiator to the engine block can be controlled by the use of a thermostat. The objective of the thermostat is to allow quick engine warm-up and then maintain the engine at a constant temperature. At low temperatures, the output of the thermostat is completely blocked, recirculating all the coolant back through the engine. However, as the temperature of the coolant increases with engine warm-up, the thermostat begins to allow more and more coolant to be passed through its outlet.

Charged Air Cooler

A charged air cooler is in common automotive language, an intercooler. A charged air cooler is a part of the turbocharger system and is very important to making the system work the way it does. It is used to cool intake air after it has been compressed, thus heated, by the turbo but before it reaches the engine air intake manifold. The need for cooling comes from the rise in intake air temperature due to the compression of a gaseous volume (air). As air is pressurized within the turbo it rises in pressure (rise in density) and temperature, continues to the charged air cooler where it loses heat and increases its density once again. The air then flows to the intake manifold before it is eventually combined with the fuel to be used for crankshaft work; through internal combustion.

The charged air cooler is simply a heat exchanger that exchanges heat between a fluid medium and the intake air. The most common fluid medium that is used in the automotive industry today is air, which will be referred to as an Air-Air charger air cooler (CAC). However, this project is aimed to investigate the advantages of using water or coolant as the traversing fluid medium. A device working in the fashion will be referred to as a Liquid-Air charged air cooler (LCAC).

Air-Air

The fluid medium most commonly used in industry today for providing cooling to the intake are is ambient air, by means of ram air. In a fashion similar to that of radiator cooling by ambient ram air, charged intake air travels through the charged air cooler where it is traversed by cooler ram air. Based on the concept of a heat exchanger, the warmer charged intake air is cooled by the ram air. For this reason, the CAC is typically located at the front of the vehicle to have an abundant supply of ram air.

Liquid-Air

This type of charged air cooler replaces the ram air with liquid as the fluid medium. Due to this process, the charged air cooler is no longer need to be placed at the front of the vehicle. Instead, it can be placed near the intake manifold of the engine. The liquid that is traversed over the intake air is then needed to be cooled to provide a temperature drop to the intake air. This requires that the coolant flow through another heat exchanger, commonly another radiator, which is located at the front of the vehicle and cooled by ram air

Air-Conditioning System

The air conditioning (AC) system provides internal cabin temperatures which are set by passengers. This feature of an automobile has become very popular with consumers over the years. Therefore, its design is a necessity. To provide the proper functioning of this system, power is required from the engine. By using certain devices, the pressure and temperature of the coolant within the system is constantly changing. **Figure 10** shows the low and high pressure sides of an air conditioning circuit. The following sections will detail each component and their function.

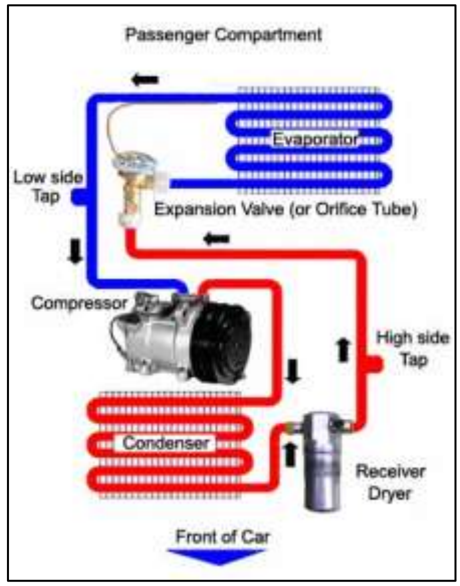


Figure 10 - Pressure distributions for a typical automotive air conditioning circuit (Bede 2012)

Evaporator

The evaporator, which is a heat exchanger, is the device which absorbs heat from the ambient cabin air. As the coolant of the AC system passes through the evaporator, it traverses cabin air and the cooler coolant, is warmed by the warmer cabin air. The evaporator is usually located in the cabin of the vehicle underneath the dash board.

AC Condenser

The condenser is the location where coolant heat dissipation occurs within the AC system. It is also another example of a heat exchanger because of its heat dissipation function. Warm compressed coolant, which is a product of the evaporator and the compressor, is traversed by a cooler fluid medium within the condenser; this causes the coolant to lose heat. Once the coolant becomes cool again, it can be delivered back to the evaporator again to provide cooling to cabin air.

Just like the charged air cooler, the condenser can also provide cooling by two different fluid mediums. Typically an Air-Air condenser (COND) is used to provide heat dissipation of the coolant. The condenser is normally located at the front of the vehicle to have access to ram air (the cooling medium) and looks similar to the radiator. Alternatively, a Liquid-Air condenser (LCOND) can be used to cool the passing coolant. This requires for the liquid cooling medium to lose its gained heat (at the condenser) somewhere else. Just like the LCAC, the LCOND will have to be placed in a loop with a radiator which provides cooling to the liquid medium.

Compressor

The compressor is known as the heart of the AC system. Although it is termed “compressor”, it is simply a pump that moves coolant through the AC circuit. This is the device that splits the system into its high and low pressure sides. The compressor is located between the evaporator and condenser and allows for the hot gases (formed in the evaporator) to be compressed into a liquid to allow for maximum heat dissipation at the condenser. The compressor is normally located near the engine and derives its power via a belt connection to the crankshaft.

Transmission Oil Cooler

The transmission cooler is similar to the radiator used to cool engine coolant, the difference being that transmission oil is the medium to be cooled versus engine coolant. The gears of the transmission create heat and friction when transmitting engine power to the axles. With the transmission filled with a fluid medium, most namely oil, the temperature of the transmission components can be controlled and the wear due to friction can be decreased. The transmission cooler offers the need heat dissipation of the oil to keep the transmission running within an optimal temperature range.

Cabin Heater Core

The cabin heater core is a device that is a simple heat exchanger. Its purpose is to heat cool cabin air through heat exchanging by hot engine coolant after the coolant has left the engine block. Coolant from the engine is always flowing to the cabin heater core but the cabin air may not be. During times when the cabin is desired to be heated, the cabin air will pass through the cabin heater core where it is warmed. If no heating is required the cabin air bypasses the cabin heater core.

Conventional TMS Design

The conventional thermal management system is what can be found in most present day automobiles. A thermal management system is a combination of multiple fluid loops that each serve to provide cooling to certain vehicle components within each loop. Each loop typically contains one or several heat exchangers, a pump, and a variety of valves. The two typical loops that can be found on a vehicle are the engine coolant loop and the air-conditioning loop. However, a vehicle that is equipped with a turbocharger requires the addition of another loop within the thermal management system. A thermal management system found in a vehicle with a turbocharger can be found in the schematic in **Figure 11**. Within the engine coolant and air-conditioning loops, a fluid is pumped through the system to provide cooling to components within each loop. As the fluid passes through the components in which cooling is supplied, the fluid gains thermal energy through the process of heat exchanging. As the fluid exits the component, it returns to another heat exchanger located at the front of the vehicle where it is traversed with vehicle ram air. At this point, the thermal energy that is gained by the fluid is dissipated to ambient air and the fluid returns to a temperature that is suitable to provide cooling to the components within each loop.

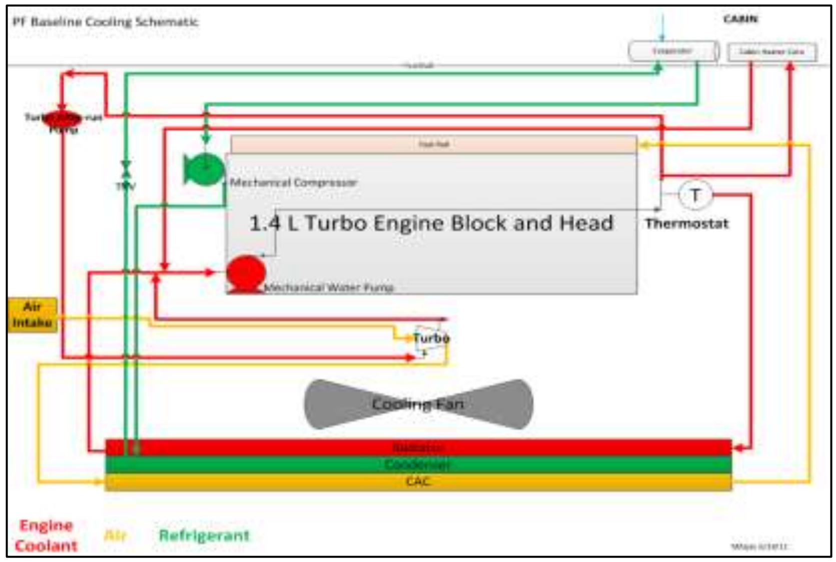


Figure 11 – Conventional TMS for a turbo charged vehicle

The specific function of the engine coolant loop is to provide cooling to the engine block. The engine block requires cooling because of the temperature increase caused from internal combustion within each cylinder of the engine. Coolant at a low temperature is pumped from the radiator to engine block where it gains thermal energy. As the coolant leaves the engine block it returns to the radiator where is dissipates the gained thermal energy by means of traversing cooler ram air to the ambient.

The air-condition loop serves to provide cooling to the evaporator, which allows for cooling of cabin air. This is done in a similar fashion to the cooling of the engine block. Refrigerant, the loop's fluid medium, is pumped at a low temperature from the condenser to the evaporator. As the refrigerant enters the evaporator, it gains thermal energy from exchanging heat with traversing cabin air. The refrigerant leaves the evaporator and returns to the condenser where it is cooled by ambient ram air. The refrigerant loses the gained thermal energy and can then return to the evaporator where the process is repeated.

The turbo-charging loop serves to provide cooling to the compressed intake air. As ambient air enters the turbo intake port, it passes through the turbocharger which compresses the air and becomes “charged”. This air, although at a high pressure, is not at the temperature that allows for maximum power output at the engine. **Figure 12** shows the effect that charged intake air temperature has on the amount of torque output of the engine. In general, the lower the charged air temperature air is the more power and torque output the drive wheels will receive. A charged air cooler, commonly known as an intercooler, is the component which provides this cooling to the charged air. The charged air is traversed by ambient ram air at the CAC and upon exiting the CAC has experienced a temperature drop that will provide for a higher vehicle power and torque output.

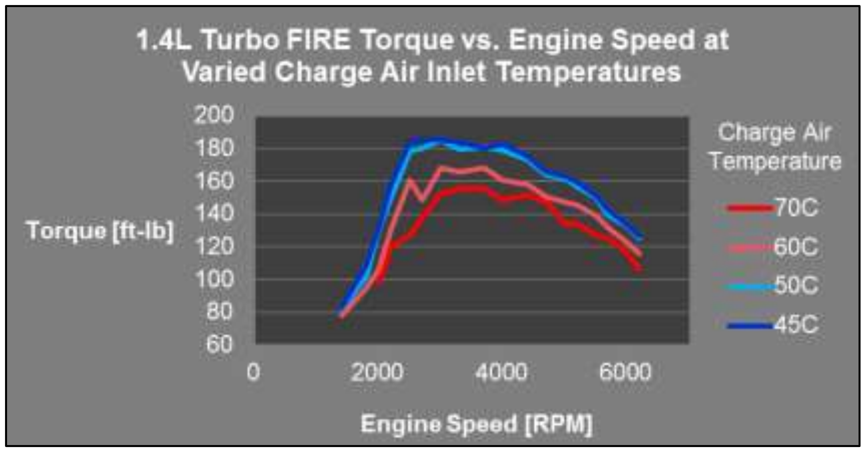


Figure 12 - Effect of air intake temperature on engine torque output

In the conventional TMS, each component that cools the loop’s fluid medium (the radiator, condenser, and charged air cooler) is all classified as an Air-Air heat exchanger. This means that each component cools the fluid medium by traversing vehicle ram air across the internal fluid medium. These three components will be further referenced at the front module or vehicle cooling module.

Dodge Dart TMS

The thermal management system that is employed on the Dodge® Dart operates in the same fashion that is stated above; it contains three different fluid loops previously mentioned. The schematic shown in **Figure 11** is the schematic for the thermal management system of the Dart. **Figure 13** shows the engine bay layout of the Dodge® Dart. Although it is hard to see each of the fluid loops within the TMS, callouts have been used to signal the general vicinity in which each is located.

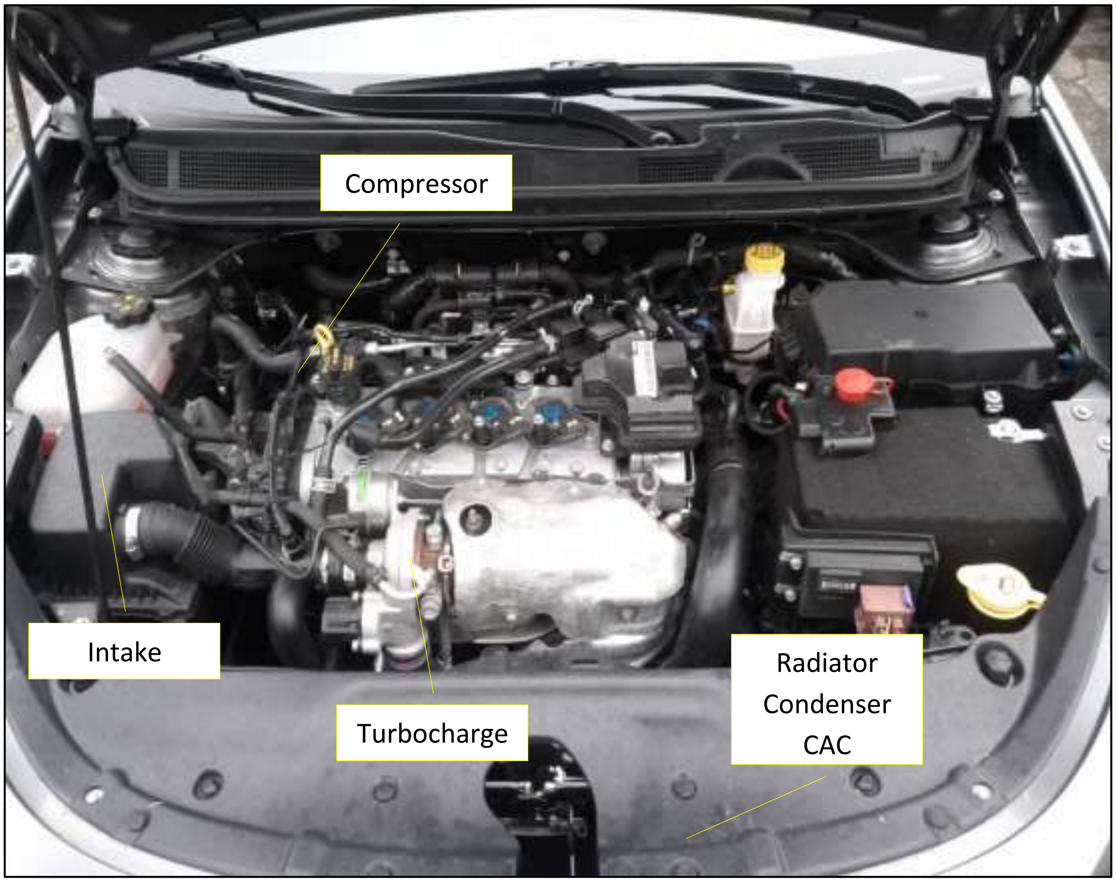


Figure 13 - Engine bay layout of Dodge Dart

Dual Level TMS Concept

The Dual Level TMS will introduce three new main components and a variety of additional components that are needed to make the total package operable. The engine coolant loop will remain the same as it was described in the baseline configuration. The air-condition loop and turbocharger loop will be the two loops that are changed. Each loop will see the addition of a new component and removal of one. Due to the implementation of new components, the overall layout of the two loops will change as well. However, due to the confidentiality of this project, only the general idea and layout of the system can be discussed.

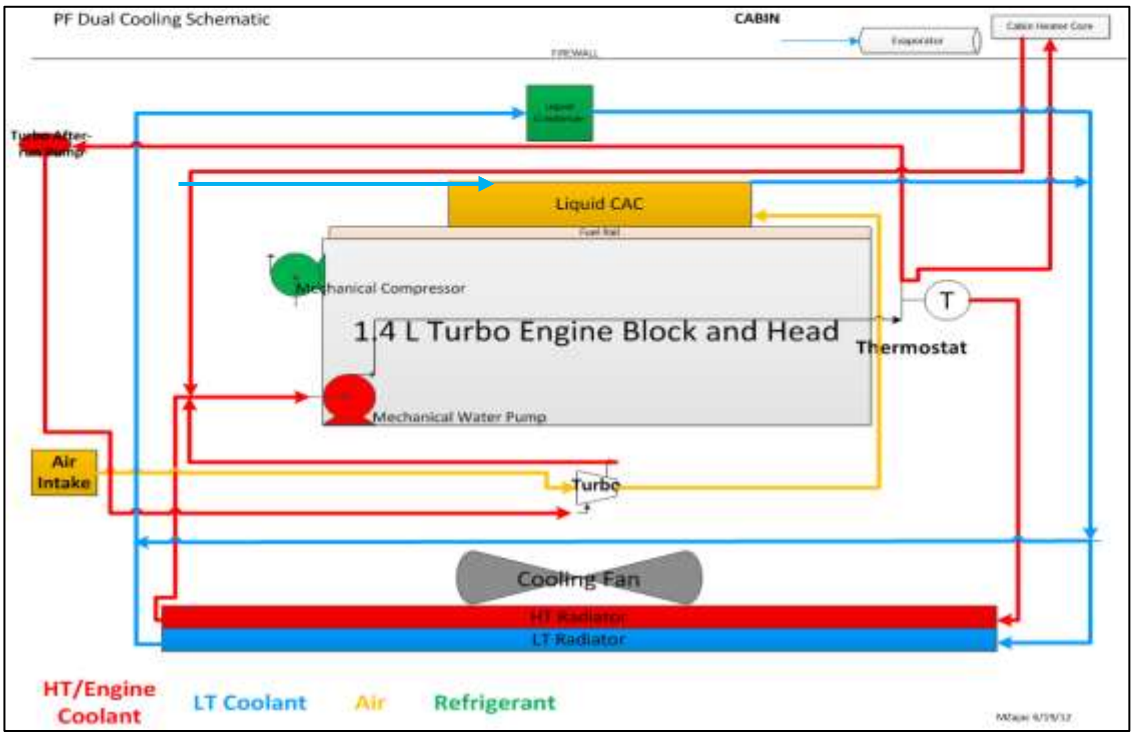


Figure 14 - Dual Level TMS schematic

The Dual Level TMS utilizes the addition of a low temperature radiator (LTR) that will supply cooling to a liquid cooled condenser (LCOND) and liquid cooled charged air cooler (LCAC). The LTR will be placed in front of the HTR and replace the space that was previously occupied by the ACAC and ACOND. **Figure 14** is the schematic for the proposed Dual Level TMS. The schematic depicts how the LCAC and LCOND will be placed in the same loop as the LTR. Although both the LCAC and LCOND will be placed inside a new loop, they will both still provide the same function to their respective loops. That is, the LCAC will still provide cooling to compressed intake air and the LCOND will still provide cooling the evaporator for cooling of cabin air.

Current Examples

This type of automotive cooling system is in its very early stages of development. This system design initiative is a product of the joint efforts between Fiat and Chrysler. Fiat has recently investigated this type of cooling system integration into one of their passenger vehicles. For this reason, they will serve as the standard for design. From their thermal management system design, they showed a slight increase of fuel economy and a positive impact on air conditioning cooling performance (Malvicino 2012). It also has allowed for the simplification and standardization of the front end module.

Benefits

A dual level cooling concepts offers many benefits to the manufacturer and consumer. Due to the transfer from an air-air cooling concept to a liquid to air cooling concept, each component can provide the same amount of cooling (as compared to the conventional design) with an overall decrease in power consumption. This results from the heat capacity of the desired liquid being greater than that of air. In other words, a smaller volume of liquid will provide the same amount of cooling as a greater volume of air. Since a smaller volume of liquid is achievable, the total size of the condenser and CAC can also be reduced.

The consumer sees the benefits of the decrease in power consumption by the increased fuel economy of the vehicle. The increased fuel economy also offers Chrysler a gain from the marketing perspective because consumers are more likely to purchase fuel efficient vehicles. The reduction of component sizing is also a plus for Chrysler because it offers more available engine compartment space from the reduction of component sizing.

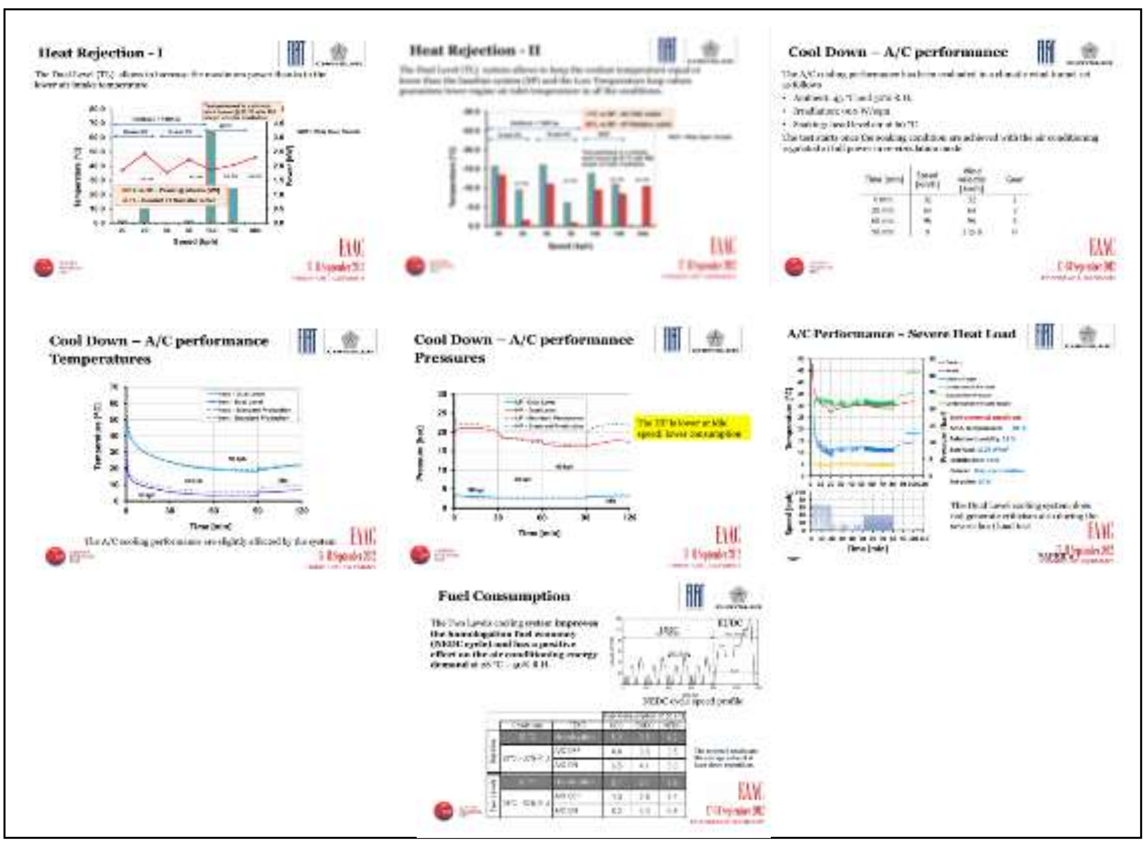


Figure 15 - CRF Benchmarking Results

There exists proof of added fuel economy, AC system, and performance benefits with dual level cooling as well. This has been demonstrated with the work CRF has completed and has proved to be a major resource for this project. Fuel economy, AC system, and performance results are shown in **Figure 15**. The heat rejection graphs show improvement in performance because of controlled, lower engine temperature capabilities. The AC system shows a large reduction in refrigerant pressures, amount of charge, and decreased cabin temperatures (the ultimate goal.) Fuel consumption, shown at the bottom of this figure, is also improved from baseline to dual level cooling. These results serve as the reasoning behind the feasibility of this project.

The benefits listed above will all be realized to an even greater degree through the calibration of specific engine components. Adjusting the vehicle fuel map, the torque and power curves of the engine, and other thermally driven and effected powertrain components will optimize the effects of the application of dual level cooling. It should be noted that the application of this project is to show, most completely, the ability to control and maintain engine charge air temperatures.

Design

Design Requirement

The requirement of this project is to completely integrate a Fiat thermal management system concept into a Chrysler vehicle. Integration requires the sizing and procurement of new system components to develop and analyze a Dual Level TMS. The development of a Dual Level TMS will be evaluated by an A-B comparison of overall system performance; specifically CAC and AC performance to show an overall reduction in power consumption. System integration is also evaluated on the packaging requirement (weight and volume) for each system.

Design Process

To implement a dual level cooling system into the test vehicle, there are a number of heat exchangers, valves, and pumps that need to be designed, specifically for the new low temperature circuit that is being introduced. This is needed because two of the existing components, the charged air cooler and condenser, are being redesigned. These components will no longer function with the conventional air to air cooling process, but with the liquid to air cooling process. Since Chrysler is not the company that heads up the design of all the new desired components, cooperation with outside suppliers is needed. Working with suppliers can be an iterative process to finally arrive at a component design that performs optimally within the system. The design process that was used to size the components for the dual level system is as follows (Hornback 2012):

Step 1: Define a design point for the thermal system. This design point represents a challenging condition for the thermal system. An example is:

i. Continuous 3000RPM

ii. 150Nm of torque

iii. 30°C ambient temperature

For the design point, the thermal management system must be able to withstand that design point for a continuous amount of time. However, this design point is not the worst condition the system could experience because that may only happen for a small percentage of the time that the system is operating. If the system was designed at the worst case scenario, it would be overdesigned for most of the time during normal operation. Heat rejection and pressure drop targets are also defined to give to the supplier.

Step 2: Contact the supplier to see if they have any products that already fit the system we are trying to build.

Step 3: If no components exist, the supplier sizes their products to meet the heat rejection and pressure drop targets for the defined design point.

Step 4: CAD models are given from the suppliers to see how the component will fit into the full engine and vehicle CAD model. The supplier also gives the performance map for the heat exchanger. This defines the heat rejection and fluid pressure drops at various steady state inlet fluid temperatures and flow rates.

The above four steps are completed for each heat exchanger, valve, and pump needed within the system.

Step 5: If all the components will fit into the CAD model, a fluid circuit simulation model can be created using Flowmaster.

Step 6: Run the model simulation to see how each component works together within the system. By analysis of the outputs, the need for any design changes to a component can be determined. If changes are needed, go back to Step 3.

Step 7: Once each component has been verified within the CAD model and simulation model, the design becomes "frozen". The supplier gives a quote for the desired components and the affordability is considered.

Step 8: If the quote looks affordable, a purchase order is sent to the supplier and a MRD (Materials ready for development) date is established.

Once each component had arrived at Chrysler facilities, the build of the dual level thermal management system could be started. With the new thermal management system installed into the vehicle, the same testing sequence could be completed to

However, before the build could begin the baseline system had to be evaluated to provide results for comparison between each system at the end of the project. The testing of the baseline configuration yielded results that could establish performance points. These performance points were used within the comparison of current production and possible future production systems as the level sought to be over achieved.

Controls Development

The addition of actuated devices to the system demands the use of a new, state of the art controls strategy. For the purpose of this project, the advanced powertrain controls development team at Chrysler was utilized. The nature of their controls strategy cannot be fully disclosed because of the possible Intellectual property, but the general principle behind the control scheme can be discussed.

It is common knowledge to those involved with thermal design, that **Equation 1** is used to for determining the total heat rejection across a temperature gradient when the mass flow and specific heats are known. In the same sense, specific heat can be determined if mass flow and the temperature gradient are known. Lastly, mass flow can be determined if the specific heat of the fluid in question as well as the temperature gradient are known. This is the strategy employed here.

The control scheme revolves around the calculation of mass flow: 1) based on predictions and calibrations for the temperature gradient across the liquid cooled charge air cooler, and thus total heat rejection projections across that component, as well as; 2) based on predictions and calibrations for the heat rejection across the liquid cooled condenser based on a specific relationship derived between component heat rejection and current instrumented HVAC measurements.

Again, the specific details of this NEW strategy cannot be explicitly discussed as the full development is still underway. At this point, the control system has been used in a manual fashion. In order to implement this scheme on the vehicle, Intecrio, an ETAS software and hardware configuration has been utilized. Intecrio acts as a parasitic control mechanism. That is, using the ETK, the Intecrio software attaches itself to the original engine controller and allows for additional parameters to be added to and/or read from the control of the engine itself. In this case, Intecrio affects the way the grille shutters and engine cooling fan behave by adding additional responsibilities (cooling the low temp circuit) to its logic. Automated control will come, but for now, fan duty cycle, grille shutter opening, pump speed, and the position of the

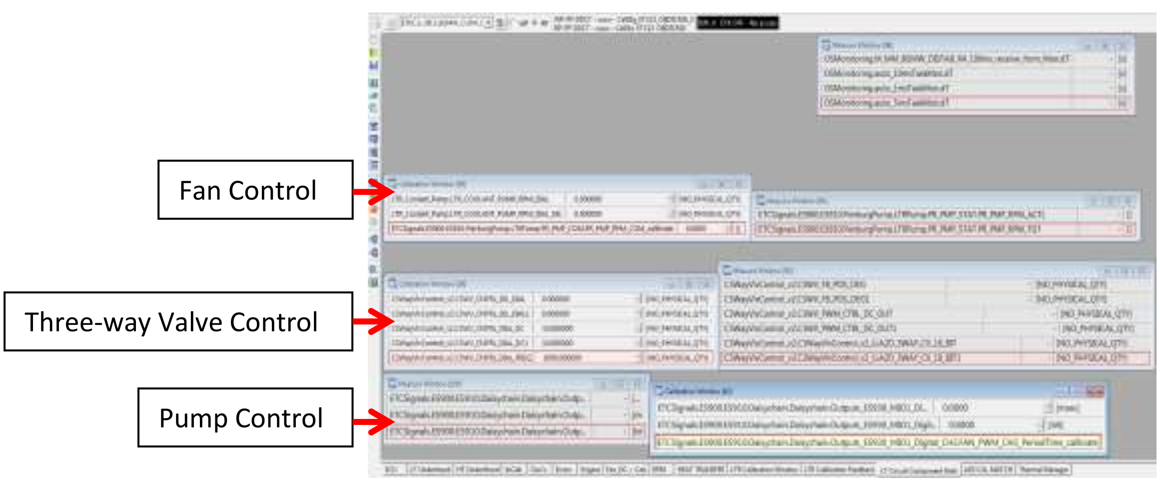


Figure 16 - Inca Experiment: New Device Control

two three-way valves is controlled on the screen shown in **Figure 16** below.

The manual controllability of these components is very important to the final stages of the project as far as the control strategy is concerned. Because much of the control logic is based on component data sheets as provided by each component supplier, calibration of the model is no only important, but essential to the accuracy of the model when it reaches the automated stage. By manually dialing the components and verifying temperature, pressure drop, and flow values of the system, the data sheet information relating specifically to heat exchanger effectiveness can be verified and/or adjusted appropriately so as to accurately model the system.

Testing

One of the most important parts of this report's validation and verification of the Dual Level Cooling system rests on the successful completion and analysis of experimental vehicle testing for the baseline thermal management system. From the information obtained during this portion of the project, conclusions can be made in regards to the validity of the aforementioned Flowmaster model and, thus, the final VehEbalance simulation model used for predicting vehicle fuel economy.

The sections below describe the specific tests, broken into three distinct categories: Fuel Economy Tests; Performance Tests; and Climate Tests. Furthermore, the second portion of this section takes an in depth look at the instrumentation strategy used in outfitting the baseline PF vehicle. Next, the results of the baseline test procedures are documented and analyzed. Finally, the results of the Dual Level Cooling tests are documented and analyzed at the end of this section. The conclusions about the improvement of the overall powertrain thermal management system are characterized based on the analysis and comparison between the two rounds of vehicle testing that are described here.

Test Description

The subsections for each category of test below include a table showing: how each test is run; test purpose; and acceptance criteria for each test. A description of the importance and interpretation of specific monitored variables follows each table and represents the basis for the A-B comparison to be completed by simulation models for this project and experimentally in work to follow.

Performance

Performance tests are completed on the outdoor track at CPG. The Straightaway and Oval were the primary location of this outdoor testing. Before testing commences, the vehicle is warmed up by driving steady state laps around the oval before moving to the Straightway to begin the testing procedures. These tests are meant to serve as a baseline analysis of the system in order to compare, and verify, the improvement when applying the Dual Level Cooling scheme. The performance test descriptions, purposes, and acceptance criteria for each test are summarized in **Table 1** below:

PROCEDURE OR STANDARD	TEST DESCRIPTION	PURPOSE	ACCEPTANCE CRITERIA
Coast Down	1)Vehicle instrumented 2) Vehicle & driver weighed 3) Vehicle driven to 70 MPH 4) Shift to neutral 5) Split Coast Down - Coast down from 70 to 45 MPH, 45 to 10 MPH 6) Record data; use to derive Polynomial Force Coefficient from velocity, time and mass	Necessary to set chassis dynamometer road load to reflect actual vehicle characteristics - Aero drag, tire roll resistance, wheel bearing and brake drag, axle and trans spin loss, drivetrain inertia	Results of production vehicle, range of production values
0-100 (saej1491)	Perform wide open throttle (WOT) accelerations from a standing start and record the following: • Launch Response Time (Control Input to Initial Vehicle Movement {IVM} - 1 foot traveled) • Acceleration Response Time (IVM to test end speed) Also perform the following test at wide-open-throttle: • 64 to 97 km/h (40 to 60 mph) – Elapsed Time	Measures launch response and acceleration performance	A-B increase in performance for Acceleration Response Time - results comparable to CRF results
In Gear acceleration test	Rolling 1krpm (4th and 6th) --> Accelerate to 100mph/5k	Comparison of time to boost curves; to evaluate effect on Time-to-boost and turbo-lag	A-B increase in performance for Time to MAP

Table 1 – Performance test descriptions, purposes, and acceptance criteria for each test from DVP&R. In depth DVP&R is included in Appendix B

As shown in the table above, the Coast Down is the first and most crucial of all road/performance tests. It allows for accurate drive cell test completion by determining the aerodynamic drag and other losses that exist in this specific test vehicle. This is important so that when fuel economy tests commence within vehicle drive cells, the cell rollers are calibrated in such a way to represent actual vehicle movement on the open road. While this test follows the general description as portrayed in the table above, a complete test description is found in the “US Coast down Testing and Reporting Process: As performed at Chelsea Proving Grounds” presentation available ONLY to Chrysler employees with access to the CPG Perfec network. The results of this test are what are known as Coast Down Coefficients.

The “0-100 (saej1491)” test is a wide-open-throttle (WOT) test that measures the acceleration and launch performance for a vehicle moving from rest until it reaches the 100 mph mark. The critical variables that are monitored in this test are:

- Launch response time – time for the vehicle to move one foot (initial vehicle movement – IVM)
- Acceleration response time – time between IVM and end of test
- Time to Manifold Absolute Pressure (MAP) – the MOST important variable measured with respect to the performance testing portion of the A-B comparison of technology. MAP is a measure of air pressure within the engine intake manifold

Time to MAP is important because it is directly related to the mass flow of the charged air entering the vehicle engine. The shorter the time required to get the air in the engine intake manifold charged to its maximum achievable value, the faster that charged air can be injected into the engine and the faster power will be generated and applied to the drive wheels. This change in time to boost effectively eliminates the contribution of sluggish air flow to what turbocharged vehicle drivers known as “turbo-lag.”

The In Gear Acceleration Test is a straight forward test that sets out to measure one variable: Time to MAP. This test provides a better overall representation of the characteristic of time to MAP because it effectively eliminates the other factors that contribute to the recording of this time. In a standard 0-100 WOT test; other factors come into play in determining the time it takes for the vehicle to accelerate and reach MAP; such variables as pedal decompression and throttle body opening. The In Gear Acceleration Tests starts with partial pedal decompression and an atmospherically pressurized throttle bottle. Thus, this test monitors strictly the travel of cooled charged air into the engine intake.

In terms of the second round of testing, two more tests will be added to the list. These two tests are known as “V max” and “Davis Dam”. “V max” is a test that is used to characterize system capacity at steady state, high load, high velocity conditions. The test is run at maximum velocity until steady state conditions are achieved. This test will be compared to CRF results in order to verify the capacity of this new system and that the heat exchangers, specifically the LTR, are adequately sized. The same is true for “Davis Dam”. It is run under full load, with a trailer, in high ambient conditions, again monitoring system capacity under such conditions to be compared to CRF test data.

Fuel Economy

Fuel economy tests are completed in the drive cells on large dynamometers at CPG. These cells, using the Coast Down coefficients determined from performance testing, allow for specific drive cycles to be driven with vehicle. In order to run these tests, a driver sits within the vehicle while it is strapped down to a large dynamometer and follows a trace as generated on a digital screen by appropriately functioning between the accelerator and brake pedals. The specific drive cycles can be varied from cell to cell. Some cycles require a “cold start” which is characterized by starting the vehicle for the first time within the drive cell and not allowing any pre-test warm up time. The fuel economy test descriptions, purposes, and acceptance criteria for each test are summarized in **Table 2** below.

PROCEDURE OR STANDARD	TEST DESCRIPTION	PURPOSE	ACCEPTANCE CRITERIA
FTP-75	ran on dynamometer, city cycle, transient cycle, 10 min pause, highway cycle, 22°C	city mpg, highway mpg, averaged mpg	Baseline to Dual Cool improvement - 1-2% increase in fuel economy
SFTP-US06 22°C	The US06 Supplemental Federal Test Procedure is used in addition to the above-mentioned FTP-75. The US06 simulates aggressive acceleration, higher speed driving behavior. Also included are rapid speed fluctuations and driving behavior following start-up. The cycle takes 596 seconds (nearly 10 minutes) to complete, with a total distance of 8.01 miles travelled. The maximum speed of the cycle is 80.3 mph. The average speed of the cycle is 48.4 mph.	To compensate for the shortcomings of the FTP-75 that includes aggressive high speed driving.	Baseline to Dual Cool improvement - 1-2% increase in fuel economy
SFTP-US06 35°C	Same as 004, but at higher temperature	To evaluate the benefit of a liquid cooled CAC	Baseline to Dual Cool improvement - 1-2% increase in fuel economy
SFTP-SC03	The US SC03 Speed Correction Driving Schedule is used in addition to the above-mentioned FTP-75. It simulates urban driving and engine load with the air-conditioning unit turned on for the entire duration of the test (A/C fan speed to be determined). The cycle takes 596 seconds (nearly 10 minutes) to complete, with a total distance of 3.6 miles travelled. The maximum speed of the cycle is 54.8 mph. The average speed of the cycle is 21.6 mph. 35°C	To compensate for the shortcomings of the FTP-75 that includes the use of air conditioning.	Baseline to Dual Cool improvement - 1-2% increase in fuel economy
FTP-20 COLD Test (20°F)	ran on dynamometer, city cycle, transient cycle, 10 min pause, highway cycle	city mpg, highway mpg, averaged mpg - for five cycle	Baseline to Dual Cool improvement - 1-2% increase in fuel economy
NEDC at 20°C	The entire cycle includes four ECE segments, repeated without interruption, followed by one EUDC segment. The urban economy is measured using the test cycle known as ECE-15. It simulates a 2.518 mile urban trip at an average speed of 11.6 mph and at a maximum speed of 31 mph. The extra-urban cycle or EUDC lasts 400 seconds (6 minutes 40 seconds) at an average speed of 39 mph and a top speed of 74.6 mph.	Comparison to European Standards	Baseline to Dual Cool improvement - 1-2% increase in fuel economy

Table 2 – Fuel Economy test descriptions, purposes, and acceptance criteria for each test from DVP&R. In depth DVP&R is included in Appendix B

The tests highlighted in **tan** (FTP-75, SFTP-US06 22°C, SFTP SC03, and FTP-20) represent those that are used in deriving the EPA 5-Cycle rating for emissions. The EPA 5-Cycle rating is determined by a weighted Litmus Test that is established by the Environmental Protection

Agency (EPA). This calculator information is attached in the **appendix**. The other two tests, highlighted in **grey** (SFTP-US06 35°C and NEDC at 20°C), represent tests specific to this study that are being used to compare alongside CRF specific data as well as evaluating the specific benefits of components to be replaced within the Dual Level Cooling system. These tests are meant to serve as a baseline analysis of the system in order to compare, and verify, the improvement when applying the Dual Level Cooling scheme.

As mentioned in the table above, the FTP-75, also known as the EPA City and Highway test, is comprised of a standardized city drive cycle, a 10 minute pause, and concluded with a standardized highway cycle. This "cold start" test, characterized as such by the fact that the engine is started for the first time at the beginning of the test, is used by ALL manufacturers who sell vehicles in the United States in order to all be measured by the same standard. This test, along with all other drive cell tests, uses exhaust particulates in order to calculate the overall vehicle fuel economy. This test, broken into two separate tests when considering the overall vehicle 5-cycle rating, plays a significant role in the calculation of that number. Efficiencies of the new, Dual Level Cooling components will impact the overall vehicle fuel economy.

The US06 test is a variation, as mentioned in the table, of the EPA city/highway test. It takes into consideration an aggressive standardized driving cycle. The test applies rapid acceleration and reaches a maximum speed of around 80 miles per hour; simulating speeds that are more applicable as United States road speeds. This test helps to identify gains in fuel economy as a result of a variation in charge air cooling components. The reason for the US06 test at a high ambient temperature (35°C) is to evaluate the performance and effect on fuel economy of the LCAC. Because these tests were run with AC on, it will also be a useful test in order to evaluate the LCOND performance.

Similar to the purpose of the US06, the SC03 test is run as a variation to the EPA city/highway test. Instead of focusing on engine performance, this test is run with AC on and over a standardized drive cycle. This test, along with the US06 test, compensate for the shortcomings of the EPA city/highway test in the way that they more closely relate to "real world" situations the impact fuel economy.

The last contributor to the 5-cycle rating is the FTP-20. This follows the same drive cycle trace as the EPA city/highway test. The difference is, this test, rather than being run at the standard 22°C temperature, is run at a temperature of -6.67°C. The purpose of this test is to compensate for the shortcomings of the EPA city/highway with respect to temperature. "Cold starts", in general, require a lot of energy and have a significant impact on the vehicle fuel economy. This is especially true as ambient temperatures decrease because of the temperature difference between the optimum engine operating temperature and ambient temperature increases; requiring more fuel to provide energy to bride this gap.

The NEDC test is the European EPA city/highway equivalent test. It takes into considerations an urban and extra-urban (city and highway) cycle. As is mentioned in the table on the previous page, this test consists of four continuous urban/city cycles (ECE-15) followed by an extra urban/highway cycle (EUDC). This test is run in order to correlate with the results found by CRF on their own test vehicle.

Climate

Among the three stages testing completed, climate testing is arguably the most ignored yet has the most direct impact on car buyers. Because of the acknowledgment of the importance of this phase of testing, Chrysler AC system engineers were used as direct references for the test selection, instrumentation (to be discussed in the next section), and understanding of test results. The overall purpose of these climate tests are to understand the capacity of the AC system; particularly the condenser. These tests are meant to serve as a baseline analysis of the system in order to compare, and verify, the improvement when applying the Dual Level Cooling scheme.

Baseline Instrumentation

In order to fully understand the operation of both baseline and dual level cooling components, thermal and pressure conditions around each component must be understood, along with the flow characteristics of the fluid medium. This implies that temperature readings must be completed upstream and downstream of each component. The same is true about the pressure of the fluid medium. In the case of understanding flow rate, it is important to have one flow meter per fluid circuit in a location that captures the flow to the component under investigation.

In terms of the instrumentation orientation on this PF vehicle, it will be the first instrumented PF to achieve the thoroughness of data acquisition required for a full understanding of the entire

Baseline Instrumentation List - 1.4L Turbo Dual Cooling Project				
UNDERHOOD				
TC	Baseline	17	type k	
PRESSURE TRANSDUCERS	Baseline	16	11	0-75psi
			5	0-500psi
FLOW METERS	Baseline	2	One - 1 1/4"	
			One - 3/8"	
IN CABIN				
VENTS		4	type k	
FLOOR		4	type k	
CEILING		4	type k	
STICK-MAN		1	type k	
TOTALS				
TC		29	type k	
PRESSURE TRANSDUCERS		11	0-75psi	
		5	0-500psi	
FLOW METERS		2	One - 1 1/4"	
			One - 3/8"	
STICK-MAN		1	type k	

Figure 17 – Baseline Instrumentation Lists

system operation. In all, there are 29 thermocouples and 1 Stickman (a climate test tool with multiple type k thermocouples), 16 pressure transducers, and 2 flow meters.

Figure 17 shows the number of sensors used in each vehicle configuration. Appendix D shows a detailed list of all instrumented channels including the channels used on the vehicle ECU for engine control variables.

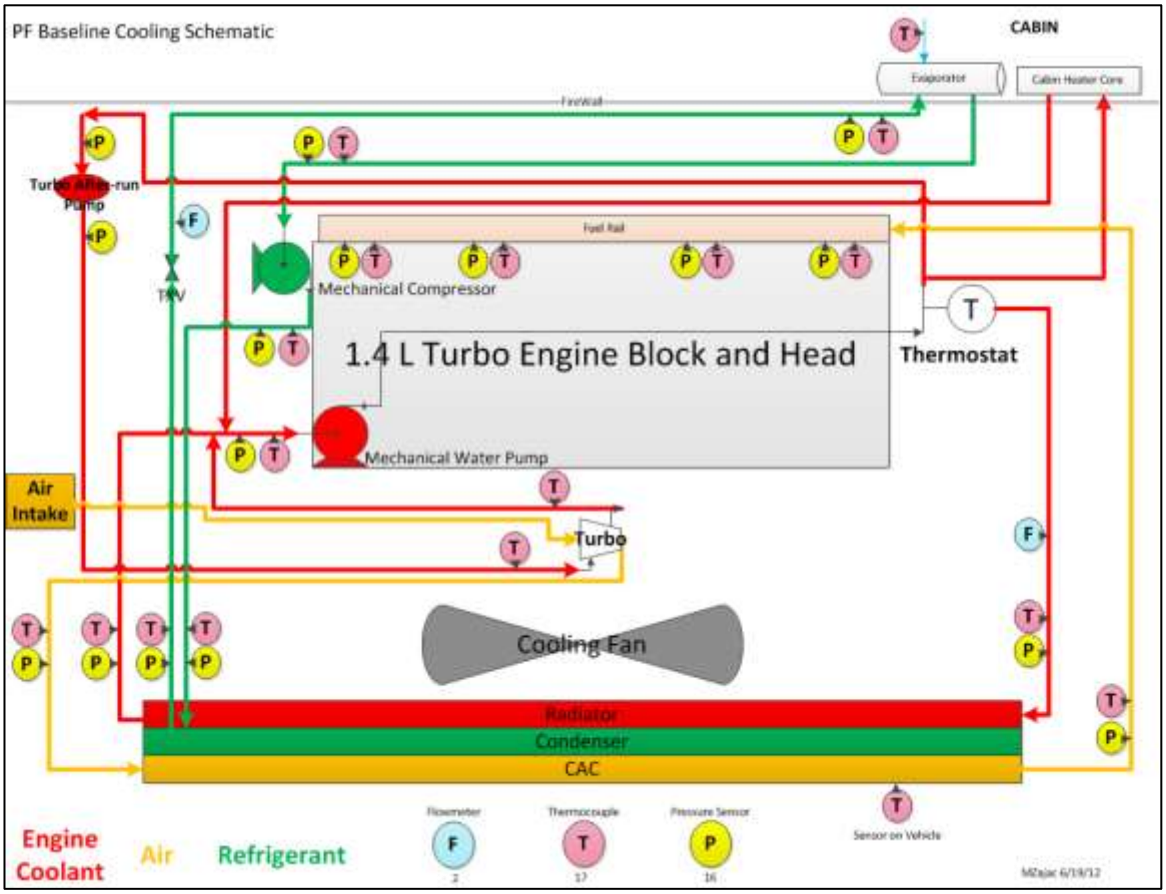


Figure 18 - Baseline Instrumentation Schematic

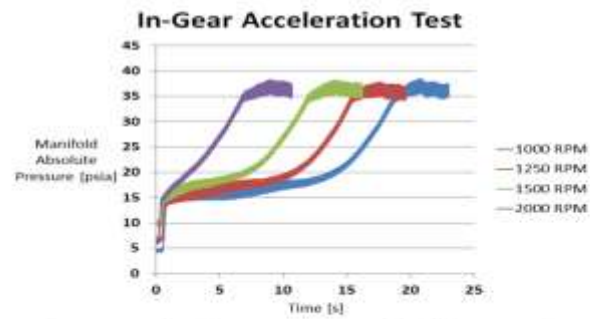
Figure 18 shows the instrumentation schematic that is unique to this project. Shown in the figure are ONLY the under-hood component thermocouples, pressure transducers, and flow meters. A similar schematic has been created for dual level cooling, but because it contains information of a proprietary nature, cannot be depicted in this report.

Baseline Results

Below are the results of important characteristics of each type of baseline test. Because the climate testing has not been fully completed to date, the climate portion examined for this line of testing comes from the SC03 test results. Plots are followed by an interpretation of these test results.

Performance

Time to Boost is shown in **Figure 19**.



Gear 4 Starting Engine Speed [rpm]	Baseline Time to reach max MAP [s]
1000	20.4
1250	17.1
1500	13.6
2000	8.6

Figure 19 - Baseline Time to Boost Results

ACT is shown in **Figure 20** for the HOT US06 test.

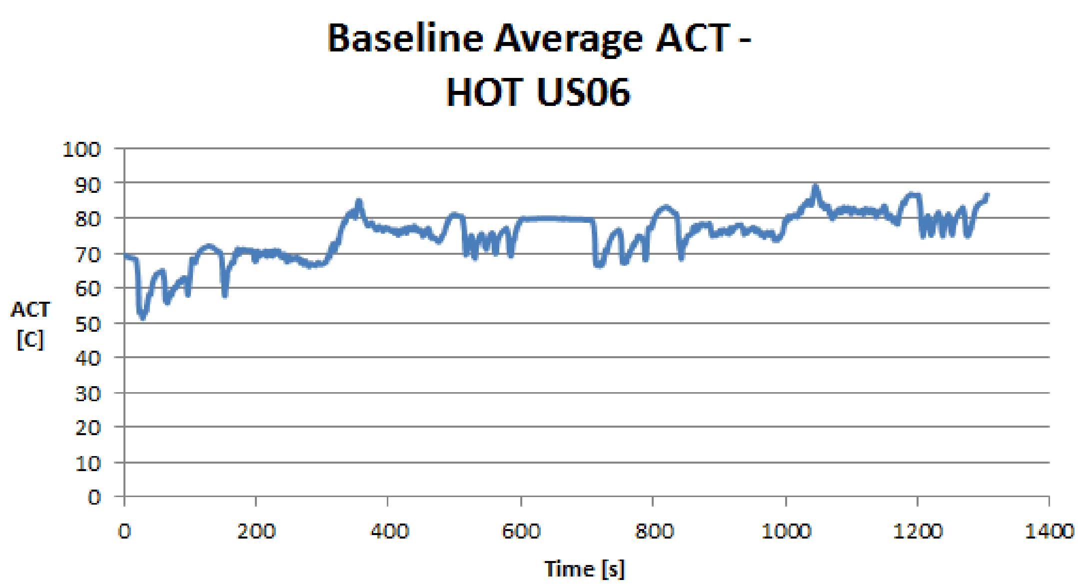


Figure 20 - HOT US06 Baseline ACT

Fuel Economy

Fuel Economy results shown in Table 3.

Test	Baseline Results [mpg]
FTP 75	24.3
HWFE	34
EPA CTY/HWY	28
US06	28.3
SC03	22.6
HOT US06	23

Table 3- Baseline Vehicle Fuel Economy Results Compiled

Climate

AC system condenser outlet pressure, cabin temperatures, and cooling fan duty cycle due to AC pressure demand are plotted below in **Figure 21**, **Figure 22**, and **Figure 23** for the SC03 drive cycle.

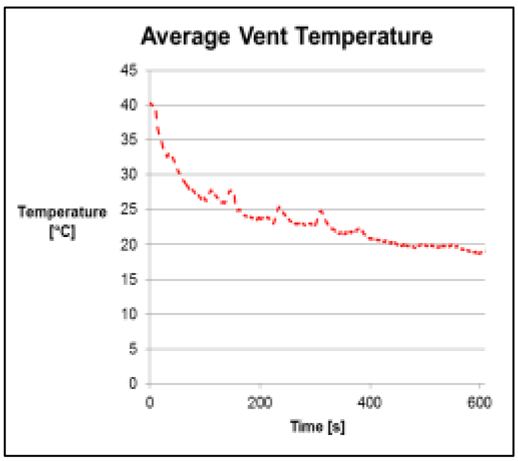


Figure 21 - Average Cabin Vent Temperature - SC03

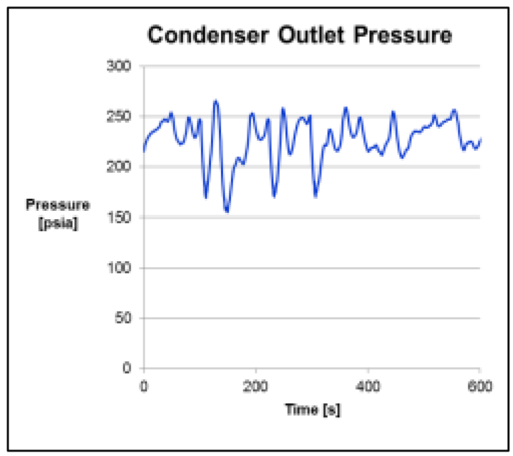


Figure 22 - Condenser Refrigerant Outlet Pressure

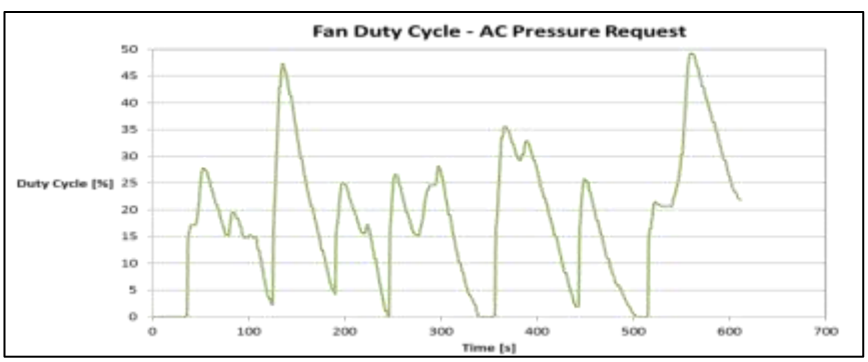


Figure 23 - Cooling Fan Duty Cycle Response from AC System Demand

Baseline Testing Validation: Comparison with production testing results and Statistical Analysis

Baseline tests were compared using MiniTab 16. The standard deviation of the sets of three separate tests were analyzed after being scaled according to the standards practiced by the CPG Performance group. The values for fuel economy were found to be within the statistical bounds of accuracy.

Equation	Description
$\bar{y} = (\Sigma x_i) / n$	*Mean Value Calculation* $\bar{y}$ = Mean x_i = Measured Value n = Number of Measured Values
$\sigma = \{ [\Sigma(x_i - \bar{y})] / n\}^{(1/2)}$	*Standard Deviation Calculation* σ = Standard Deviation from the Mean $\bar{y}$ = mean x_i = measured value n = number of measured values

Table 4 - Table of Statistical Comparison Equations

Interpretations of Results

It will be important to compare these results to the dual level cooling and simulation results. As of now, it is important to note that these results are, on average, slightly lower than what is expected from the baseline vehicle. Also, in Appendix C is the EPA FE calculator used to determine the 5-cycle rating of this particular PF. While this test failed (a rating used by the EPA to award credits for fuel efficient vehicles) the production level vehicle passed. Should Dual Level Cooling result in passing Litmus test results, this will yield the understanding of a realized improvement of vehicle fuel economy with a dual level cooling configuration.

Dual Cooling Instrumentation

The second round of testing for dual level cooling is set to include four additional thermocouples, six additional pressure transducers, and two additional flow meters.

Dual Level Instrumentation List - 1.4L Turbo Dual Cooling Project				
UNDERHOOD				
TC	Dual Cooling	21	type k	
PRESSURE TRANSDUCERS	Dual Cooling	22	17	0-75psi
			5	0-500psi
FLOW METERS	Dual Cooling	4	One - 1 1/4"	
			Three - 3/4"	
IN CABIN				
VENTS		4	type k	
FLOOR		4	type k	
CEILING		4	type k	
STICK-MAN		1	type k	
TOTALS				
TC		33	type k	
PRESSURE TRANSDUCERS		17	0-75psi	
		5	0-500psi	
FLOW METERS		4	One - 1 1/4"	
			Three - 3/4"	
STICK-MAN		1	type k	

Figure 24 - Dual Level Cooling Instrumentation List

Dual Level Cooling Results

For the purpose of this report, only two experimental test results are covered. The purpose of selecting only two results is in order to establish the fundamentals behind this technology, without giving too much information about the specifics of this Chrysler LLC sponsored project. Thus, this report will focus only on performance tests and the Hot US06 test looking at ACT, namely, as well as fuel economy improvements on this cycle as they compare to the use of liquid cooled charge air cooling over air cooled charge air cooling.

Performance

Vehicle performance, as is someone intuitive, depends on many factors. To safely say that intake air characteristics directly impact vehicle performance is true, however, other contributing factors must be understood in order to appropriately characterize the effect of intake air parameters on a vehicles final performance. That being said, this performance section will illustrate parameters such as ACT, engine RPM, and MAP.

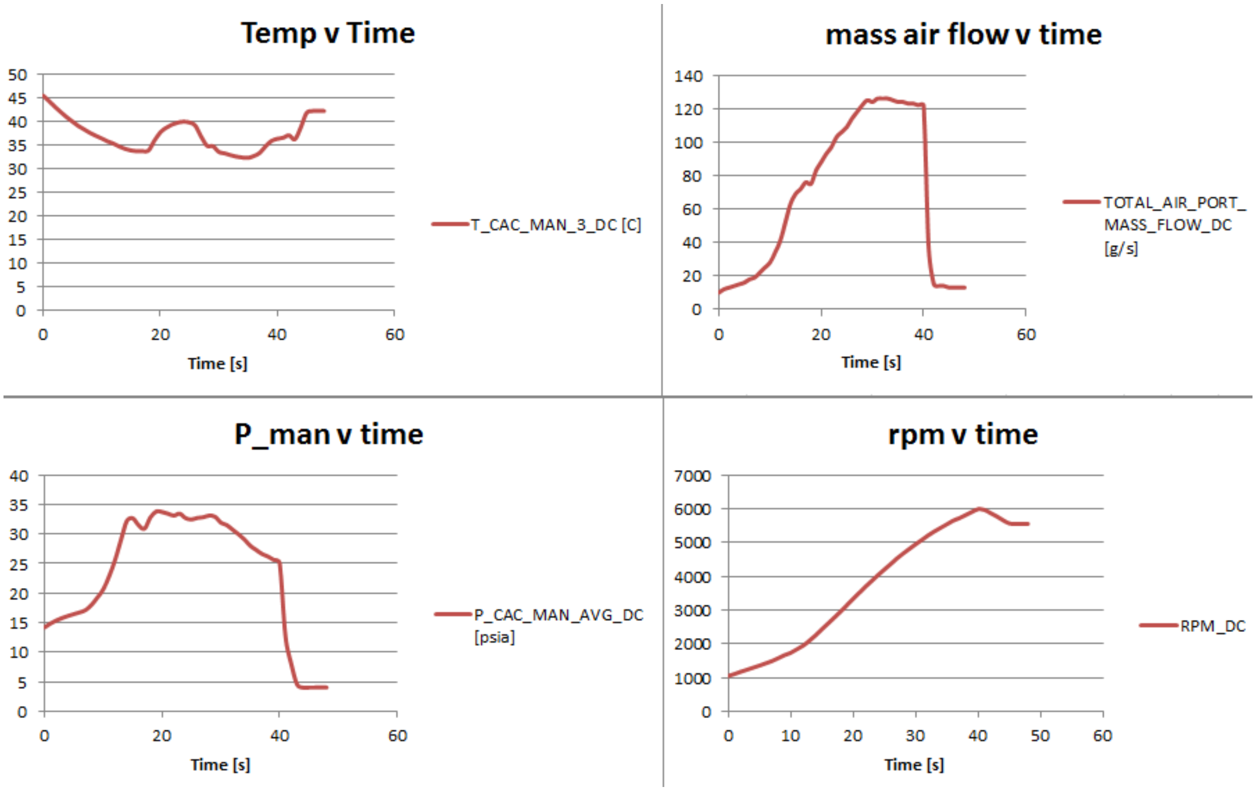


Figure 25 - WOT Performance for Dual Level Cooling

Fuel Economy

Much like vehicle performance, if not more-so, vehicle fuel economy depends on many more factors than just intake air characteristics. For the purpose of this report, the two main parameters identified as driving factors in fuel consumption are ACT and Fan Duty Cycle (characterized by duty cycle). Only test realized at this time is the HOT US06 test. This is an important test because of its high ambient thermal conditions as well as it aggressive drive

Test	Dual Cooling Results [mpg]
HOT US06	28.4

Figure 26 - Dual Level Cooling Fuel Economy

cycle. Fuel economy results are shown in **Figure 26** below.

ACT is shown in **Figure 27** for the HOT US06 test

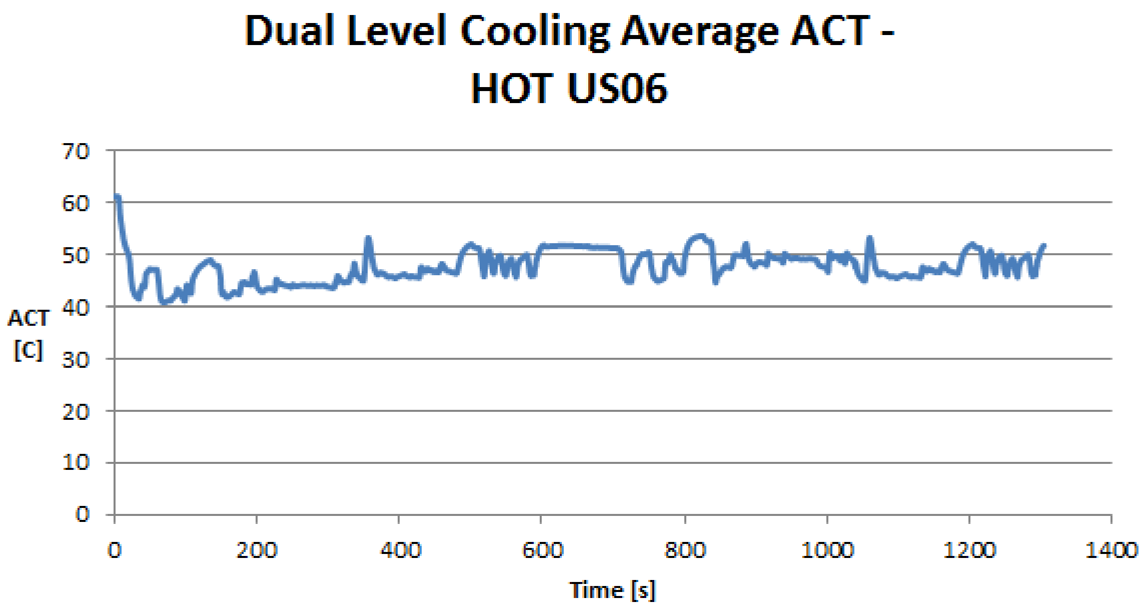


Figure 27 - HOT US06 Dual Cooling ACT

Dual Level Cooling Testing Validation: Statistical Analysis

Dual Level Cooling tests were compared using MiniTab 16. The standard deviation of the sets of three separate tests were analyzed after being scaled according to the standards practiced by the CPG Performance group. The values for fuel economy were found to be within the statistical bounds of accuracy based on equations within Table 5.

Equation	Description
$\bar{y} = (\Sigma x_i) / n$	*Mean Value Calculation* $\bar{y}$ = Mean x_i = Measured Value n = Number of Measured Values
$\sigma = \{ [\Sigma(x_i - \bar{y})] / n\}^{(1/2)}$	*Standard Deviation Calculation* σ = Standard Deviation from the Mean $\bar{y}$ = mean x_i = measured value n = number of measured values

Table 5 - Table of Statistical Comparison Equations

Interpretations of Results

In general, the Dual Level Cooling scheme has performed as expected. ACTs are lower and more steadily maintained throughout the duration of a given test and/or performance maneuver. The comparison of the two systems will be characterized below. Climate testing has not yet been realized, BUT similar resulting improvements are expected.

System Comparison

This section includes the comparison of the physical make up of each configuration as well as an analysis of the dual level cooling experimental results with respect to actual baseline experimental results. Also contained in this section, are the works going into the initial and the second stages of the simulation efforts. It is important to note that the area in which these systems are compared in terms of vehicle dynamics is by way of fuel economy in the simulation section.

Experimental Results Comparison

Performance results provide evidence that more understanding of the vehicle powertrain is needed. The results show only a slight improvement in areas like MAP, Time to Boost, and Time to RPM. Additional work will go into the integration of existing powertrain components and the new Dual Level Cooling components. The results in regards to these parameters are characterized graphically below.

The parameters shown that respond as expected are: Time to Boost, mass air flow versus time, and temperature versus time. There is an error that can be seen with respect to air flow and pressure, however. The MAP does not reach the same value in the Dual Cooling test as it does in the Baseline test. At the point where it essentially “dies off”, the mass air flow drops as well.

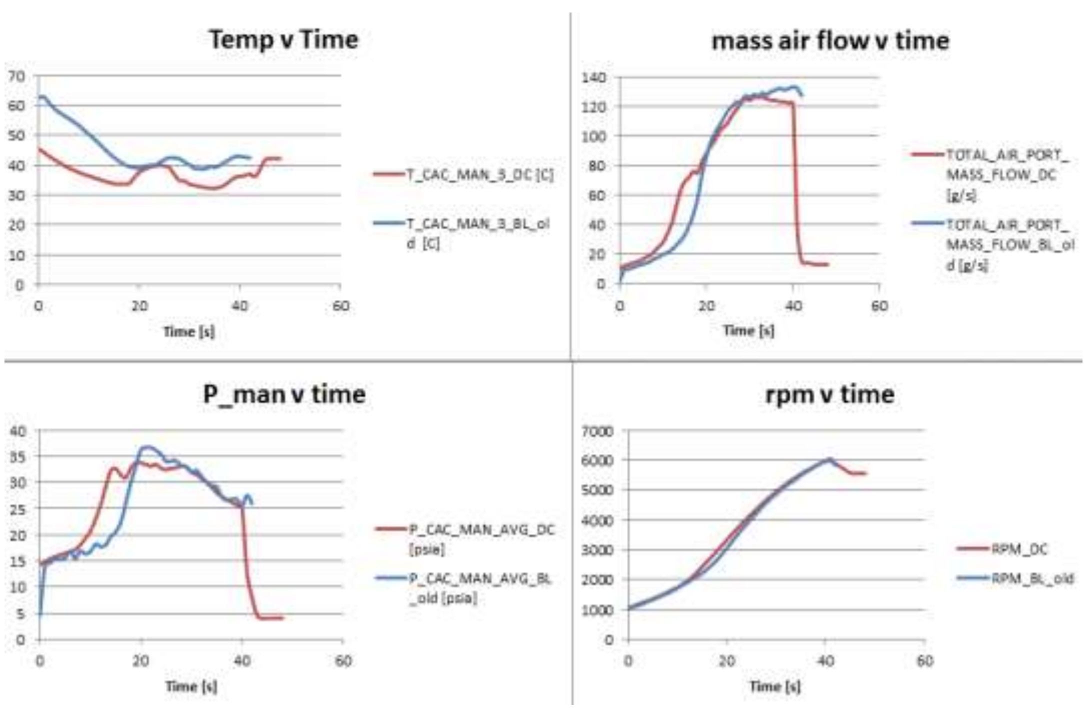


Figure 28 - WOT Test Performance Parameters Comparison

This connection is not by coincidence. It can be pointed out that there is a mechanical issue that occurs here. HOWEVER, the overall time to boost max is improved (2 seconds) as expected from the bench marking process. Final characterization will occur when the vehicle integration can be completed. Changes in ACT are governed by the equations in Table 6. Reductions in time to boost; pressure vs. time, mass air flow vs. time, and rpm vs time are all directly vary with the volumetric reduction in intake line size as described in the mass and volumetric comparison section of this report.

Equation	Description
$Q = m_{dot} * C_p * \Delta T$	*General Equation for Heat Transfer* Q = heat transfer m_{dot} = mass flow rate of medium C_p = constant pressure heat transfer coefficienct of medium ΔT = Difference in two medium temperatures
$Q_c = h_c * A_c * \Delta T$	*General Equation for Heat Transfer* Q_c = convective heat transfer h_c = convection heat transfer coefficient A_c = cross-sectional area ΔT = Difference in two medium temperatures

Table 6 - Table of Heat Transfer Equations

Fuel economy results provide are promising. The results show an improvement of 5 miles per gallon. It is understood that ACT and Fan Duty Cycle (characterized by fan speed here) are major fuel consumption factors. These values dramatically improved. Because of the overall dramatic improvement, much more will go into determining the reason behind said improvement and additional tests to ensure accuracy. The results in regards to these parameters are characterized graphically below.

Test	Dual Cooling Results [mpg]	Baseline Results [mpg]
HOT US06	28.4	23
FE Delta	5.4 mpg	
FE Percent Improve	23%	

Figure 29 - HOT US06 FE Comparison

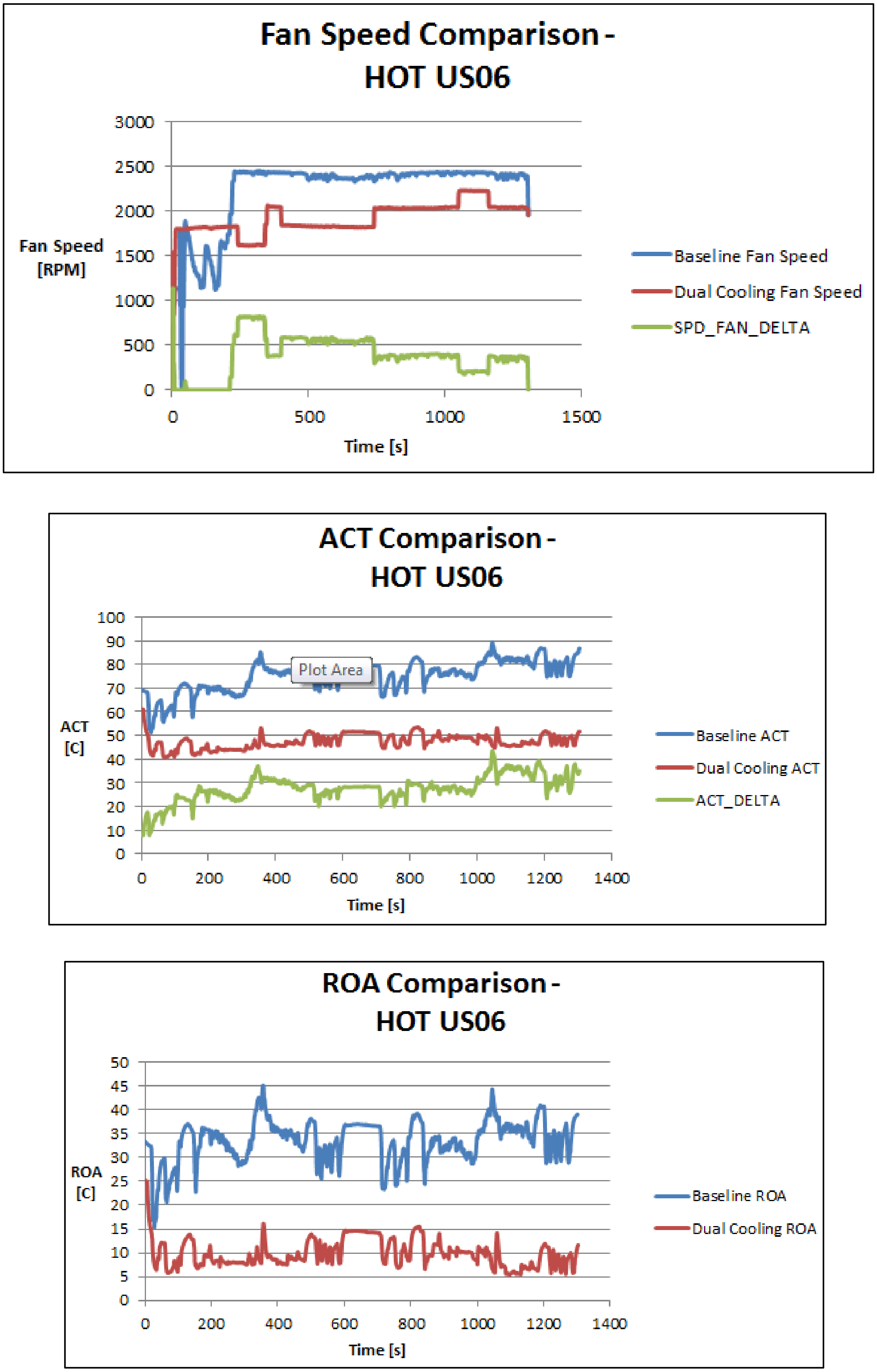


Figure 30 - Comparison of ACT and Fan Speed Results during HOT US06

Effectiveness Study

In understanding the effectiveness of the baseline versus dual level cooling heat exchangers, the approach must be a "systems" approach. That is, the air intake cooling system and the refrigerant system but be looked at as a whole, rather than by component analysis.

In the baseline consideration, the "system" consists of the air cooled charge air cooler on the air intake side and of the air cooled condenser on the refrigerant side; while these "systems" are in fact components, they make up the entire intake air cooling system and refrigerant cooling/condensing system respectively.

In the dual level cooling consideration, the "system" consist of the low temperature radiator AND the liquid cooled charge air cooler on the air intake side and of the low temperature radiator AND liquid cooled condenser on the refrigerant side; each system now consists of TWO components.

Below is an analysis of "system" effectiveness for the baseline and dual level cooling configurations. For each system type, a design point for inlet temperatures of the hot and cold fluid were established and the outlet temperature was dependent on that condition in each system. It is shown that the overall system effectiveness is IMPROVED when switching from an air cooled to liquid cooled system scheme. Effectiveness is determined using .

$$Effectiveness = (T_{h,in} - T_{h,out})/(T_{h,in} - T_{c,in})$$ **Equation 2 - Effectiveness**

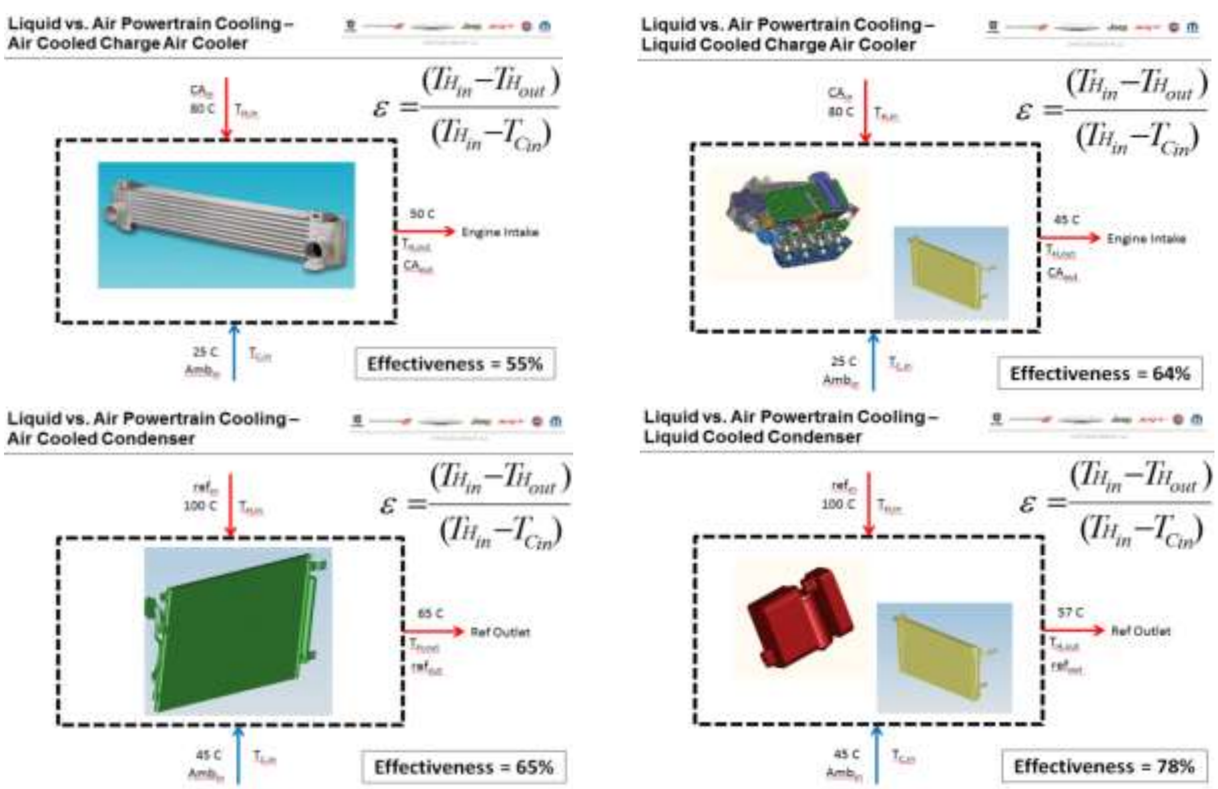


Figure 31 - Effectiveness Analysis

Simulation Results Comparison

Model calibration is necessary before comparing experimental results to simulation results. In order to achieve this, a model was created and run for fuel economy results for the baseline system. In doing so, model calibration coefficients were determined for each type of vehicle

Test	Baseline Results		
	Experimental [mpg]	Simulation Model [mpg]	Model Calibration Coefficient
FTP75	24.3	23.88	1
HWYFE	34	34.04	1.19
EPA CTY/HWY	28	28.21	0.85
US06	28.3	28.54	1.12
SC03	22.6	22.91	1
FTP20	29.2	29.26	0.8

Figure 33 - Baseline Simulation and Experimental Comparison for determination of Model Calibration Coefficient

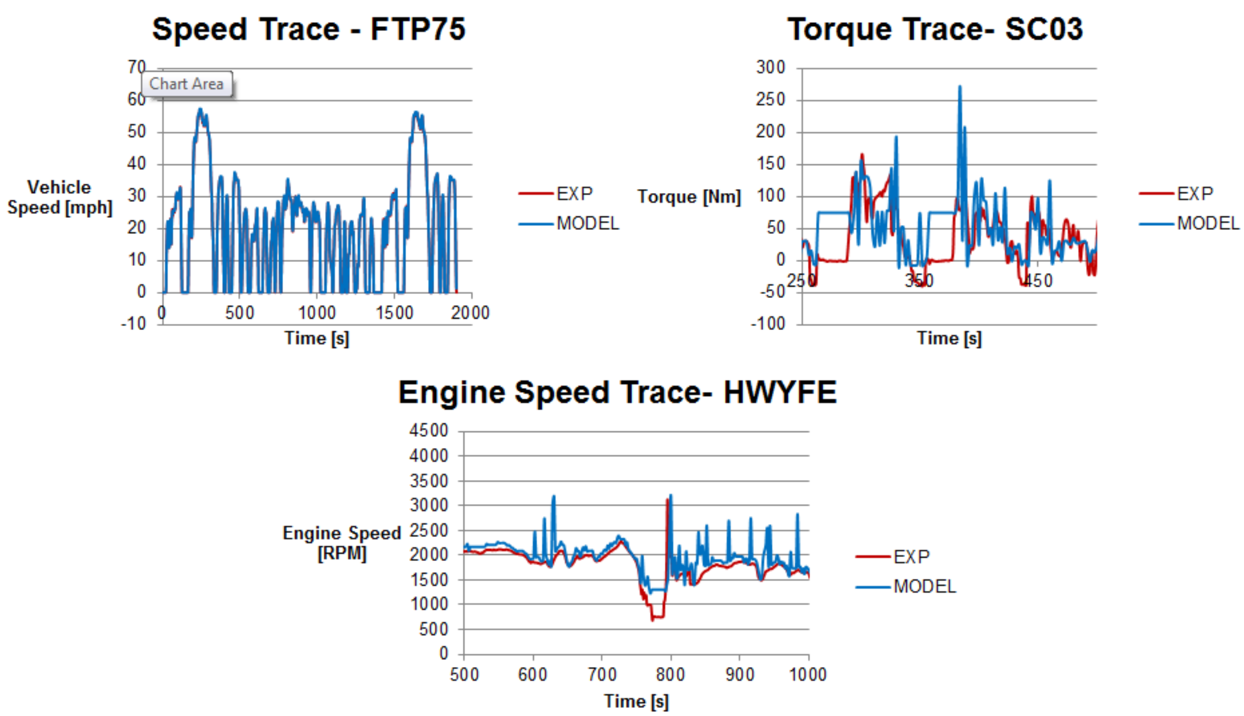


Figure 32 - Model Correlation Plots

test. Separate coefficients were needed because of the variety in testing procedure and characteristics between each test. **Figure 33** shows the comparison between the baseline simulation and experimental results. **Figure 32** shows a validation of the accuracy of the model, as well as the need for calculated calibration for each test. Here, the vehicle speed, engine speed, and vehicle torque values are compared between actual vehicle and simulation models.

After verifying the model for accuracy, it is then possible to run the simulation model for Dual Level Cooling. In doing so, because of the proprietary nature of the data, only percentage increases are able to be reported in this report. **Table 7** shows these results below.

Test	Baseline Simulation Model [mpg]	Dual Level Cooling Improvement
FTP75	23.88	4.90%
HWYFE	34.04	5.26%
EPA CTY/HWY	28.21	5.05%
US06	28.54	5.18%
SC03	22.91	4.93%
FTP20	29.26	4.69%

Table 7 - Dual Level Cooling Fuel Economy Improvement

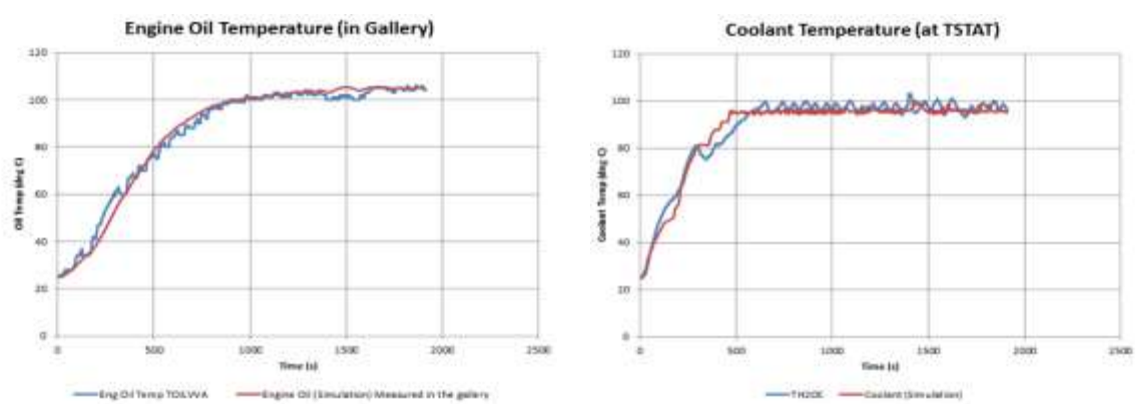


Figure 34 - Model 2 Correlation to Baseline

$$VE(RPM, MAP) = 12 + \frac{\frac{RPM}{60} * MAP}{320} + \frac{MAP}{2.67} - \frac{RPM}{960} + \frac{6000}{RPM} \quad \textbf{Equation 3}$$

These results are then again validated by **Equation 3**. The approximate improvement in vehicle charge and temperature, while unable to be reported because of its proprietary nature, is known and used in determining the improvement in volumetric efficiency of the engine. Both of these results show an improvement of around 5% in terms of fuel consumption at every test.

The second portion of simulation is being used by properly calibrating the baseline Flowmaster model in order to manually drive the system inputs in order to understand how fluid temperatures respond throughout the system. This is in the initial stages and correlation efforts are underway. This data is shown below. At the end, there will be a fully functioning model that will apply external conditions to the math model system in order to calculate fluid temperatures over any given drive cycle.

Packaging Study

When you look at the engine bay layout of a traditional vehicle today, one can notice that there is not a great amount of open space. Components are carefully designed and packaged so that vehicles are not required to be oversized, thus making a vehicle larger and heavier. When a vehicle is in the development stages before production, designers can dream up the most ideal components to achieve the greatest vehicle performance. However, these components may be too large or unique in shape that they introduce many packaging issues. If components are able to be manufactured into smaller volumes while still providing their specific function, they will be desired over a larger counterpart. As previously mentioned, a Dual Level TMS will allow for a better overall packaging layout. This is a result of the transfer from air-air cooling to liquid-air cooling.

Another byproduct of the ability to decrease packaging size is the location where the condenser can be placed. The condenser contains refrigerant, usually R-134a, which is known for some of its ozone depletion properties and toxic traits when exposed to high temperatures. During vehicle front end crashes, the refrigerant can be leaked if damage to the condenser is extreme. This is desired to be avoided and with movement of the condenser, the possibility of refrigerant leakage to the atmosphere is reduced.

Charged Air Cooler

The charged air cooler is packaged in front of the HTR on the baseline configuration and is a part of the front cooling module. **Figure 35** shows the location of the ACAC in the front cooling module. The dimensions that are listed in the table are the outer dimensions of the ACAC, which will be used in calculating the overall volume requirement of the ACAC.

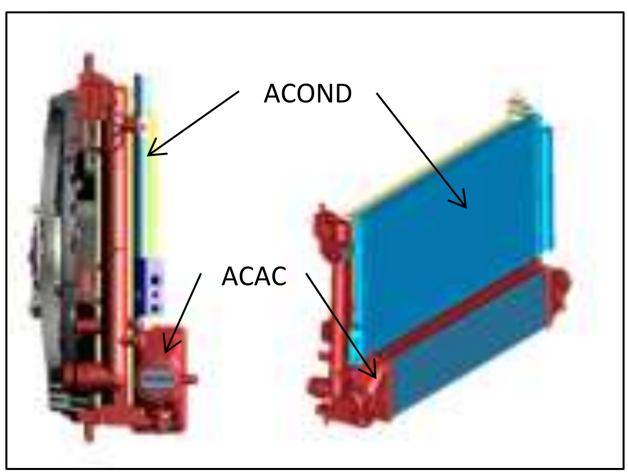


Figure 35 - Location of ACAC and ACOND in front cooling module

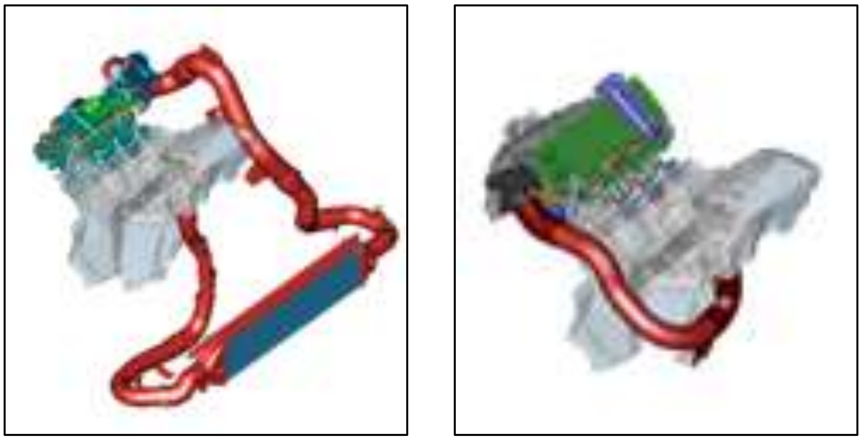


Figure 36 - (Left) ACAC shown with plumbing connected to the intake manifold. (Right) LCAC and intake manifold combination mounted atop the

The LCAC will reduce the overall volumetric requirement that is needed for the charged air cooler. This component will no longer be packaged at the front of the vehicle. Instead, it will be manufactured in combination with the intake manifold. This allows for placement onto the top of the engine where the intake manifold is mounted. **Figure 36** shows the comparison of the baseline and dual level configuration of the charged air cooler. As it can be seen, the integration of the charged air cooler and intake manifold offers a reduction in the total volumetric requirement and amount of plumbing needed to transfer air from the charged air cooler to the intake.

Condenser

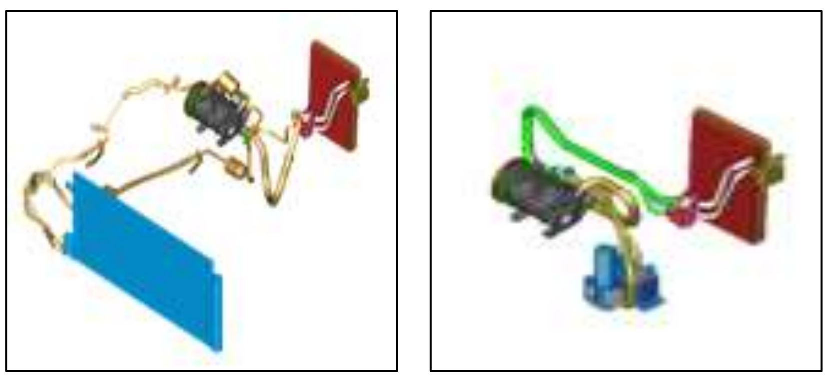


Figure 37 - (Left) ACOND, shown in blue, connected to all AC loop components in the baseline configuration. (Right) LCOND, shown in blue, connected to all AC loop components in the dual level configuration

In the baseline configuration, the condenser is packaged within the front cooling module, found at the front of the engine bay. It is placed atop of the ACAC and in front of the HTR. **Figure 35** above shows the location of the ACOND within the front cooling module. With the transition to a liquid cooled condenser, the overall system was able to decrease the volumetric requirement as well as decrease the total length of refrigerant lines needed. In the Dual Level configuration, the condenser can be moved from its baseline location and be placed between the engine and vehicle firewall. By placing it closer to the evaporator, the system is able to achieve a reduction in plumbing as previously mentioned. **Figure 37** shows the baseline and dual level configurations for the air conditioning loop. By comparison of the condenser for each configuration, shown in blue, it is evident that the overall weight and volume requirement will be significantly reduced.

Front Cooling Module

The design transition of replacing air cooled components with liquid cooled components will introduce another radiator, the low temperature radiator. This will be placed in the area that the ACAC and ACOND previously occupied. Although the low temperature loop is comprised of three heat exchangers, rather than two, the overall size of each is heat exchanger is smaller which allows for a variety of packaging combinations. **Figure 38** shows the two configurations for the front cooling module. With the LTR replacing the ACAC and ACOND, the overall thickness of the front cooling module is slightly reduced.

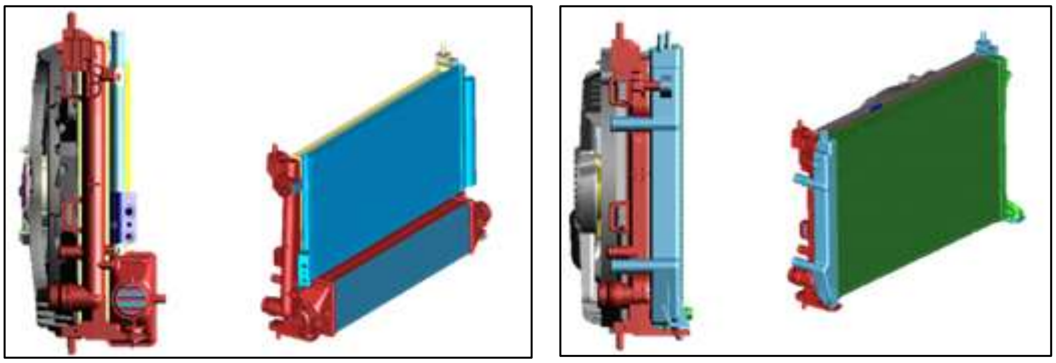


Figure 38 – (Left) shows baseline configuration for the front module. (Right) shows the LTR that replaces the ACAC and ACOND.

Volume and Weight Improvements

The low temperature loop addition allows for a reduction in both weight and volume of each component mentioned above. **Figure 40** shows the amount of weight reduction that is seen between the Baseline and Dual Level TMS. The most significant reduction in weight is seen at the condenser and that is apparent from the conclusions drawn above. With a reduced weight in each component, the vehicle can become lighter. Although this is not a significant amount of weight reduction when compared to the overall vehicle weight, every amount of weight that can be reduced has an impact on the overall fuel consumption needed to propel the vehicle. **Figure 39** shows the volumetric requirement for both the Baseline and Dual Level TMS. Due to the condenser's internal fin geometry and tubular design, it requires much more weight from internal supporting materials because of the high fluid pressure that the condenser must be able to withstand. The LTR will not contain coolant that is near the

Comparison Summary		
Component	Weight	Volume
CAC		
Baseline	12.64 lbs	3713.09 cm3
Dual Level	12 lbs	1863.225 cm3
% Reduction	5.06%	49.82%
COND		
Baseline	7.32 lbs	4506.13 cm3
Dual Level	6 lbs	1192.8 cm3
% Reduction	18.03%	73.53%
Front Module		
Baseline (ACAC+ACOND)	18.01 lbs	8219.22 cm3
Dual Level (LTR)	16.5 lbs	6618.996 cm3
% Reduction	8.38%	19.47%

Table 8- Volume and Weight Improvements Comparison Summary

pressures that are present in the air-conditioning loop. Therefore, it does not need the amount of internal support that the condenser does. A summary of these results is shown in **Table 8**.

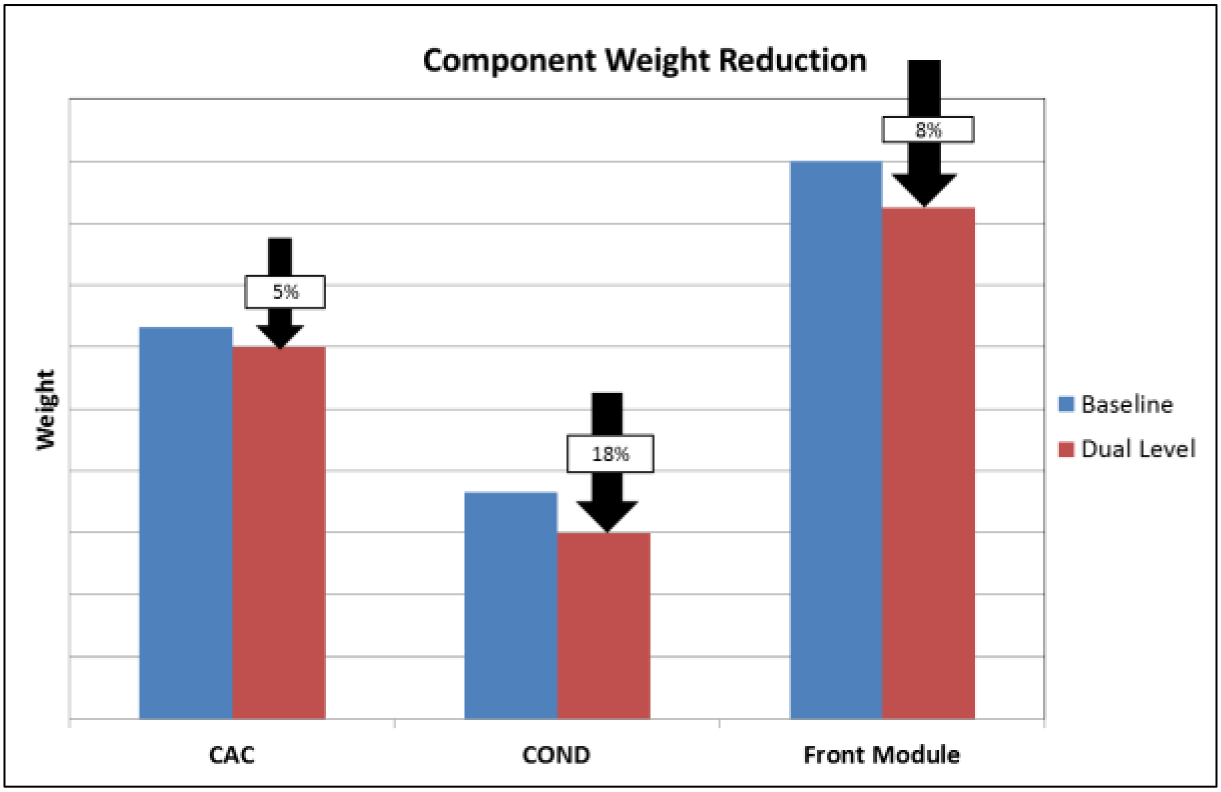


Figure 40 - the overall weight reduction of each component in the TMS

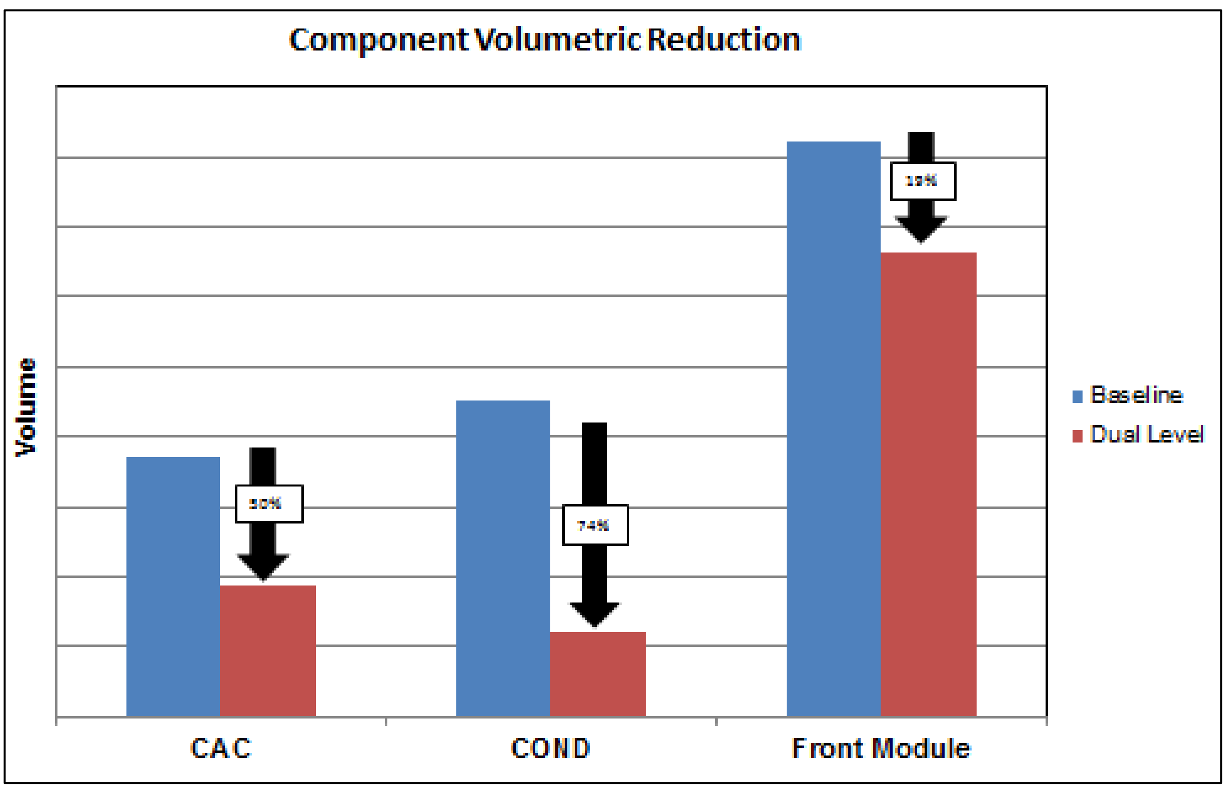


Figure 39 - the overall volumetric reduction of each component in the TMS

Conclusion

Proof of concept for Dual Level Cooling technology was initiated with this project. In completing this work, the groundwork has been laid for future work in this area. There has been a full development and understanding of the geometrical and theoretical advantages to implementation of this technology, as well as full test scheduling and planning for the way in which baseline testing was completed and for the model that dual level cooling testing will follow for comparison purposes. The final results of this project at its current stage indicate an overall improvement in fuel economy based on experimental and simulated dual level cooling results with respect to baseline experimental results. From the same data, it can be hypothesized, based on heat rejection capabilities of new components, that dual level cooling will prove to impact the AC Performance and CAC performance of the new system, resulting in faster time to boost numbers and lower cabin panel temperatures. In order to fully appreciate the benefits of said technology, completion of testing at a level that involves all groups related to powertrain and performance is required. The concept is, to the degree that production teams could fully calibrate the new vehicle components, focusing on system integration, realizable.

Works Cited

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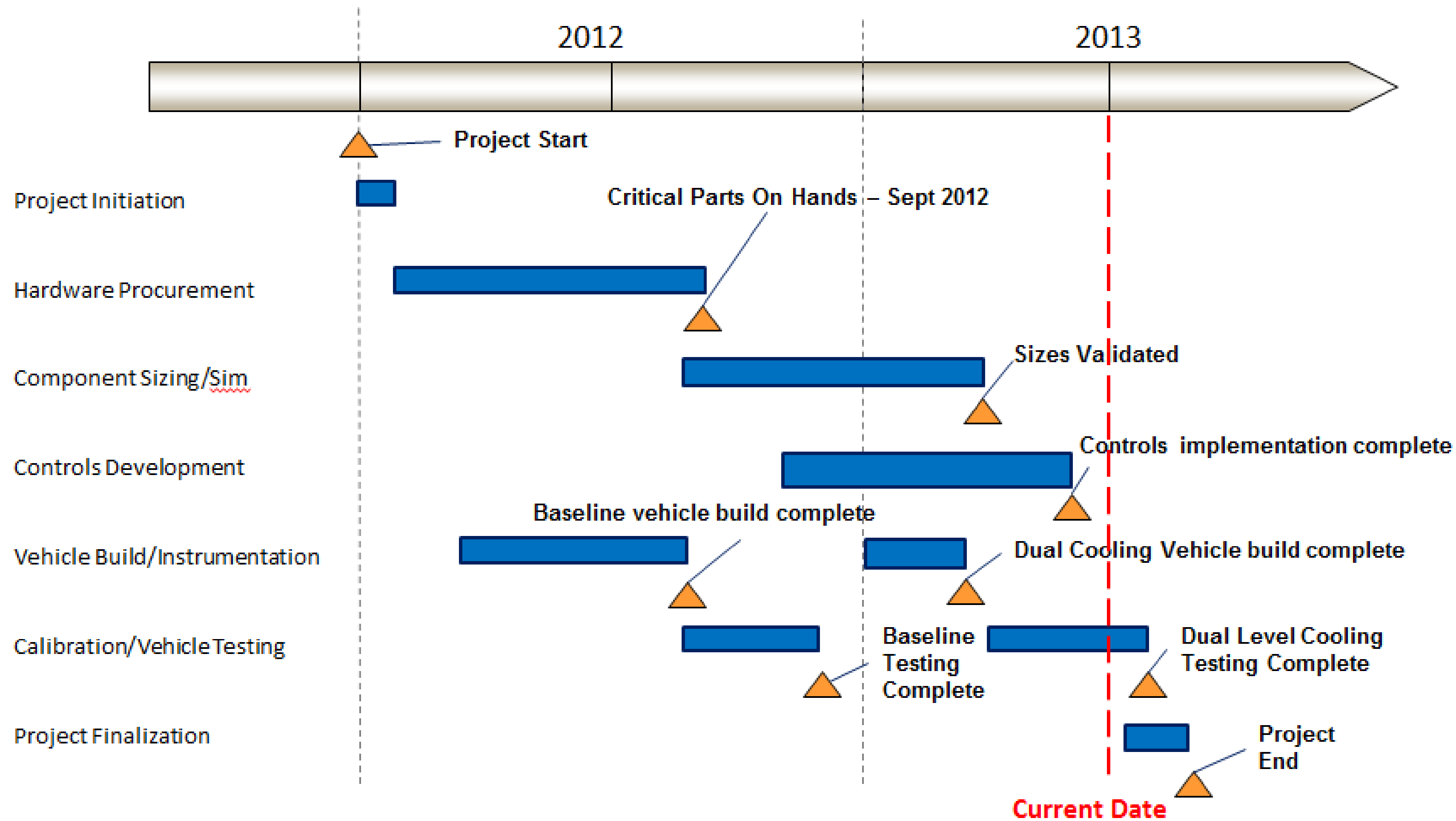
Appendix A

Timeline

The timeline that is presented here forth is the project timeline that was established during the planning phases of this project. The timeline presented is a two year timeframe that was condensed into one year time slot. It must be noted that the timeline presented was a best case scenario. With many project obstacles, certain dates were pushed back and as unexpected events arose throughout the project, the timeline had to be adjusted accordingly. Although the timeline lists more tasks that what was accomplished, this does not mean that project goals were not met. It is simply a proof that a two year time frame is more appropriate for future references purposes. The following table names each task and specifies the anticipated dates in which each was to be completed. The overall Gantt chart is shown after the task list table.

	Task Name	Duration	Start	Finish	Predecessors	Location	Performed By
1	1.4 L Turbo Dual Level Cooling Project	238 days	Thu 1/5/12	Tue 12/4/12			
2	Project Initiation	30 days	Thu 1/5/12	Wed 2/15/12			
3	MILESTONE 1: Project kick-off meeting	0 days	Thu 1/5/12	Thu 1/5/12			
4	Establish online work sharing site OI list timeline etc.	2 wks	Thu 1/5/12	Wed 1/18/12	3		
5	CTC and CPG Meetings	4 wks	Thu 1/19/12	Wed 2/15/12	4		MZ
6	Sizing of thermal system components	81 days	Fri 2/10/12	Fri 6/1/12			
7	Low Temp Circuit	25 days	Mon 4/30/12	Fri 6/1/12			MC/MZ
8	Generate sizing inputs for LT Electric Coolant Pump	1 wk	Mon 5/28/12	Fri 6/1/12	62FS+5 days		MC/MZ
9	Generate sizing inputs for Liquid Cooled CAC	1 wk	Mon 4/30/12	Fri 5/4/12			MC/MZ
10	Generate sizing inputs for Liquid Cooled Condenser	1 wk	Mon 5/7/12	Fri 5/11/12	9		MC/MZ
11	Generate sizing inputs for LTR	1 wk	Mon 5/14/12	Fri 5/18/12	10		MC/MZ
12	Generate sizing/gather information inputs for LT Valve(s)	1 wk	Mon 5/21/12	Fri 5/25/12	11		MC/MZ
13	High Temp Circuit	10 days	Mon 5/7/12	Fri 5/18/12			MC/MZ
14	Generate sizing inputs for Mech Coolant Pump	1 wk	Mon 5/7/12	Fri 5/11/12	3FS+5 days		MC/MZ
15	Generate sizing inputs for HTR	1 wk	Mon 5/14/12	Fri 5/18/12	14		MC/MZ
16	MILESTONE 2.1: All Components Sized	0 days	Fri 2/10/12	Fri 2/10/12			
17	Hardware Procurement	140 days	Fri 2/10/12	Thu 8/23/12			
18	Mule vehicle available for development	0 days	Tue 8/14/12	Tue 8/14/12	85		
19	Component prototype builds	96 days	Fri 2/10/12	Fri 6/22/12			
20	CAC prototype build	8 wks	Fri 2/10/12	Thu 4/5/12		CRF	CARLOANDREA
21	LT Coolant Pump prototype build	3 wks	Mon 6/4/12	Fri 6/22/12	8	CRF	
22	LTR Protoype build	2 wks	Fri 2/10/12	Thu 2/23/12		CRF	CARLOANDREA
23	Condenser prototype build	2 wks	Fri 2/10/12	Thu 2/23/12		CRF	CARLOANDREA
24	LT Valve(s) prototype build	1 wk	Fri 2/10/12	Thu 2/16/12		CTC	
25	Mech Coolant Pump prototype build	0 wks	Mon 5/14/12	Mon 5/14/12		ON MULE	NA
26	HT Valve(s) prototype build	0 wks	Mon 5/14/12	Mon 5/14/12		ON MULE	NA
27	HTR prototype build	0 wks	Mon 5/14/12	Mon 5/14/12		ON MULE	NA
28	Obtain instrumentation and DAQ hardware for vehicle build	2 wks	Fri 8/10/12	Thu 8/23/12	84FS-5 days		
29	MILESTONE 4: Prototype hardware MRD - all components	0 days	Thu 8/23/12	Thu 8/23/12	28	CRF	
30	Simulation	145 days	Fri 2/10/12	Thu 8/30/12			
31	Baseline Simulation Model	41 days	Mon 4/30/12	Mon 6/25/12			
32	Flowmaster	18 days	Mon 5/14/12	Wed 6/6/12			HC
33	1D modeling for initial HTR design	3 days	Mon 5/14/12	Wed 5/16/12			HC
34	1D modeling for initial Mech Coolant Pump design	3 days	Thu 5/17/12	Mon 5/21/12	33		HC
35	1D modeling for initial Cooling Fan design	3 days	Tue 5/22/12	Thu 5/24/12	34		HC
36	1D modeling for initial AC Compressor design	3 days	Fri 5/25/12	Tue 5/29/12	35		HC
37	1D modeling for initial Air CAC design	3 days	Wed 5/30/12	Fri 6/1/12	36		HC
38	1D modeling for initial Air Cooled Condenser design	3 days	Mon 6/4/12	Wed 6/6/12	37		HC
39	Develop entire Baseline thermal system prediction model (VehBalance)	41 days	Mon 4/30/12	Mon 6/25/12			HC/MZ
40	Gather engine vehicle trans. inputs for global vehicle energy model	7 days	Mon 4/30/12	Tue 5/8/12	60		MZ
41	Build global vehicle energy model for Baseline	8 days	Thu 6/7/12	Mon 6/18/12	38		HC
42	Iterate and optimize thermal system for FE performance using vehicle energy model	1 wk	Tue 6/19/12	Mon 6/25/12	41		HC/MZ
43	MILESTONE 5: Simulation Model for Baseline Complete	0 days	Mon 6/25/12	Mon 6/25/12	31		
44	Dual Level Simulation Model	69 days	Mon 4/30/12	Thu 8/2/12			HC/MZ
45	Flowmaster	12 days	Tue 6/26/12	Wed 7/11/12			HC
46	1D modeling for LTR design	3 days	Tue 6/26/12	Thu 6/28/12	43		HC
47	1D modeling for LT Electric Coolant Pump design	3 days	Fri 6/29/12	Tue 7/3/12	46		HC
48	1D modeling for Liquid Cooled CAC design	3 days	Wed 7/4/12	Fri 7/6/12	47		HC
49	1D modeling for Liquid Cooled Condenser design	3 days	Mon 7/9/12	Wed 7/11/12	48		HC
50	1D modeling for LT 3-way by-pass Valve design	0 days	Wed 7/11/12	Wed 7/11/12	49		HC
51	Develop entire Dual Cooling thermal system prediction model (VehBalance)	69 days	Mon 4/30/12	Thu 8/2/12			HC/MZ
52	Assemble Design Spec's of CRF Components	1 wk	Mon 4/30/12	Fri 5/4/12			MZ
53	Build global vehicle energy model using initial designs for each component (VehEBalance)	8 days	Thu 7/12/12	Mon 7/23/12	50		HC/MZ
54	Iterate and optimize thermal system for FE performance using vehicle energy model	8 days	Tue 7/24/12	Thu 8/2/12	53		HC/MZ
55	Refine component designs (HXs valves pumps etc.)	4 wks	Fri 8/3/12	Thu 8/30/12	54		MC/MZ
56	MILESTONE 6: Simulation Model for Dual Cooling Complete	0 days	Thu 8/2/12	Thu 8/2/12	44		
57	Run vehicle energy model with frozen designs for each component	2 wks	Fri 2/10/12	Thu 2/23/12			HC/MZ
58	MILESTONE 7: Fuel economy prediction for new thermal system	0 days	Thu 8/2/12	Thu 8/2/12	56		HC/MZ

	Task Name	Duration	Start	Finish	Predecessors	Location	Performed By
59	Baseline Testing	79 days	Mon 4/30/12	Thu 8/16/12			
60	Mitch Begin Internship	0 days	Mon 4/30/12	Mon 4/30/12			MZ
61	Complete DVP&R for baseline testing	2 wks	Mon 4/30/12	Fri 5/11/12			MC/MZ
62	Obtain test vehicle from Chrysler - begin break in (= 4000 miles)	0 days	Mon 5/21/12	Mon 5/21/12		CPG/Road	KL/DH
63	Install baseline instrumentation	3 wks	Mon 5/21/12	Fri 6/8/12	62	Livonia	LIVONIA - JOHN GREEN
64	Set up INCA experiment configure all sensors	10 days	Mon 5/28/12	Fri 6/8/12	63FS-10 days		
65	Update Vehicle Electrical	2 days	Tue 6/5/12	Wed 6/6/12	63FS-4 days	CTC	LIVONIA - DAVE WARDELL
66	CPG Vehicle Testing	14 days	Mon 6/11/12	Thu 6/28/12			BRIAN BASS
67	Coast Down	2 days	Mon 6/11/12	Tue 6/12/12	63		
68	Performance Testing	1 day	Tue 6/26/12	Tue 6/26/12			
69	WOT Tests	1 day	Tue 6/26/12	Tue 6/26/12	67		
70	Acceleration test on Oval	1 day	Tue 6/26/12	Tue 6/26/12	67		
71	22C Testing	3 days	Wed 7/18/12	Fri 7/20/12			
72	SFTP-US06	3 days	Wed 7/18/12	Fri 7/20/12	70		
73	FTP-75	3 days	Wed 7/18/12	Fri 7/20/12	70		
74	35C Testing	3 days	Mon 7/23/12	Wed 7/25/12			
75	SFTP-US06	3 days	Mon 7/23/12	Wed 7/25/12	73		
76	SFTP-SC03	3 days	Mon 7/23/12	Wed 7/25/12	73		
77	FTP-75 COLD Test (20F)	3 days	Thu 7/26/12	Mon 7/30/12	76		
78	NEDC (20C)	2 days	Tue 7/31/12	Wed 8/1/12	77		
79	CTC Vehicle Testing	1 day	Thu 8/2/12	Thu 8/2/12			ANDY YOUNG
80	6525i	1 day	Thu 8/2/12	Thu 8/2/12	78		
81	USCTY	1 day	Thu 8/2/12	Thu 8/2/12	78		
82	CD25i	1 day	Thu 8/2/12	Thu 8/2/12	78		
83	MILESTONE 3: Baseline Testing Complete	0 days	Thu 8/2/12	Thu 8/2/12	82		
84	Analyze baseline performance and establish performance	2 wks	Fri 8/3/12	Thu 8/16/12	83		MC/MZ/DH
85	Installation and Hardware Un-install	1 wk	Wed 8/8/12	Tue 8/14/12	83FS+3 days		LIVONIA - JOHN GREEN
86	Controls Development	111 days	Mon 6/4/12	Mon 11/5/12			
87	Develop preliminary control algorithm for actuated devices	1 wk	Mon 6/4/12	Fri 6/8/12	8		MZ
88	Optimize control strategy within vehicle energy model (VehEBalance)	2 wks	Mon 6/11/12	Fri 6/22/12	87		MZ/SK
89	Generate C code for ECU-based control of actuated devices	3 wks	Mon 6/25/12	Fri 7/13/12	88		Controls Team
90	MILESTONE 8: Preliminary control system complete	0 days	Fri 7/13/12	Fri 7/13/12	89		
91	Implement thermal control system in HIL environment - optimize	3 wks	Mon 7/16/12	Fri 8/3/12	23 90		
92	Revise calibration of actuated devices based on HIL results	2 wks	Mon 8/6/12	Fri 8/17/12	91		
93	Implement thermal control system on mule vehicle	2 wks	Mon 8/20/12	Fri 8/31/12	92		
94	Revise calibration of actuated devices based on vehicle test results	2 wks	Tue 10/23/12	Mon 11/5/12	107		
95	MILESTONE 9: Final thermal system calibration complete	0 days	Mon 11/5/12	Mon 11/5/12	94		
96	Dual Cooling Vehicle Build and Instrumentation	20 days	Fri 8/24/12	Thu 9/20/12			
97	Vehicle modifications with all new components	15 days	Fri 8/24/12	Thu 9/13/12			
98	Modify coolant circuit with new components	1 wk	Fri 8/24/12	Thu 8/30/12	28	Livonia	
99	Modify oil circuits with new components (if applicable)	1 wk	Fri 8/31/12	Thu 9/6/12	98	Livonia	
100	Install all pressure flow temperature sensors	2 wks	Fri 8/24/12	Thu 9/6/12	28	Livonia	
101	Install new ECU (w/ ETK) and configure engine cal.	1 wk	Fri 9/7/12	Thu 9/13/12	99	Livonia	
102	Set up INCA experiment configure all sensors	1 wk	Fri 9/7/12	Thu 9/13/12	100	Livonia	
103	Debug instrumentation identify/repair fluid leaks on-road verification	1 wk	Fri 9/14/12	Thu 9/20/12	102	Livonia	
104	MILESTONE 10: Vehicle Build Complete - Ready for Testing	0 days	Thu 9/20/12	Thu 9/20/12	103		
105	Dual Cooling Testing	33 days	Thu 9/6/12	Mon 10/22/12			
106	Complete DVP&R for Dual Level Cooling testing	2 wks	Thu 9/6/12	Wed 9/19/12		CPG	
107	Vehicle testing	22 days	Fri 9/21/12	Mon 10/22/12			
108	Performance and drive cycle testing at CPG	3 wks	Tue 9/25/12	Mon 10/15/12	109	CPG	
109	Climate drive cycle testing at CTC	2 days	Fri 9/21/12	Mon 9/24/12	104	CTC	
110	Steady state RPM testing for thermal model correlation	1 wk	Tue 10/16/12	Mon 10/22/12	108 109	CPG	
111	MILESTONE 11: Vehicle Testing Complete	0 days	Mon 10/22/12	Mon 10/22/12	110		
112	Project Finalization	30 days	Tue 10/23/12	Tue 12/4/12			
113	Final project reporting	20 days	Tue 10/23/12	Mon 11/19/12	111		
114	Generate project report with recommendations	4 wks	Tue 10/23/12	Mon 11/19/12			
115	Generate preliminary DFMEA for thermal system	1.5 wks	Tue 10/23/12	Thu 11/1/12	111		
116	Generate Production Feasibility of new system	1.5 wks	Thu 11/1/12	Mon 11/12/12	115		
117	MILESTONE 12: Technical feasibility of new technologies demonstrated	0 days	Mon 11/19/12	Mon 11/19/12	113		
118	MILESTONE 13: Senior Design Presentation	0 days	Tue 12/4/12	Tue 12/4/12			


2012
2013
Project Start
Project Initiation
Critical Parts On Hands – Sept 2012
Hardware Procurement
Component Sizing/Sim
Sizes Validated
Controls Development
Controls implementation complete
Baseline vehicle build complete
Vehicle Build/Instrumentation
Dual Cooling Vehicle build complete
Calibration/Vehicle Testing
Baseline Testing Complete
Dual Level Cooling Testing Complete
Project Finalization
Project End
Current Date

Appendix B

DVP&R

DESIGN VERIFICATION PLAN AND REPORT CHRYSLER GROUP LLC WESTERN MICHIGAN UNIVERSITY		DVP NUMBER:	1	DEPT #:	12507880
		PLAN DATE:	5/21/2012	PLAN ORIGINATOR:	MITCHELL ZAJAC, MATT CUTLER, DAN HORNBACK
		CONCURRENCE:		MANAGER APPV'L:	
COMPONENT / ASSEMBLY :	1.4L TURBO PF	REPORT DATE:	5/4/2012	REPORTING ENGR:	MITCHELL ZAJAC
MY:	APPLICATION :	REVISION DATE:	6/1/2012		

TEST PLAN

TEST NO	PROCEDURE OR STANDARD	TEST DESCRIPTION	PURPOSE	ACCEPTANCE CRITERIA	TEST RESP.	Phase	Qty.	Planned Start	Days	Start	Complete	City FE	Hwy FE	Notes
001	Coast Down	1) Vehicle instrumented 2) Vehicle & driver weighed 3) Vehicle driven to 70 MPH 4) Shift to neutral 5) Split Coast Down - Coast down from 70 to 45 MPH, 45 to 10 MPH 6) Record data; use to derive Polynomial Force Coefficient from velocity, time and mass1	Necessary to set chassis dyno road load to reflect actual vehicle characteristics - Aero drag, tire roll resistance, wheel bearing and brake drag, axle and trans spin loss, drivetrain inertia	results of production vehicle, range of production values	CPG Brian Bass	Baseline	2	6/11/2012	1					Follow Chrysler Coastdown CPG Process - see comments
						Dual Cooling	2	8/27/2012	1					
002	0-100 (saej1491)	Perform wide open throttle (WOT) accelerations from a standing start and record the following: • Launch Response Time (Control Input to Initial Vehicle Movement (IVM) - 1 foot traveled) • Acceleration Response Time (IVM to test end speed) Also perform the following test at wide-open-throttle: • 64 to 97 km/h (40 to 60 mph) – Elapsed Time	Measures launch response and acceleration performance	A-B increase in perfromance for Acceleration Response Time - results comparable to CRF results	CPG Brian Bass	Baseline	3 pairs	6/11/2012	1					1 pair consists of two runs in opposite directions – 1 minute delay between runs – see saej1491 doc for entire test procedure - see comment
						Dual Cooling	3 pairs	8/27/2012	1					
003	Acceleration test on Oval	Rolling 1krpm (2-6th) --> Accelerate to 100mph/5k	Comparison of time to boost curves; to evaluate effect on Time-to-boost and turbolag	A-B increase in perfromance for Time to MAP	CPG Brian Bass	Baseline	2	6/26/2012	1					Follow Acceleration (Time_to_MAP) Test procedure - see coments
						Dual Cooling	2	8/27/2012	1					
004	FTP-75	ran on dyno, city cycle, transient cycle, 10 min pause, highway cycle	city mpg, highway mpg, averaged mpg	Baseline to Dual Cool improvement - 1-2% increase in fuel economy	CPG Brian Bass	Baseline	3	6/13/2012	3					FTP-75 Standard Test Procedure
						Dual Cooling	3	8/28/2012	3					
005	SFTP-US06 22°C	Eurpean counterpart to 002; The US06 Supplemental Federal Test Procedure is used in addition to the above-mentioned FTP-75. The US06 simulates aggressive acceleration, higher speed driving behaviour. Also included are rapid speed fluctuations and driving behaviour following start-up. The cycle takes 596 seconds (nearly 10 minutes) to complete, with a total distance of 8.01 miles travelled. The maximum speed of the cycle is 80.3 mph. The average speed of the cycle is 48.4 mph.	To compensate for the shortcomings of the FTP-75 that include aggressive high speed driving.	Baseline to Dual Cool improvement - 1-2% increase in fuel economy	CPG Brian Bass	Baseline	3	6/13/2012	3					US06 Standard Test Procedure at standard temperature - Follow FTP-75 in same cell, same day
						Dual Cooling	3	8/28/2012	3					
006	SFTP-US06 35°C	Same as 004, but at higher temperature	To evaluate the benefit of a liquid cooled CAC	Baseline to Dual Cool improvement - 1-2% increase in fuel economy	CPG Brian Bass	Baseline	3	6/18/2012	3					US06 Standard Test Procedure at HIGH temperature
						Dual Cooling	3	9/4/2012	3					

DESIGN VERIFICATION PLAN AND REPORT
CHRYSLER GROUP LLC
WESTERN MICHIGAN UNIVERSITY

COMPONENT / ASSEMBLY :	1.4L TURBO PF	DVP NUMBER:	1	DEPT #:	12507880
		PLAN DATE:	5/21/2012	PLAN ORIGINATOR:	MITCHELL ZAJAC, MATT CUTLER, DAN HORNBACK
		CONCURRENCE:		MANAGER APPV'L:	
		REPORT DATE:	5/4/2012	REPORTING ENGR:	MITCHELL ZAJAC
MY:	APPLICATION :	REVISION DATE:	6/1/2012		

TEST PLAN

TEST NO	PROCEDURE OR STANDARD	TEST DESCRIPTION	PURPOSE	ACCEPTANCE CRITERIA	TEST RESP.	Phase	Qty.	Planned Start	Days	Start	Complete	City FE	Hwy FE	Notes
007	SFTP-SC03	The US SC03 Speed Correction Driving Schedule is used in addition to the above-mentioned FTP-75. It simulates urban driving and engine load with the air-conditioning unit turned on for the entire duration of the test (A/C fan speed to be determined). The cycle takes 596 seconds (nearly 10 minutes) to complete, with a total distance of 3.6 miles travelled. The maximum speed of the cycle is 54.8 mph. The average speed of the cycle is 21.6 mph.	To compensate for the shortcomings of the FTP-75 that include the use of air conditioning.	Baseline to Dual Cool improvement - 1-2% increase in fuel economy	CPG Brian Bass	Baseline	3	6/18/2012	3					SC03 Standard Test Procedure at standard temperature - 10 min soak at 95C immediately following US06 Test
						Dual Cooling	3	9/4/2012	3					
008	FTP-20 COLD Test (20°F)	ran on dyno, city cycle, transient cycle, 10 min pause, highway cycle	city mpg, highway mpg, averaged mpg - for five cycle	Baseline to Dual Cool improvement - 1-2% increase in fuel economy	CPG Brian Bass	Baseline	3	6/21/2012	3					FTP-75 Standard Test Procedure
						Dual Cooling	3	9/7/2012	3					
009	NEDC at 20°C	The entire cycle includes four ECE segments, repeated without interruption, followed by one EUDC segment. The urban economy is measured using the test cycle known as ECE-15. It simulates a 2.518 mile urban trip at an average speed of 11.6 mph and at a maximum speed of 31 mph. The extra-urban cycle or EUDC lasts 400 seconds (6 minutes 40 seconds) at an average speedn 39 mph and a top speed of 74.6 mph.	Comparison to European Standards	Baseline to Dual Cool improvement - 1-2% increase in fuel economy	CPG Brian Bass	Baseline	2	6/27/2012	2					
						Dual Cooling	2	9/13/2012	2					
010	6525I	SEG0 - 10 min eng off, windows down, 65mph wind SEG0 - approach 65mph m in SEG1 - 65 mph 30 min SEG2 - 25mph 20 min SEG3 - 30 min park idle	Stability of System	**See Comments**	CTC	Baseline								Follow 6525I procedure - see comment
						Dual Cooling								
011	USCTY (Las Vegas)	1.5hr; 0 to 40 (1 hr); 0 to 10 (30 min)	HARSHEST Conditions	**See Comments**	CTC	Baseline								Follow USCTY Test Standard version 6 procedure - see comment
						Dual Cooling								
012	CD25 (Harmonized cool down)	1. 25 MPH for 30 minutes a. For automatic transmissions: - Set drive cell wind speed to 25 MPH 2. Drive idle for 2 minutes - Wind 0MPH 3. 65MPH for 13 minutes Shift into 3rd gear and slow vehicle speed to match 5th gear engine rpm. 4. Park idle for 20 minutes - Wind 0 MPH	HVAC Performance - Total Capacity	**See Comments**	CTC	Baseline								Follow CD25I procedure - see comment
						Dual Cooling								

Appendix C

EPA Fuel Calculator

	Fuel Economy Test Results				
FTP 75°F	Test FE	Bag1	Bag2	Bag3	Bag4
AVG	31.1000	28.8000	30.4000	34.9000	
HFET	Test FE				
AVG	48.1000				
US06	Test FE	Bag1 (City)	Bag2 (Hwy)		
AVG	28.3000	18.0000	33.7000		
FTP 20°F	Test FE	Bag1	Bag2	Bag3	
AVG	29.2000	25.2000	29.1000	33.7000	
SC03	Test FE				
AVG	22.6000				

Enter additional information to identify this "group" of tests
Note: This block of data is not used in any calculation.
It is only provided to the user for data tracking/logging purposes.

Engine Family / Test Group	1.4L Turbo Fire
Model Year	2013
Manufacturer	EPA
Division	-
Carline Code	-
Carline Name	-
Engine	1.4L Turbo Fire
Transmission	ddct
Model Type Index	-
Base Level Index	-
Configuration Index	-
Subconfiguration Index	-

	Vehicle Specific 5-Cycle	Modified 5-Cycle	Derived 5-Cycle	V5C Litmus Value		D5C Litmus Threshold
Required Data	Std-3	Std-3	Valid	Valid		Valid
Start Fuel 75	0.02184814	0.02184814				
Start Fuel 20	0.03603222					
Start FC City	0.00203250					
Running FC City	0.03536308					
FE City	24.20072185	24.26171636	24.26171636	24.20072185		24.26171636
City (4)	24.2007	24.2617	24.2617	x 1.00		x 0.96
City Label	24	24	24	24.2	>=	23.3
				Litmus City		PASS
Start FC Hwy	0.00013889	0.00016688				
Running FC Hwy	0.02870168	0.02851389				
FE Hwy	31.37941083	31.55424192	34.04621338	31.37941083		34.04621338
Hwy (4)	31.3794	31.5542	34.0462	x 1.00		x 0.95
Hwy Label	31	32	34	31.4	<	32.3
				Litmus Hwy		FAIL
FE Comb	26.97800456	27.07777888	27.86539197			
Comb (4)	26.9780	27.0778	27.8654	Qualify For:	==>	Modified 5C
Comb Label	27	27	28			

This spreadsheet contains a macro that performs ASTM rounding.
When opened, select "enable macros" to make it available.

The "Fuel Economy Test Results" should be ASTM rounded to 1 decimal place by the user of this tool if the value is derived from a single test. If the value is derived from multiple tests harmonically averaged together, then the value should be ASTM rounded to 4 places. **It is the responsibility of the user to round the input values appropriately PRIOR to using this tool**. **Data that contains more than 4 decimal places will NOT be accepted.**

If a calculated cell reads, "-" then there is insufficient data, or the data does not fit that particular calculation. The number of FTP 75°F bags entered, and test types that have data will determine the calculation type(s) enabled.

"Litmus Test" calculations are based on the official tests within an Engine Family/Test Group. There is ONLY 1 official test for each test type. Therefore, if using this calculator for litmus test purposes, each test result should be rounded to a tenth. **If ANY of the test results have been entered to more than a tenth, the litmus test calculations will be disabled.**

***** See Notes at the bottom of this page *****

Note: The constant in the Modified 5-Cycle "Start FC Hwy" equation was corrected from 0.0055155 to 0.005515.
Note: The input rounding for both Model Type Derived 5-Cycle calculations was changed from 1 decimal digit to 4 decimal digits.
Note: The "Litmus Test" calculations are based on a single test of each type, so in all cases the input rounding should be 1 decimal digit.

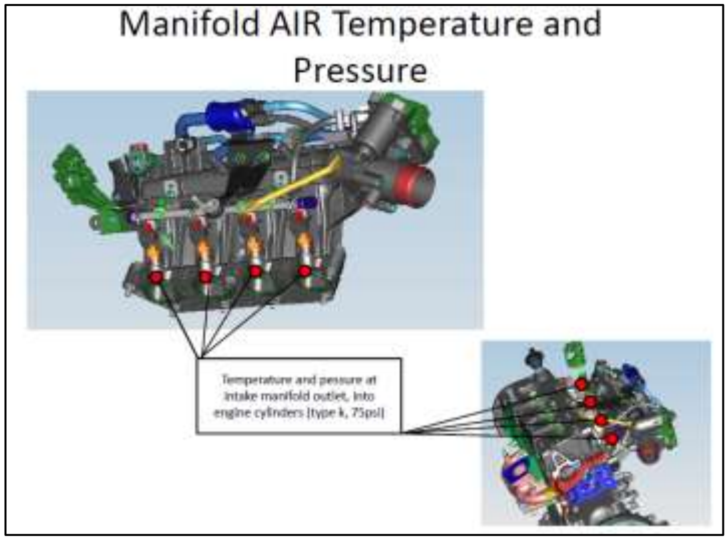
Notes based on: Federal Register / Vol. 74, No. 226 / Wednesday, November 25, 2009 / Rules and Regulations

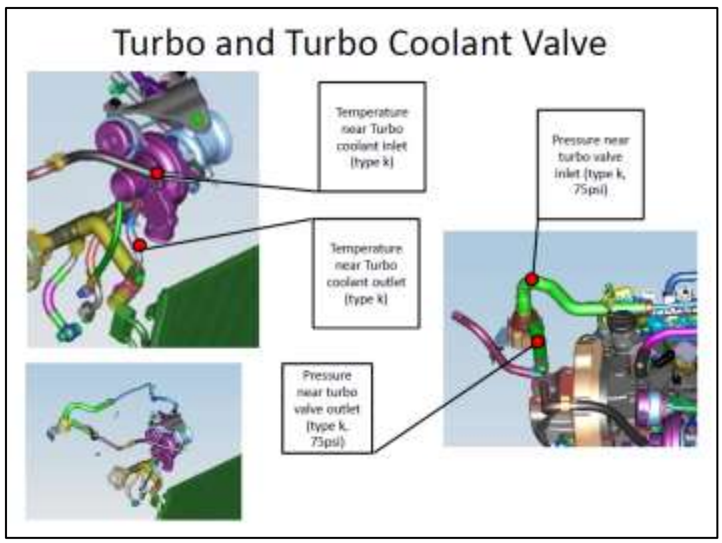
The EPA Calculator found on the previous page is given to Chrysler from the Environmental Protection Agency and is used to calculate the fuel economy that represents the city and highway miles per gallon. Each fuel economy test results in a Bag Summary Report that lists the fuel economy achieved during each. Each test is ran a multiple number of times; therefore, the average from all of the tests are the values that should be entered into the orange cell on the right side of the calculator sheet. Other rules specific to the calculator can be found on the right of the grey cells.

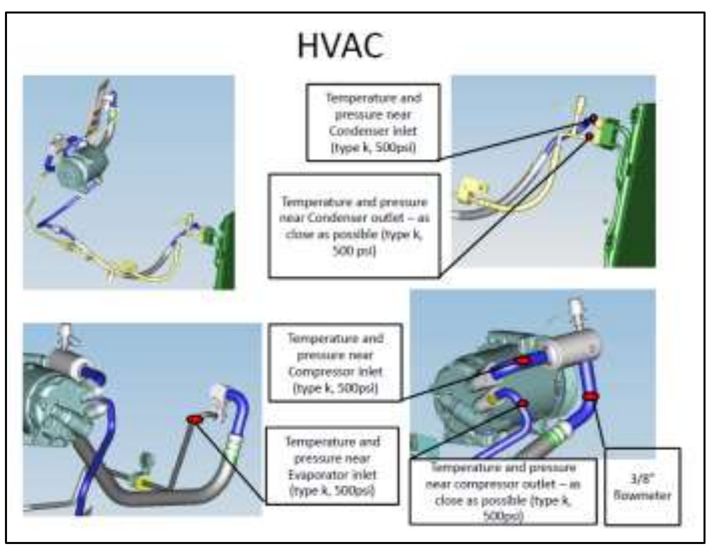
Based on internal logic equations within the calculation sheet, the quality for the fuel economy calculation can be evaluated. As it is seen in the EPA Calculator, the quality is only for the Modified 5C (five-cycle) fuel economy result.

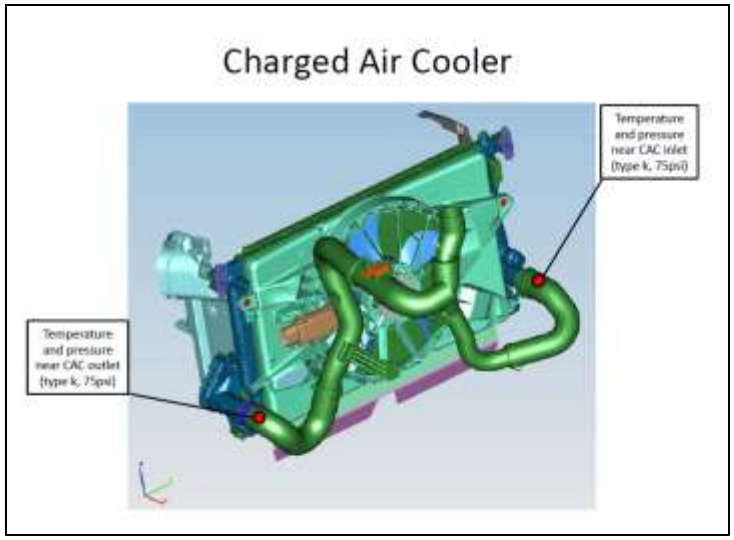
Appendix D

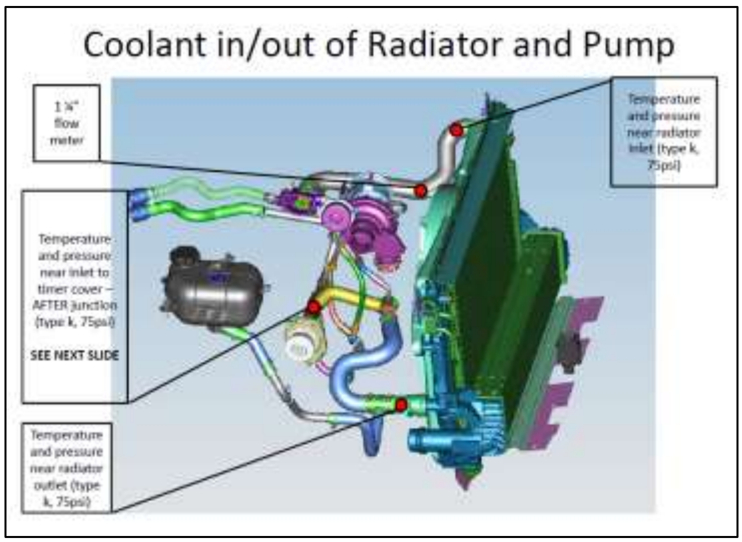
Instrumentation Placements

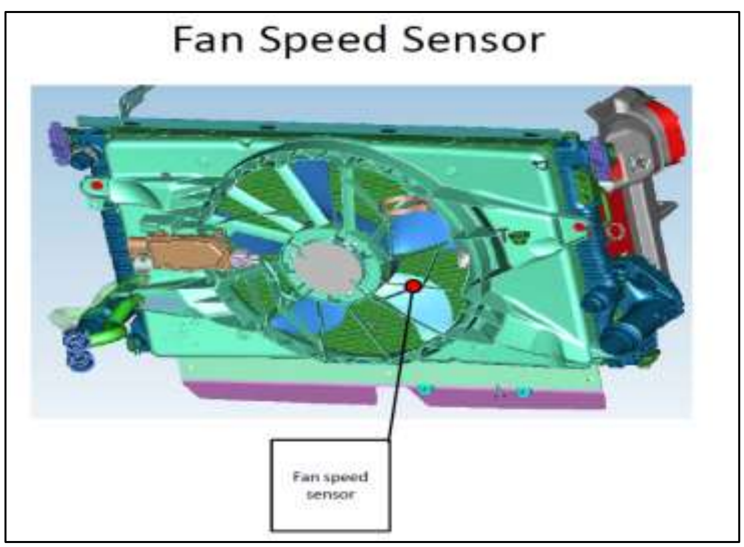

Manifold AIR Temperature and Pressure
Temperature and pessure at intake manifold outlet, into engine cylinders (type k, 75psi)

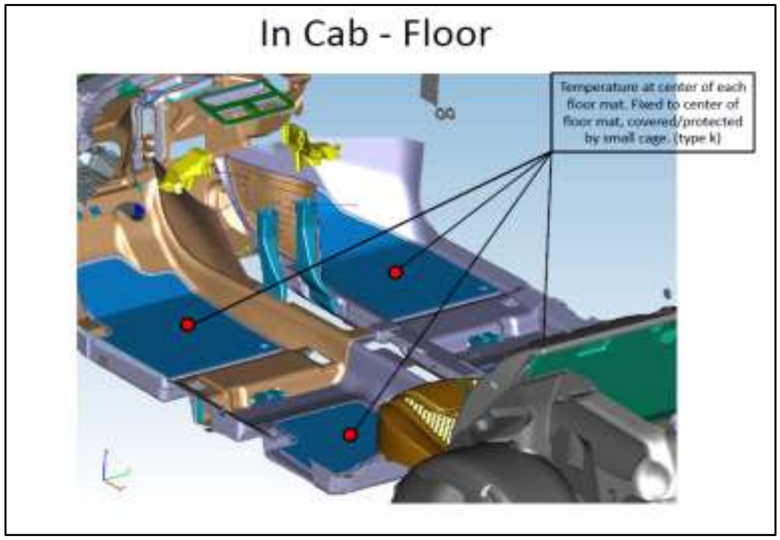

Turbo and Turbo Coolant Valve
Temperature near Turbo coolant inlet (type k)
Temperature near Turbo coolant outlet (type k)
Pressure near turbo valve inlet (type k, 75psi)
Pressure near turbo valve outlet (type k, 75psi)


HVAC
Temperature and pressure near Condenser inlet (type k, 500psi)
Temperature and pressure near Condenser outlet – as close as possible (type k, 500 psi)
Temperature and pressure near Compressor inlet (type k, 500psi)
Temperature and pressure near Evaporator inlet (type k, 500psi)
Temperature and pressure near compressor outlet – as close as possible (type k, 500psi)
3/8" flowmeter

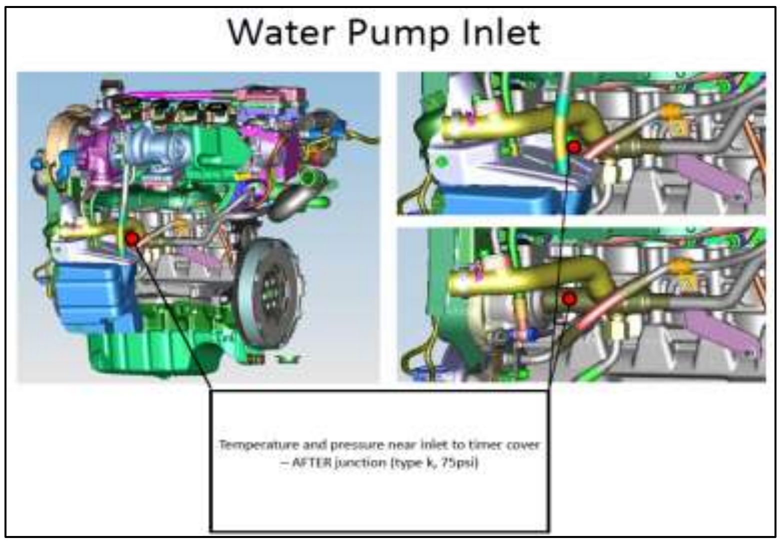

Charged Air Cooler
Temperature and pressure near CAC inlet (type k, 75psi)
Temperature and pressure near CAC outlet (type k, 75psi)


Coolant in/out of Radiator and Pump
1 ¼" flow meter
Temperature and pressure near radiator inlet (type k, 75psi)
Temperature and pressure near inlet to timer cover – AFTER junction (type k, 75psi)
SEE NEXT SLIDE
Temperature and pressure near radiator outlet (type k, 75psi)

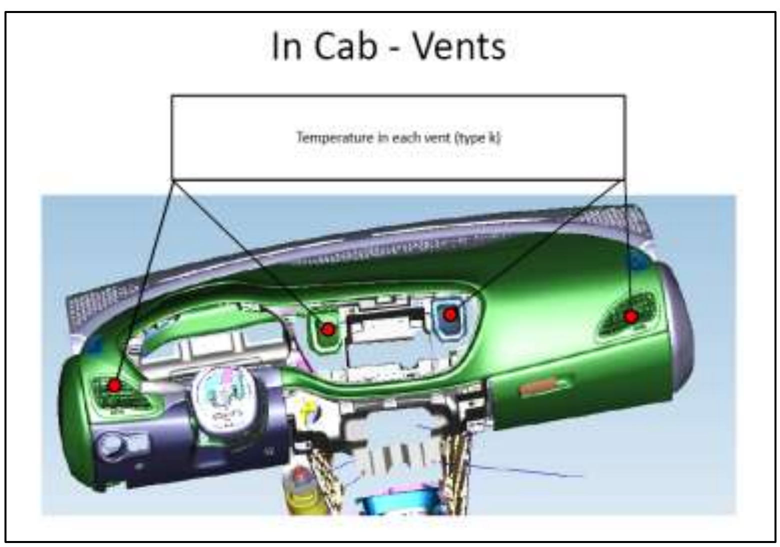

Fan Speed Sensor
Fan speed sensor



In Cab - Floor
Temperature at center of each floor mat. Fixed to center of floor mat, covered/protected by small cage. (type k)



Water Pump Inlet
Temperature and pressure near inlet to timer cover – AFTER junction (type k, 75psi)



In Cab - Vents
Temperature in each vent (type k)

In Cab - Ceiling