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Request for GHG Off-Cycle Credit for Pulse Width Modulated HVAC Brushless Motor Power Controller Technology

Introduction

Pursuant to 40 CFR § 86.1869-12(d), 49 CFR 531.6(b), and 49 CFR 533.6(c) Toyota Motor Corporation (herein referred to as "Toyota") requests the following Greenhouse Gas (GHG) off-cycle CO_2 credits for Pulse Width Modulated (PWM) HVAC Brushless Motor (BLM) Power Controller Technology.

Table 1 PWM BLM Credit Request

	Total credit (g CO_2 / mi)	A/C On (g CO_2 / mi)	A/C Off (g CO_2 / mi)
Manual A/C	0.4	0.2	0.2
Automatic A/C	0.4	0.3	0.1

Blower motor controls which limit wasted electrical energy, including PWMs, is listed on the EPA US Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards credit menu (40 CFR 86.1868-12). Pulse width modulation turns the switch between supply and load on and off at a high frequency to control the output power to an electrical device. The advantage of PWM is reduced power loss as in both ON and OFF scenarios there is either low current or low voltage. SAE J3109 is an established SAE methodology for validating the saving of pulse width modulated controllers. The standard gives the framework for measuring the efficiency of controllers. The intention of the standard is for OEMs to demonstrate compliance to regulatory agencies.

For this study Toyota followed J3109's bench test criteria and did A to B comparison testing of the PWM brushed motor (BMM) and PWM BLM to obtain the additional power saving of the BLM. This methodology demonstrates the emission reduction of pulse width modulated controls compared to traditional HVAC blower controllers. Toyota will separately apply for the menu credit for PWM blower motor controls which limit wasted electrical energy.

Per the recommendation in 40 C.F.R. § 86.1869-12(d)(1), Toyota met with the EPA for informal discussions on two separate occasions (04/20/2017 and 6/25/2017) to review the proposed plan and confirm application direction from the EPA. In each of the meetings the EPA was agreeable with the Toyota proposed method and the EPA's comments were reflected in the process. After discussions with the EPA it was determined that the portion of the PWM BLM benefit that occurs during A/C on conditions falls under the A/C Cap.

Description of Technology

The key difference between the BMM and BLM is that the brushed motor uses mechanical switching while the BLM uses circuit switching. A BMM uses brushes to deliver current to the motor windings on the rotor. BLM technology uses a magnet on a rotor with an electromagnetic static coil (stator) surrounding the magnet. A driver (commutator) changes the current direction in the magnetic coil which changes the magnetic field direction causing the rotor to turn (repel and/or attract against permanent magnets). The benefit of the BLM is there is removal of frictional loss, by eliminating the consumable brush and physical touch between stator and commutator, which reduces the amount of power lost to heat. The BLM also has 10 times the lifespan of the brushed motor.

Rationale for Alternative Method Off Cycle Application

The off-cycle credit program was created to support the creation and adoption of fuel saving technologies which reduce real world greenhouse gas emissions but cannot be accurately captured in two cycle tests. Since the HVAC is not used in the 2-cycle testing, one of two other methods need to be used to quantify the CO_2 reduction benefit: 5-cycle testing or alternative application. The EPA's standard 5-Cycle testing has two modes that use the HVAC, Cold FTP and SC03. The airflow and HVAC mode usage in these two tests does not sufficiently represent the wide range of customer usage of HVAC blower motors due to the specified nature of the testing. Furthermore, the benefit of this technology is relatively small and is difficult to see with clarity in vehicle level testing.

With the above restrictions, it was necessary to pursue an alternative method to accurately quantify the CO_2 reduction benefit of the technology.

Proposed Alternative Demonstration Method

A. <u>System Selection</u>

DENSO's AC1 HVAC module was used as the representative for testing. Since testing was done in the same blower case, the AC module type was not a factor in the result. By using the same blower case the motor type was the only changing factor.

To remove the impact of additional factors, the same AC1 module was used for both the BMM and BLM testing with only blower motor being exchanged at each condition.

Toyota's intention for this application is to use the previously established process of SAE J3109 which can be used to certify a HVAC blower motor's PWM controller matches the required efficiency to receive the EPA's menu credit. Vehicle testing is not required for the use of J3109 so worst-case vehicle selection was not necessary for worst case selection.

B. Bench Testing Methodology and Results

1. Bench Testing Methodology

Blower motor controls which limit wasted electrical energy, including PWM's, is listed as an EPA menu off-cycle credit technology. SAE J3109 was written as a methodology to show compliance to this menu item and outlines the test procedure and required equipment for determining the weighted power saving of a HVAC blower motor. Toyota used this standard as a basis to confirm the CO_2 reduction potential for the BLM using the conditions listed below in Table 2. J3109 section 5 outlines the test set up for the BMM. All the required test equipment outlined in the standard was used for testing. Table 2 shows each of the J3109 test conditions (low through high) and indicates the J3109 fixed values (columns B, E, F,K,O). The other columns indicate the values that were collected in the test or the values that were calculated from test results.

Table 2 PWM Test Matrix Showing J3109 Criteria

Condition	BMM								BLM					N: Power saving [W]	O: Weighting	P: Weighted power saving [W]
	A:	B:	C:	D:	E:	F	G:	H:	I:	J:	K:	L:	M:		factor [%]	
	Duty cycle [%]	Voltage input [V]	Current input [A]	Power input [W]	Voltage output [V]	Current output [A]	Power output [W]	RPM	RPM	Duty cycle [%]	Voltage input [V]	Current input [A]	Power input [W]			
Low		13.5			4	23%×Hi					13.5				35	
Medium low		13.5			6	35%×Hi					13.5				22	
Medium		13.5		B×C	8.3	54%×Hi					13.5		K×L	M-D	20	N×O
Medium high		13.5			10.5	75%×Hi					13.5				12	
High		13.5			12.5	Hi					13.5				10	
* Red indicates J3109 constants															ΔP =	W

The BMM was tested first to capture its power consumption as a baseline using the SAE J3109 methodology. The load at the power input is controlled at 13.5V (columns B and K). To reach the required output voltage (E) the duty cycle was adjusted. The inlet and outlet of the HVAC module was blocked to match the specified output current (F). The definition in J3109 was used to determine the output current for the high condition. The definition states, "Hi is defined as 1A beneath the lower tolerance of the rated current.” With that definition, 20A was determined to be high. The input current, rpm, and size of the outlet and inlet blockage were recorded at that condition.

The BMM was then replaced with the BLM. The outlet and inlet blockage was maintained at each of the specified conditions to maintain the same load. After changing to the BLM, the duty cycle (J) was adjusted to reach the BMM’s recorded rpm (H). The input current (A) was recorded after reaching that rpm. The BLM power was then calculated using the input current.

After completion of each condition the weighted power saving delta of the BMM and BLM was calculated. The weighting factor is based on the percent usage of different voltages in the field (J3109). This final power saving was used to calculate the credit amount.

2. Bench Test Results

To confirm repeatability, the test was run three times. The result of each test is in the appendix. Table 3 shows result of case 3 (power saving of 16.36 W). The average power saving of the BLM was 16.85 W.

Table 3 J3109 AC1 Bench Test Result (Case 3 of 3)

Case 3	BMM								BLM					Power saving [W]	Weighting factor [%]	Weighted power saving [W]
	Duty cycle [%]	Voltage input [V]	Current input [A]	Power input [W]	Voltage output [V]	Current output [A]	Power output [W]	RPM	RPM	Duty cycle [%]	Voltage input [V]	Current input [A]	Power input [W]			
Low	26.3	13.5	1.8	24.3	4	4.5	18	1149	1146	25.5	13.5	1.2	16.5	7.8	35	2.7405
Medium low	39.3	13.5	3.7	50	6	6.9	41.3	1757	1762	38.8	13.5	2.8	37.9	12	22	2.6433
Medium	55	13.5	7.3	99.1	8.3	10.6	88.4	2537	2537	55.3	13.5	5.9	79.5	19.6	20	3.915
Medium high	69.1	13.5	12.7	171.5	10.5	14.8	155.1	3162	3160	68.5	13.5	10.6	142.4	29	12	3.483
High	82	13.5	19.6	264.6	12.5	19.9	248	3567	3554	77	13.5	17	228.8	35.8	10	3.5775
															Total saving	16.3593

C. Benefit Calculation Methodology and Result

1. Benefit Calculation Methodology

SAEJ3019 provides a method to measure the efficiency of a blower controller but it does not provide a means to estimate the GHG emissions reduction. SAE3174 is the supporting standard that is being written for the calculating the emissions reductions. The calculation accounts for the blower usage, alternator efficiency, engine efficiency, vehicle lifetime mileage, vehicle CO_2 emissions, the gasoline heating value, and the calculated power saving from the bench test. The values used in the standard are based on the 2009 Motor & Equipment Manufacturers Association’s (MEMA) response to NHTSA 2009-0059 and EPA-HQ-OAR-2009-0472, the EPA final ruling, and other industry accepted values. Figure 1 visualizes the calculation and Equation 1 shows the final CO_2 emission reduction calculation.

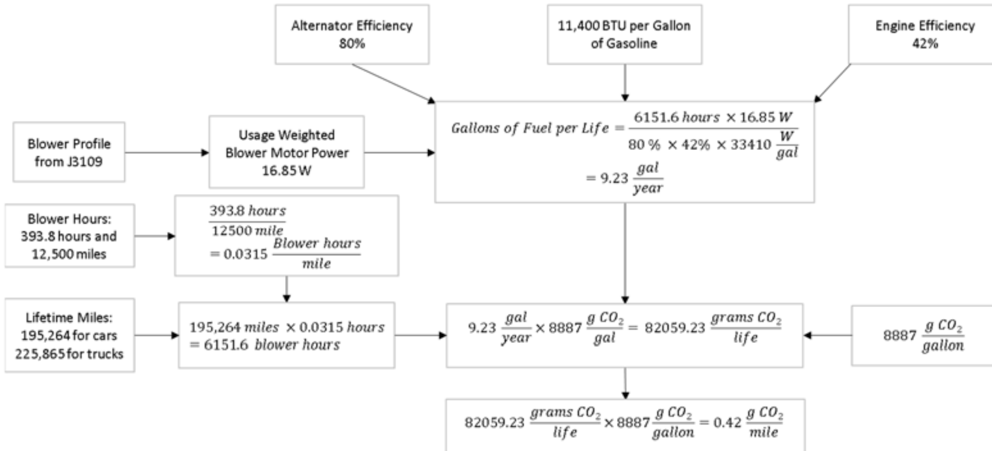

Figure 1 Credit Calculation Method

$$CO_2\ emission\ reduction\ \frac{g}{mile} = \frac{\dfrac{6151.6\ hours\ \times\ \Delta P\ W}{80\ \%\ \times 42\%\ \times 33410\ \dfrac{W}{gal}} \times 8887\ \dfrac{g\ CO_2}{gal}}{195{,}264\ \dfrac{miles}{life}}$$

$$= 0.025\ \times\ \Delta P\ \frac{g}{mile} \qquad (1)$$

$$CO_2 emissions\ reduction = 0.025\ \times 16.85 \frac{g}{mile} = 0.42 \frac{g\ CO_2}{mile} \qquad (2)$$

Where:

$$Blower\ Usage\ (LDV) = 6151.6\ hours$$
$$Blower\ Usage\ (LDT) = 7115.7\ hours$$
$$Weighted\ Power\ Saving = \ 16.85\ W\ (average\ of\ 3\ tests)$$
$$Gasoline\ Heating\ Value\ = 33410\ \frac{W}{gal}$$
$$CO_2 emission\ per\ gallon\ gasoline\ = 8887\ \frac{g\ CO_2}{gal}$$
$$Alternator\ Efficiency = 80\%$$
$$Engine\ Efficiency = 42\%$$
$$Vehicle\ Lifetime\ Mileage\ (LDV) = 195{,}264$$
$$Vehicle\ Lifetime\ Mileage\ (LDT) = 225{,}865$$

2. *Benefit Calculation Result*

Using the method outlined above and in J3174 using a BLM instead of BMM in the vehicle's HVAC system yielded a CO_2 reduction of 0.4 g CO_2/mile total (equation 2). For comparison, the generic conversion of 100W to 3.2g CO_2/mile from the

2017 EPA and NHTSA Joint Technical Support Document (TSD Chapter 5, 5.2.1, pg. 5-64) for reducing/offsetting electrical loads was used to calculate an alternate saving amount equal to 0.5g CO_2/mile. Since the saving amount from J3174 is more conservative and is an accepted standard for blower motors, 0.4 g CO_2/mile was chosen for the base credit level.

During initial discussions with the EPA Toyota was advised to separate the credit between time when the blower is used with the AC "ON" and time with the AC "OFF". For time when the AC is "ON" the AC cap should be applied to the AC usage portion of the total saving. The CO_2 reduction outside of AC usage (i.e heater) is not limited by the AC cap. Using the AC "ON" and AC "OFF" percentage breakdown from MEMA's response document the total credit amount can be divided into the respective categories. Their percentage breakdown is based on an A/C usage profile and the Bureau of Transportation Statistics US DOT Household Travel Survey.

Table 4 MEMA US Air Conditioning Usage Profile

	Ignition On Time (hrs)	A/C On Time (hrs, %)	A/C Off Time (hrs, %)	Driving Distance Per Year (miles)	Fleet Composition (%)
Manual A/C	393.8	175.6 (44.6%)	218.2 (55.4%)	12500	65
Automatic A/C	393.8	276.8 (70.3%)	117.0 (29.7%)	12500	35

Applying the percentage division above to the conservative, base credit level of 0.4 g/mile CO_2, the following A/C On and A/C Off credit application can be determined:

Table 5 PWM BLM Credit Breakdown

	Total Credit (g CO_2/mile)	A/C On (g CO_2/mile)	A/C Off (g CO_2/mile)
Manual A/C	0.4 g/mile	0.18 g/mile (44.60%)	0.22 g/mile (55.40%)
Automatic A/C	0.4 g/mile	0.28 g/mile (70.30%)	0.12 g/mile (29.70%)

D. *Credit Grouping Application Strategy*

Table 6 shows the respective credit amount per each HVAC type that utilizes PWM BLMs.

Table 6 PWM BLM Vehicles

A/C Type	AC On Credit (g/mile)	AC Off Credit (g/mile)
Manual	0.2	0.2
Auto	0.3	0.1

BLM PWMs in the rear HVAC would have some saving but at this time Toyota is only applying for credit for the front HVAC. Toyota may apply for rear HVAC credit in the future.

Durability Assessment

Toyota Mobile Air-Conditioning (MAC) systems including the condenser, compressor, evaporator, thermal expansion valve and HVAC module are required to pass stringent durability requirements to ensure a useful life time of the components. Testing includes meeting the rigorous 10 years/120,000 mile requirements to achieve the CO_2 -related efficiency menu credits for both refrigerant-leakage and high efficiency air conditioning technology. Further durability testing on the HVAC module include door operation durability, vibration durability, thermal shock, high temperature durability, servo motor lock durability, dust durability and oil return.

Based on meeting these internal and EPA MAC durability requirements, Toyota is confident that the HVAC PWM BLM can meet the requirements for the vehicle lifetime durability with no degradation in the CO_2 reduction benefit of the HVAC PWM BLM. Detailed results of the durability testing are included in the appendix

Conclusion

Based on the above bench test results, Toyota hereby requests the following off cycle greenhouse gas credit for the following BLM configurations for all vehicles equipped with this technology:

Table 7 HVAC PWM BLM Credit Request

A/C Type	AC On Credit (g/mile)	AC Off Credit (g/mile)
Manual	0.2	0.2
Auto	0.3	0.1

These credits have been conservatively based on an established bench test method. Detailed model year and the requested HVAC PWM BLM credit are included in the attachments. Thank you in advance for your consideration.

Toyota Motor Engineering and Manufacturing North America

Supporting Materials and Documentation

Attachment A: Bench Test Results
Attachment B: Technology Adoption Plan (Confidential)
Attachment C: Technology Description (Confidential)
Attachment D: J3109 SAE Standard (Confidential)
Attachment E: Durability Tests (Confidential)
Attachment F: Motor & Equipment Manufacturers Association's response to NHTSA 2009-0059 and EPA-HQ-OAR-2009-0472 (Confidential)

AC1 HVAC Result (N=3)

Condition 1	BMM								BLM					Power saving [W]	Weighting factor [%]	Weighted power saving [W]
	Duty cycle [%]	Voltage input [V]	Current input [A]	Power input [W]	Voltage output [V]	Current output [A]	Power output [W]	RPM	RPM	Duty cycle [%]	Voltage input [V]	Current input [A]	Power input [W]			
Low	26.1	13.5	1.8	24.2	4.0	4.5	18.0	1132	1131	25.2	13.5	1.2	15.7	8.5	35	2.97675
Medium low	39.2	13.5	3.7	49.7	6.0	6.8	40.7	1830	1830	40.3	13.5	2.7	35.8	13.9	22	3.0591
Medium	54.5	13.5	7.4	99.9	8.3	10.4	86.0	2565	2565	56.0	13.5	5.8	78.4	21.5	20	4.293
Medium high	69.0	13.5	12.6	170.1	10.5	14.5	152.3	3211	3211	69.5	13.5	10.8	145.1	25.0	12	2.997
High	82.0	13.5	19.6	264.6	12.5	19.3	241.3	3643	3640	79.0	13.5	17.3	232.9	31.7	10	3.1725
															Total saving	16.49835

$0.025 * \Delta P_{AC1} = 0.4$ g/mile

Condition 2	BMM								BLM					Power saving [W]	Weighting factor [%]	Weighted power saving [W]
	Duty cycle [%]	Voltage input [V]	Current input [A]	Power input [W]	Voltage output [V]	Current output [A]	Power output [W]	RPM	RPM	Duty cycle [%]	Voltage input [V]	Current input [A]	Power input [W]			
Low	26.1	13.5	1.7	23.2	4.0	4.5	17.8	1129	1132	25.3	13.5	1.1	15.3	8.0	35	2.78775
Medium low	39.2	13.5	3.6	49.0	6.0	6.8	41.0	1825	1815	40.1	13.5	2.7	36.2	12.8	22	2.8215
Medium	54.4	13.5	7.3	99.0	8.3	10.5	86.9	2549	2538	55.3	13.5	5.5	74.7	24.3	20	4.86
Medium high	69.0	13.5	12.4	167.4	10.5	14.6	152.9	3158	3160	68.4	13.5	10.2	137.8	29.6	12	3.5478
High	82.0	13.5	19.6	264.6	12.5	19.5	243.0	3593	3593	77.7	13.5	16.9	227.9	36.7	10	3.672
															Total saving	17.68905

$0.025 * \Delta P_{AC1} = 0.4$ g/mile

Condition 3	BMM								BLM					Power saving [W]	Weighting factor [%]	Weighted power saving [W]
	Duty cycle [%]	Voltage input [V]	Current input [A]	Power input [W]	Voltage output [V]	Current output [A]	Power output [W]	RPM	RPM	Duty cycle [%]	Voltage input [V]	Current input [A]	Power input [W]			
Low	26.3	13.5	1.8	24.3	4.0	4.5	18.0	1149	1146	25.5	13.5	1.2	16.5	7.8	35	2.7405
Medium low	39.3	13.5	3.7	50.0	6.0	6.9	41.3	1757	1762	38.8	13.5	2.8	37.9	12.0	22	2.6433
Medium	55.0	13.5	7.3	99.1	8.3	10.6	88.4	2537	2537	55.3	13.5	5.9	79.5	19.6	20	3.915
Medium high	69.1	13.5	12.7	171.5	10.5	14.8	155.1	3162	3160	68.5	13.5	10.6	142.4	29.0	12	3.483
High	82.0	13.5	19.6	264.6	12.5	19.9	248.0	3567	3554	77.0	13.5	17.0	228.8	35.8	10	3.5775
															Total saving	16.3593

$0.025 * \Delta P_{AC1} = 0.4$ g/mile