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Request for GHG credit for Denso SES compressor with variable crankcase suction valve technology

Following the provisions of 40 CFR § 86.1869-12(d), Hyundai Motor Group, represented by the Hyundai America Technical Center, Inc. (HATCI), requests off-cycle greenhouse gas (GHG) credits of 1.4 grams CO2 per mile for the use of the Denso SES air conditioner compressor with variable crankcase suction valve (CSV) technology. This more efficient compressor technology is applied on the MY 2015, 2016, 2017 Hyundai Sonata, which includes 1.6L-T, 2.0L-T, and 2.4L engines. This technology may be further adopted across the Hyundai / Kia lineup in the future.

Background

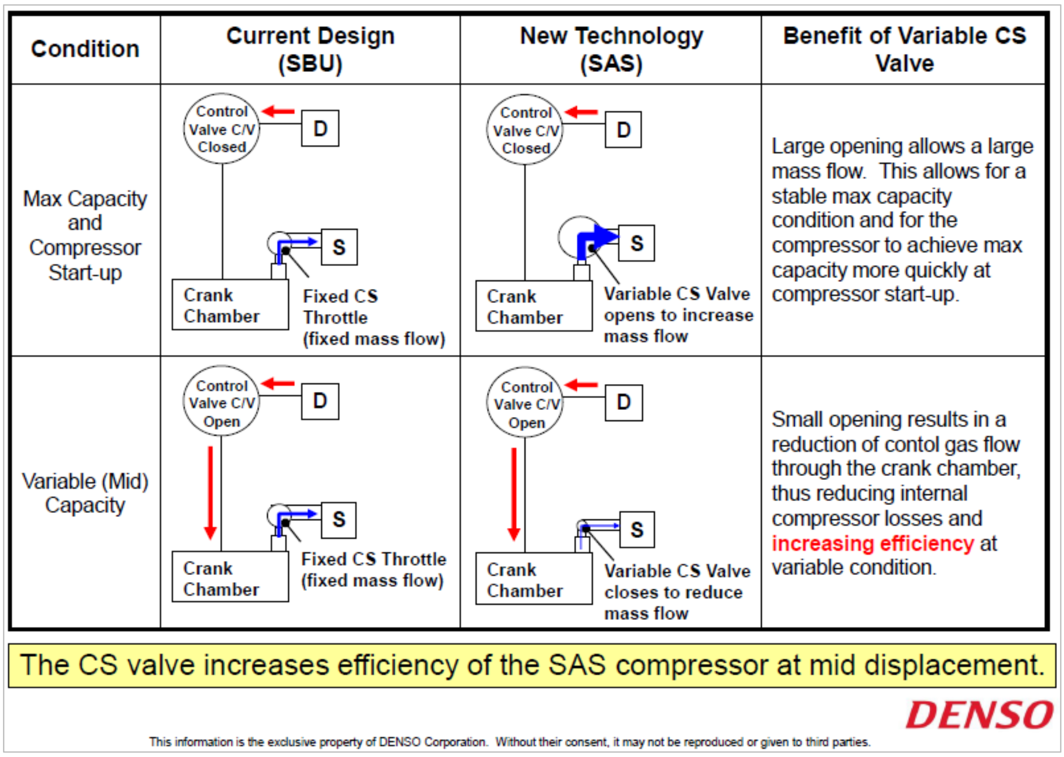
Greenhouse gas emission standards through 2025 represent a major initiative in US energy and climate policy. EPA and DOT have issued a joint rule-making that set greenhouse gas emissions and fuel economy standards for the largest sources of greenhouse gases from transportation, including cars, light trucks, and heavy-duty trucks. Over the course of the program, light-duty GHG regulations are projected to: cut 6 billion metric tons of GHG emissions, nearly double vehicle fuel efficiency while protecting consumer choice, reduce America's dependence on oil and provide significant savings for consumers at the fuel pump. To achieve these worthy goals, a key regulatory element is the ability for manufacturers to have a variety of options and flexibilities in meeting the standards.

A key flexibility is the off-cycle credits provision; off-cycle credits are an opportunity for manufacturers to generate credits for technologies that provide CO2 reductions not captured by the traditional 2-cycle (FTP, HWFET) emissions tests conducted on a chassis dynamometer. There are three pathways by which a manufacturer may accrue off-cycle credits. The first is a pre-determined menu of credit values for specific off-cycle technologies. In cases where additional lab testing can demonstrate emission benefits of a technology, a second pathway allows manufacturers to use a broader array of emission tests known as 5-cycle testing, which captures more elements of real-world driving, including high speeds and hard acceleration (US06), solar loads, high temperature, and A/C use (SC03), and cold temperatures (cold FTP). The third pathway allows manufacturers to seek EPA approval to use an alternative methodology for determining the off-cycle credits.

The Denso SES air conditioner compressor with variable crankcase suction valve technology is not included in the EPA's pre-determined menu. Additionally, the five-cycle test option would not adequately measure the real-world GHG reduction benefits of the technology. Only one of the five tests is conducted with the A/C switched on. Since it is conducted at a high ambient temperature of 95F, high solar load of 850 W/m^2, and high relative humidity of 40%, the demanding climatic conditions result in the air conditioning systems being operated at maximum capacity throughout the test. The technology under investigation provides their benefits under milder ambient conditions when the A/C is not operating at maximum capacity. For these reasons, HATCI is pursuing additional off-cycle credits via the alternative methodology pathway.

Technology Description

The Denso SES design improves the internal valve system within the compressor to reduce the internal refrigerant flow necessary throughout the range of displacements that the compressor uses during its operating cycle. This is achieved through the addition of a variable crankcase suction valve. Conventional compressors have a fixed crankcase to suction bleed that regulates the flow of refrigerant exiting the crankcase. The sizing of the bleed is a compromise among the conditions when either a high or low rate of flow would be more ideal. In conditions where maximum air conditioner capacity is not needed, this fixed bleed creates unnecessary reduction of volumetric efficiency for the compressor. In contrast, a variable crankcase suction valve can provide a larger mass flow under maximum capacity and compressor start-up conditions, when high flow is ideal; it can then reduce to smaller openings with reduced mass flow in mid or low capacity conditions. Thus, overall, the refrigerant exiting the crankcase is optimized across the range of operating conditions, improving system efficiency and therefore lowering indirect CO2 emissions due to use of the air conditioning system.



Condition	Current Design (SBU)	New Technology (SAS)	Benefit of Variable CS Valve
Max Capacity and Compressor Start-up	Control Valve C/V Closed; D; S; Crank Chamber; Fixed CS Throttle (fixed mass flow)	Control Valve C/V Closed; D; S; Crank Chamber; Variable CS Valve opens to increase mass flow	Large opening allows a large mass flow. This allows for a stable max capacity condition and for the compressor to achieve max capacity more quickly at compressor start-up.
Variable (Mid) Capacity	Control Valve C/V Open; D; S; Crank Chamber; Fixed CS Throttle (fixed mass flow)	Control Valve C/V Open; D; S; Crank Chamber; Variable CS Valve closes to reduce mass flow	Small opening results in a reduction of contol gas flow through the crank chamber, thus reducing internal compressor losses and increasing efficiency at variable condition.

The CS valve increases efficiency of the SAS compressor at mid displacement.

DENSO

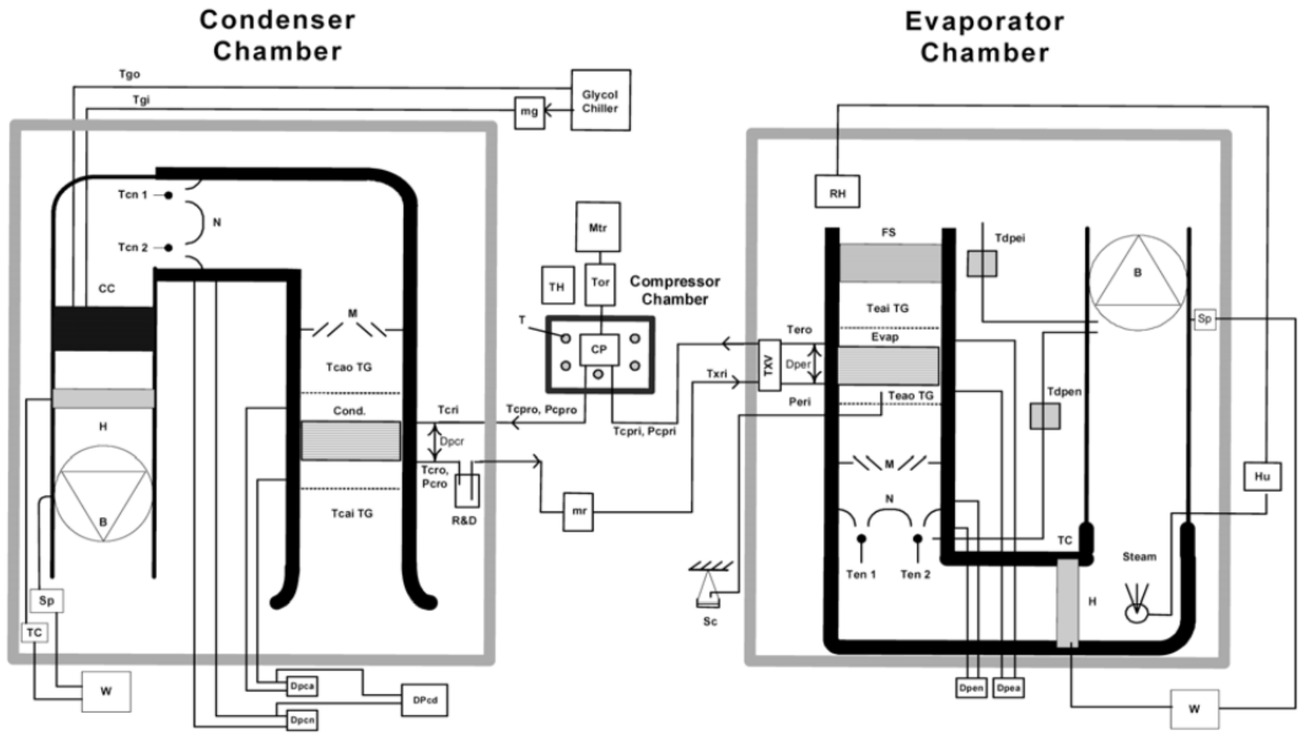
Test Methodology

The test methodology used to quantify the technology benefit consists of 4 steps:

1. Bench testing (SAE J2765) – measure coefficient of performance (COP) at various (40) conditions
2. Life Cycle Climate Performance (LCCP) modeling and analysis (SAE J2766) – convert COP to gCO2/mile based on climate data and vehicle and A/C usage across the United States
3. LCCP weighted average – weight results of model to a single representative value
4. AC17 confirmatory testing – measure vehicle-level A/C impact in a lab setting

① Bench testing (SAE J2765)

SAE standard J2765 is a procedure for measuring system COP of a mobile air conditioning system on a test bench. It covers 40 different operating conditions at various compressor speeds, temperatures, and humidity levels. The procedure was designed to give maximum repeatability and minimum error in determining cooling capacity and efficiency of the entire refrigeration system. A sample configuration of the test facility is provided below (credit: *SAE J2765 standard*).



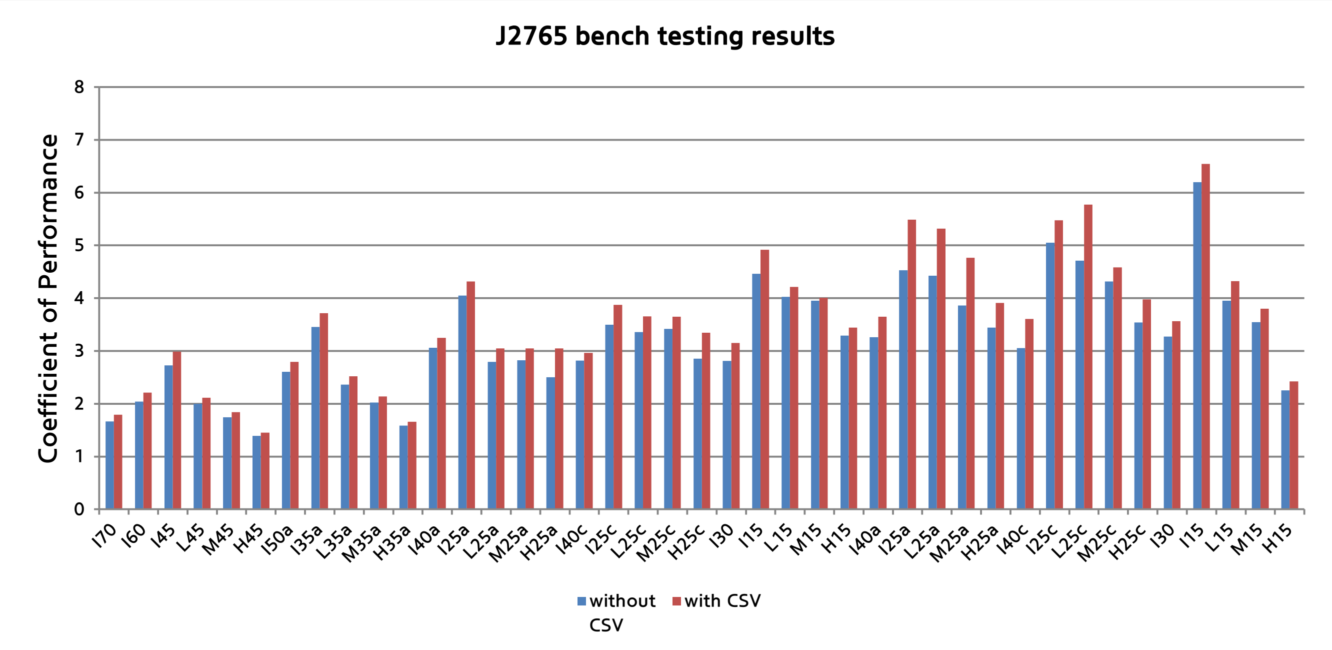
B - Blower, **CP** - Compressor, **CC** - Cooling Coil, **CH** - Glycol Chiller, **Cond** - Condenser, **Dp** - Differential Pressure Transducer, **Evap** - Evaporator, **FS** Flow Straightener, **H** - Heater, **Hu** - Humidifier, **mg** - Glycol Mass Flow Meter, **mr** - Refrigerant mass Flow Meter, **Mtr** - Motor, **N** - Nozzle, **P** - Pressure Transducer, **RH** - Relative Humidity Probe, **Sc** - Condensate Scale, **Sp** - Speed Controller and Tachometer, **T** - Thermocouple, **TC** - Temperature Controll **TG** - Thermocouple Grid, **Tor** - Torque Transducer, **W** - Watt Transducer, **TXV** - Thermal Expansion Valve
Indices : **a** - air, **c** - condenser, **cp** - comp ressor, **e** - evaporator, **g** - glycol, **I** - inlet, **n** - nozzle, **o** - outlet, **r** - refrigerant,

A summary of the test conditions run during standard best testing procedure:

Test Name	Ambient Temp. [°C]	Compressor Speed [RPM]	Condenser		Evaporator				Target Air Temp. Downstream of Evap. [°C]
			Temp. [°C]	Face Velocity [m/s]	Temp. [°C]	Humidity [%]	Mass Flow [kg/min]	Simulated Air Selection	
I70	45	900	70	1.5	35	25	9.0	RECIRC	3
I60	45	900	60	1.5	35	25	9.0	RECIRC	3
I45	45	900	45	1.5	35	25	9.0	RECIRC	3
L45	45	1800	45	2.0	35	25	9.0	RECIRC	3
M45	45	2500	45	3.0	35	25	9.0	RECIRC	3
H45	45	4000	45	4.0	35	25	9.0	RECIRC	3
I50a	35	900	50	1.5	35	40	9.0	OSA	3
I35a	35	900	35	1.5	35	40	9.0	OSA	3
L35a	35	1800	35	2.0	35	40	9.0	OSA	3
M35a	35	2500	35	3.0	35	40	9.0	OSA	3
H35a	35	4000	35	4.0	35	40	9.0	OSA	3
I40a	25	900	40	1.5	25	80	6.5	OSA	3 / 10
I25a	25	900	25	1.5	25	80	6.5	OSA	3 / 10
L25a	25	1800	25	2.0	25	80	6.5	OSA	3 / 10
M25a	25	2500	25	3.0	25	80	6.5	OSA	3 / 10
H25a	25	4000	25	4.0	25	80	6.5	OSA	3 / 10
I40c	25	900	40	1.5	25	50	6.5	OSA	3 / 10
I25c	25	900	25	1.5	25	50	6.5	OSA	3 / 10
L25c	25	1800	25	2.0	25	50	6.5	OSA	3 / 10
M25c	25	2500	25	3.0	25	50	6.5	OSA	3 / 10
H25c	25	4000	25	4.0	25	50	6.5	OSA	3 / 10
I30	15	900	30	1.5	15	80	6.5	OSA	3 / 10

I15	15	900	15	1.5	15	80	6.5	OSA	3 / 10
L15	15	1800	15	2.0	15	80	6.5	OSA	3 / 10
M15	15	2500	15	3.0	15	80	6.5	OSA	3 / 10
H15	15	4000	15	4.0	15	80	6.5	OSA	3 / 10

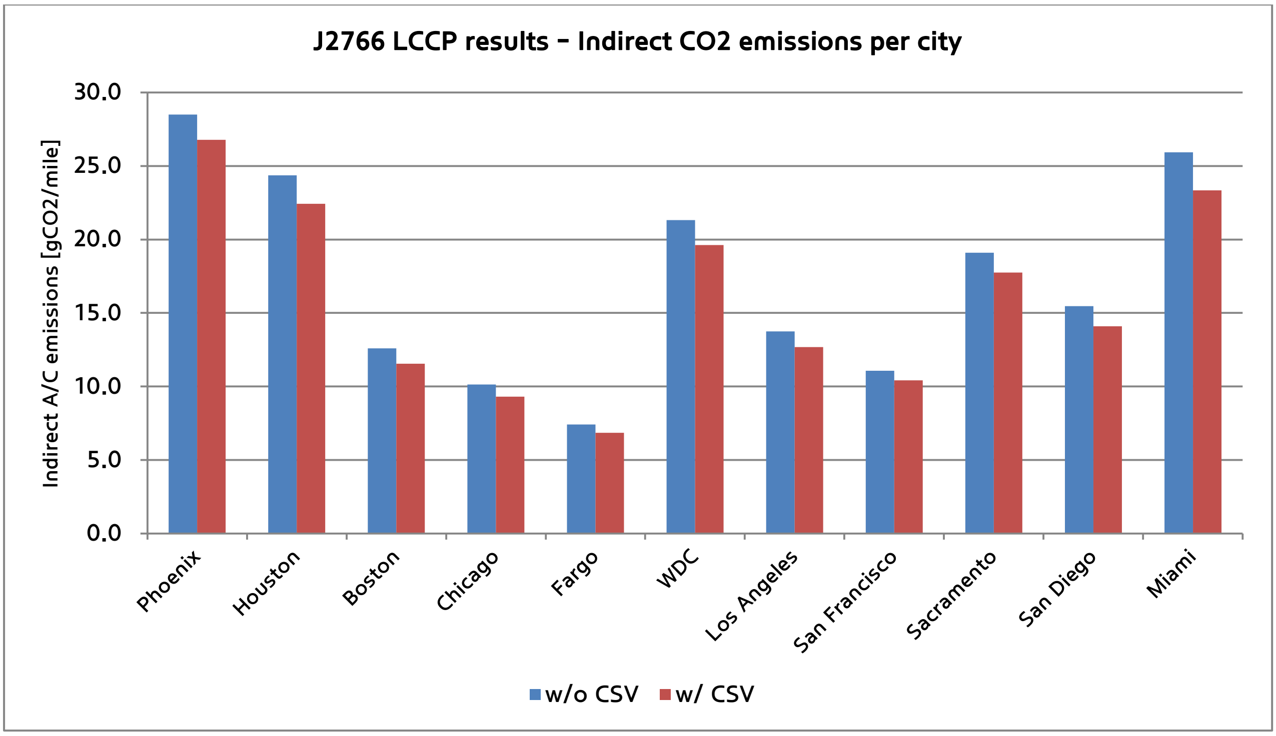
Two compressors were tested following the SAE J2765 standard – one without the crankcase suction valve to serve as a baseline, and a second compressor with the CSV to quantify the technology benefit. The results are displayed below.



② LCCP analysis (SAE J2766)

Following bench testing, the COP results and other system specifications are fed into the GREEN MAC LCCP model (**G**lobal **R**efrigerants **E**nergy and **EN**vironmental – **M**obile **A**ir **C**onditioning – **L**ife **C**ycle **C**limate **P**erformance). This model, jointly developed by General Motors, EPA, the Japanese Automobile Manufacturers Association, and SAE, was created to evaluate the CO2-equivalent emissions of an A/C system, including both the direct and indirect emissions. Direct emissions result from direct leaks of the refrigerant into the atmosphere, and are primarily evaluated based on the global warming potential of the refrigerant and the mass emitted. Indirect emissions result from the energy consumption associated with manufacturing, operation, and disposal of the A/C system.

This model represents a harmonization effort to investigate and quantify the climate change impact of alternative refrigerants and technologies, considering various climatic conditions, driving habits in different parts of the US and world, different vehicle platforms, and different fuels; it is based on research and data from National Renewable Energy Laboratory (NREL), Energy Information Administration (EIA), and the Department of Energy (DOE), as well as the contributors previously mentioned. Combining the J2765 bench test COP data with J2766 model data provides a simulation of average GHG emissions due to usage of an air conditioning system across several US cities. This model, therefore, can be used to quantify and compare indirect CO2 emissions based on bench test data.



The full analysis was completed with both compressors (baseline and Denso SES) and run for each of the three powertrain options in order to quantify the benefit of the crankcase suction valve technology.

③ LCCP weighted average

The output of indirect CO2 emissions due to A/C use in individual cities from the LCCP model can then be weighted to a single gCO2/mile value for each technology, which represents the US average GHG emissions. The weighting is based on vehicle registration in each city/region.

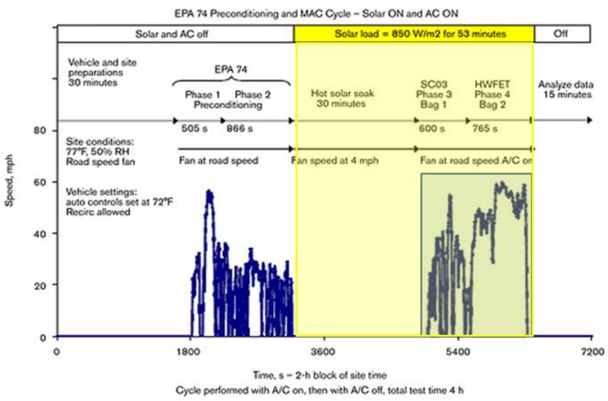
Performing the weighted analysis of the Denso SES compressor with crankcase suction valve technology results in a US average of 15.5 gCO2/mile indirect emissions due to A/C use. The baseline technology (without CSV) results in 16.9 gCO2/mile. From this analysis, vehicles equipped with the SES compressor and CSV technology should receive an off-cycle GHG credit of 1.4 gCO2/mile. This benefit was the same for all three engine options (same bench test data used, LCCP run independently for each).

		Phoenix	Houston	Boston	Chicago	Fargo	WDC	Los Angeles	San Francisco	Sacramento	San Diego	Miami	US total
[%]	Vehicle Weight:	*2.9%*	*13.2%*	*8.1%*	*24.0%*	*10.3%*	*13.6%*	*7.6%*	*1.5%*	*0.9%*	*2.5%*	*15.4%*	**100%**
Base (A)	*w/o CSV*	28.5	24.4	12.6	10.1	7.4	21.3	13.8	11.1	19.1	15.5	25.9	
	w/o CSV, weighted	0.8	3.2	1.0	2.4	0.8	2.9	1.0	0.2	0.2	0.4	4.0	**16.9**
Tech (B)	*w/ CSV*	26.8	22.4	11.6	9.3	6.9	19.6	12.7	10.4	17.8	14.1	23.4	
	w/ CSV, weighted	0.8	3.0	0.9	2.2	0.7	2.7	1.0	0.2	0.2	0.4	3.6	**15.5**
												A/B Δ	**1.4**

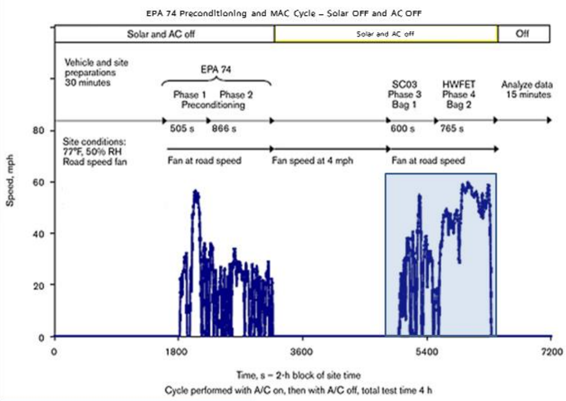
④ AC17 confirmatory testing

The combination bench test and national simulation of the technology provides an accurate measurement of the expected benefits, however, documenting the benefits at a vehicle level is also important for the off-cycle credit application. To quantify benefits at the vehicle-level, the AC17 test was conducted. AC17 is test used by OEMs and the EPA to confirm the GHG reduction benefit of other A/C efficiency technologies; relative to SC03, this test has more moderate load conditions.

A/C on, solar load on



A/C off, solar load off



Emissions are measured during the SC03 and HWFET phases.

Compared to other standard chassis dynamometer tests, the AC17 test is quite complex. It involves the use of a special environmental chamber to create the necessary test conditions – solar load, road speed fan, temperature and humidity specifications, etc. – plus is a test that takes approximately 4 hours to complete. This environmental chamber is under very high demand given its 5-cycle certification and range of capabilities, even beyond AC17 testing. For these reasons, only a limited number of AC17 tests were run to confirm the benefit of the technology.

Date	Test	Condition	AC on average	AC off average	Δ CO2	% Difference
9/13/16	AC17	B – w/CSV	259.0	240.1	19.0	7.9%
9/20/16		A – w/o CSV	269.6	241.4	28.2	11.7%
				A/B Δ	**9.3**	**3.8%**

The confirmatory AC17 test shows the directional benefit of the technology (ie vehicle CO2 emissions are lower with technology). The benefit does not perfectly match the model predictions; however, discerning the small difference (1.4 gCO2/mile benefit) compared to relatively large tailpipe CO2 emissions (~260 gCO2/mile) is quite difficult considering they are only approximately 0.5%. Considering test variability, this application is based on the more conservative and precise bench test data, with AC17 testing serving as a vehicle level confirmation.

Durability

Durability of the SES compressor has been thoroughly tested by both Denso and HMG and is already in production in one of Hyundai's highest-volume vehicles – the Sonata. Other development durability tests include: high refrigerant charge, low charge, vibration, corrosion, liquid slugging, clutch durability, resonant speed, control valve, start-stop cycling, reverse torque, over voltage, jump start, power temperature cycling, and humid heat cycling. The durability evaluation does not predict any expected in-use emission deterioration rate over the full useful life of the vehicle.

Comparison to previous GM application

In December of 2014, General Motors authored an off-cycle credit application to the EPA, requesting additional GHG credits for their Denso SAS compressor with variable crankcase suction valve technology. Based on GM's bench test and vehicle test data combined with the LCCP model, GM requested and was granted an off-cycle credit value of 1.1 gCO2/mile applied to 14 models in the 2013, 2014, and 2015 model year range. This represented a conservative estimate to be applied across their fleet, per their application.

HATCI is applying for a different value for several reasons: the LCCP model is specific to a vehicle (compressor speed as a function of engine speed, being one key input); every vehicle has a different layout, especially refrigerant plumbing; and the contributing load, and therefore potential benefit, on the engine from the A/C is dependent on engine displacement. Since this application is for one specific vehicle within Hyundai's product offering, the confidence of the estimate is high, even though it may be different than GM's testing and reasoning previously showed. Additionally, the 0.3 gCO2/mile difference compared to a roughly 300 g/mile tailpipe is 0.1%, a very small discrepancy. If anything, having the two applications closely match on predicted CO2 savings speaks to the robustness of the test and analysis procedures.

Based on our experience, an additional recommendation and consideration for future applications with this technology is to accept official bench test data from Denso for the A/C system, rather than repeating it for each vehicle; the LCCP model can then be used to determine the off-cycle benefit specific to a vehicle and/or powertrain. Considering the high test burden and cost posed by bench testing and specificity required for quantifying real-world benefits of off-cycle credits, this is a fair engineering balance.

Conclusion

Based on the bench and vehicle test data presented in this application, combined with the Lifecycle Climate Change Performance model, Hyundai Motor Group, represented by HATCI, hereby requests that the EPA approve an off-cycle GHG credit of 1.4 gCO2/mile for all 2015, 2016, and 2017 Hyundai Sonata vehicles equipped with the Denso SES compressor with variable crankcase suction valve technology. This 1.4 gCO2/mile credit has been estimated to be representative of the indirect fuel savings and subsequent GHG emissions that can be expected from this technology in real-world usage in US national average climate conditions.

Thank you for your consideration of this application for off-cycle GHG credits.

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Attachments:
- Off-cycle GHG credits – Denso SES; presentation, October 2016
- Off-cycle GHG credits – Denso SES; spreadsheet and calculations
- Denso presentation to EPA, April 2013
- HMG Denso SES sales volume (Confidential Business Information)