Impact of Active Climate Control Seats on Energy Use, Fuel Use, and CO_2 Emissions: Test and Analysis

Cory Kreutzer, John Rugh, Bidzina Kekelia, Gene Titov

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Executive Summary

Characterizing the performance of climate control seating in the light-duty automotive sector is challenging because their impact is dependent on the vehicle occupant(s). Although automotive HVAC systems are designed to provide climate control to the occupant, they do so indirectly by controlling surrogate metrics such as cabin air temperature. Therefore, careful experimental design integrating both human occupant thermal comfort/sensation feedback and existing automotive HVAC performance is required in order to properly characterize climate control seats. Similarly, estimating the performance of climate control seats at the national scale through analysis poses significant challenges. Automotive HVAC system performance is strongly dependent on environmental conditions, vehicle use behaviors such as time-of-day of driving and trip duration, and the vehicle platform itself. Integrating human thermal comfort/sensation analysis at the national scale is prohibitive due to model complexity and associated simulation time. Capturing system performance requires limiting complexity while capturing a large range of input conditions.

A project was developed through collaboration between Gentherm and NREL to determine the impact of climate control seats for light-duty vehicles in the United States. The project used a combination of experimentation and analysis, with experimental results providing critical input to the analysis process. First, outdoor stationary vehicle testing was performed at NREL's facility in Golden, CO using multiple occupants. Two preproduction Ford Focus electric vehicles were used for testing; one containing a standard inactive seat and the second vehicle containing a Gentherm climate control seat. Multiple maximum cool-down and steady-state cooling tests were performed in late summer conditions. The two vehicles were used to determine the increase in cabin temperature when using the climate control seat in comparison to the baseline vehicle cabin temperature with a standard seat at the equivalent occupant whole-body sensation. The experiments estimated that on average, the climate control seats allowed for a 2.61°C increase in vehicle cabin temperature at equivalent occupant body sensation compared to the baseline vehicle. The increased cabin air temperature along with their measured energy usage were then used as inputs to the national analysis process.

The national analysis process was constructed from full vehicle cabin, HVAC, and propulsion models previously developed by NREL. In addition, three representative vehicle platforms, vehicle usage patterns, and vehicle registration weighted environmental data were integrated into the analysis process. Both the baseline vehicle and the vehicle with climate control seats were simulated, using the experimentally determined cabin temperature offset of 2.61°C and added seat energy as inputs to the climate control seat vehicle model. The U.S. composite annual fuel use savings for the climate control seats over the baseline A/C system was determined to be 5.1 gallons of gasoline per year per vehicle, corresponding to 4.0 grams of CO_2/mile savings. Regional CO_2 emissions savings were also determined and are provided in Figure 1. Finally, the potential impact of 100% adoption of climate control seats on U.S. light-duty fleet A/C fuel use was calculated to be 1.3 billion gallons of gasoline annually with a corresponding CO_2 emissions reduction of 12.7 million tons (Table 1).

Direct comparison of the impact of the CCS to the ventilated seat off-cycle credit was not possible because the NREL analysis calculated a combined car/truck savings and the baseline A/C CO_2 emissions were higher than EPA. To enable comparison, the CCS national A/C CO_2 emissions were split into car/truck components and the ventilated seat credit was scaled up. The split CO_2 emissions savings due to the CCS were 3.5 g/mi for a car and 4.4 g/mi for a truck. The CCS saved an additional 2.0 g/mi and 2.5 g/mi over the adjusted ventilated seat credit for a car and truck, respectively.

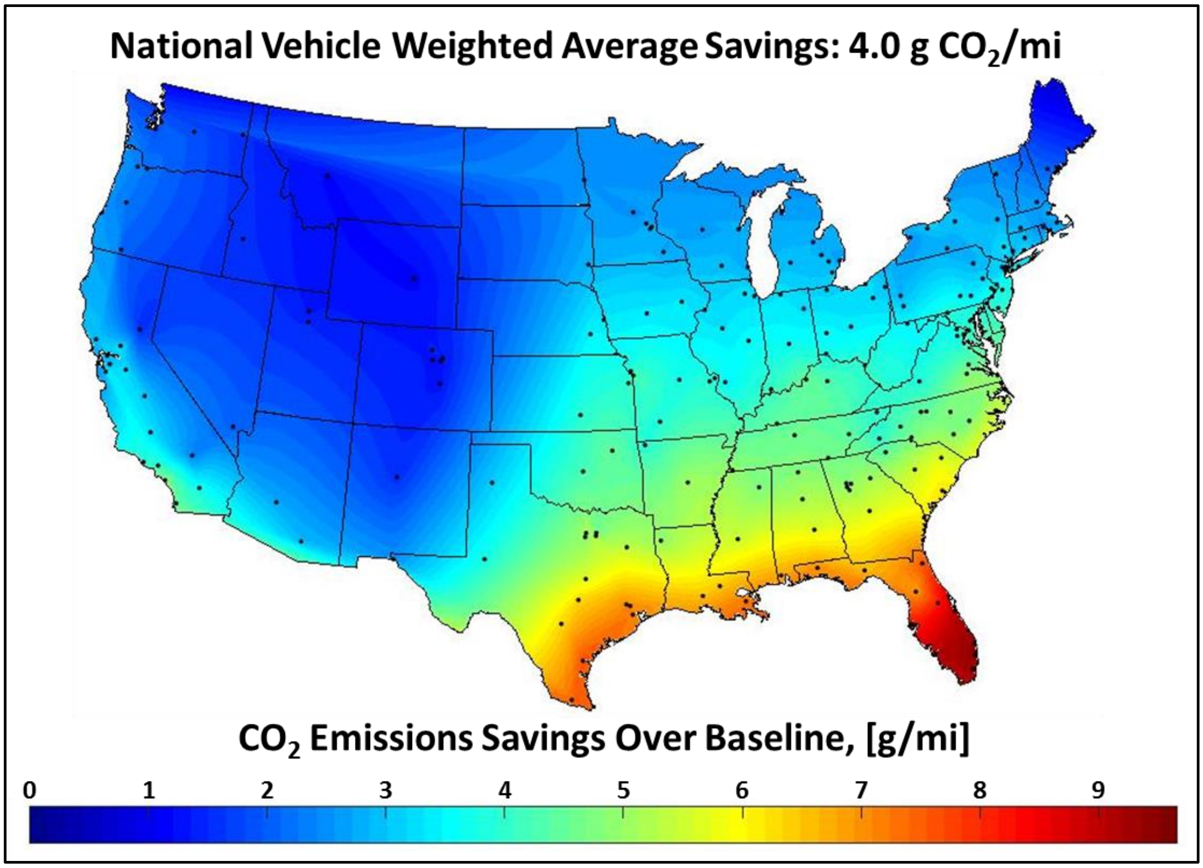

Figure 1. Annual carbon dioxide emissions reduction due to climate control seats

Table 1. Potential impact of climate control seats on individual and U.S. fleet A/C fuel use and associated carbon dioxide emissions

Vehicle Configuration	Individual Vehicle A/C Fuel Use [Gal/year]	U.S. Light-Duty Fleet A/C Fuel Use [Gal/year] *	U.S. A/C Carbon Dioxide Emissions [Tons/year] **
Baseline Vehicle A/C With Standard Seat	30.0	7. 59 billion	74.3 million
Vehicle A/C with Climate Control Seat	24.9	6.29 billion (100% adoption)	61.6 million (100% adoption)
Savings With Climate Seat	**5.1**	**1.30 billion (100% adoption)**	**12.7 million (100% adoption)**

* Based on U.S. light-duty vehicle fleet size of 252,714,871 vehicles [2], individual vehicles traveling 11346 miles/year [3] ** Based on 8887 grams of CO_2 per gallon of gasoline [4]

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Background

Off-cycle credits for solar/thermal control technologies are provided in the Final Rule for Model Year 2017 and Later Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards [1]. In the off-cycle menu (Table 2), active seat ventilation is listed at 1.0 and 1.3 g/mi for cars and trucks, respectively. In addition, solar/thermal technologies are limited to a maximum combined credit of 3.0 and 4.3 g/mi for cars and trucks, respectively. The credit value for the ventilated seat was determined by the governing agencies by using previous data collected by NREL on the ability of the technologies to reduce the cabin air soak temperature, correlating to a reduction in A/C energy. In addition, the governing agencies used a maximum A/C related CO_2 emissions impact of 13.8 and 17.2 g/mi for cars and trucks, respectively. These maximum A/C emissions impacts were determined through vehicle simulations on an SC03 drive cycle using a fixed displacement compressor. The simulations also used an A/C system power consumption curve at 27°C and 60% relative humidity as representative of the entire United States environmental conditions during A/C operation.

The established credit for active seat ventilation in the off-cycle technologies table was determined by the governing bodies by applying a previous NREL study [5] that estimated a 7.5% reduction in A/C related emissions could be realized through active seat ventilation. The 1.0 and 1.3 g/mi active seat ventilation credits were derived by applying this 7.5% to the estimated maximum A/C system impact of 13.8 and 17.2 g/mi. Additional information on the methods and procedures used by the U.S. EPA and NHTSA to establish the credits can be found in the published joint technical support document [6].

Table 2. Existing Off-Cycle Technologies and Credits for Solar/Thermal Control Technologies for Cars and Light Trucks in the 2017 and later light-duty vehicle GHG emissions and CAFÉ standards.

	Credit [g CO_2/mi]	
Thermal Control Technology	**Car**	**Truck**
Glass or Glazing	Up to 2.9	Up to 3.9
Active Seat Ventilation	**1.0**	**1.3**
Solar Reflective Paint	0.4	0.5
Passive Cabin Ventilation	1.7	2.3
Active Cabin Ventilation	2.1	2.8
Maximum Combined Solar/Thermal Credit	3.0	4.3

While a seat containing an air-based thermoelectric device (TED) may meet the definition of active seat ventilation, the potential impact of a TED seat may be larger than a standard ventilated seat. Characterizing the performance of climate control seating in the light-duty automotive sector is challenging because their impact is dependent on feedback from the occupant. In addition, light-duty vehicle A/C energy use and corresponding fuel consumption and CO_2 emissions are dependent upon environmental conditions, A/C system performance, vehicle platform, vehicle use behaviors such as time-of-day of driving and trip duration, and vehicle drive cycle. Currently, no standardized tool exists that incorporates the described elements in order to properly evaluate the performance of a TED containing seat such as the Gentherm CCS. For example, the Green-MAC-LCCP calculation tool [7] was developed for the purpose of calculating the greenhouse gas emission of mobile air conditioning refrigerants and has been extended to provide estimates of indirect carbon dioxide emissions of various mobile air conditioning technologies. While this tool has some of the critical elements for determining the performance of the CCS, it does not contain all of the major elements necessary, most notably a vehicle cabin model.

The purpose of this project is to incorporate both experimentation and analysis to provide the information necessary to rigorously estimate the national performance of the Gentherm CCS. Specifically, the project goal is to determine the national average light-duty vehicle A/C fuel use reduction and carbon dioxide emissions savings due to the use of a CCS. Although the off-cycle credit exists for active seat ventilation, the performance of a TED seat is not included in the table. It is possible that the CCS seat will have a larger reduction in A/C system fuel use than the standard active seat. In addition, the existing active seat ventilation off-cycle credit was determined with significant underlying assumptions and models which do not capture the broad conditions that affect both baseline vehicle A/C and active seat performance. Therefore, it is necessary to develop a new process that captures previously ignored or simplified assumptions to establish the Gentherm CCS's potential for reducing vehicle fuel use and emissions.

Approach

The project was split into testing and analysis components, with critical results obtained through testing as input to the analysis process. The analysis process was then used to evaluate the performance of the CCS in a significantly broadened set of conditions to determine the national level impact.

Experimental Testing

The primary objectives of experimental testing were the following:

- Quantify the allowable increase in cabin air temperature during summer testing conditions with the use of CCS using human test subjects as feedback
- Use a combination of experimental manikins and sensor instrumentation to collect data necessary for a quantitative comparison of human subjects and virtual thermal manikin occupant sensation and comfort
- Measure the added electrical load on the vehicle due to the operation of the CCS

Vehicle Test Setup

The vehicle platform used for testing were two 2012 pre-production Ford Focus Electric vehicles (Figure 2). These vehicles were essentially used as an outdoor climate chamber and Ford did not have direct involvement in the project. The vehicles were located at NREL's Vehicle Testing and Integration Facility and were oriented facing south for the duration of testing in order to maximize the solar heat gain into the vehicles. The vehicles were previously instrumented by NREL and included a number of vehicle surface and air temperature measurements.

Existing air and surface thermocouples used were k-type and were calibrated to within a U95 uncertainty of 0.18°C. These thermocouples included the eight thermocouples used to determine the mean air temperature: breath level and footwell air temperature measurements for the four primary seating positions (front and rear driver, front and rear passenger). In addition to the existing instrumentation, a grid of additional (+/- 1°C) thermocouples was installed on the seats to capture temperature boundary conditions between the occupant and the seating. In addition, heat flux gauges were installed on the seats to provide heat flux boundary condition information. Heat flux sensors were button type, provided by Gentherm, and installed at the locations shown in Figure 3 based on previous data collected by Gentherm using a higher resolution heat flux grid (recommendations provided by Daniel Guerithault).

Figure 2. Ford Focus experimental test platform at NREL facility

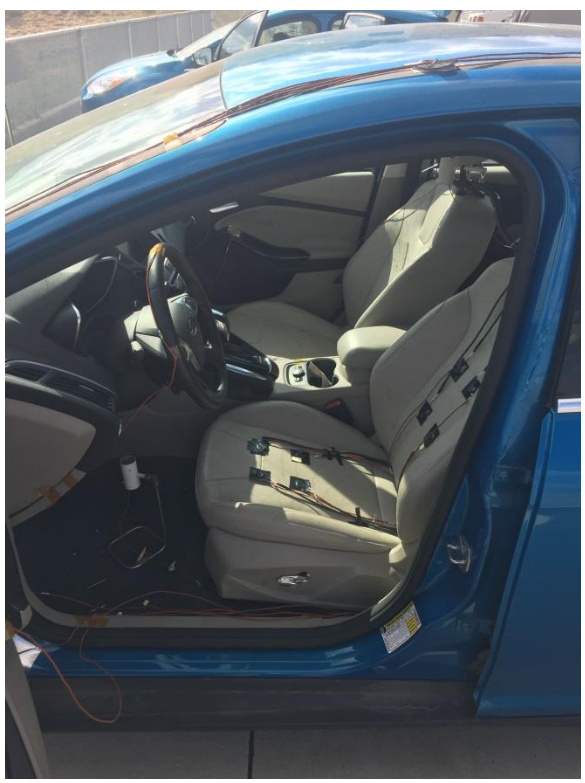

Figure 3. Heat flux sensor installation on experimental test seat

The two experimental test vehicles were instrumented with Ohio Semitronics split core power meters (Model Number: PC6-001-02EY114). The power meters were installed on the high voltage traction battery, providing traction battery power throughout the duration of the tests. In addition to the traction battery power, the test vehicle containing the CCS was instrumented with current shunts and voltage references for both the TED and blower devices in the seat. Independent power supplies were used to control the power to the TED and the blower due to different target voltages recommended by Gentherm. The target setpoints for the CCS is provided in Table 3.

Table 3. Power supply setpoints for CCS

Setting	Thermoelectric Device	Blower
High	16 VDC	13 VDC
Medium	10 VDC	11 VDC
Low	OFF	9 VDC

The experimental setup used a combination of National Instruments SCXI and cDAQ data acquisition systems for data acquisition purposes. Data was collected at 1 Hz, and a running average of all data was kept for 10 seconds, recording the running average data to a file at 0.1 Hz.

Climate Control Seat

The baseline vehicle used standard production seats which did not include a climate function. The seats in the climate control vehicle were modified to include a combination of active and passive cooling. Active cooling to the seat back was provided by the installation of two (2) thermoelectric devices (TED) and a blower which provided positive, temperature controlled airflow pushed towards the test occupant. The seat cushion was conditioned by the use of a blower operating in a pull mode, drawing the air surrounding the customer into the cushion. See Figure 4. The foams in both seating surfaces were modified to include a textile spacer fabric that facilitated lateral airflow under occupant load. The seat covers were made of cloth and backed by an additional layer of textile spacer fabric to promote airflow to the occupant. These modifications were consistent with design approaches in production climate seats.

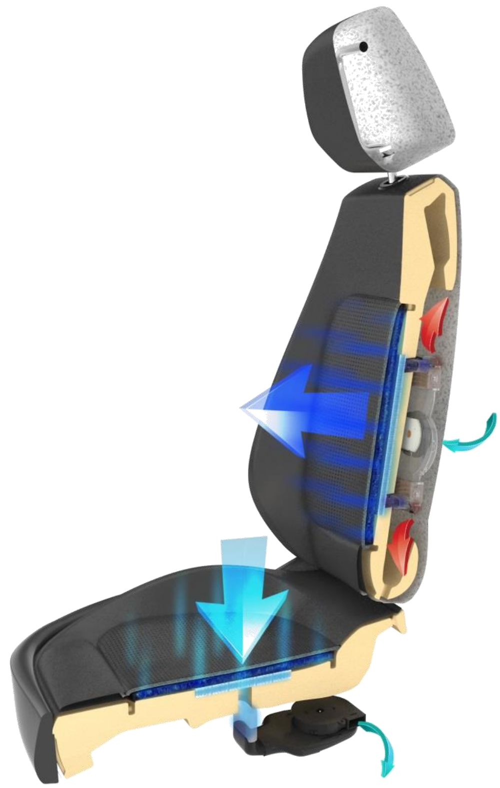

Figure 4. Climate Control Seat

Test Methodology

Experimental testing used a three-phase approach, consisting of an occupant and vehicle thermal preconditioning phase, followed by a transient maximum cooldown phase, and ending in a steady-state cooling phase. A summary of the test strategy is provided in Figure 5. In the first phase, both the baseline and climate control seat vehicles and the occupants were thermally preconditioned. The two vehicles were soaked in outdoor summer environment at the test facility, while the occupants preconditioned in an office environment 30 minutes prior to the start of the next phase of the test. Occupants were instructed to wear business casual attire representative of summer conditions and were not allowed to eat or drink during any portion of the test. At the end of the preconditioning phase of the tests, the occupants briefly walked outside to the vehicles and started the max cooling portion of the test. The testing was scheduled such that the max cooling phase of the test was started at 9:30 MST (10:30 Mountain Daylight Time). During the max cooling phase of the test, the vehicles' HVAC settings were configured using the "Max A/C" button which configured the system for maximum blower, minimum temperature, recirculation, and panel and floor vent mode. In addition, the CCS was set on high, corresponding to the values set in Table 3 for the TED and blower. During the max cooling phase, occupants supplied their whole body comfort and sensation votes as their sensation values changed, referred to as "on-the-fly". The max cooling portion of the test was completed after occupants in both vehicles attained a target whole body sensation value (this value was specific to the occupant and was between -2 and -2.5 on the Berkeley thermal scale).

After the max cooling portion of the test was completed, the occupants immediately reconfigured both vehicles' HVAC systems to fully automatic temperature control (FATC). The time at which the steady-state portion of the test was initiated was 10:00 MST (11:00 MDT) and lasted approximately 1 hour. During this portion of the test, the baseline vehicle was set to FATC with a temperature setpoint of 72°F. The CCS vehicle was set to FATC but with an elevated temperature setpoint which was selected by the occupant. During this phase, the occupant in the CCS vehicle adjusted both the FATC temperature setpoint and the CCS seat intensity until they attained the same whole body sensation that was recorded by them in the baseline vehicle at FATC 72°F settings. For example, on Day 1 in the baseline vehicle during the steady-state phase, Occupant A recorded a whole body sensation of +1.0. The next test day, Occupant A would test in the CCS vehicle and would adjust both the CCS seat intensity and the FATC setpoint until they attained a whole body sensation of +1.0. The steady-state portion of the test was continued until the CCS vehicle occupant conditions were stabilized for an extended duration in order to quantify the true cabin temperature elevation attained in the vehicle. The entire test procedure took approximately 2.5 hours each day including preconditioning.

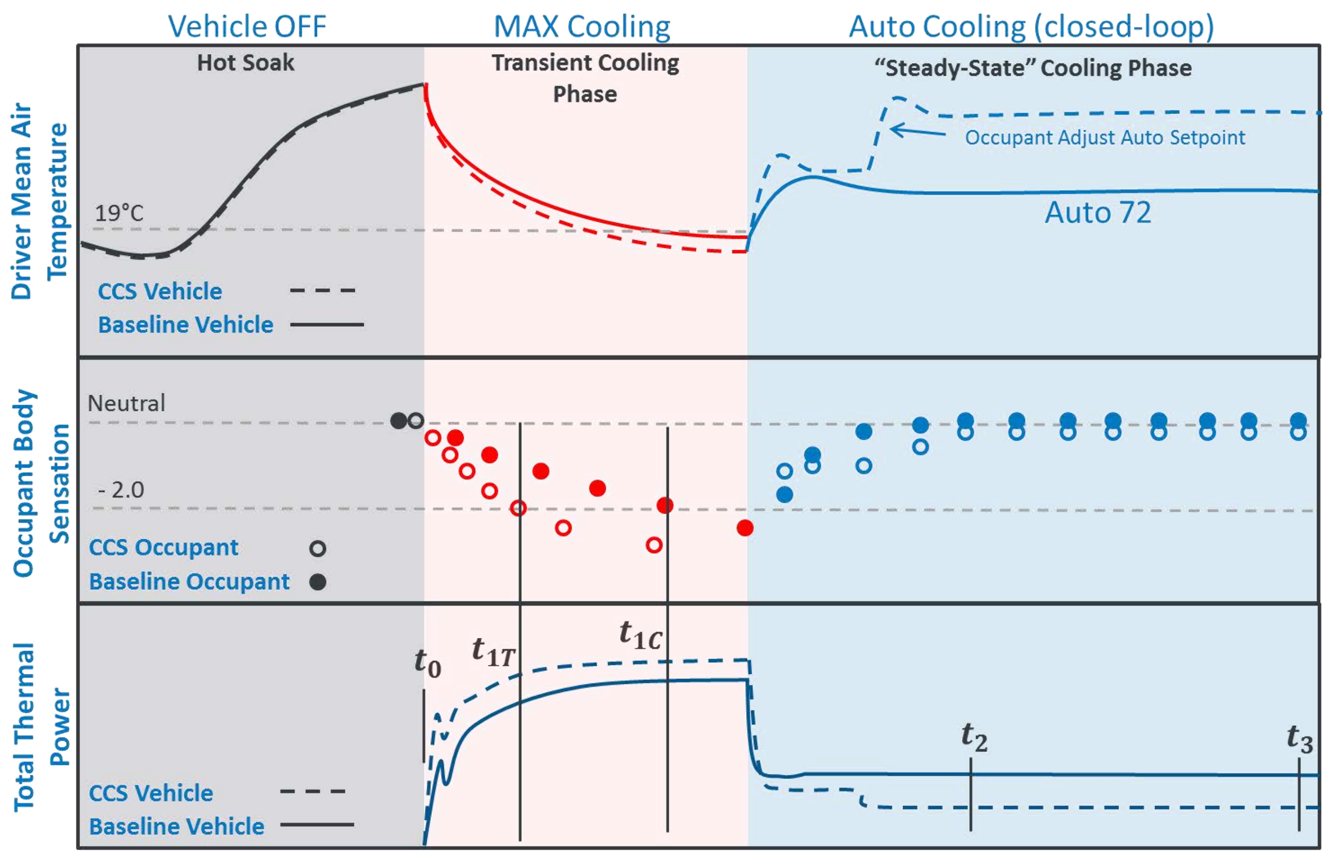

Figure 5. Cartoon summary description of experimental outdoor vehicle testing procedure

Human Subject Testing

Due to Department of Energy human subject testing requirements, approval by the Department of Energy Institutional Review Board was necessary to complete the experimental testing that involved human subjects. Human subjects were selected based on their availability and previous experience in automotive thermal management. Prior to testing, a training session was held to verify that each participant was comfortable with and understood the human thermal sensation and comfort scales used (Berkeley scales). Participants were instructed to wear representative clothing, consistent through all of the tests. A summary of the occupant demographics are provided below:

Test Personnel	Gender	Height [in]	Weight [lbs]	Age [years]
Occupant A	Male	72	195	46
Occupant B	Male	74	163	53
Occupant C	Male	71	212	46
Occupant D	Male	70	205	36

Manikin Testing

A testing manikin was provided by Thermetrics in order to provide a quantitative comparison against human subject testing. Existing manikins available for automotive testing are not capable of measuring both the boundary condition from a climate control seat and front side air conditioning. Instead, an Automotive HVAC Manikin System [8] was provided by Thermetrics to provide front side boundary conditions including air velocity, temperature, radiant heat flux, and relative humidity. The information collected from the manikin system was combined with seat heat flux and temperature measurements for evaluation in the ThermoAnalytics Human Thermal Module software, providing a virtual manikin sensation and comfort response output. The HVAC manikin was placed in the passenger seat of the baseline vehicle alongside the human test subject for a portion of the experimental tests, and in the passenger seat of the CCS vehicle for the remainder of the tests.

In addition to the HVAC Manikin system, a STAN (Seat Test Automotive Manikin) was also provided by Thermetrics for evaluation of its ability to characterize seat heat flux [9]. The STAN test manikin is an 8-zone seat testing manikin capable of supplying a fixed temperature boundary condition approximating that of a human, while simultaneously quantifying the heat flux through each zone. In addition, the STAN manikin can be loaded with weights to approximate the contact pressure obtained by various human sizes. For this project, the STAN manikin was weighted such that the contact pressure from the manikin represented a 50th percentile western male. Due to the weight and complexity of the STAN manikin system, it was not used during the human subject experiments. Instead, an independent study was performed using STAN to characterize the heat transfer characteristics of both the baseline and the CCS. Images of both the HVAC manikin and the STAN manikin are provided in Figure 6.

Figure 6. HVAC (left) and STAN (right) testing manikins used for experimental testing

National Level Analysis

The goal of the national level analysis was to develop a process to calculate national-level fuel use from A/C operation and use the developed process to determine the national fuel use and CO_2 emissions impact of the CCS vehicle based on critical information obtained through experimentation. The development of the national level analysis process leveraged previous work from NREL's light-duty vehicle A/C fuel use methodology [10] and heavy-duty vehicle thermal load and idle reduction analysis process [11]. NREL also leveraged thermal and vehicle simulation analysis tools developed under recent DOE Vehicle Technologies Office Vehicle Systems' projects. These tools include: CoolCalc, a rapid heating, ventilation, and cooling load estimation software [12]; CoolSim, a MATLAB/Simulink thermal modeling framework [13]; and FASTSim, a high-level advanced vehicle powertrain systems analysis tool [14]. A visual diagram highlighting the analysis process is provided in Figure 7. The national analysis process uses three primary components: a vehicle cabin thermal model, an A/C system performance model, and a vehicle powertrain performance model. These models are used to provide an estimation of fuel use and CO_2 emissions starting from ambient weather conditions and vehicle configurations, calculation of associated vehicle thermal loads (evaporator thermal demand), calculation of A/C system performance and conversion to vehicle accessory load, and finally conversion of accessory load to vehicle fuel use. A further description of the assumptions and model components is provided in subsequent sections.

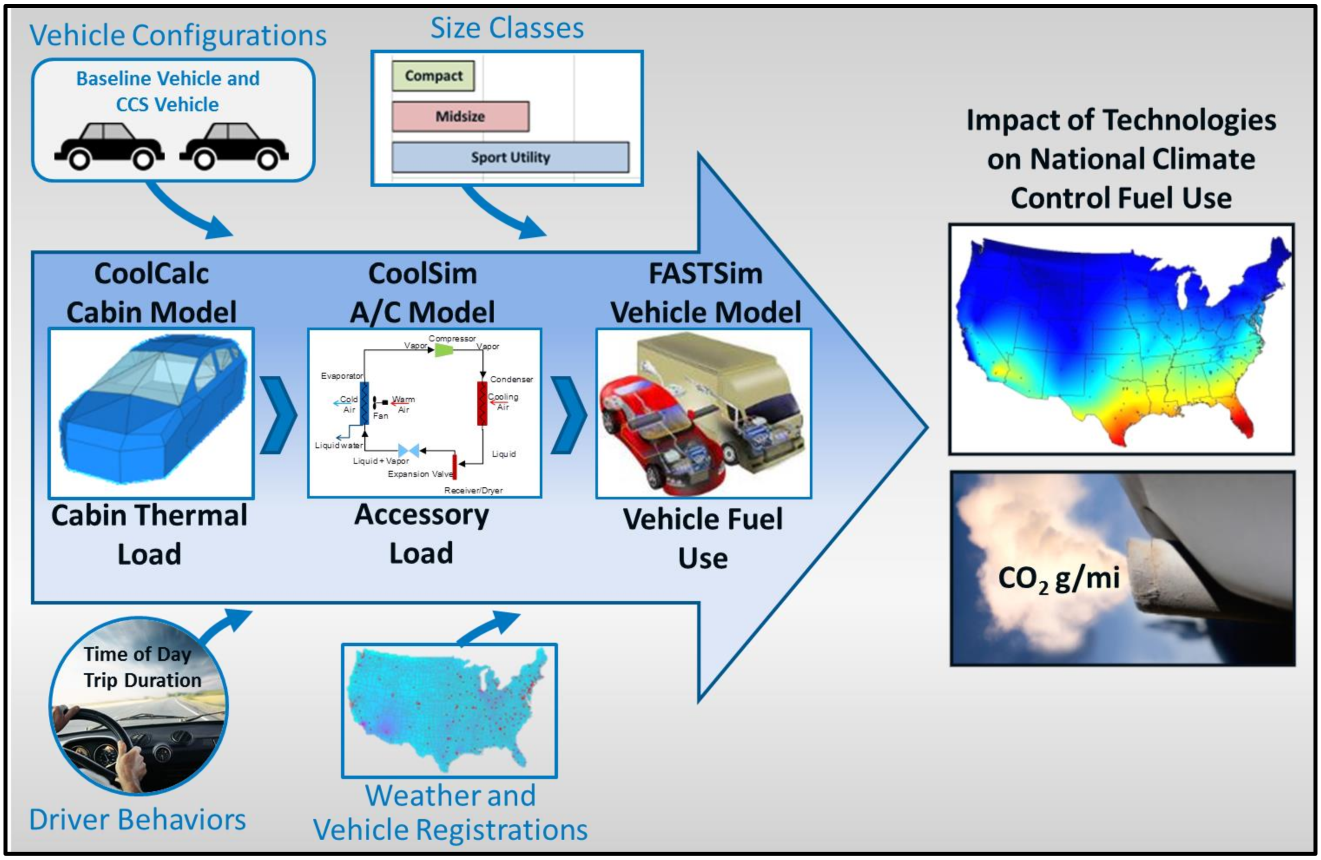

Figure 7. Overview of national level A/C fuel use analysis process

Vehicle Cabin Thermal Model: CoolCalc

CoolCalc is a simplified, physics-based HVAC load estimation tool that has flexible geometry, uses a single zone air node, and excludes model complexity encountered in computational fluid dynamics systems. The model simulates heat transfer between the vehicle cabin and an external environment defined by typical meterological year (TMY3) weather data for select locations in the United States [15]. CoolCalc calculates cabin interior heat transfer and the evaporator capacity required to maintain the interior cabin air temperature at a user-defined setpoint for each prescribed timestep (1 minute) for the entire representative annual TMY weather data for each specified location. To construct CoolCalc vehicle thermal models for the analysis, the U.S light-duty vehicle fleet was simplified into three vehicles types: compact, mid-size sedan, and SUV. Using Polk automotive registration data [2], detailed vehicle body type classifications and registration counts were collapsed into the three simplified groupings resulting in a compact, mid-size sedan, and SUV platform, with weightings of 18%, 30%, and 52%, respectively. Once the three size classes and weighting factors were identified, thermal models were built using CoolCalc software [12].

The development of the three thermal models began with geometric construction of the vehicles in CoolCalc. Geometric renderings of the three vehicle platforms are shown in Figure 8. After each vehicle geometry was defined, material properties and wall constructions were defined for the solid and glazing vehicle surfaces and an HVAC system object was integrated into the model. The three models were then validated against previous experimental thermal soak and cooldown data collected at NREL. For the analysis, the CoolCalc vehicle models positioned at a fixed vehicle orientation relative to solar coordinates. Defining the vehicle orientation relative to the sun was critical because the orientation of a parked or moving vehicle has a significant impact on the resulting thermal load. To determine the impact of orientation on thermal loads, TMY data representing three cities (Golden, Phoenix, and Minneapolis) were used to evaluate the annual A/C thermal load with the vehicle facing in the four cardinal directions. The A/C thermal loads in the west direction had the smallest deviation from the four-direction average and was therefore determined to be the most representative direction and selected for the full analysis. Performing simulations at each of the four orientations was prohibitive due to the increased computations that would have been necessary.

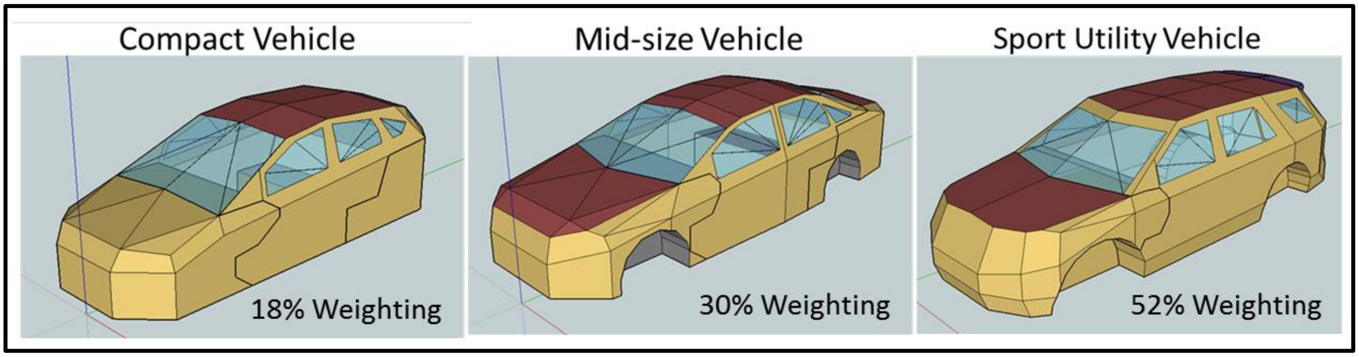

Figure 8. CoolCalc geometric renderings of the three vehicle platforms

The CoolCalc thermal models were used to calculate vehicle surface and interior temperatures while the vehicles were stationary in a parked configuration. During drive events, evaporator thermal load was calculated based on the A/C system target setpoint and the vehicle thermal state. The baseline vehicle CoolCalc A/C control strategy was defined to maintain an interior air temperature of 20°C. In addition, a piecewise A/C cabin air recirculation strategy dependent on ambient temperature was implemented to represent national-level operation. The recirculation strategy is defined below:

- Recirculation is 0% when $T_{ambient}$ is < 35°C
- Recirculation is 50% when $T_{ambient}$ is > 45°C
- recirculation is a linear function between 0 and 50% when 35°C < $T_{ambient}$ < 45°C

U.S. Locations

Light-duty vehicle registration data for each county within the United States was obtained through the Polk database [2]. Similarly, TMY weather data is provided by NREL from over 900 weather stations throughout the United States. Simulating all U.S. weather station locations in the analysis process requires prohibitively large computations, so a two-step process was used to reduce the number of simulated locations. First, county vehicle registrations were assigned to the geographically closest TMY3 weather station based on the distance from the county center. After this process was completed, 839 locations remained due to some weather stations not having any associated registrations. Next, locations were further reduced by sequential elimination of the location with the smallest number of county registrations, with reassignment of the eliminated registrations to the nearest remaining location. In addition, at least one weather location per state was retained regardless of the number of registrations to avoid inadequate coverage in the northwestern part of the United States. Locations were eliminated until the next location elimination would require moving 0.25% of the national vehicle registrations. Maps of the initial 839 U.S. weather locations and remaining 206 locations after completion of the down-selection process are provided in Figure 9.

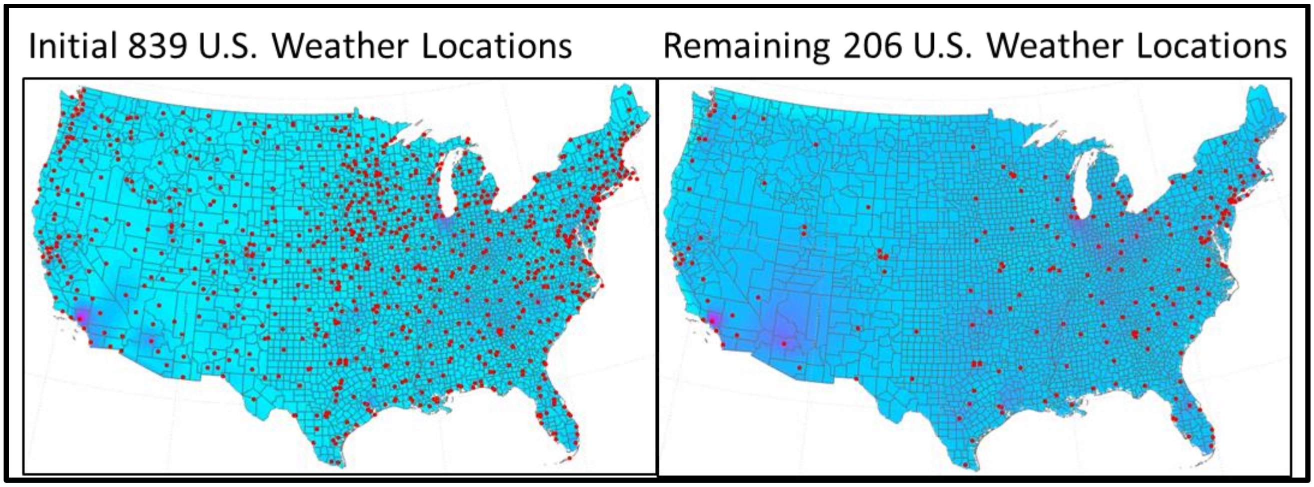

Figure 9. Down selection of light-duty vehicle registration weighted weather locations for the analysis process (Alaska and Hawaii not shown)

Vehicle Usage Patterns

Time of Day of Travel

Information from the 2009 National Household Travel Survey (NHTS) [16] was used to determine light-duty vehicle travel behaviors. The following vehicle types that represent the majority of light-duty vehicles in the survey were selected: automobile/car, van, SUV, and pickup truck. Due to diurnal fluctuations in the environment, the time of day a vehicle is used strongly influences the interior temperatures at the start of the drive and also the thermal loads necessary to cool the vehicle. NHTS frequency-of-trips data were sorted into 60-minute intervals for the entire day with time-based groupings determined by trip start time, provided in Figure 10. The distribution was then divided into three groups representing morning, mid-day, and evening drive events. The three-group time range, average time within each range, and group weighting factor is provided in Table 4. For the analysis, vehicles were operated starting at the average times provided in Table 4, with corresponding weighting factors applied to the results.

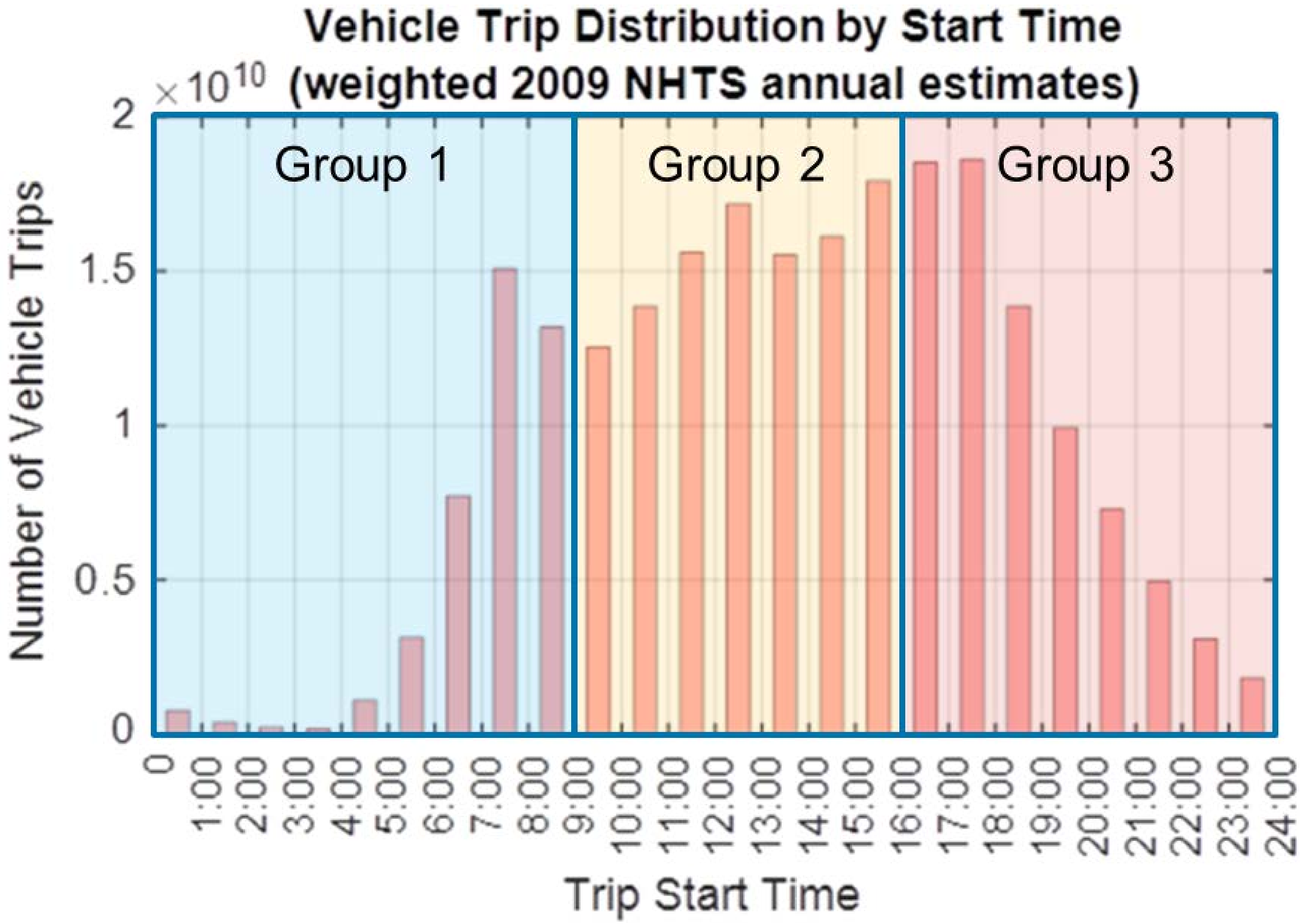

Figure 10. Distribution of light-duty vehicle time of day of travel in one hour intervals, grouped by trip start time

Table 4. Representative times of day of travel groupings, average time within each grouping, and associated weighting factors

Time Range	0:00–9:00	9:00–16:00	16:00–24:00
Average Time	7:06	12:35	18:26
Weighting Factor	0.183	0.476	0.341

Thermal Soak Duration

The length of time a vehicle soaks in the sun prior to a drive event influences the interior temperatures at the start of the drive and the thermal loads necessary to cool the vehicle. Short thermal soak durations reduce the thermal load necessary to cool the vehicle while long thermal soak durations increase the load necessary to cool the vehicle. The 2009 NHTS survey provided data for the time spent between trips for all trips in the database and this information was plotted as a cumulative distribution function, provided in Figure 11. In order to represent both short and long thermal soak durations, the time between trips distribution was divided evenly into two groups. The first group represented short soak duration events and includes soak durations from 0-50 minutes with an average duration of 17 minutes. The second group represented long soak duration events and includes soak durations from 50 minutes to a full day with an average duration of 232 minutes. For the analysis, vehicles were operated immediately following both short and long duration soak events. The representative thermal soak duration groupings and their associated weighting factors is provided in Table 5. In the CoolCalc model, the short duration soak group used a vehicle cabin thermal conditioning predrive that ended 17 minutes before the drive of interest. Therefore, the vehicle cabin experienced a 17-minute solar soak after the interior was cooled by the vehicle A/C prior to the target drive event. Data were unavailable for the frequency in which vehicles are parked in the shade or in buildings, and therefore these use cases are assumed to be represented by the short duration soak group.

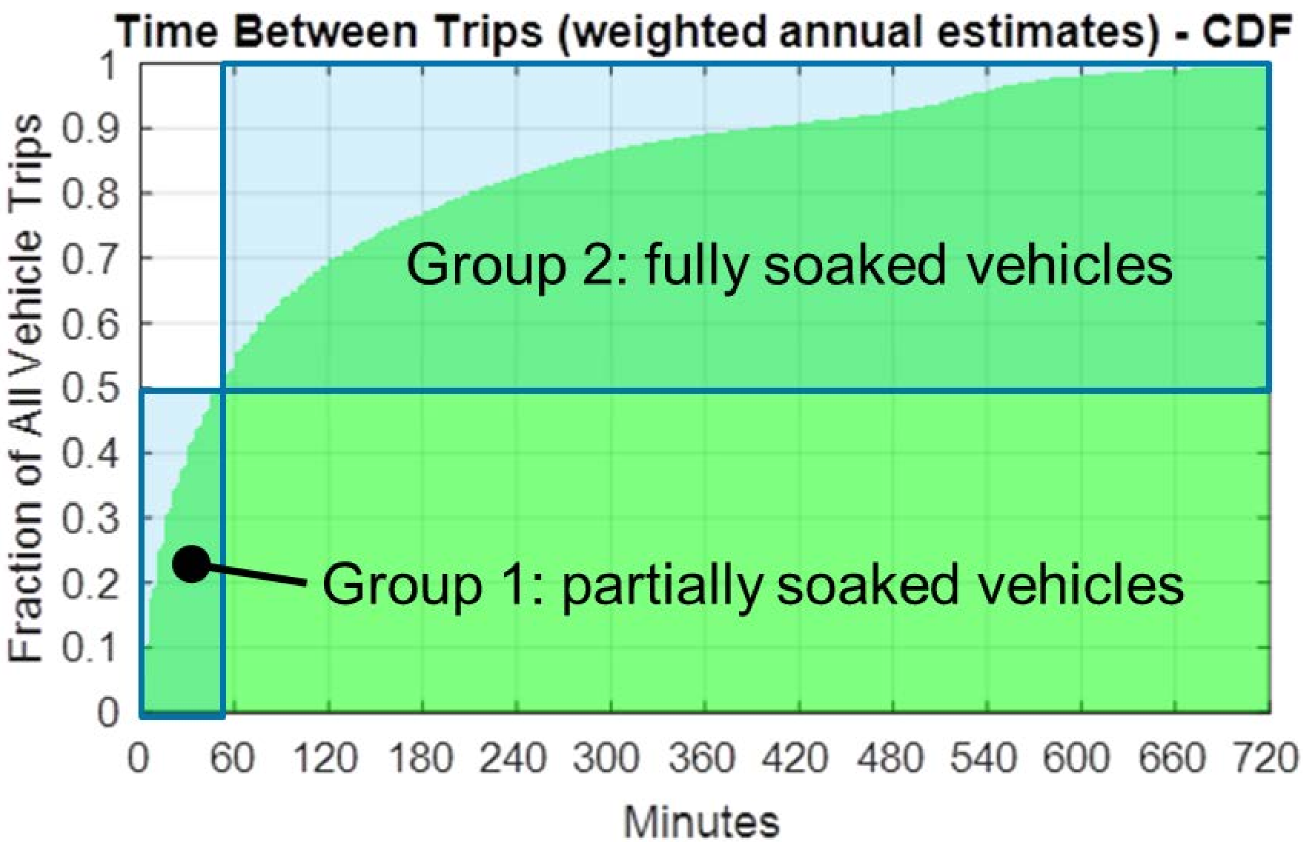

Figure 11. 2009 Cumulative distribution plot of time between trips for light-duty vehicles in the 2009 NHTS, and grouping of the data into two representative cases

Table 5. Representative light-duty vehicle thermal soak durations, and their average soak times and associated weighting factors

Representative Grouping	**Short Soak Duration**	**Long Soak Duration**
Time Range (min)	**0–50**	**50–full day**
Average Time (min)	17	232 (~ 4 hr)
Weighting Factor	0.50	0.50

Trip Duration

The length of a drive is an important vehicle usage pattern because it contributes to the amount of time that the vehicle spends in transient and steady-state cooling conditions. To determine representative trip durations for the analysis, a distribution plot of trip durations was created from the NHTS database by sorting the data into 15-minute intervals, shown in Figure 12. From the data, three representative groupings were established. Due to the low frequency of occurrence, trips greater than 30 minutes were grouped into a single bin. Trips between 0 and 15 minutes formed a group, with the remaining group 15 to 30 minute trip durations. The average trip duration within each group was calculated along with the group weighting factor. The three resultant trip durations represent a high-frequency short drive, a medium duration drive typical of a commute, and finally a long-duration drive. Table 6 shows the trip duration bins and weighting factors. For the analysis, the three representative trip durations were used and their associated weighting factors applied to the results.

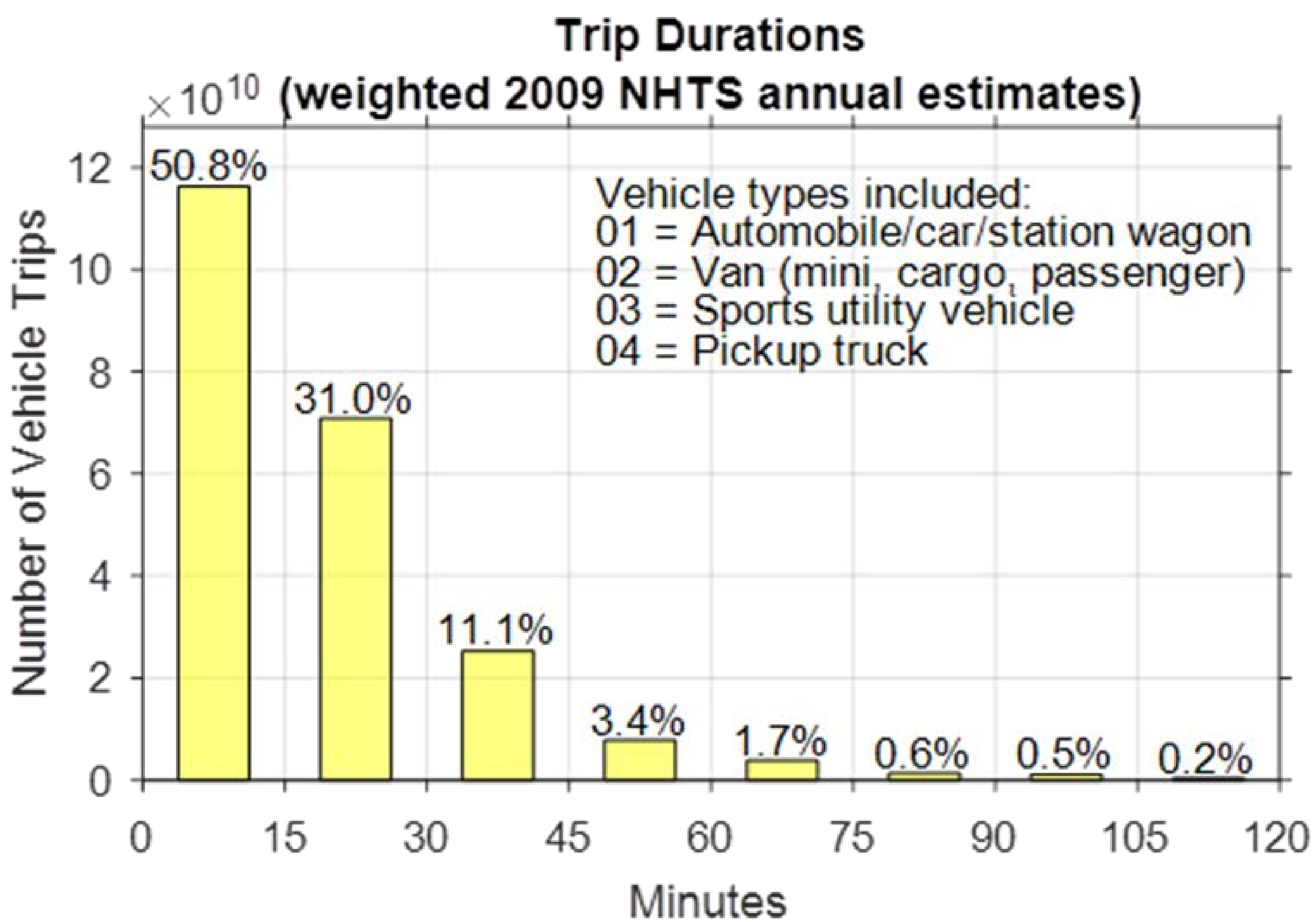

Figure 12. Distribution plot of light-duty vehicle trip durations in the 2009 NHTS

Table 6. Representative light-duty vehicle trip durations and their average time and associated weighting factors

Time Range (min)	0–15	15–30	30+
Average Time (min)	7.2	18.4	49.4
Weighting Factor	0.508	0.310	0.182

A/C System Model

An A/C system model representative of a 2007 model year vehicle was developed using CoolSim software [13]. The A/C system selected for the analysis used R134a refrigerant and a belt-driven (mechanical) fixed displacement compressor with a displacement of 200cm^3 pulley ratio of 1.37. Superheat was controlled by a thermal expansion valve in the model. The model control strategy utilized clutch cycling of the compressor in order to maintain an evaporator air discharge temperature of 3°C and avoid condensate freezing on the evaporator. If a low or high system pressure limit was exceeded, the compressor was disengaged for a minimum duration of five seconds. In addition to the described operation, some vehicle A/C systems and/or modes of operation overcool the supply air with subsequent reheating from the heater core. This reheat strategy results in significant additional A/C loads, and the implication of not considering it will underpredict A/C fuel use. For this reason, a strategy was developed to incorporate increased A/C loads associated with reheating. For a given vehicle trip simulated in CoolCalc, the thermal load profile was evaluated using two parallel methods. In the standard method, accessory loads were calculated for each thermal load throughout the duration of the vehicle trip. In the reheat method, the maximum thermal load was identified within the vehicle trip and was then used for the remainder of the trip, replicating a reheat scenario after the peak trip load occurred. In the analysis, the reheat calculation method was assigned a 38% weighting factor while the standard method was assigned a 62% weighting factor based on the EPA/NHTSA final rulemaking [6].

Because a simulation using CoolSim executes in approximately real-time, a national-level co-simulation with the CoolCalc cabin model is computationally prohibitive. Therefore, a decoupled approach was chosen where the – performance of the CoolSim A/C model performance was precalculated parametrically as a function of input variables that affect system performance. Due to the evaporator capacity being dynamically dependent on the drive cycle conditions, decoupling the A/C and cabin models introduced the assumption that instantaneous A/C system performance is equivalent to performance obtained using the precalculated method. To check this assumption, a separate study was performed comparing dynamic performance for representative drive cycles compared to the precalculated performance. The difference for the 18.4 minute representative drive cycle was found to be within 10%, which was considered acceptable due to prohibitive computational times for a co-simulated analysis. The final precalculated performance of the A/C system was calculated as a function of seven input variables and and applied to the resulting CoolCalc thermal loads after the CoolCalc simulations were completed. Linear interpolation was used where necessary, and extrapolation was eliminated by coercing a value outside of the bounds to the closest bound. The seven input variables and values used are provided below:

Engine speed: 800, 1400, 2000, 2500, 3000 [rpm]

Evaporator inlet temperature: 15, 32.5, 50 [°C]

Evaporator inlet relative humidity: 20, 50, 80 [%]

Condenser inlet temperature: 15, 30, 45 [°C]

Condenser inlet relative humidity: 20, 50, 80 [%]

Vehicle velocity: 0, 12, 26 [m/s]

Evaporator capacity: 1000, 3000, 5000, 8000 [W]

A representative plot of actual evaporator capacity as a function of engine speed and target evaporator capacity is shown for the A/C system model in Figure 13A. At high engine speeds, evaporator capacity demand can be attained, however at lower engine speeds and high target capacities, the delivered capacity is somewhat reduced. To resolve the conflict, the CoolCalc vehicle cabin model maximum thermal load capacity was limited to 7kW for the compact vehicle, 8kW for the mid-size vehicle, and 9kW for the SUV, which avoids unachievable capacity demands in the A/C system model for most input cases. Similarly, a plot of system coefficient of performance as a function of evaporator capacity and engine speed for the A/C system model is provided in Figure 13B. System coefficient of performance (COP) computed by CoolSim was calculated based on compressor power. Both engine speed and evaporator capacity affect system performance although performance has a higher sensitivity to engine speed. In the A/C system model, after the compressor power was calculated, an average condenser fan power of 75W was added to the accessory load when the A/C system was in operation. Since the HVAC blower was assumed to be operating at all times when the vehicle was operated regardless of A/C operation, a 150-W load was incorporated into the base accessory load regardless of the vehicle configuration.

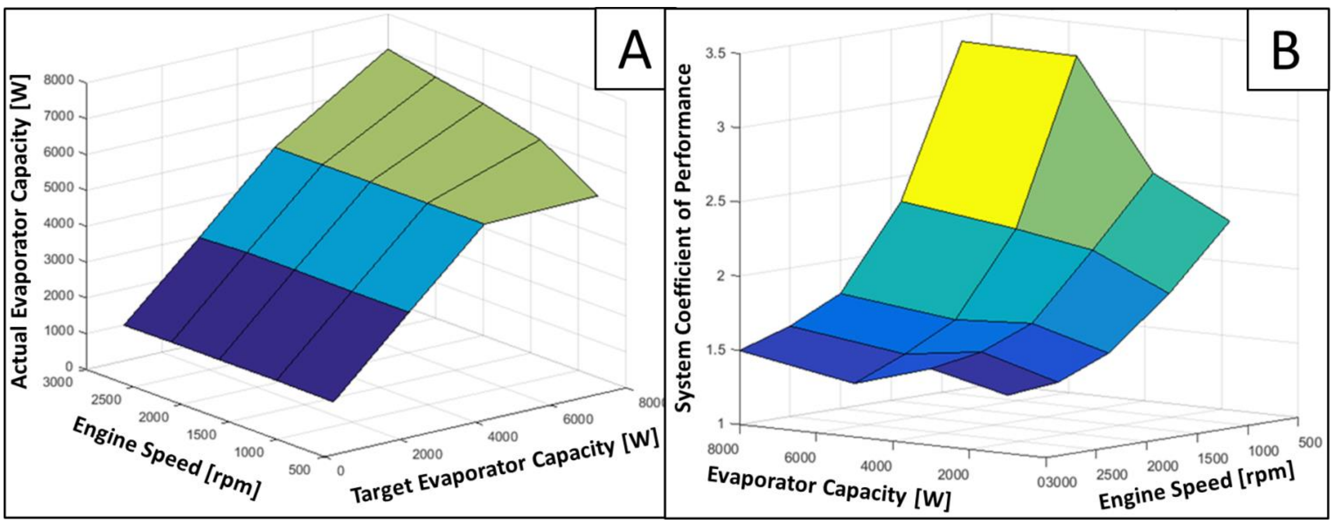

Figure 13. A/C system model evaporator capacity as a function of engine speed and target capacity (A), and system performance as a function of engine speed and evaporator capacity (B). For the plots, other input variables were fixed at a constant value: vehicle velocity = 12 m/s, ambient temperature = 30°C, evaporator inlet temperature = 32.5°C, ambient relative humidity = 50%, evaporator air inlet humidity = 50%.

Vehicle Fuel Use Model

Vehicle models were developed in FASTSim [14] for each of the three representative vehicle platforms in order to calculate the impact of the A/C system accessory load on vehicle fuel use and associated carbon dioxide emissions. FASTSim is a simplified vehicle simulation tool that enables the user to define powertrain components including engine and electric motor as well as battery and auxiliary loads. FASTSim is validated for hundreds of vehicles, and vehicle performance can be calculated over standard and real-world drive cycles.

NREL's Transportation Secure Data Center (TSDC) was used to evaluate and identify a representative drive cycle for each of the three drive lengths [17]. For each of the three representative drive durations, all drive events from the TSDC with drive times similar to the target drive time were extracted and aggregate statistics computed. A table showing drive cycle statistics from NREL's TSDC is provided in Table 7. For each trip, deviation statistics were calculated, and a representative cycle was selected by selecting the cycle with the minimum composite deviation. Vehicle speed versus time plots for the selected vehicle drive cycles for the 7, 18, and 49 minute representative drives are provided in Figure 14. The representative drive cycles were used in the calculation of fuel use in the vehicle models. In addition, the drive cycle vehicle speed versus time was used in the CoolCalc cabin model to supply wind speeds for the vehicle in order to calculate heat transfer on the external vehicle surfaces.

Table 7. Calculated drive cycle statistics extracted from NREL's TSDC for each of the three representative drive times

Vehicle Trip	Short	Medium	Long
Trip Time	6.9 – 7.2 min	18.1 – 18.6 min	49.1 – 49.6 min
Cycles Evaluated	2243	860	101
Avg. Distance [miles]	2.6	8.5	28.4
Avg. Idle [%]	17.0	18.9	14.5
Avg. Driving Speed [mph]	25.3	33.2	39.6
Avg. Acceleration [mph/s]	1.1	0.9	0.8

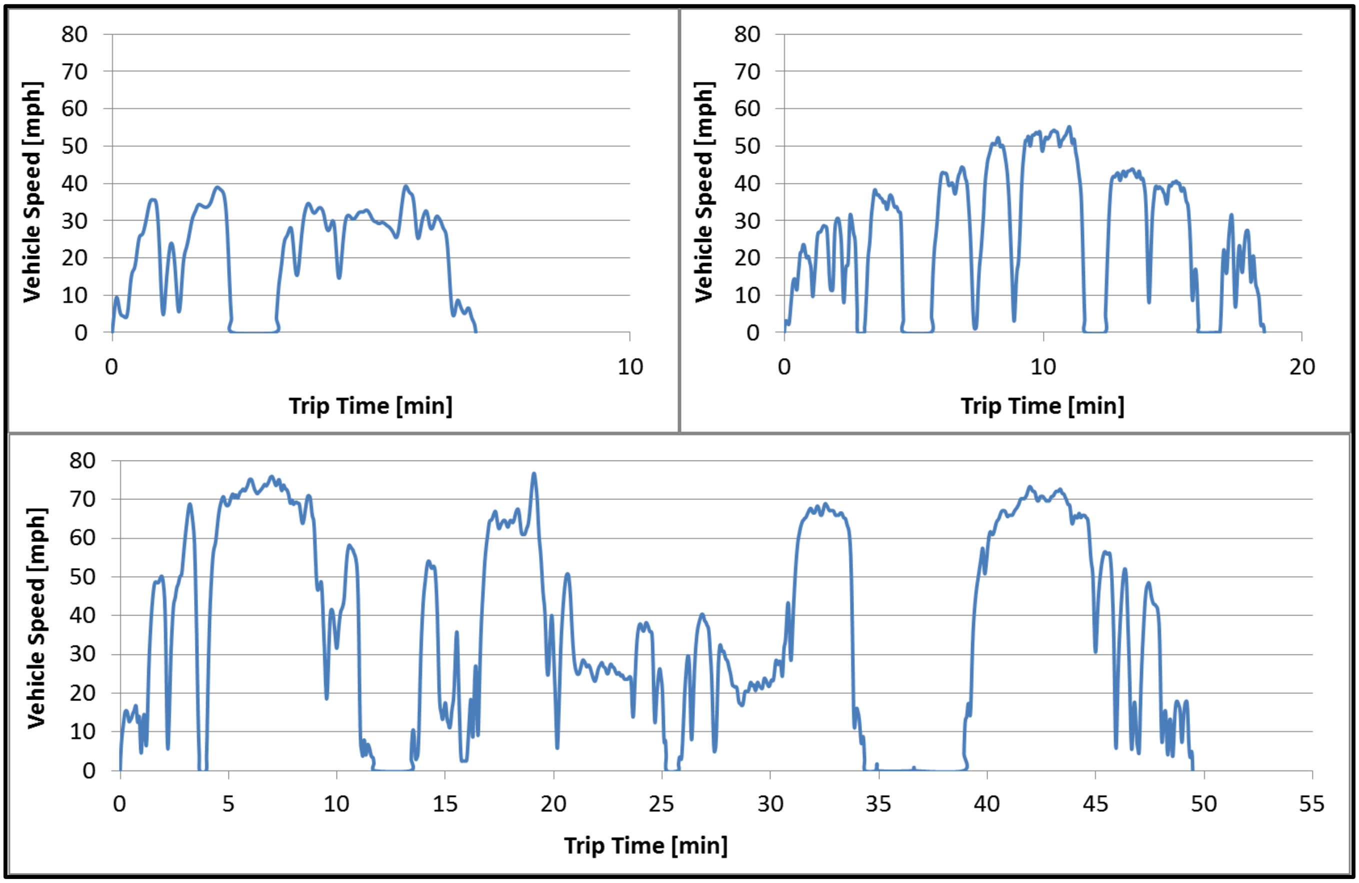

Figure 14. Representative drive cycles for 7 (top left), 18 (top right), and 49 minute (bottom) drives

Once representative drive cycles were selected, the FASTSim models of the three vehicles were used to evaluate vehicle performance over a range of accessory loads for each of the cycles. A vehicle performance map was created with fuel use as a function of drive cycle, vehicle type, and accessory load. The impact of the A/C load on fuel economy for the three vehicles on the 18-minute drive cycle is shown in Figure 15.

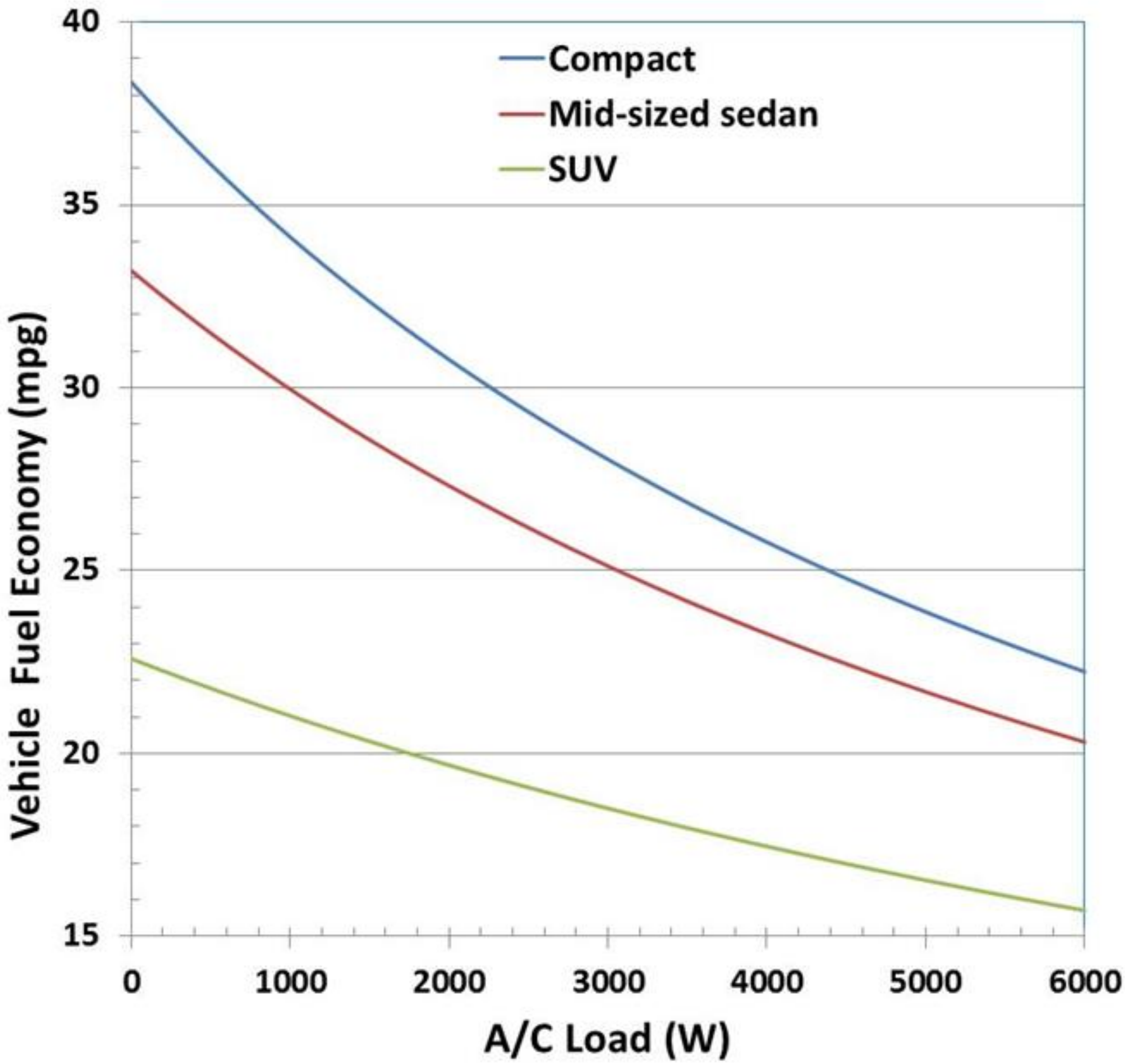

Figure 15. Vehicle fuel economy as a function of A/C load for three vehicles over the 18 minute drive

National A/C Fuel Use Analysis Process

To complete the national level analysis process, a full factorial simulation was performed in order to incorporate representative national vehicle use cases. For the analysis, the three vehicle platforms were simulated, in addition to the down-selected 206 registration weighted locations, three representative time-of-day of travel, two representative time between trips (dwell/soak time), three trip durations and associated representative drive cycles. All simulations were completed for both the baseline vehicle configuration and three CCS vehicle configurations. The three CCS vehicle configurations differed by the cabin temperature offset used in the CoolCalc mode, the first being the average cabin temperature offset obtained in the experimental section, and the second and third being the low bound and high bounds of the 90th percent confidence interval for the cabin temperature offset. Full factorial analysis resulted in 3708 simulations for each of the three vehicle configurations (baseline, CCS at avg. temperature offset, CCS at low bound temperature offset), resulting in a total of 14832 annual simulations with 1 minute timesteps. Due to the large number of simulations necessary, NREL's Windows-based, high-performance computing system was used for parallel simulation [18]. The CoolCalc simulation results were aggregated using post-processing and appropriate weighting factors were applied to incorporate the relevancy of each use case simulated. To account for different locations and weather environments, the results were weighted by the registered vehicles assigned to each location as previously described. With this process, the national-weighted fuel use and CO_2 emissions were calculated for baseline vehicles and the CCS vehicle.

Incorporating the CCS required changes to components in two sections. First, the A/C system in the CoolCalc model required changing the target temperature setpoint from the baseline value (20°C) to the increased value(s) obtained with the climate control seats in the experimental section of the project. This change allowed the CoolCalc A/C model to calculate evaporator capacity at each timestep with an elevated cabin temperature setpoint, representing the CCS vehicle configuration. In addition to the change in the CoolCalc model, the electrical accessory load for the vehicle model was also increased when the A/C system was in operation to account for the added electrical load from the CCS. Finally, due to the complexity associated with adding an additional thermal heat source in the CoolCalc cabin model, the vehicle cabin heat added from the CCS blower and TED were not included in the CoolCalc model. The addition of the CCS heat load on the vehicle cabin is a potential opportunity for future work. The impact of the CCS was then computed by taking the difference between the CCS vehicle and the baseline vehicle performance. A high-level overview of the process for both the baseline vehicle and the CCS vehicle is provided in Figure 16.

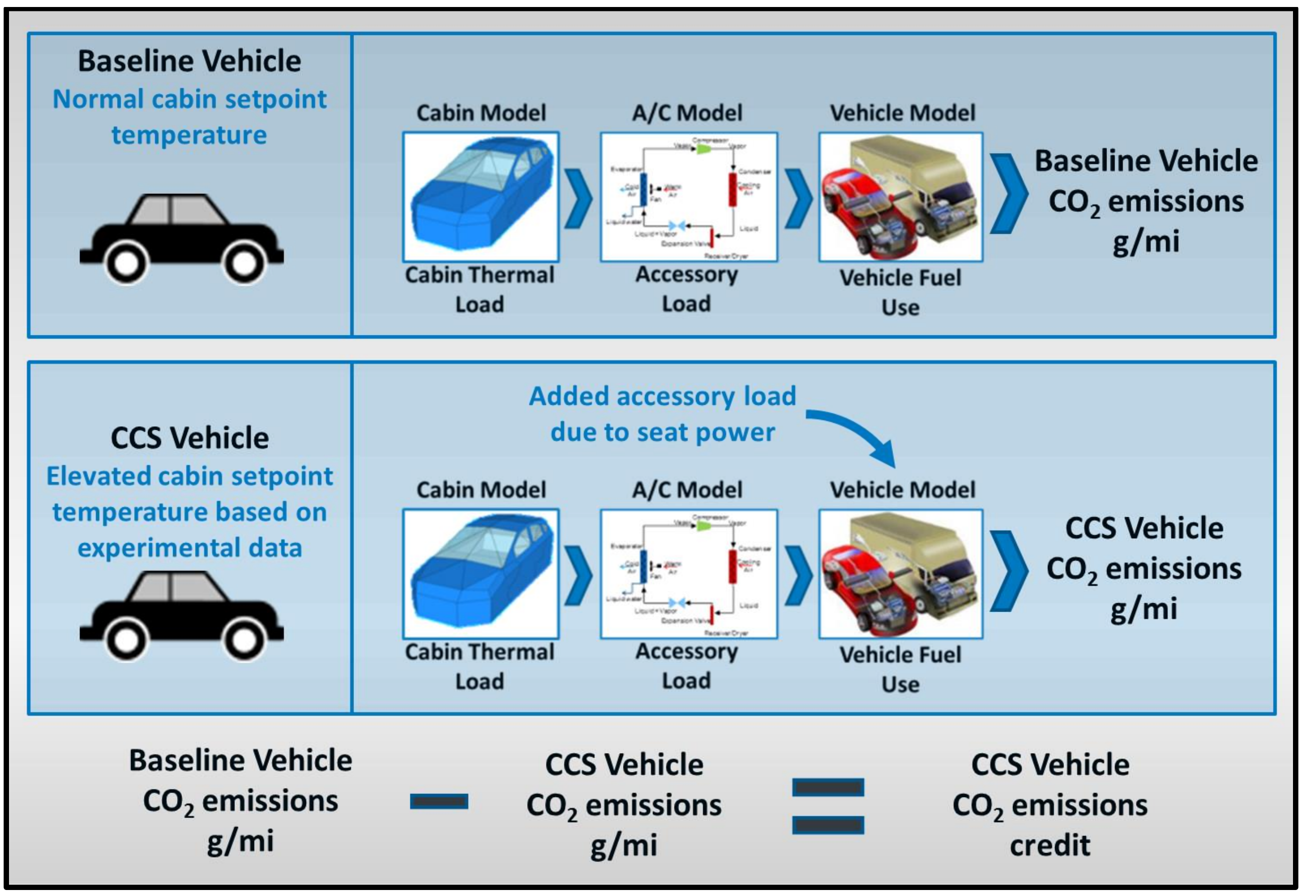

Figure 16. Pathway for calculation of climate control seat fuel use and CO_2 emissions reduction

Results

Experimental Testing

A summary of the test days and weather conditions during the experimental tests are provided in Table 8. A total of eight test days were collected. Clearness index was calculated as the ratio of the integrated direct solar load divided by the integrated direct extraterrestrial solar load (above the atmosphere) over the duration of the test. Tests on 9/20 and 9/21 had poor solar conditions and for this reason were identified as poor test days. During the two poor test days, intermittent solar conditions caused rapid changes in the occupants' frontside thermal environment, preventing the occupants from providing a stable and repeatable whole body sensation vote.

Table 8. Summary of experimental test dates and average weather conditions during each test

Test Date	Clearness Index	Ambient Temp. [°C]	Wind Speed [m/s]	Relative Humidity [%]	Test Day Quality
9/18/2016	0.71	26.2	3.4	18.6	Good
9/19/2016	0.72	27.0	2.8	19.2	Good
9/20/2016	**0.15**	26.1	1.6	18.8	Poor
9/21/2016	**0.07**	23.1	2.2	27.3	Poor
9/23/2016	0.70	23.4	4.7	39.9	Good
9/26/2016	0.73	18.8	2.6	29.0	Good
9/27/2016	0.73	20.7	2.1	28.6	Good
9/29/2016	0.67	19.6	2.3	36.1	Good

A summary of the elapsed time taken to attain target whole body sensation for the occupants is provided in Table 9. This table is provided for informational purposes only and comparisons between occupants should not be performed because during the test, Occupant C had a different target whole body sensation than Occupants A, B, and D. However, it can be noted that for all tests in good weather conditions, the occupant in the CCS vehicle attained their target whole body sensation in a shorter time than in the baseline vehicle. Time to sensation performance comparisons should be made for an individual test subject due to the testing methodology and variations in occupant sensation between individuals.

Table 9. Vehicle occupant test summary with time to target sensation values for the transient max cooling phase of the test

Test Date	Baseline Vehicle Occupant	CCS Vehicle Occupant	Baseline Vehicle Time to Sensation	CCS Vehicle Time to Sensation	Test Day Quality
9/18/2016	Occupant A	Occupant B	20.9	16.7	Good
9/19/2016	Occupant B	Occupant A	19.8	14.8	Good
9/20/2016	Occupant C	Occupant D	19.0	21.0	Poor
9/21/2016	Occupant D	Occupant C	17.6	17.8	Poor
9/23/2016	Occupant D	Occupant B	18.7	14.7	Good
9/26/2016	Occupant C	Occupant D	15.9	12.5	Good
9/27/2016	Occupant C	Occupant A	29.1	16.1	Good
9/29/2016	Occupant A	Occupant C	17.4	16.2	Good

The time-to-target sensation for all tests grouped by test subject is provided in Table 10. The two poor weather test days are highlighted in gray and were omitted from the weighted average performance. Occupant A had an average 19.1% improvement in time-to-target sensation, while Occupant B had a 12.1% improvement, Occupant C had a 44.4% improvement, and Occupant D had a 32.9% improvement. Because Occupants A and B had two sets of tests, the good weather group test average was calculated with Occupant A and B results having twice the weighting factor as Occupants C and D. The group average improvement in time-to-target whole body sensation for the CCS vehicle was determined to be 23.3%.

Table 10. Time-to-target sensation summary statistics for each test subject during the transient max cooling phase of the test

	Time to target sensation [min]				
	Baseline Vehicle		CCS Vehicle		
Occupant	Test 1	Test 2	Test 1	Test 2	Improvement [%]
Occupant A	20.9	17.4	14.8	16.1	19.1
Occupant B	19.8	15.9	16.7	14.7	12.1
Occupant C	29.1		16.2		44.4
Occupant C: Poor Test Day	19.0		17.8		6.3
Occupant D	18.7		12.5		32.9
Occupant D: Poor Test Day	17.6		21.0		19.1
Good Weather Group Test Average (Weighted)					**23.3%**

The two critical inputs to the analysis process are the mean vehicle cabin air temperature offset from the climate control seat compared to the baseline vehicle and the added energy needed for operation of the climate control seat. An example plot of the vehicle cabin mean air temperature for the test duration on 9/26/2016 is provided in Figure 17. For the tests, the mean cabin air temperature offset was calculated during the steady-state phase after the cabin temperature had stabilized after the transition and while the occupant steady-state whole body sensation was attained. During this time, the CCS vehicle seat average power was also determined. An example plot of the climate control seat power for the duration of the test for 9/26/2016 is provided in Figure 18. On the example test day, the climate control seat power level was “high” for the transient cooling phase, followed by “medium” for the steady-state portion of the test. Although the seat power was prescribed to be “high” for the transient portions of all tests performed, the seat power was adjusted by the occupant during the steady-state period and therefore varied across tests. The results of the climate control seat power, vehicle cabin mean air temperatures, and associated increase in mean air temperature due to the climate control seat is provided in Table 11. Four critical values in Table 11 were then extracted for use in the national level analysis. First, for conservative performance estimation and because a large amount of light-duty drives are short duration drives, the average climate control seat power from the transient phase (85.9 W) was used as the added electrical load for the CCS vehicle in the analysis. Second, the average increase in mean air temperature from the climate control seats (2.61°C) was used as the target A/C system offset from the baseline vehicle to represent the CCS vehicle. In addition, for conservative estimation due to potential bias associated with subject testing that was not performed blind, the low bound of the 90$^{\%}$ confidence interval (2.00°C) was used to represent a second conservative CCS vehicle configuration. Finally, the high bound of the 90th confidence interval (3.21°C) was used to represent a maximum performance CCS vehicle configuration.

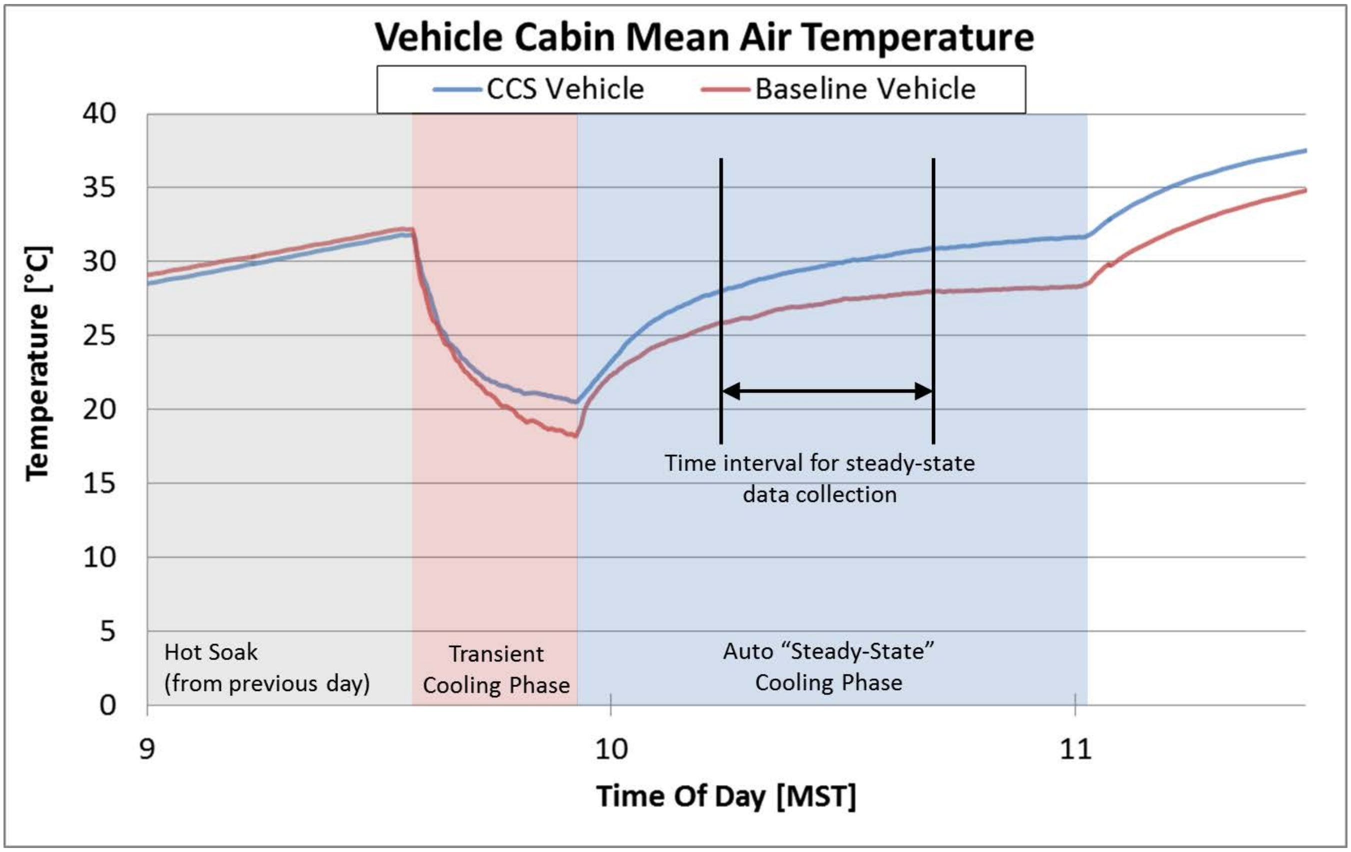

Figure 17. Vehicle cabin mean air temperature for both baseline and CCS vehicles for the duration of the test performed on 9/26/2016

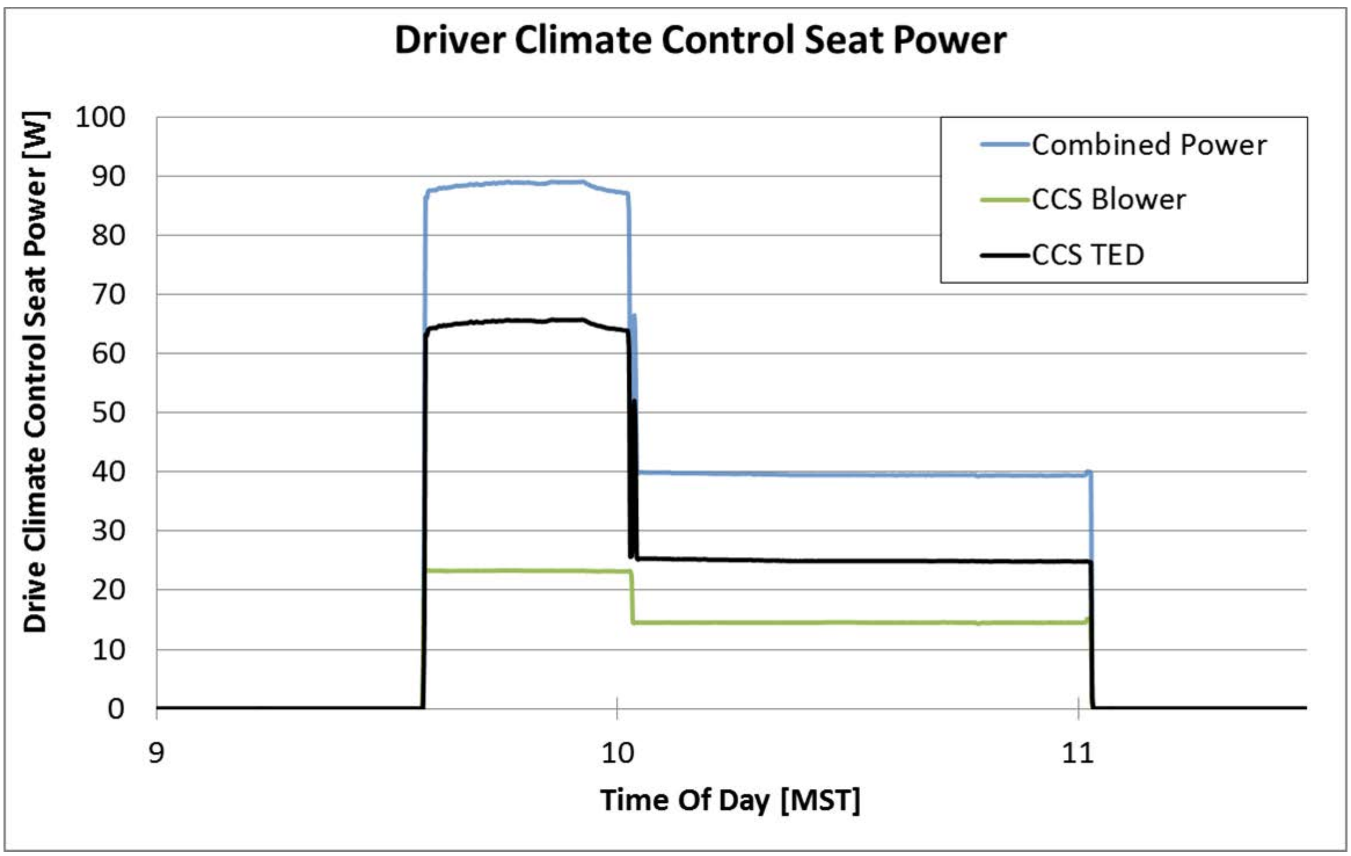

Figure 18. Instantaneous power from TED, blower, and combined power for the climate control seat for the duration of the test performed on 9/26/2016

Table 11. Results of climate seat power, cabin mean air temperatures, and increase in cabin mean air temperature for the climate control seat vehicle for all tests with calculated statistics for good weather test days (poor tests shown in grey).

Test Date	Average Climate Seat Power [W]		Vehicle Mean Air Temp. (MAT) [°C]		Increase in MAT from CCS [°C]
	Transient Phase	Steady-state Phase	Baseline Vehicle	CCS Vehicle	
9/18/2016	84.5	86.4 (high)	26.7	30.5	3.78
9/19/2016	85.1	39.7 (med)	27.6	30.6	3.01
9/20/2016	83.3	8.0 (low)	24.5	28.5	4.03
9/21/2016	86.2	39.1 (med)	25.0	28.3	3.33
9/23/2016	85.0	39.5 (med)	27.8	29.8	1.98
9/26/2016	87.1	84.4 (high)	27.2	29.9	2.60
9/27/2016	86.4	39.7 (high)	28.5	31.0	2.54
9/29/2016	87.4	54.8 (med/high)	28.7	30.4	1.72
Good Weather Average	**85.9**	**54.8**	**27.8**	**30.4**	**2.61**
Standard Dev.	**1.18**	**23.71**	**0.75**	**0.45**	**0.74**
90% Confidence Low Bound	**84.9**	**35.3**	**27.1**	**30.0**	**2.00**
90% Confidence High Bound	**86.9**	**74.3**	**28.4**	**30.7**	**3.21**

Manikin Test Results

Although all experimental work has been completed for both the HVAC and STAN manikins, post-processing of the data has not yet been completed.

National Level Analysis Results

To calculate the performance of the climate control seats, it was first necessary to calculate the baseline A/C fuel use for light-duty vehicles in the United States using the method described in the Approach section. While the baseline fuel use for light-duty vehicles in the U.S. was calculated by the EPA and NHTSA as part of the rulemaking [6], it is the author's opinion that the approach used here captures more critical elements that affect A/C fuel use. A contour plot of the national baseline annual A/C fuel use for the United States is provided in Figure 19, and includes the calculated overall national baseline A/C fuel use of 7.6 billion gallons per year based on individual location fuel use in gallons/year times the estimated number of light-duty vehicles [2] and miles traveled [3]. In addition to the baseline national average light-duty A/C fuel use, the national average light-duty vehicle fuel use and CO_2 emissions were calculated for the CCS vehicle at + 2.0°C cabin temperature offset, + 2.61°C cabin temperature offset, and +3.21°C cabin temperature offset. The results are provided in Table 12.

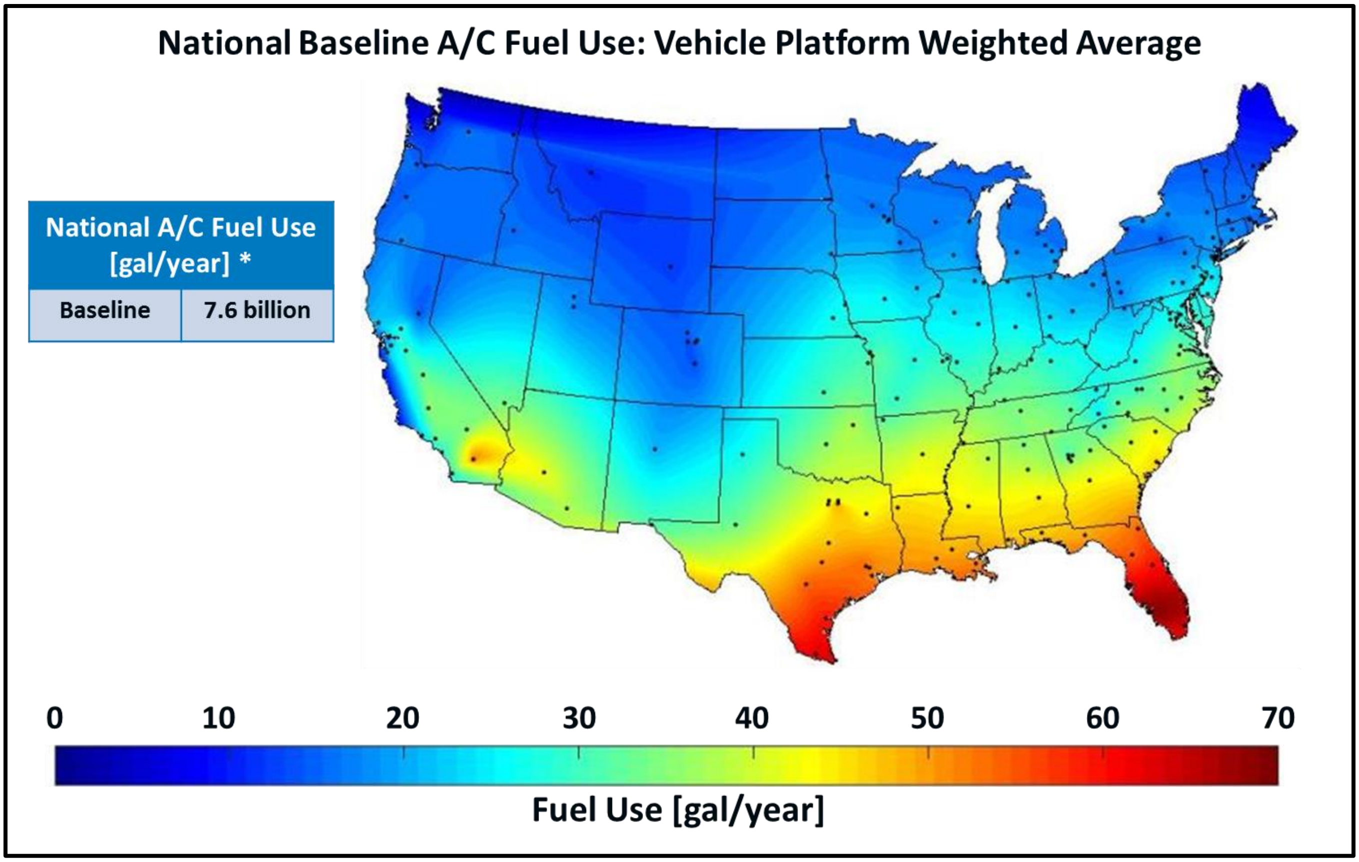

Figure 19. Contour plot of national baseline A/C fuel use for the United States

Table 12. National A/C fuel use and CO_2 emissions calculated for baseline vehicle and CCS vehicle configurations

Vehicle Configuration	Individual Vehicle A/C Fuel Use [Gal/year]	U.S. Light-Duty Fleet A/C Fuel Use [Gal/year] *	U.S. A/C Carbon Dioxide Emissions [Tons/year] **
National Baseline Vehicle	30.0	7. 59 billion	74.3 million
CCS Vehicle +2.0°C cabin offset (low bound confidence)	26.5	6.69 billion (100% adoption)	65.5 million (100% adoption)
CCS Vehicle +2.6°C cabin offset (average)	24.9	6.29 billion (100% adoption)	61.6 million (100% adoption)
CCS Vehicle +3.2°C cabin offset (high bound confidence)	23.4	5.91 billion (100% adoption)	57.9 million (100% adoption)
Savings With Climate Seat (Low bound, 90% Confidence)	**3.5**	**0.9 billion (100% adoption)**	**8.8 million (100% adoption)**
Savings With Climate Seat (average)	**5.1**	**1.30 billion (100% adoption)**	**12.7 million (100% adoption)**
Savings With Climate Seat (High bound, 90% Confidence)	**6.6**	**1.67 billion (100% adoption)**	**16.4 million (100% adoption)**

* Based on U.S. light-duty vehicle fleet size of 252,714,871 vehicles [2], individual vehicles traveling 11346 miles/year [3]
** Based on 8887 grams of CO_2 per gallon of gasoline [4]

Calculation of carbon dioxide emissions savings for the CCS was performed by first calculating the national annual vehicle fuel use from the analysis process in gallons per year and then converting it to carbon dioxide equivalent based on 8887 grams of CO_2 per gallon of gasoline [4], and finally dividing by the number of vehicle miles traveled in a year (11346 miles/year) based on Polk data [2]. The national CO_2 emissions for the calculated baseline vehicle and three CCS vehicle configurations are provided in Table 13 in addition to the high and low locations evaluated for the country in the analysis process. The national average carbon dioxide emissions savings for the climate control seat over the national average baseline was calculated to be 4.0 g/mi when using the experimentally obtained 2.6°C increase in cabin air temperature setpoint. Similarly, for the low bound estimate of the climate control seat at +2.0°C increase in cabin air temperature setpoint, the national average carbon dioxide emissions savings was calculated to be 2.8 g/mi. Finally, for the high bound estimate of the climate control seat at +3.2°C increase in cabin air temperature setpoint, the national average carbon dioxide emissions savings was calculated to be 5.2 g/mi. Contour plots of the U.S. annual carbon dioxide emissions savings for the CCS vehicle for the three temperature offsets are provided in Figure 20, Figure 21, and Figure 22.

Table 13. National light-duty A/C CO_2 emissions for the baseline and CCS vehicle configurations and associated savings

Vehicle Configuration	Individual Vehicle A/C CO_2 Emissions [g/mi]	Individual Vehicle CO_2 Emissions Savings [g/mi]	U.S. Location with Lowest Emissions Anchorage, AK	U.S. Location with Highest Emissions Honolulu, HI
National Baseline Vehicle	23.5		3.5 g/mi	55.4 g/mi
CCS Vehicle +2.0°C cabin offset (low bound)	20.7	2.8	0.7 g/mi savings	7.2 g/mi savings
CCS Vehicle +2.6°C cabin offset (average)	19.5	4.0	1.1 g/mi savings	10.2 g/mi savings
CCS Vehicle +3.2°C cabin offset (high bound)	18.3	5.2	1.3 g/mi savings	13.1 g/mi savings

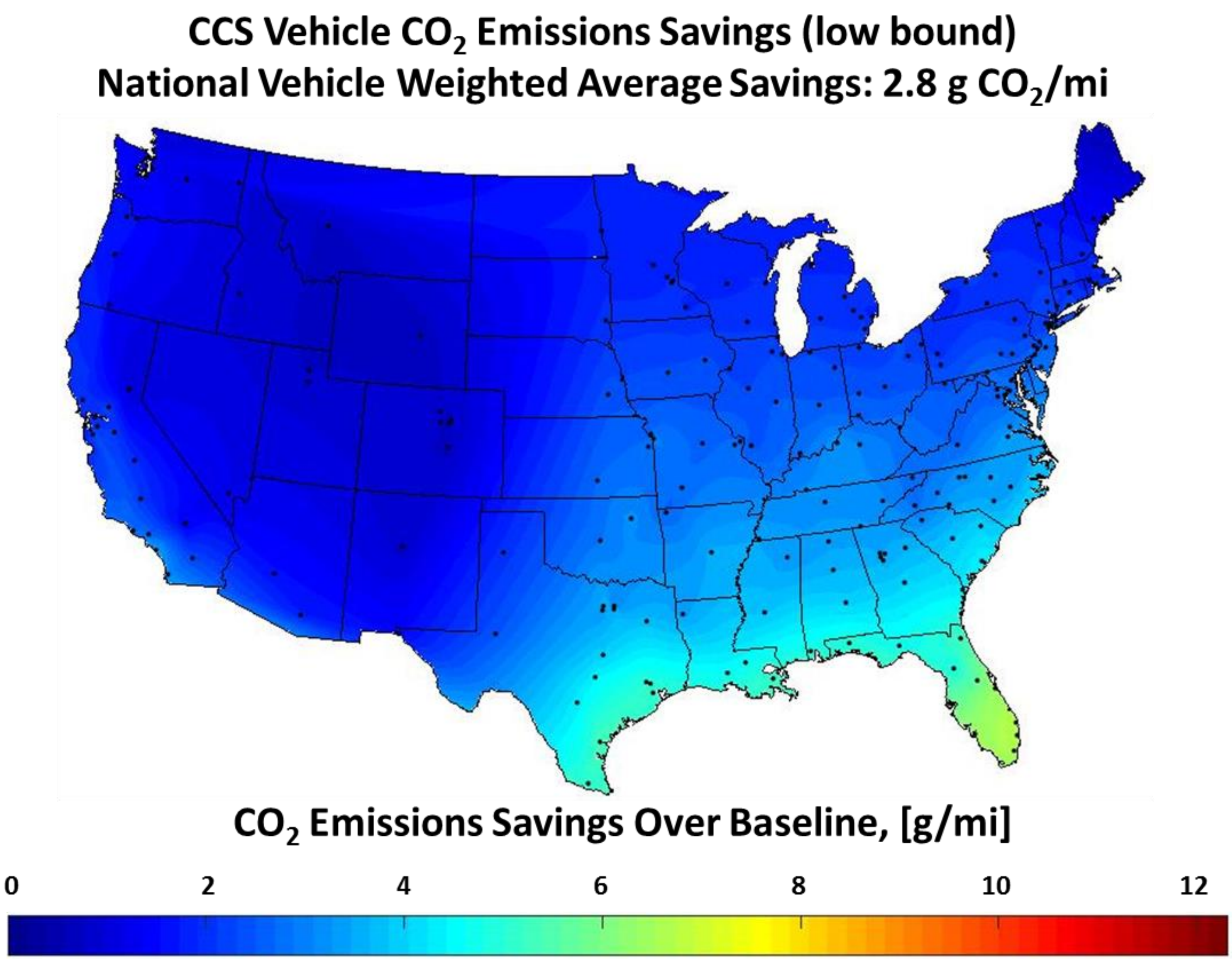

Figure 20. Contour map of U.S. annual CO_2 emissions savings for the CCS Vehicle using low bound cabin temperature offset

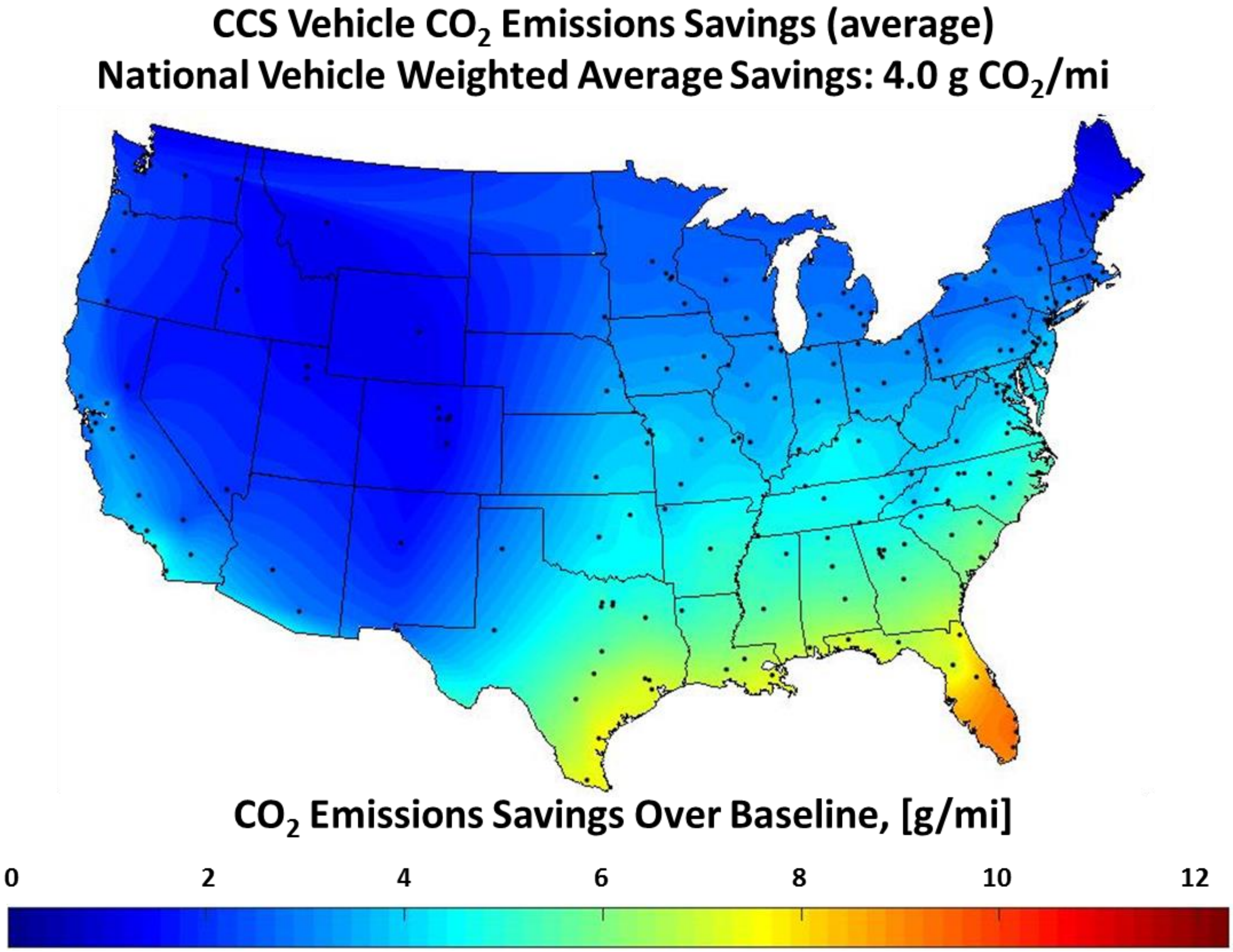

Figure 21. Contour map of U.S. annual CO_2 emissions savings for the CCS vehicle using the average cabin temperature offset

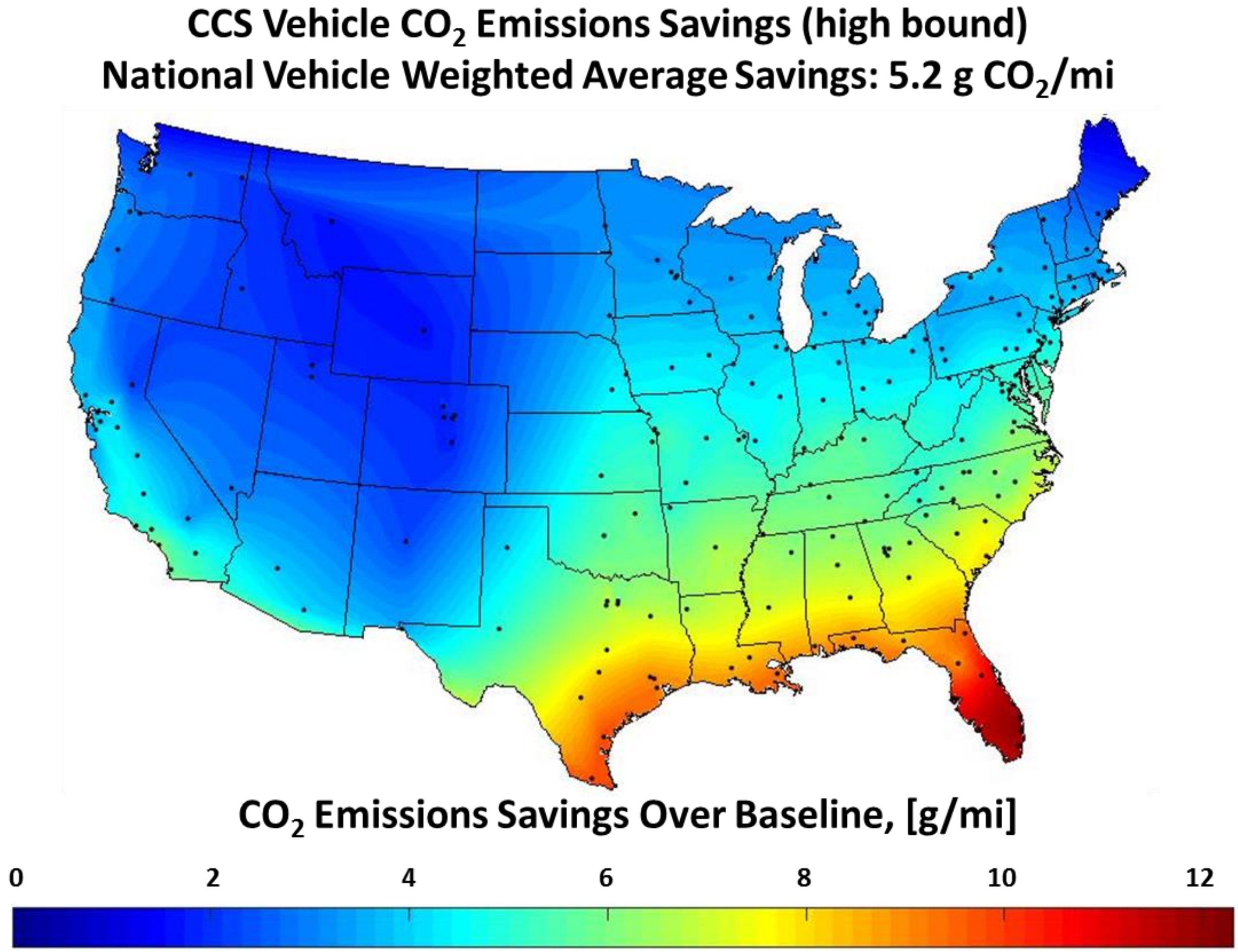

Figure 22. Contour map of U.S. annual CO_2 emissions savings for the CCS vehicle using high bound cabin temperature offset

Comparison of CCS Vehicle CO2 Emissions Savings to Existing EPA Ventilated Seat Credit

It was not possible to directly compare the CCS vehicle CO_2 emissions savings in Table 13 (4.0 g/mi) to the EPA ventilated seat off-cycle credit (1.0 g/mi for car and 1.3 g/mi truck) because the EPA provides separate credit values for cars and trucks. Additionally, the NREL national baseline vehicle CO_2 emissions due to A/C usage of 23.5 g/mi were significantly larger than the EPA baseline of 13.8 g/mi (car) and 17.2 g/mi (truck). A consequence of the higher baseline vehicle A/C CO_2 emissions was that the impact of the ventilated seat was under predicted relative to the CCS. Stated another way, the higher baseline vehicle A/C CO2 emissions means there is greater opportunity for off-cycle technologies to reduce real world emissions due to the operation of A/C.

To enable comparison of the two seating technologies, the national baseline and CCS vehicle A/C CO2 emissions were split into car and truck components. Also the EPA ventilated seat credit was scaled up to reflect the greater baseline CO_2 emissions due to A/C operation. First, a combined car/truck combined EPA emissions was calculated to be 15.6 g/mi using a weighted average based on the NREL fleet distribution of 48% cars and 52% trucks/SUVs. Then a scale factor based on the combined baseline EPA emissions was calculated to be 0.89 for a car and 1.10 for a truck.

$$Scale\ Factor, car\ = \frac{\text{EPA Baseline A/C Emissions, car}}{\text{EPA Baseline A/C Emissions, combined}}$$

$$Scale\ Factor, car\ = \frac{13.8\ \text{g/mi}}{15.6\ \text{g/mi}} = 0.89$$

These factors were then used to separate the national baseline and CCS vehicle A/C CO_2 emissions into car and truck components.

$$National\ Baseline\ A/C\ CO2\ Emissions, car\ = \text{Scale Factor, car} * \text{National Baseline A/C CO2 Emissions}$$

$$National\ CCS\ A/C\ CO2\ Emissions, car\ = \text{Scale Factor, car} * \text{National CCS A/C CO2 Emissions}$$

Using the national baseline and CCS A/C CO_2 emissions of 23.5 g/mi and 19.5 g/mi from Table 13 and the car scale factor calculated above, a national baseline and CCS A/C CO_2 emissions for a car were calculated to be 20.8 g/mi and 17.3 g/mi respectively as shown in Table 14. For a car, the CO_2 emissions savings due to the CCS is 3.5 g/mi.

The ventilated seat credit was scaled up to account for the higher national baseline vehicle A/C CO_2 emissions compared to the EPA baseline.

$$Adjusted\ ventilated\ seat\ credit, car\ = \frac{\text{National Baseline A/C CO2 Emissions, car}}{\text{EPA baseline A/C CO2 Emissions, car}} * \text{EPA ventilated seat credit}$$

For a car, the calculation is

$$Adjusted\ ventilated\ seat\ credit, car\ = \frac{20.8\ \text{g/mi}}{13.8\ \text{g/mi}} * 1\ \text{g/mi}$$

and results in an adjusted ventilated seat off-cycle credit of 1.5 g/mi. Using the CO_2 emissions savings due to the CCS of 3.5 g/mi for a car calculated above, the CCS saves an additional 2.0 g/mi over a ventilated seat for a car. The complete car and truck A/C CO_2 emissions results are shown in Table 14.

Table 14. National and CCS A/C CO2 emissions split into car/truck components and comparison to the adjusted ventilated seat credit

Vehicle Configuration	Cabin Offset (°C)	A/C CO2 Emissions (g/mi) car	CO2 Emissions Savings (g/mi) car	CCS improvement over ventilated seat (g/mi) car	A/C CO2 Emissions (g/mile) truck	CO2 Emissions Savings (g/mi) truck	CCS improvement over ventilated seat (g/mi) truck
Current Off-Cycle Ventilated Seat Menu Credit (Adjusted)			1.5			2.0	
National Baseline Vehicle		20.8			26.0		
CCS Vehicle (low bound)	2.0	18.3	2.5	1.0	22.9	3.1	1.1
CCS Vehicle	2.6	17.3	3.5	2.0	21.5	4.4	2.5
CCS Vehicle (high bound)	3.2	16.2	4.6	3.1	20.2	5.7	3.8

References

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