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Measurement of Vehicle Air Conditioning Pull-Down Period

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OAK RIDGE NATIONAL LABORATORY
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Energy and Transportation Science Division

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ABBREVIATIONS/ACRONYMS

A/C	air conditioning
Amb.	ambient
Avg.	average
ECT	engine coolant temperature
°F	degrees Fahrenheit
gal	gallon
h	hour
I4	inline four cylinder configuration
mph	miles per hour
OBD-II	on-board diagnostic system II, mandated as standard in 1996
s	second
TC	thermocouple
temp.	temperature
V6	V-six cylinder configuration

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ABSTRACT

Air conditioner usage was characterized for high heat-load summer conditions during short driving trips using a 2009 Ford Explorer and a 2009 Toyota Corolla. Vehicles were parked in the sun with windows closed to allow the cabin to become hot. Experiments were conducted by entering the instrumented vehicles in this heated condition and driving on-road with the windows up and the air conditioning set to maximum cooling, maximum fan speed and the air flow setting to recirculate cabin air rather than pull in outside humid air. The main purpose was to determine the length of time the air conditioner system would remain at or very near maximum cooling power under these severe-duty conditions. Because of the variable and somewhat uncontrolled nature of the experiments, they serve only to show that for short vehicle trips, air conditioning can remain near or at full cooling capacity for 10-minutes or significantly longer and the cabin may be uncomfortably warm during much of this time.

1. INTRODUCTION

In a previous study [1] on-road and chassis dynamometer-based experiments with a 2009 Ford Explorer and a 2009 Toyota Corolla were conducted to assess fuel consumption penalties due to air conditioner (A/C) use at idle and highway cruise conditions. Experiments included these vehicles operating with various A/C settings, with the A/C off, and with A/C off and windows open. The purpose was to better understand the actual fuel penalty due to A/C use and fuel penalty trade-off between driving using the A/C versus driving with the windows down [1]. A major portion of the previous effort involved running the A/C at maximum cooling which generates the maximum fuel penalty; clearly the fuel penalty from A/C usage is highly variable and dependent on many factors. Notable results from this previous study [1] included significant additional fuel use measured for 100% A/C duty versus no use of climate control. Specifically this was ~0.2 gal/h at idle to ~0.4 gal/h at 40-70 mph for the Explorer and ~0.13 gal/h at idle and ~0.17 gal/h at 40-70 mph for the Corolla.

During peer review of the previous study, some reviewers questioned the usefulness of examining 100% A/C duty cycle, suggesting it would be unrealistically high. Obviously 100% duty cycle is the high endpoint of A/C operation, and much A/C use involves lower duty cycles. Prior to publication the reviewers did agree that 100% duty cycle was useful for the purposes of that particular study. This questioning inspired a modest follow-up effort to examine the pull-down interval, or the time that the A/C compressor remained fully engaged. It was hypothesized that it may be common for the A/C to operate at maximum duty cycle for much of the time during short trips.

All of the authors' personal experience in summer driving would indicate 100% duty cycle is common, at least in regions with hot weather. A hot weather period was chosen to conduct experiments targeting measurement of how long A/C systems might operate at 100% duty cycle or at very high duty cycle. Because ORNL is situated in East Tennessee, hot and often humid weather occurs each summer.

2. EXPERIMENTAL SETUP

2.1 VEHICLES

The vehicles used were a 2009 Ford Explorer equipped with a 4.0 liter V6 engine and a five speed automatic transmission, and a 2009 Toyota Corolla with a 1.8 liter I4 engine and a four speed automatic transmission [1]. Both vehicles are equipped with cruise control which was used for some highway driving, and both vehicles were fueled with Halterman EEE-Lube Spec Certification Gasoline.

Thermocouples (TCs) were placed in several locations to collect both ambient and A/C system conditions. The ambient temperature TC was located under the side view mirror in order to shield it from direct sunlight. TCs were placed in front of and behind the A/C condenser to monitor the A/C system heat rejection, and also in the center dash A/C vent to monitor the temperature of the air exiting the A/C system. Additionally, vehicle cabin temperature was monitored with a TC in the second row passenger area at a position representative of the approximate location of an adult passenger's head (commonly referred to as the breath temperature [2]).

Although no solar load was measured, it is noteworthy that the Explorer has a black exterior and interior, and was equipped with only moderate window tinting. The Corolla had a light gray exterior, a light gray interior, and minimal window tinting.

2.2 DATA COLLECTION SYSTEM

Data from each vehicle's data bus were collected using the OBD-II Interface and ScanXL Professional software from Palmer Performance Engineering (www.palmerperformance.com). With this system OBD-II data including Vehicle Speed Sensor (VSS), Mass Air Flow (MAF), and Throttle Position Sensor (TPS) were collected. A diagnostics add-on capability applicable to the Ford vehicle was available from previous efforts [1] which monitored A/C clutch engagement via the OBD-II port. For the Toyota Corolla, A/C compressor status was monitored by measuring current to the magnetic clutch. The ambient and A/C system temperature data were collected using a USB TC-08 Thermocouple Data Logger from Pico Technology (www.picotech.com).

2.3 ON-ROAD SETUP AND PROCEDURES

The ORNL NTRC site is located in Knoxville and although straight and level stretches of highway are rare in this region, relatively flat roads and relatively flat sections of Interstate 75 were used for these experiments [1]. All experiments were completed during 8 test days over a 10 day hot-weather period. Vehicles were parked in the full mid-day sun in an unshaded parking lot. As expected, some variety in ambient conditions and vehicle initial conditions were observed during the experiments. Data were collected over two drive cycles, one to mimic city cycle driving and another for high-speed interstate driving, with most tests being the latter. These cycles were not consistent due to the changes in ambient and traffic conditions.

3. RESULTS

3.1 2009 TOYOTA COROLLA

Four experiments were completed with the Corolla; three with mainly highway type driving and one with city type driving. The highway driving tests began with 1-3 minutes of low-speed stop-and-go driving until major roads were reached and highway driving was maintained. These experiments are summarized in Table 1. In all experiments A/C compressor duty cycle was virtually 100% for at least 15 minutes. The times given (in Table 1) are from the A/C being turned on until the event described. The compressor command to operate stays on for a long initial period in all cases and even the shortest periods (7/17 and 7/19) were followed immediately by an extended "compressor on" period. Although the city cycle test on 7/17 shows a large time (25 minutes) for the cabin to reach the chosen metric of 80 °F, it only took about 5 minutes to reach 85 °F. For this particular drive cycle, prolonged driving at 40 mph from about 350 to 600 seconds was followed by more stop-and-go driving which reduced the engine speed, slowed the compressor speed and reduced air flow through the condenser (lowering A/C cooling capacity). There were no repeats of this individual test, therefore conclusions should be made with caution. Test 5b shows the expected result that an 80 °F cabin temperature is reached sooner with a lower cabin starting temperature.

Averaged ambient wet bulb, dry bulb and dew point temperature are reported to document that the weather was hot with significant humidity. The average ambient temperature varies from the dry bulb temperature slightly because the dry and wet bulb temperatures were averaged over different time windows (for example, the wet bulb temperature was invalid during stops due to lack of air flow and this portion of time was excluded from averaging).

Table 1. Summary of pull down experimental results for the 2009 Toyota Corolla

Test Day, Date	City or Highway Driving	Cabin Start Temp. (°F)	Avg. Amb. Temp. (°F)	Time Until Compressor First Cycles Off (s)	Time to Cabin Reaching 80 °F (s)	Ambient Wet Bulb Temp. (°F)	Ambient Dry Bulb Temp. (°F)	Ambient Dew Point Temp. (°F)
5a, 7/16	H	138	94	1500	500	74.5	94.2	65.6
5b, 7/16	H	115	91	1480	230	76.1	91.1	70.0
8, 7/19	H	138	94	440*	830	77.7	93.9	71.4
6, 7/17	C	136	98	760*	1500	76.4	98.6	70.0

*compressor cycled off very briefly during a vehicle acceleration, and then stayed on continuously for over 10 additional minutes.

Measured results for experiment 5a are shown in Fig. 1. The first compressor-off event was observed when the vehicle stopped and then accelerated at about 1500 s. Data review indicates that the compressor may be turned off briefly due to the engine state (hard acceleration) as well as cooling demand. For the 7/19 case a near-stop is made at 440 seconds followed by a hard acceleration at which point the compressor cycled off briefly and then was 100% engaged for a long period. In all cases the concept that the A/C stays at or near full-load for a short trip under common hot weather initial conditions is supported.

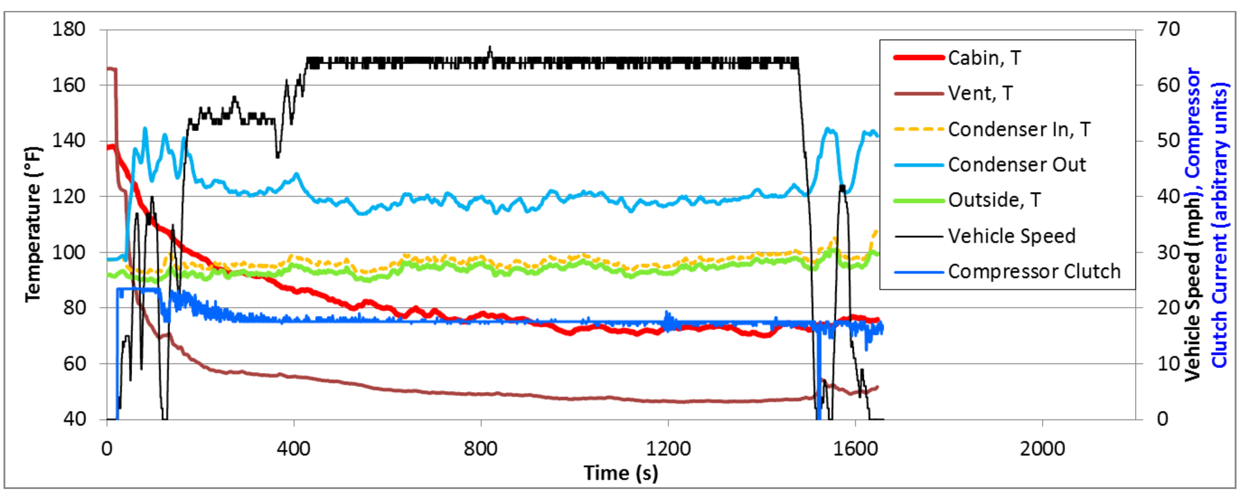

Figure 1. Results for Toyota Corolla pulldown experiment 5a. T=temperature.

3.2 2009 FORD EXPLORER

Nine experiments were completed with the Explorer, which are summarized in Table 2. Seven of the tests involved low-speed, stop and go driving for 1-3 minutes before reaching major roads at which point highway driving began. The two city driving tests involved mainly lower speed and stop and go driving. Examples of measured results from the Explorer experiments are shown in Figs. 2 and 3.

The major observation is that A/C full cooling load is observed to continue for 7-23 minutes for this range of tests. It can also be seen that hotter initial conditions for the highway driving tests consistently show longer times until the compressor cycles. As expected, the city driving also appears to increase times for continuous or near-continuous compressor operation, perhaps because the average compressor speeds are lower and there is less cooling air flow through the condenser, both of which reduce the A/C cooling capacity. Because the city cycle was only performed twice, conclusions are made with caution. The high quality A/C clutch engagement data available for the Explorer allowed estimation of compressor on-time fraction later in each test when cycling on and off was established.

Table 2. Summary of pull down experimental results for the 2009 Ford Explorer

Test Day, Date	City or Highway Driving	Cabin Start Temp. (°F)	Avg. Amb. Temp. (°F)	Time Until Compressor First Cycles Off (s)	Time to Cabin Reaching 80 °F (s)	Compressor On-time Fraction After Cycling Begins	Ambient Wet Bulb Temp. (°F)	Ambient Dry Bulb Temp. (°F)	Ambient Dew Point Temp. (°F)
1, 7/11	H	128	88	600	1500	72%	75.6	87.7	70.7
4, 7/15	H	120	90	570	560	74%	75.4	90.0	69.3
5a, 7/16	H	132	94	960	940	90%	79.3	93.8	74.0
5b, 7/16	H	106.5	95	420	340	85%	79.8	94.8	74.3
6, 7/17	H	131	95	920	800	80%	77.3	95.4	70.0
7a, 7/18	H	139	95	970	1500	88%	76.5	97.2	67.8
7b, 7/18	H	114.5	93	490	490	83%	74.3	92.9	66.1
2, 7/12	C	134	88	1400	1500	95%	74.3	89.2	67.9
3, 7/13	C	128	88	1010	860	91-95%	75.4	89.2	69.7

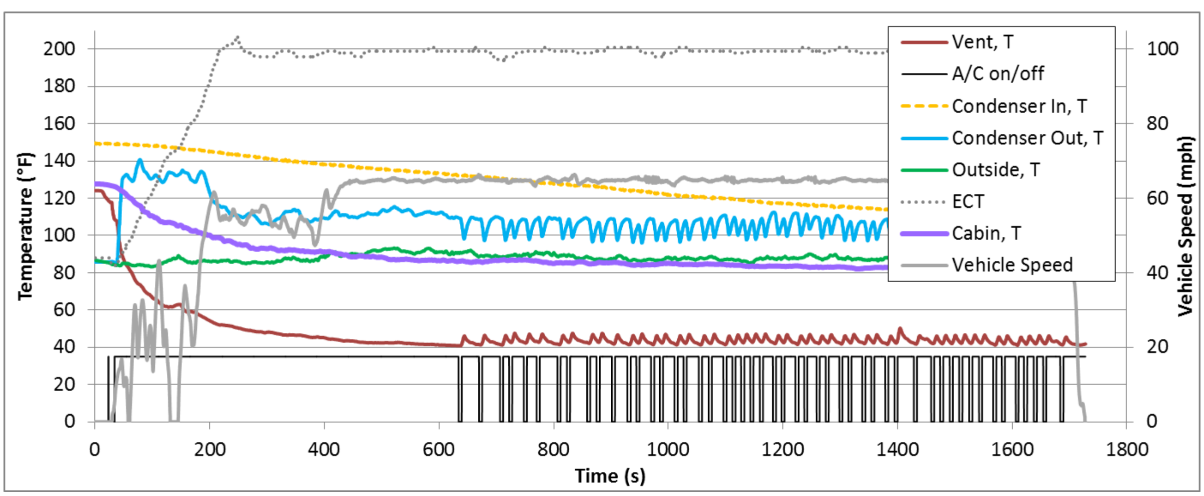

Figure 2. Results for Ford Explorer highway driving pulldown experiment 1. T = temperature, ECT = engine coolant temperature.

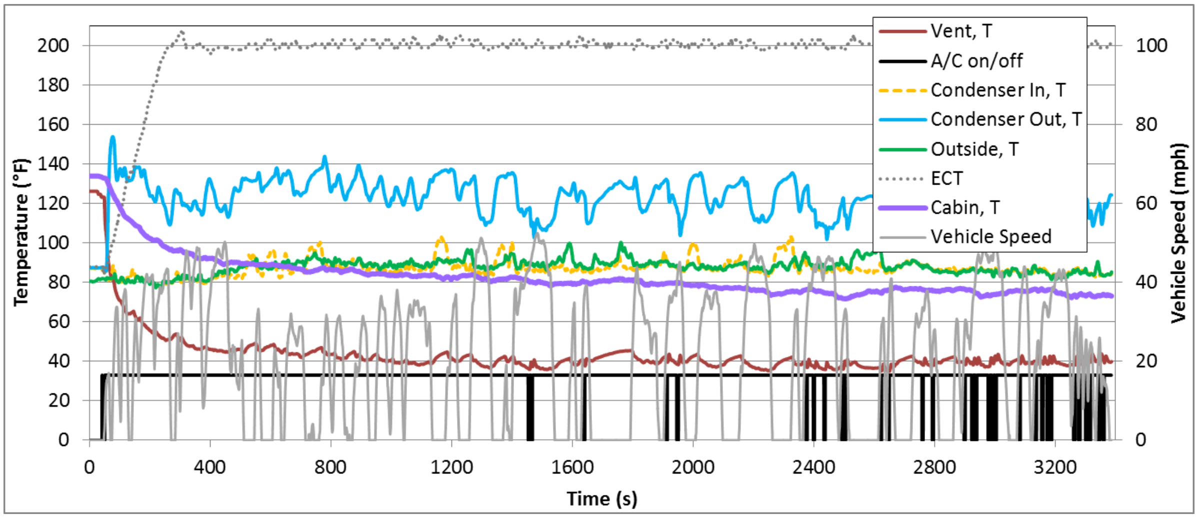

Figure 3. Results for Ford Explorer city driving pulldown experiment 2. T = temperature, ECT = engine coolant temperature.

SUMMARY AND CONCLUSIONS

A model year 2009 sedan and SUV were parked in the full mid-day sun on hot summer days allowing the cabins to reach high temperatures, typical of unshaded parking conditions in hot weather. Researchers entered the vehicles and turned the A/C systems to maximum cooling settings and then drove the vehicles to measure the time interval of 100% A/C duty cycle.

- For the conditions tested, 7-25 minutes of 100% duty cycle was recorded for both vehicles.
- After compressor cycling began, compressor on-time remained at 66-95% during the Explorer tests. Duty cycle is dependent on ambient conditions, driving cycle, etc.
- Pulldown of back seat temperature from 128-134°F initial temperature to 85°F generally took 8-12 minutes.
- For the broad range of conditions tested, it typically took 8-25 minutes for the cabin to reach 80°F.
- From the previous study [1] the additional fuel use due to running the Ford Explorer A/C at 100% duty cycle is ~0.2 gal/h at idle (a 55% increase) and ~0.4 gal/h at 40-70 mph (an increase of 27% at 40 mph and 14% at 70 mph). For the Toyota Corolla the incremental fuel consumption was ~0.13 gal/h at idle (60% increase) and ~0.17 gal/h at 40-70 mph (representing a 22% increase at 40 mph to about a 9% increase at 70 mph).
- Pull-down period is dependent on initial conditions. Parking in the shade, opening the windows briefly before or at the start of the trip, and any other means to move the cabin temperature toward the desired set point will reduce the A/C compressor load and lower the fuel penalty.

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