U.S. LIGHT-DUTY VEHICLE AIR CONDITIONING FUEL USE AND THE IMPACT OF FOUR SOLAR/THERMAL CONTROL TECHNOLOGIES

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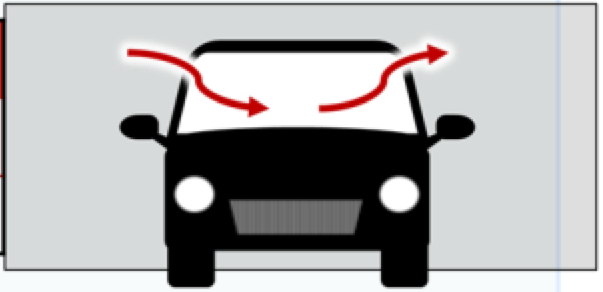
Thermal Off-Cycle Menu Credits for MY 2017 - 2025

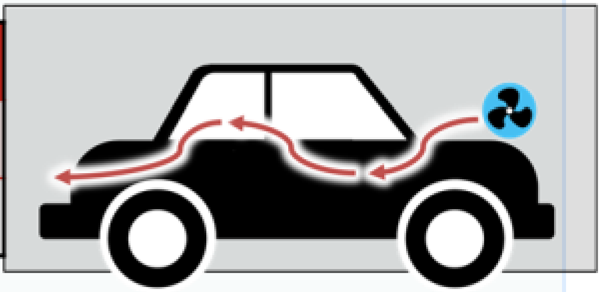
Passive Ventilation

Credit (g CO_2/mi)	
Car	1.7
Truck	2.3



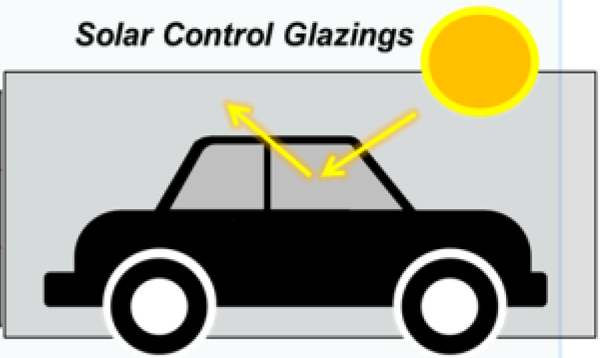
Active Ventilation

Credit (g CO_2/mi)	
Car	2.1
Truck	2.8



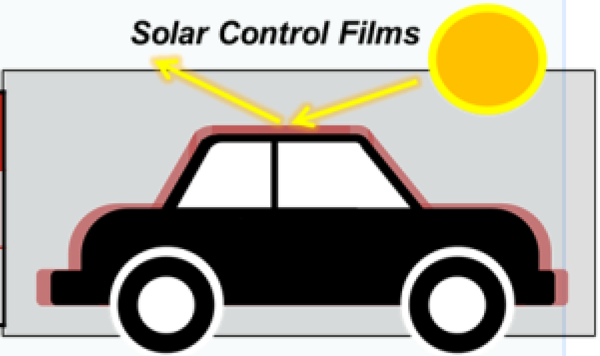
Solar Control Glazings

Credit (g CO_2/mi)	
Car	Up to 2.9
Truck	Up to 3.9



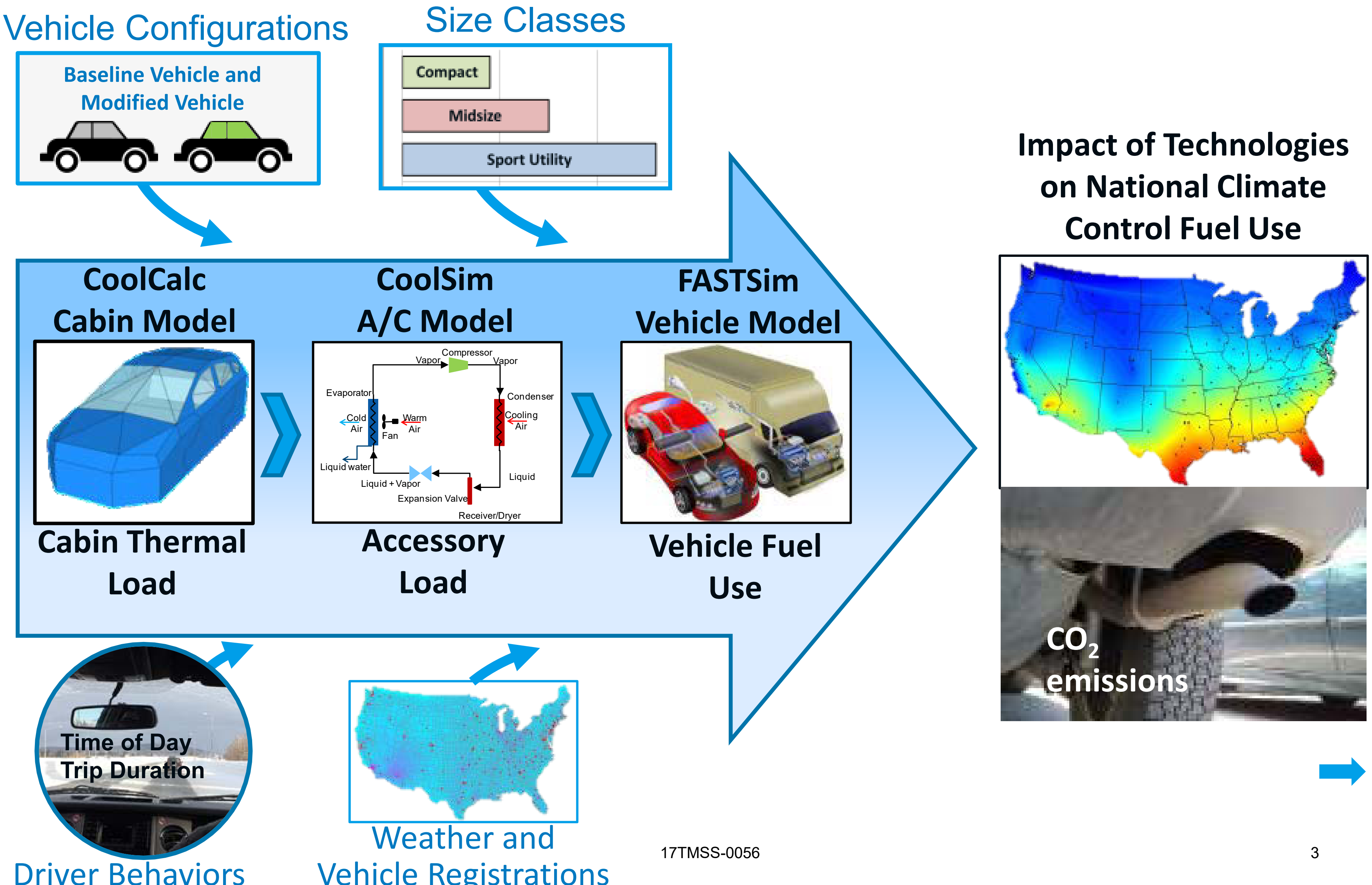
Solar Control Films

Credit (g CO_2/mi)	
Car	0.4
Truck	0.5



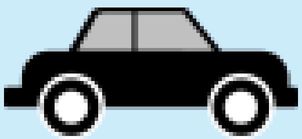
Data Source: U.S. Environmental Protection Agency and Department of Transportation. *Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards and Corporate Average Fuel Economy Standards. Available at: https://www3.epa.gov/otaq/climate/documents/420r12901.pdf, Accessed 7/2016*

National Level A/C Fuel Use Analysis Process

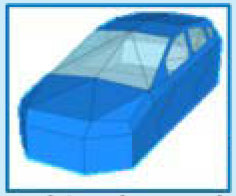


Pathway to Technology Performance Determination

Baseline Vehicle
Normal cabin setpoint temperature

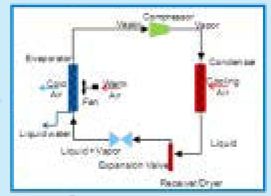


Cabin Model



Cabin Thermal Load

A/C Model



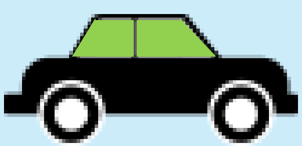
Accessory Load

Vehicle Model

Vehicle Fuel Use

Baseline Vehicle Fuel Use and CO_2 Emissions

Modified Vehicle
For Example: Modified glass radiative properties

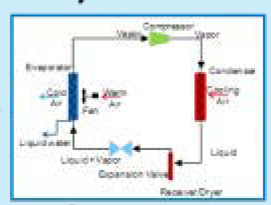


Modified properties for glass constructions

Cabin Model

Cabin Thermal Load

A/C Model



Accessory Load

Vehicle Model

Vehicle Fuel Use

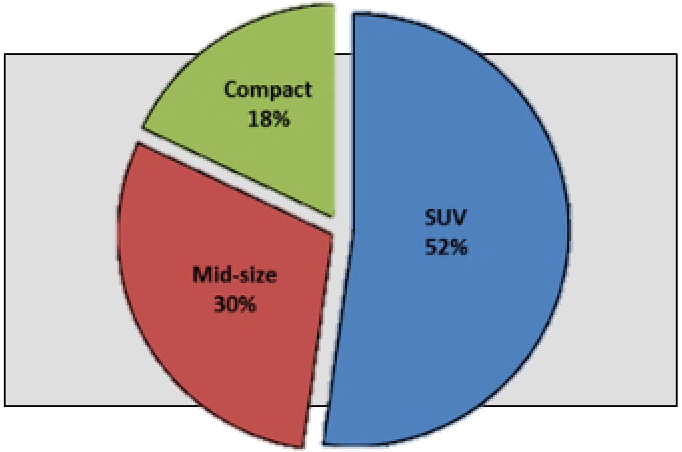
Modified Vehicle Fuel Use and CO_2 Emissions

Baseline Vehicle Fuel Use & CO_2 Emissions − **Modified Vehicle Fuel Use & CO_2 Emissions** = **Technology Fuel Use Savings CO_2 emissions reduction**

Vehicle Size Class Selection and Representative Platforms

Polk Classification	Percent of Registrations	NREL Assignment
NON LUXURY TRADITIONAL MID SIZE	14.3	Mid-Size
NON LUXURY TRADITIONAL COMPACT	13.0	Compact
NON LUXURY FULL SIZE HALF TON PICKUP	10.2	SUV
NON LUXURY TRADITIONAL FULL SIZE	7.1	Mid-Size
NON LUXURY MID SIZE SUV	6.7	SUV
NON LUXURY COMPACT CUV	6.4	SUV
NON LUXURY MID SIZE VAN	5.0	SUV
NON LUXURY MID SIZE PICKUP	5.0	SUV
NON LUXURY FULL SIZE 3 QTR TO 1 TON PICKUP	4.5	SUV
NON LUXURY FULL SIZE SUV	3.5	SUV
NON LUXURY MID SIZE CUV	3.3	SUV
LUXURY TRADITIONAL COMPACT	2.8	Compact
LUXURY TRADITIONAL MID SIZE	2.3	Mid-Size
NON LUXURY COMPACT SUV	2.2	SUV
NON LUXURY TRADITIONAL SUB COMPACT	2.0	Compact
NON LUXURY SPORT MID SIZE	1.8	Mid-Size
LUXURY MID SIZE CUV	1.6	SUV
NON LUXURY FULL 3 QTR TO 1 TON VAN	1.5	SUV
LUXURY TRADITIONAL FULL SIZE	1.4	Mid-Size
NON LUXURY SPORT	1.3	Mid-Size
LUXURY SPORT	1.1	Mid-Size
LUXURY FULL SIZE SUV	0.6	SUV
NON LUXURY FULL SIZE HALF TON VAN	0.5	SUV
NON LUXURY COMPACT VAN	0.5	SUV
NON LUXURY COMPACT PICKUP	0.4	Mid-Size
LUXURY COMPACT CUV	0.3	SUV
LUXURY MID SIZE SUV	0.2	SUV
LUXURY TRADITIONAL SUB COMPACT	0.2	Compact
COMMERCIAL TRUCK	0.1	SUV
LUXURY FULL SIZE HALF TON PICKUP	0.0	SUV
LUXURY EXOTIC	0.0	Mid-Size
LUXURY PRESTIGE FULL SIZE	0.0	SUV

Results of Size Class Simplification



Selected Representative Platforms

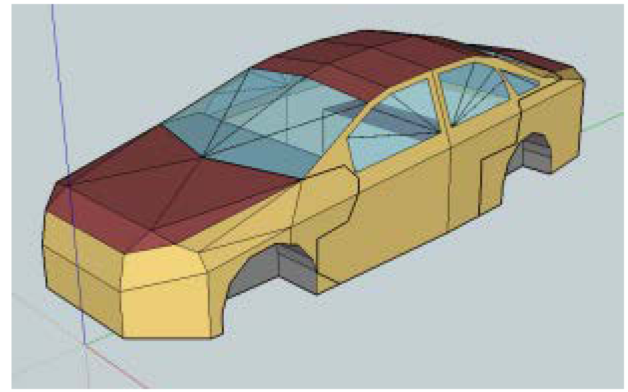
Data Source: 2014 Polk Vehicle Registration Database, currently IHS Automotive, driven by Polk, https://www.ihs.com/btp/polk.html

CoolCalc
Vehicle Cabin Thermal Model

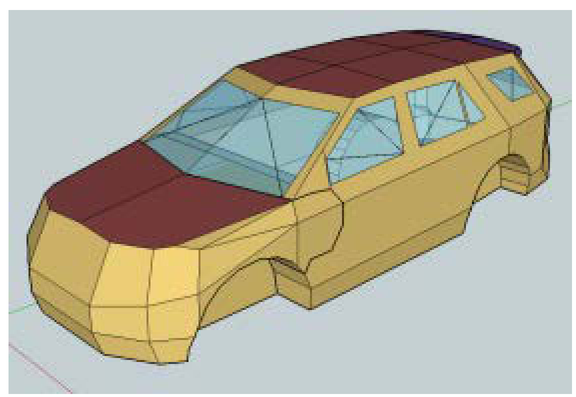
Key Features for Analysis

- Physics based tool, no meshing required
- Accurately captures solar based on location
- Direct input of key materials/properties
- Annual simulations with 1 minute timesteps

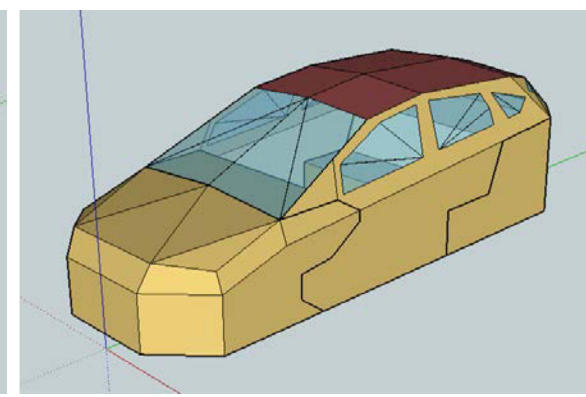
Mid-size Vehicle



Sport Utility Vehicle



Compact Vehicle



Driver Behaviors
Representative Trip Durations

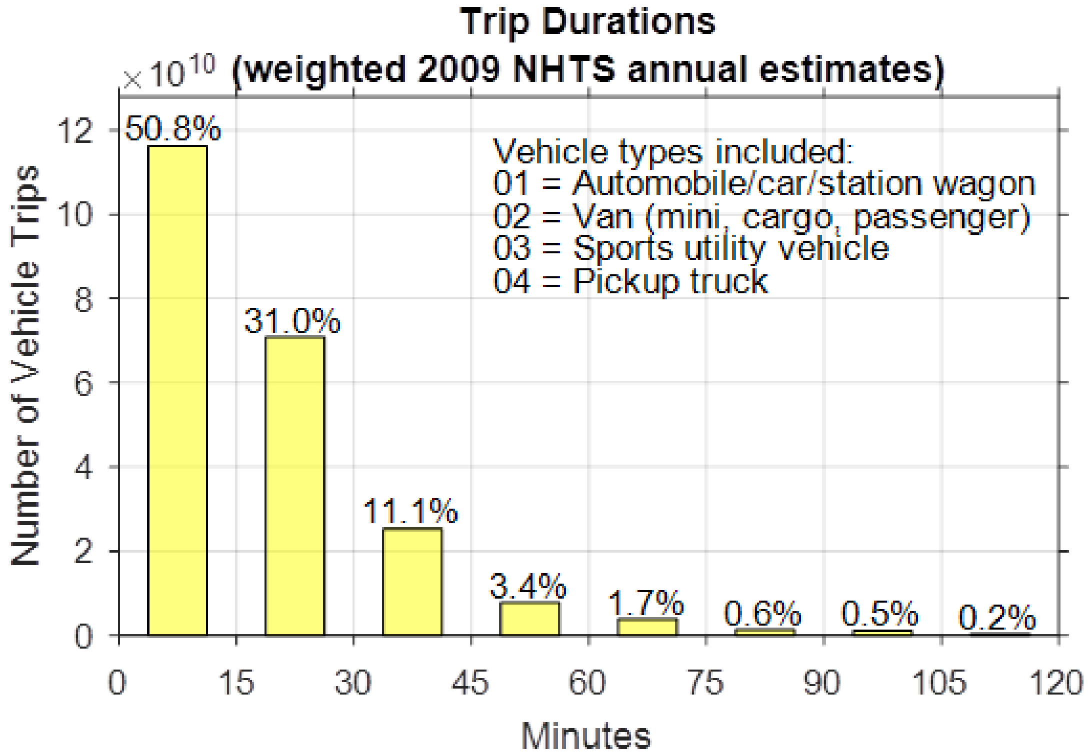
Method For Trip Durations

Select data for specific vehicle types

Sort data into 15 min intervals

Calculate weighting factors

Calculate average within each interval

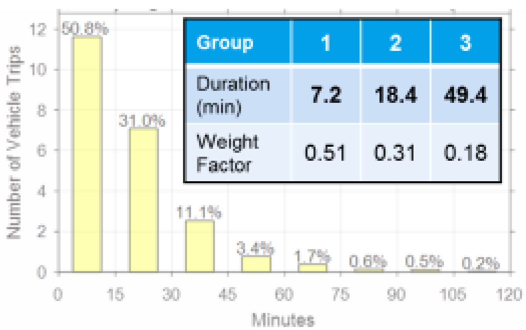


Time Range (min)	(0 – 15)	(15 – 30)	30 +
Average Time (min)	7.2	18.4	49.4
Weighting Factor	0.508	0.31	0.182

Data Source: "National Household Travel Survey. 2009," http://nhts.ornl.gov, accessed 5/2016

Drive Cycle Selection

Previously Defined Trip Durations



Group	1	2	3
Duration (min)	7.2	18.4	49.4
Weight Factor	0.51	0.31	0.18

NREL Transportation Secure Data Center

Subset of Cycles at Specified Duration

Drive Cycle 1

Drive Cycle 2

Drive Cycle 3

■ ■ ■

Drive Cycle X

Subset of Cycles at Specified Duration

Drive Cycle 1

Drive Cycle 2

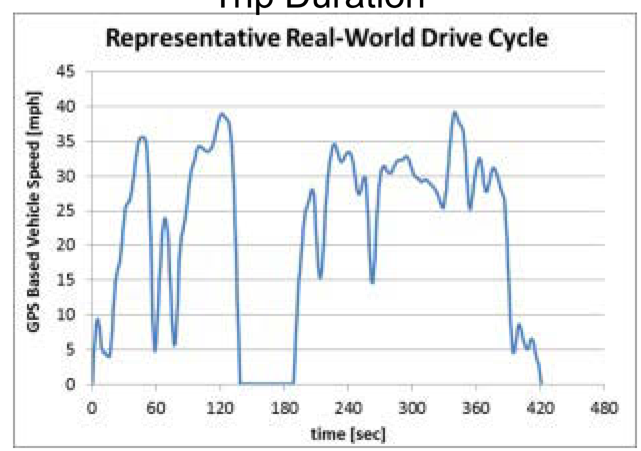
Drive Cycle 3

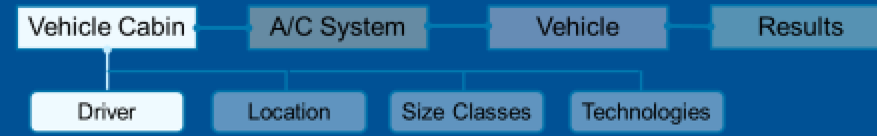
■ ■ ■

Drive Cycle X

Selection of Most Representative Cycle

Representative Cycle at Specified Trip Duration

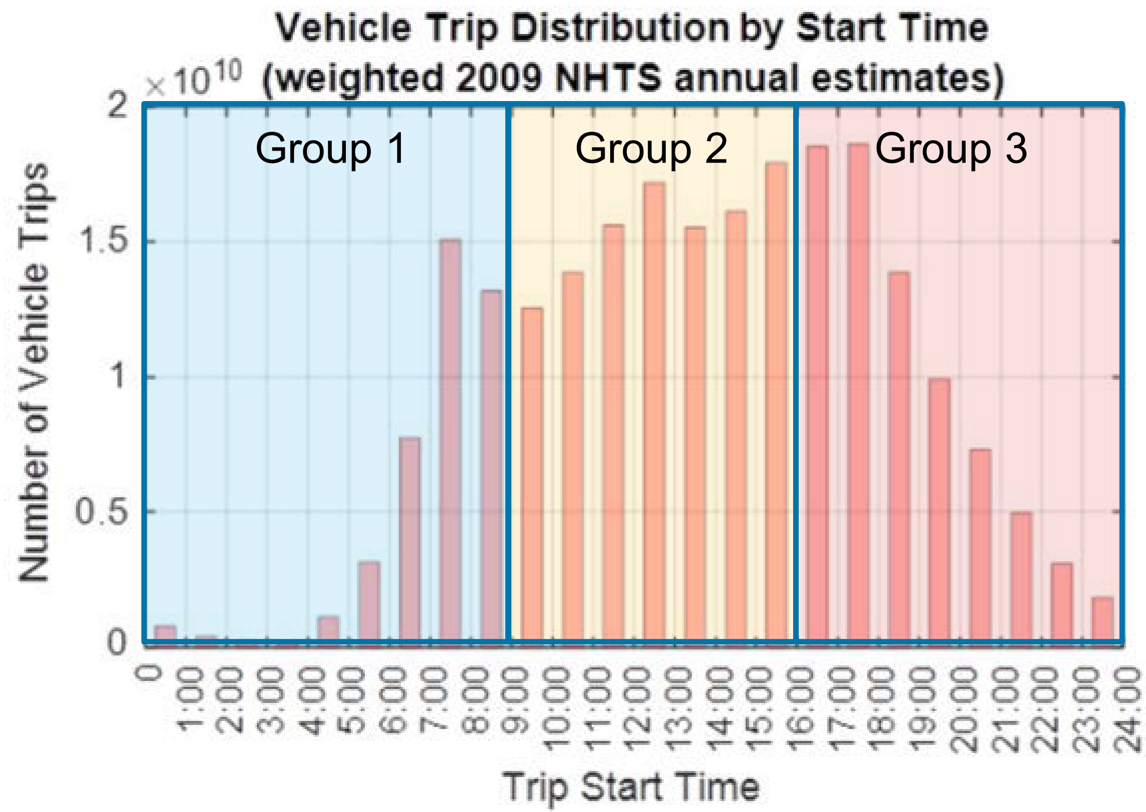




Driver Behaviors
Time of Day of Travel

Method For Time of Day

- Select data for specific vehicle types
- Sort data into 60 min intervals
- Determine groupings Based on Distribution
- Calculate average within each grouping



Time Range	(0:00 – 9:00)	(9:00 – 16:00)	(16:00 – 24:00)
Average Time	7:06	12:35	18:26
Weight Factor	18.3%	47.6%	34.1%

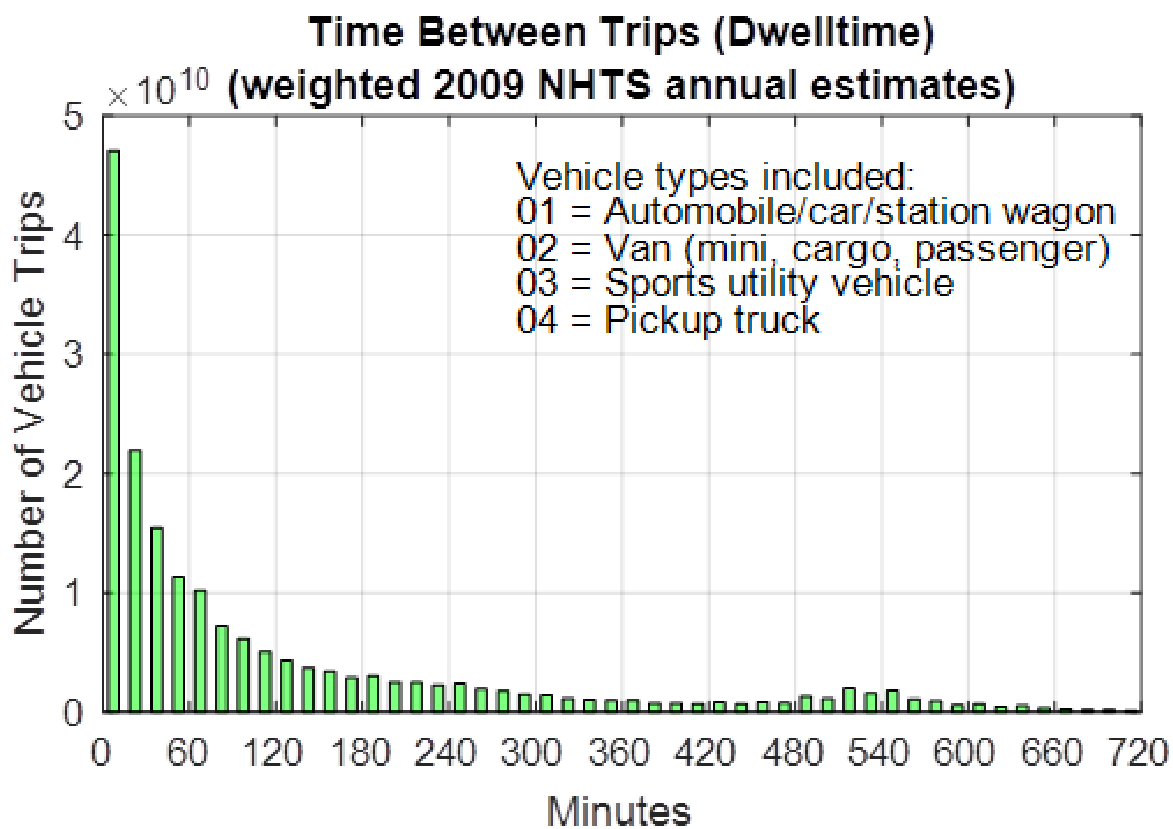
Data Source: "National Household Travel Survey. 2009," http://nhts.ornl.gov, accessed 5/2016

Driver Behaviors
Time Between Trips (Dwell Time)

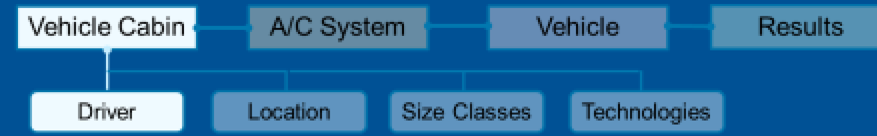
Method For Time Between Trips

- Select data for specific vehicle types
- Sort data into intervals
- Determine groupings Based on Distribution
- Calculate average within each grouping

Goal: Represent A/C performance for both fully and partially soaked vehicle conditions

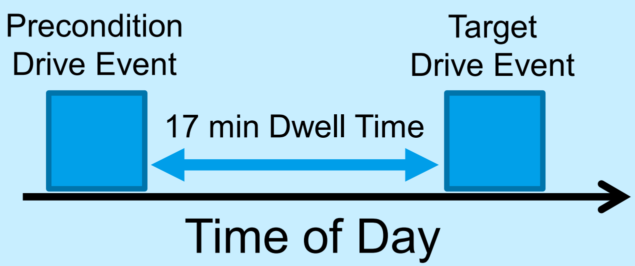


Data Source: "National Household Travel Survey. 2009," http://nhts.ornl.gov, accessed 5/2016

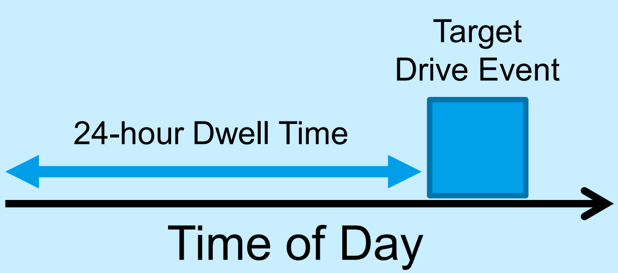


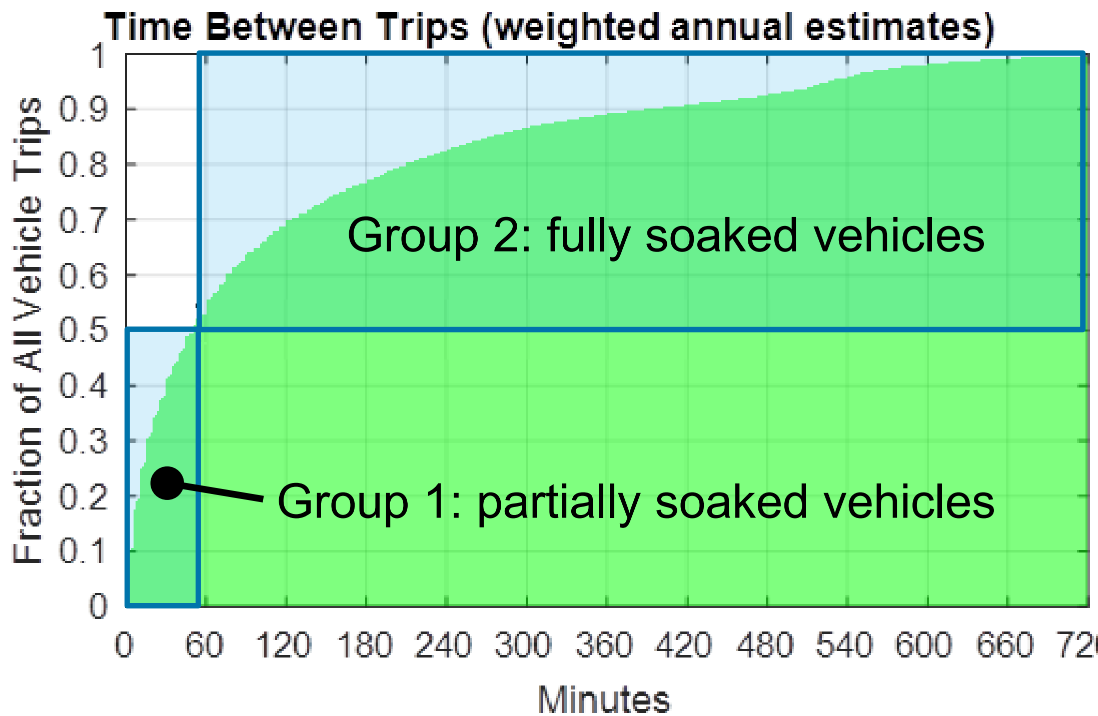
Driver Behaviors
Time Between Trips (Dwell Time)

Modeling Approach for Group 1:



Modeling Approach for Group 2:





Time Range (min)	(0 – 50)	(50 – end)
Average Time (min)	17	232 (~4 hr)
Weighting Factor	0.5	0.5

Data Source: "National Household Travel Survey. 2009," http://nhts.ornl.gov, accessed 5/2016

Representative Locations and Weather

Vehicle Cabin | A/C System | Vehicle | Results

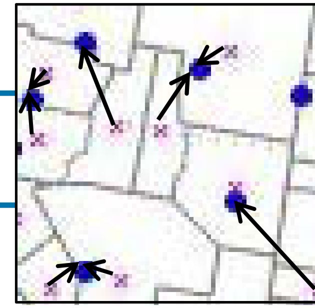
Driver | Location | Size Classes | Technologies

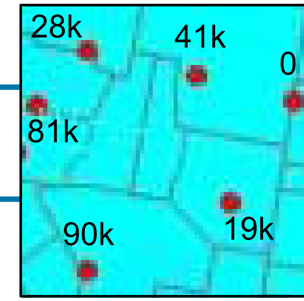
Registration Assignment Process

Legend

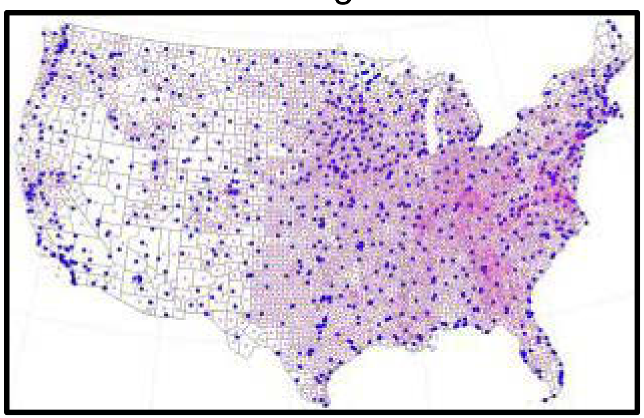
Geographic Center of County

TMY3 Location

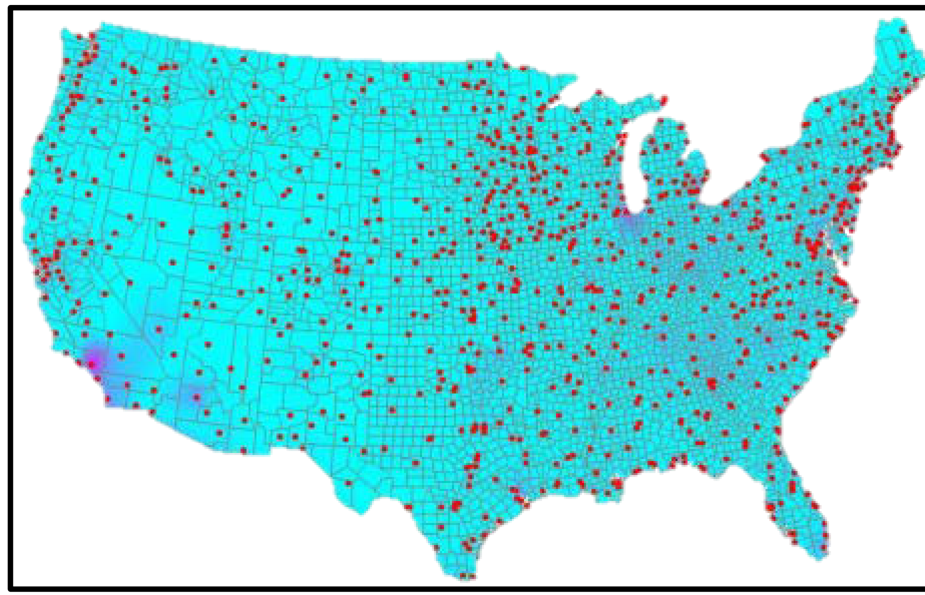




Independent TMY3 Weather Locations and US County Light-Duty Vehicle Registrations

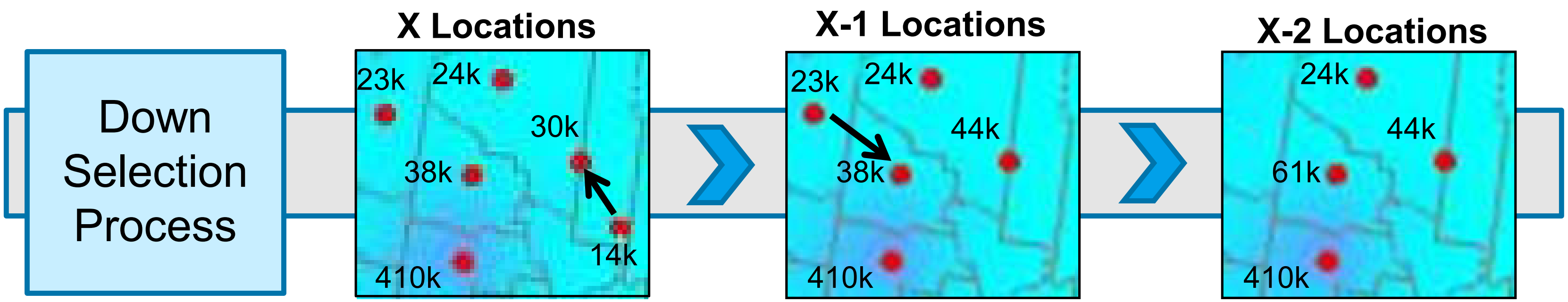


839 Registration Weighted Locations

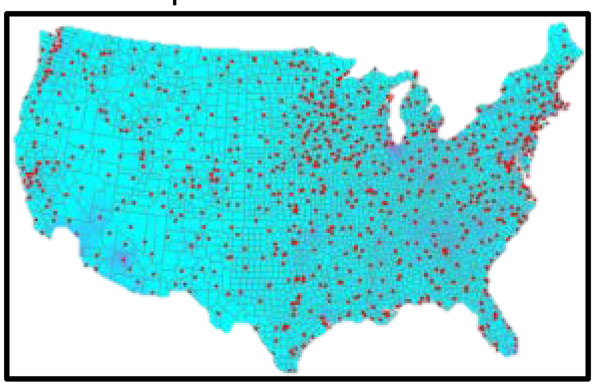


Millions of Vehicle Registrations

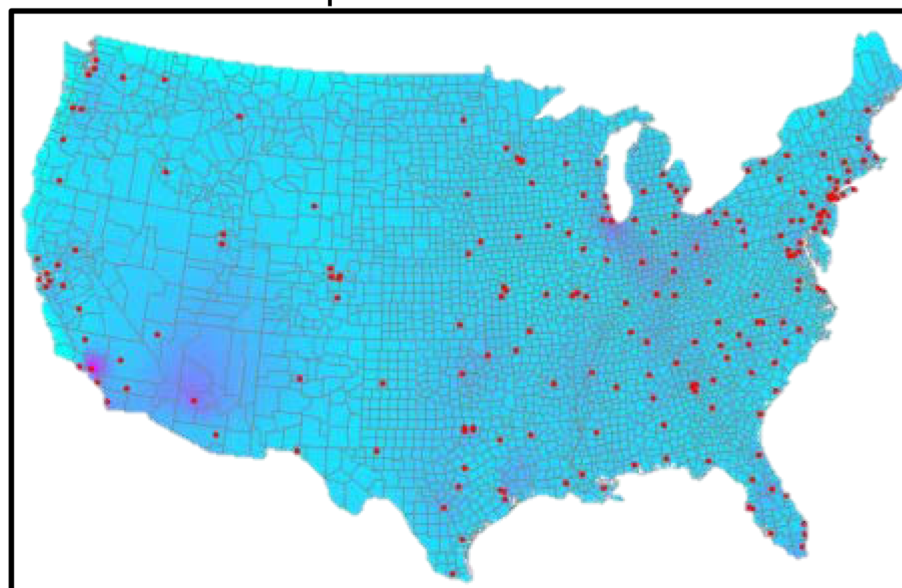
Representative Locations and Weather



839 Representative Locations



204 Representative Locations



Millions of Vehicle Registrations

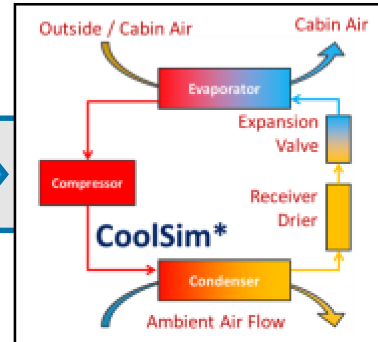
Thermal Load to Accessory Load CoolSim Mapping

A/C System Mapping Process

Parametric Variables

Evaporator Thermal Load
Engine Speed
Ambient T, RH
Vehicle Cabin T, RH
Recirculation Fraction

CoolSim Model

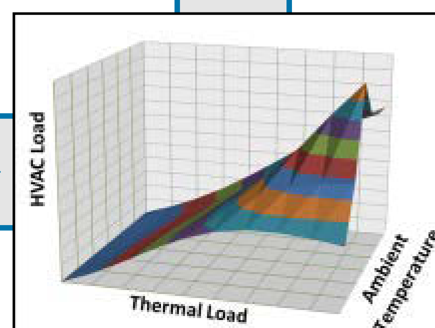


Thermal to Accessory Load Conversion Process

Vehicle Cabin Thermal Load Data

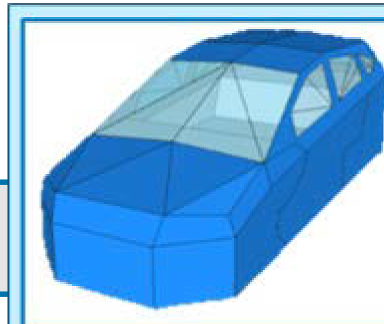
Evaporator Load

Ambient Conditions



CoolSim generated HVAC performance map

Vehicle Accessory Load Data



Vehicle Accessory Load

Vehicle Modeling - FASTSim

Simplified vehicle simulation tool

- **Uses speed vs. time drive cycles**
- **Standard or user defined cycles**
- **Powertrain Components:**
  - Engine, motor, battery, auxiliary loads
- **Validated for hundreds of vehicles**

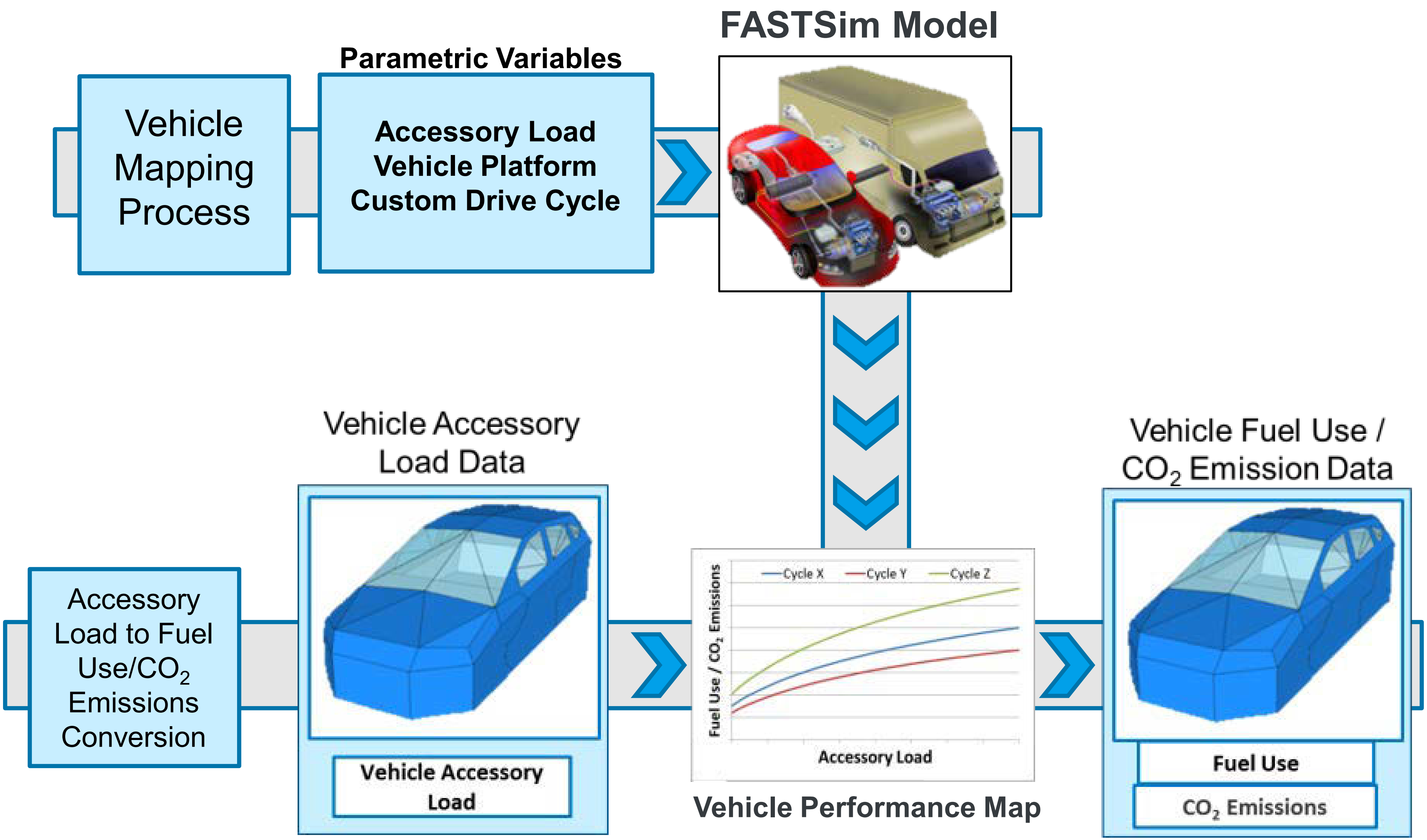
FASTSim Vehicle Modeling Tool

Brooker, A., Gonder, J., Wang, L., Wood, E. et al., "FASTSim: A Model to Estimate Vehicle Efficiency, Cost and Performance," SAE Technical Paper 2015-01-0973, 2015, doi:10.4271/2015-01-0973.

FASTSim Vehicle Modeling

Vehicle Cabin | A/C System | Vehicle | Results

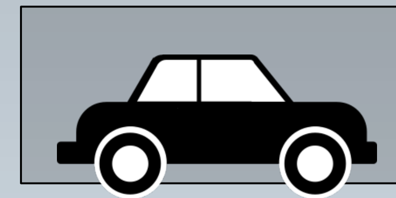
Driver | Location | Size Classes | Technologies



Implementation of Technologies Baseline and Improved

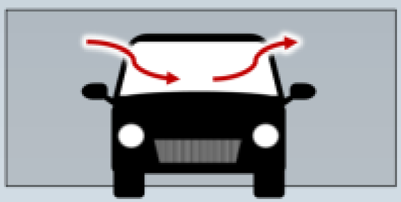
Baseline Configuration

Infiltration Rate: fixed infiltration rate
SR Paint: National avg. estimated from national paint sales data
Glass Transmittance: Solar management, absorbing for SUV rear



Passive Ventilation

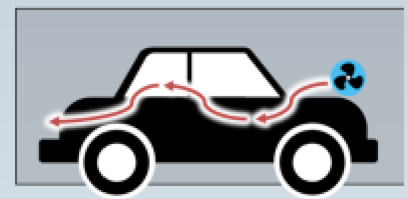
CoolCalc Parameter
Infiltration rate



Elevated infiltration rate

Active Ventilation

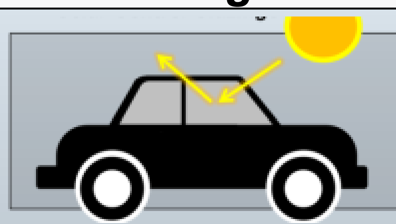
CoolCalc Parameter
Infiltration rate



Elevated outside air flowrate 15 minutes prior to drive

Solar Control Glazings

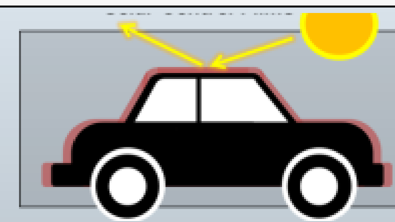
CoolCalc Parameter
Glass Transmittance



max reflectance on non-absorbing glass

Solar Reflective Paint

CoolCalc Parameter
Paint Solar Reflectance



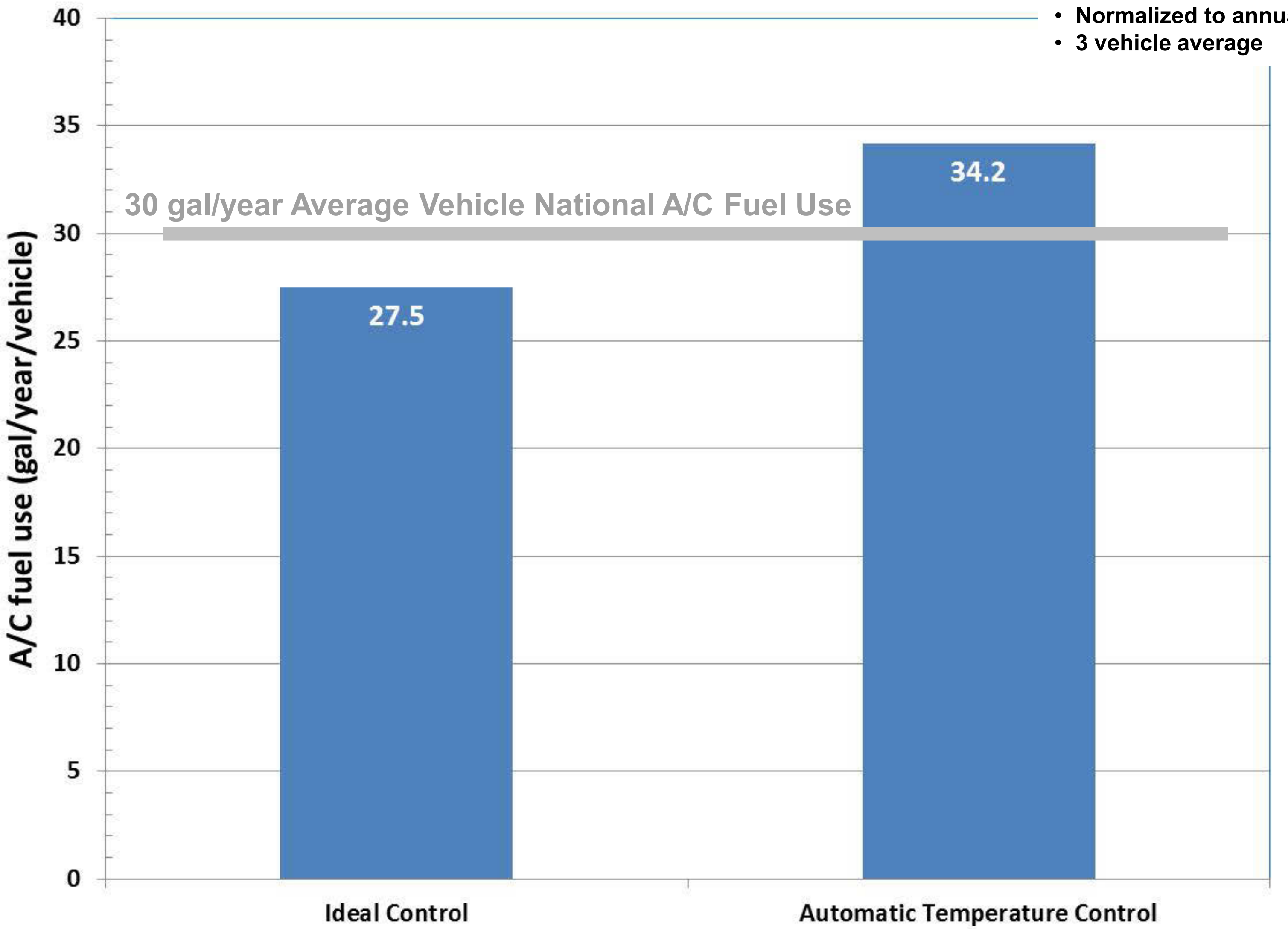
Equivalent to 65% reflectance in Infrared

Key A/C Assumptions

- **~ MY2010 A/C system modeled to be comparable to IMAC and EPA**
  - Fixed displacement compressor
  - Midsized sedan
- **A/C control**
  - Ideal – A/C capacity exactly matches thermal load of the cabin
  - Automatic Temperature Control (ATC) - A/C capacity set at a high level: air is overcool and then reheated with waste engine heat
- **A/C control split: 62% ideal, 38% ATC**
- **A/C operation for dehumidification at temperatures below cabin setpoint was not modeled**
- **Recirculation: ramp up to 50% between 35°C and 45°C at ambient temperatures**
- **Cabin setpoint 20°C**
- **A/C capacity capped at**
  - Compact 7 kW
  - Midsized 8 kW
  - SUV 9 kW
- **Vehicle orientation – west**
  - Thermal load in west direction ≈ 4 direction average cooling & heating load for three representative cities.

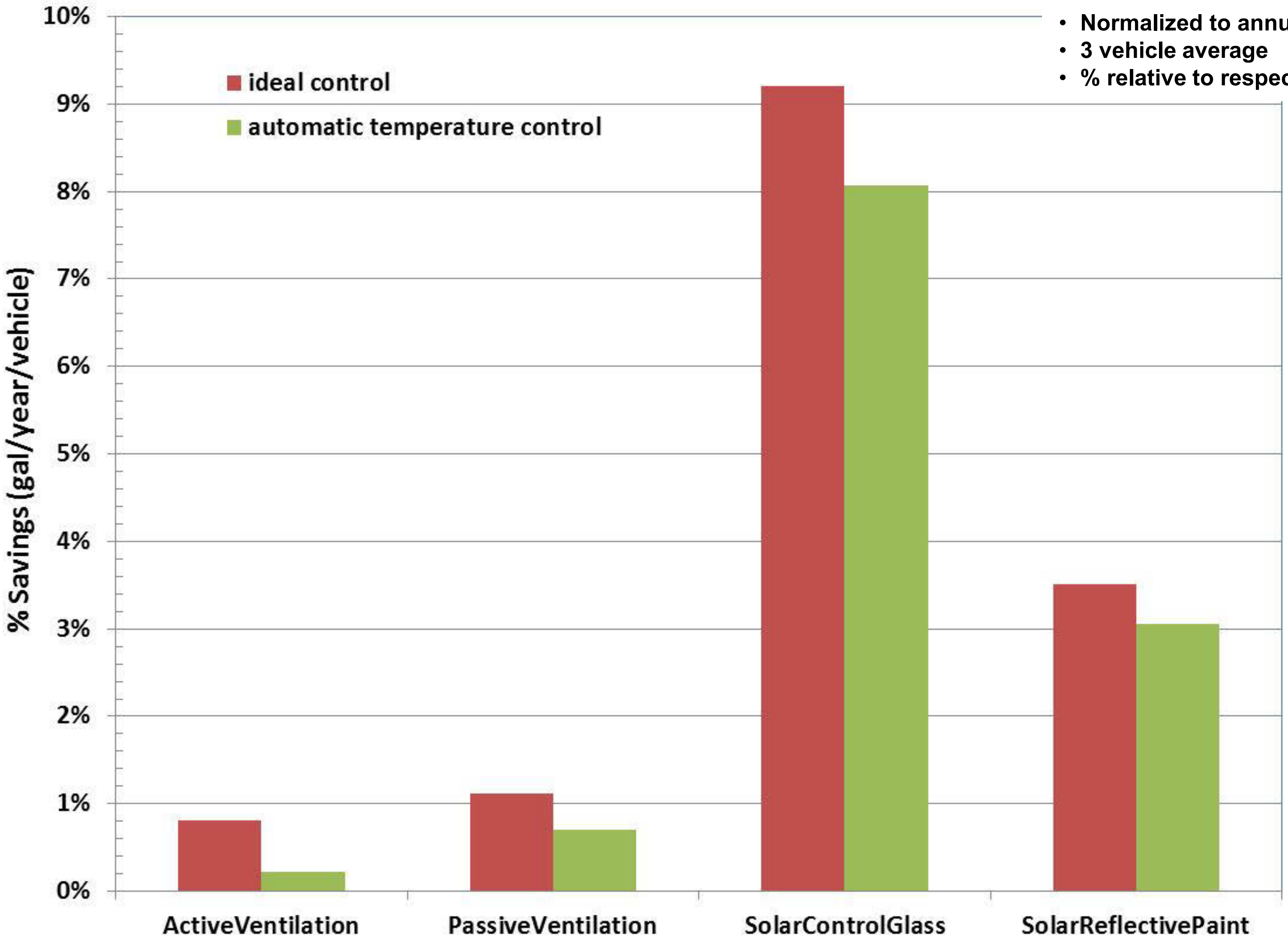
Impact of A/C Control Strategy – Baseline A/C Fuel Use

- Normalized to annual VMT
- 3 vehicle average



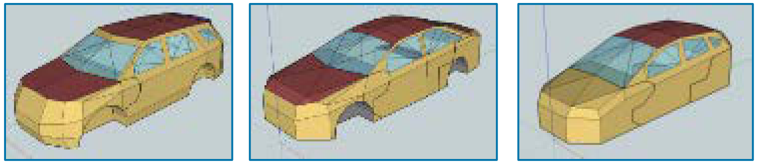
Impact of A/C Control Strategy – % Savings: A/C Fuel Use

- Normalized to annual VMT
- 3 vehicle average
- % relative to respective baseline



Full Factorial Simulations

Three Representative Vehicle Platforms



Five Vehicle Configurations

Baseline Vehicle and Modified Vehicle

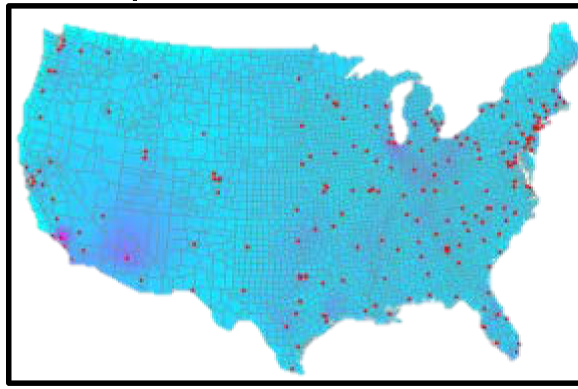
Three Representative Drive Durations

Time Range (min)	[0 – 15)	[15 – 30)	30 +
Average Time (min)	7.2	18.4	49.4
Weighting Factor	0.508	0.31	0.182

Two Representative Soak Conditions

Time Range (min)	[0 – 50)	[50 – end]
Average Time (min)	17.0	232 (~4 hr)
Weighting Factor	0.5	0.5

206 Representative Locations



Three Representative Drive Start Times

Time Range	[0:00 – 9:00)	[9:00 – 16:00)	[16:00 – 24:00)
Average Time	7:06	12:35	18:26
Weight Factor	18.3%	47.6%	34.1%

3 vehicles * 2 configurations * 3 durations * 2 soaks * 3 start times * 206 locations = 55,620 annual CoolCalc simulations at 1 minute timestep

Three Representative Drive Durations

Three Representative Vehicle Platforms

Five Vehicle Configurations

Baseline Vehicle and Modified Vehicle

Three Representative Drive Durations

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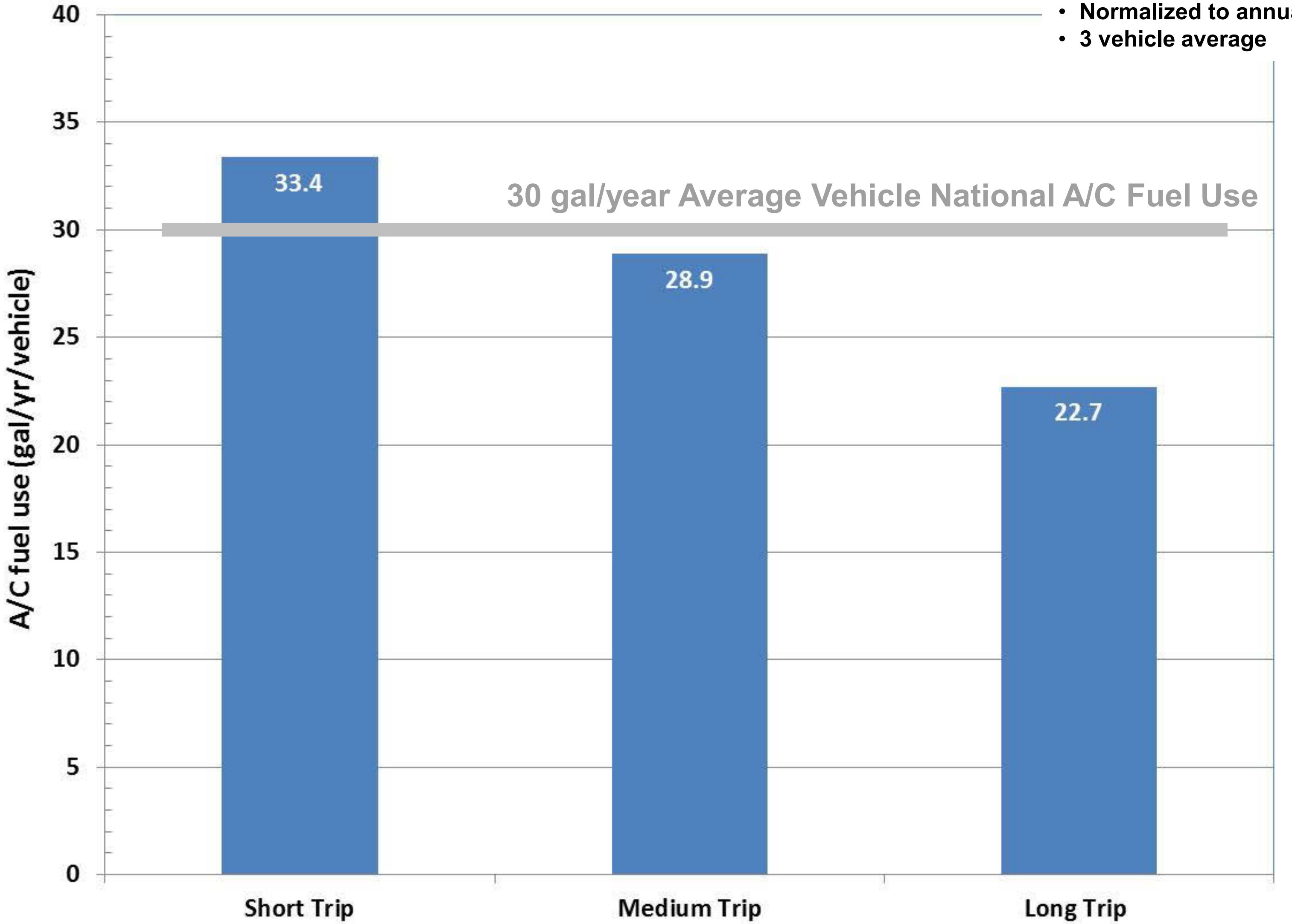
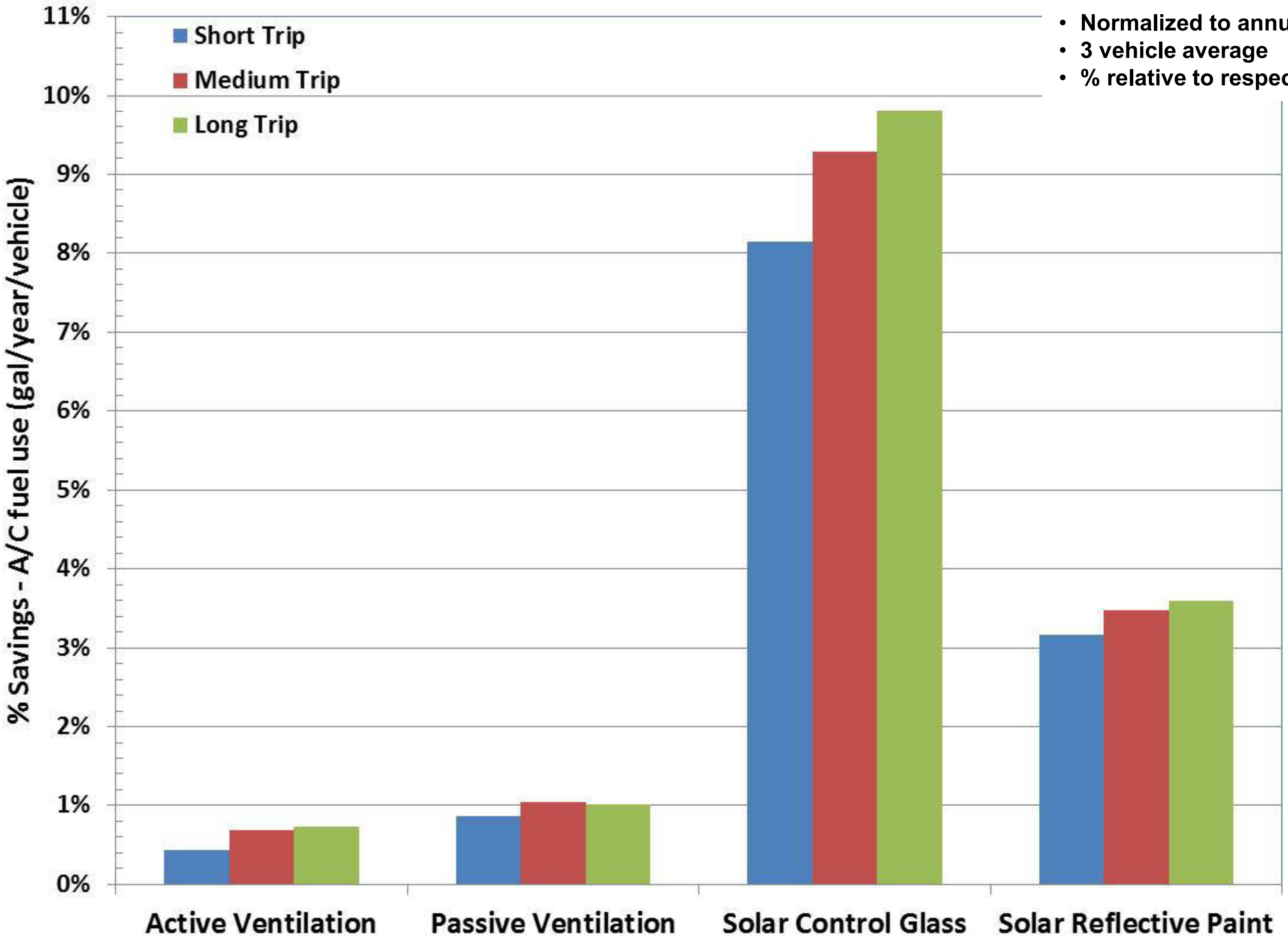
3 vehicles * 2 configurations * 3 durations * 2 soaks * 3 start times * 206 locations
= 55,620 annual CoolCalc simulations at 1 minute timestep

Three Drive Durations – Baseline A/C Fuel Use

- Normalized to annual VMT
- 3 vehicle average



Three Drive Durations – % Savings: A/C Fuel Use



- Normalized to annual VMT
- 3 vehicle average
- % relative to respective baseline

Two Representative Soak Conditions

Three Representative Vehicle Platforms

Three Representative Drive Durations

Time Range (min)	[0 – 15)	[15 – 30)	30 +
Average Time (min)	7.2	18.4	49.4
Weighting Factor	0.508	0.31	0.182

Three Representative Drive Start Times

Time Range	[0:00 – 9:00)	[9:00 – 16:00)	[16:00 – 24:00)
Average Time	7:06	12:35	18:26
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Five Vehicle Configurations

Baseline Vehicle and Modified Vehicle

Two Representative Soak Conditions

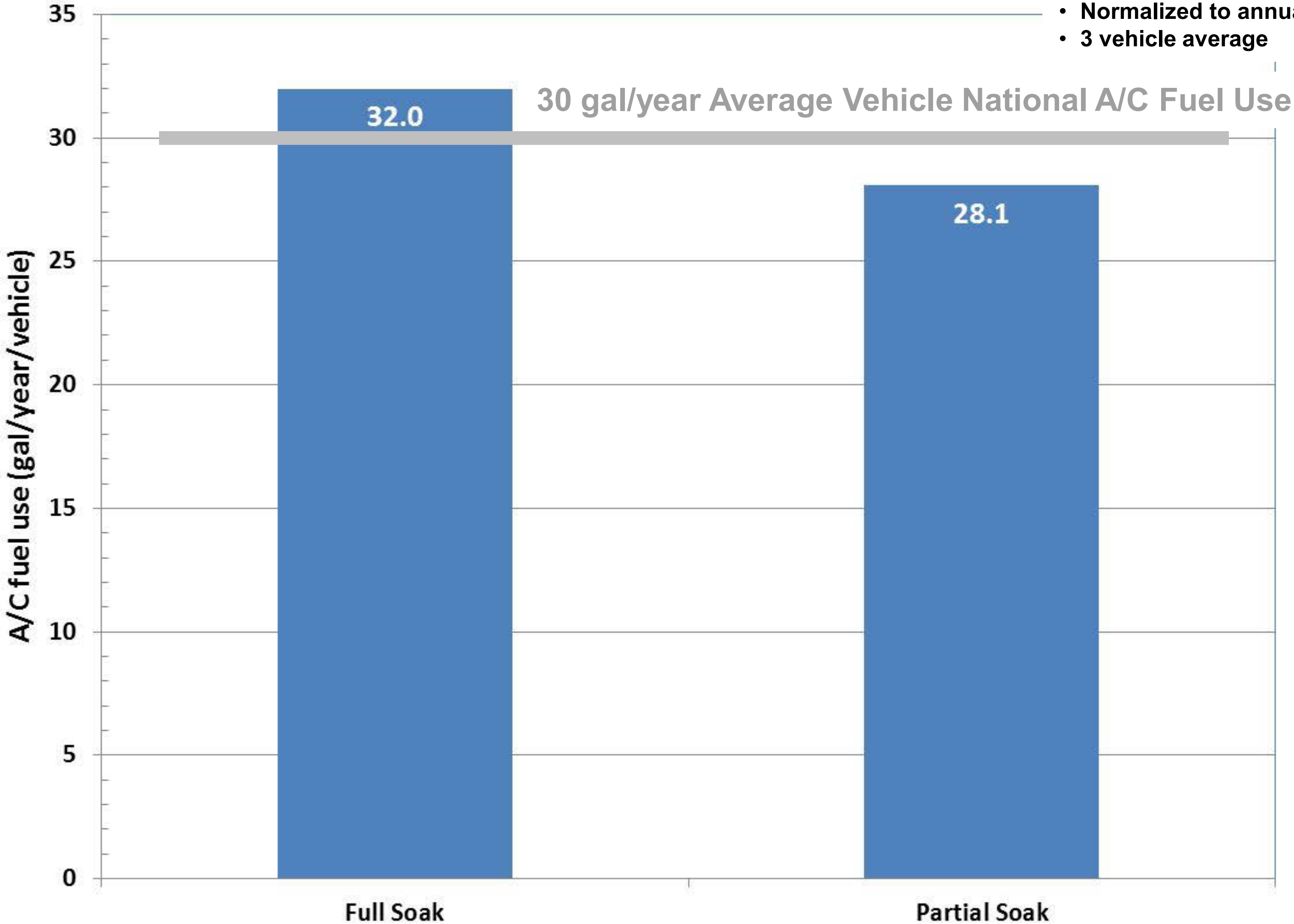
Time Range (min)	[0 – 50)	[50 – end]
Average Time (min)	17.0	232 (~4 hr)
Weighting Factor	0.5	0.5

206 Representative Locations

3 vehicles * 2 configurations * 3 durations * 2 soaks * 3 start times * 206 locations = 55,620 annual CoolCalc simulations at 1 minute timestep

Two Soak Conditions – Baseline A/C Fuel Use

- Normalized to annual VMT
- 3 vehicle average



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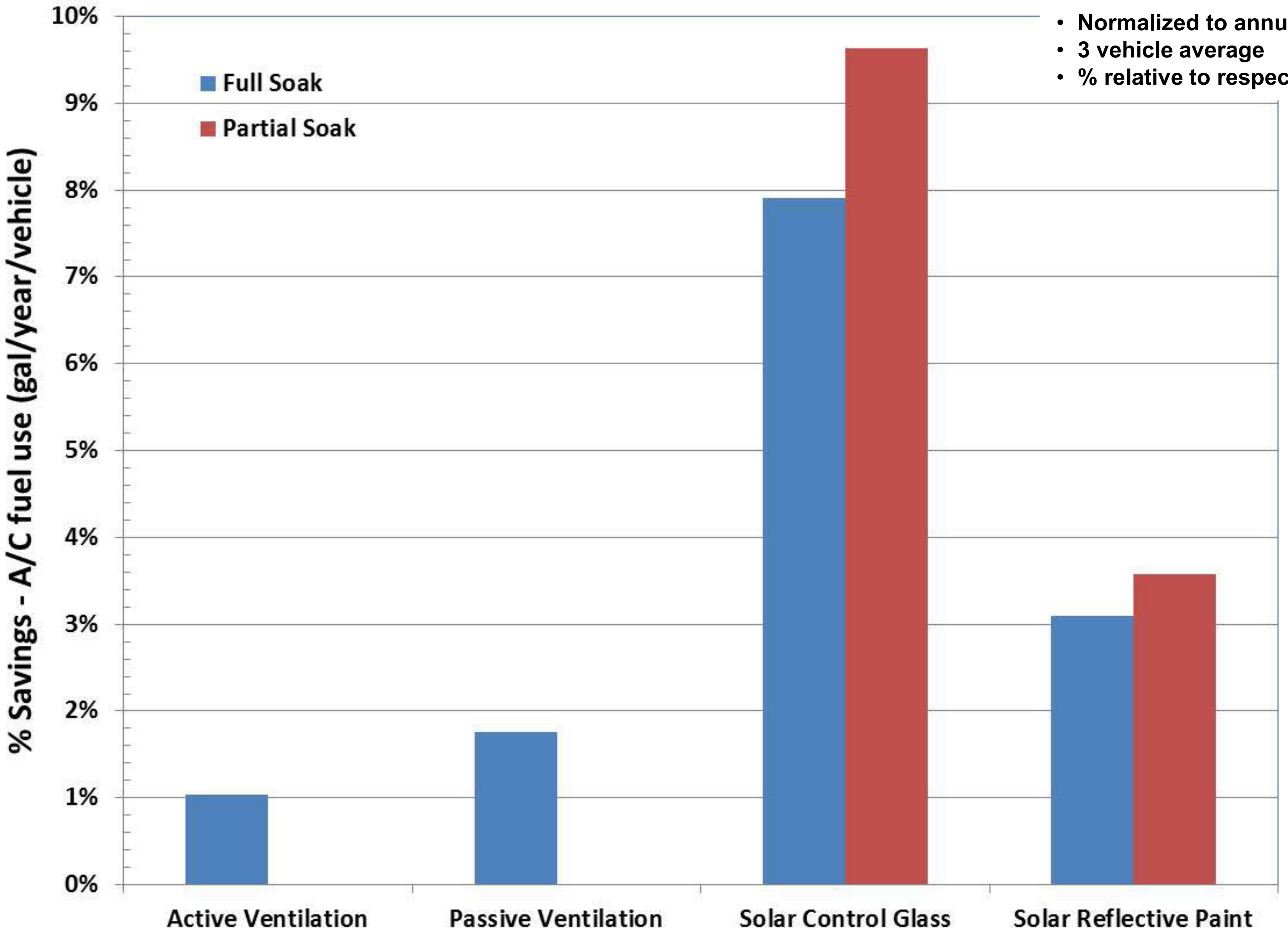

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Three Drive Start Times – Baseline A/C Fuel Use

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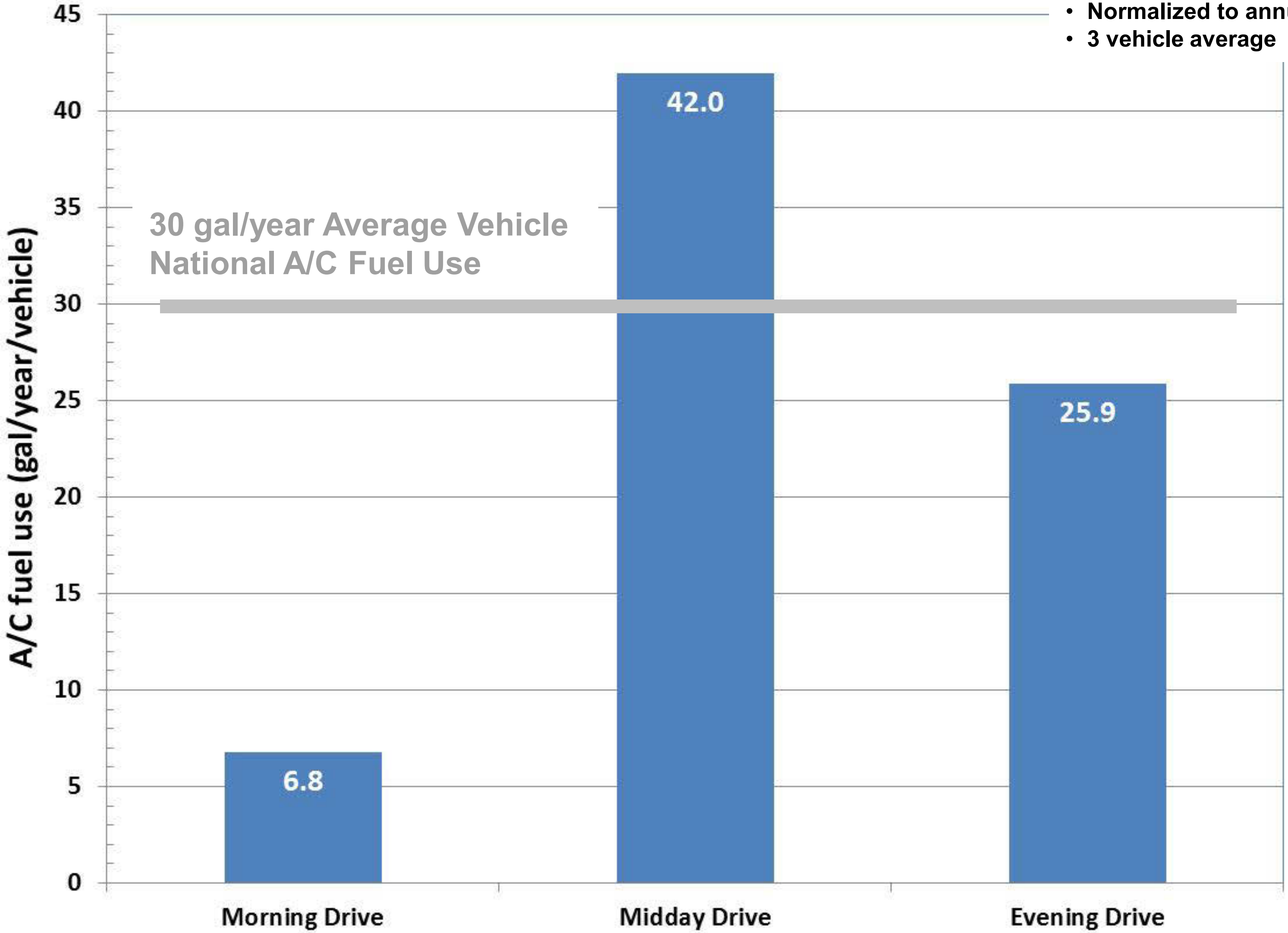
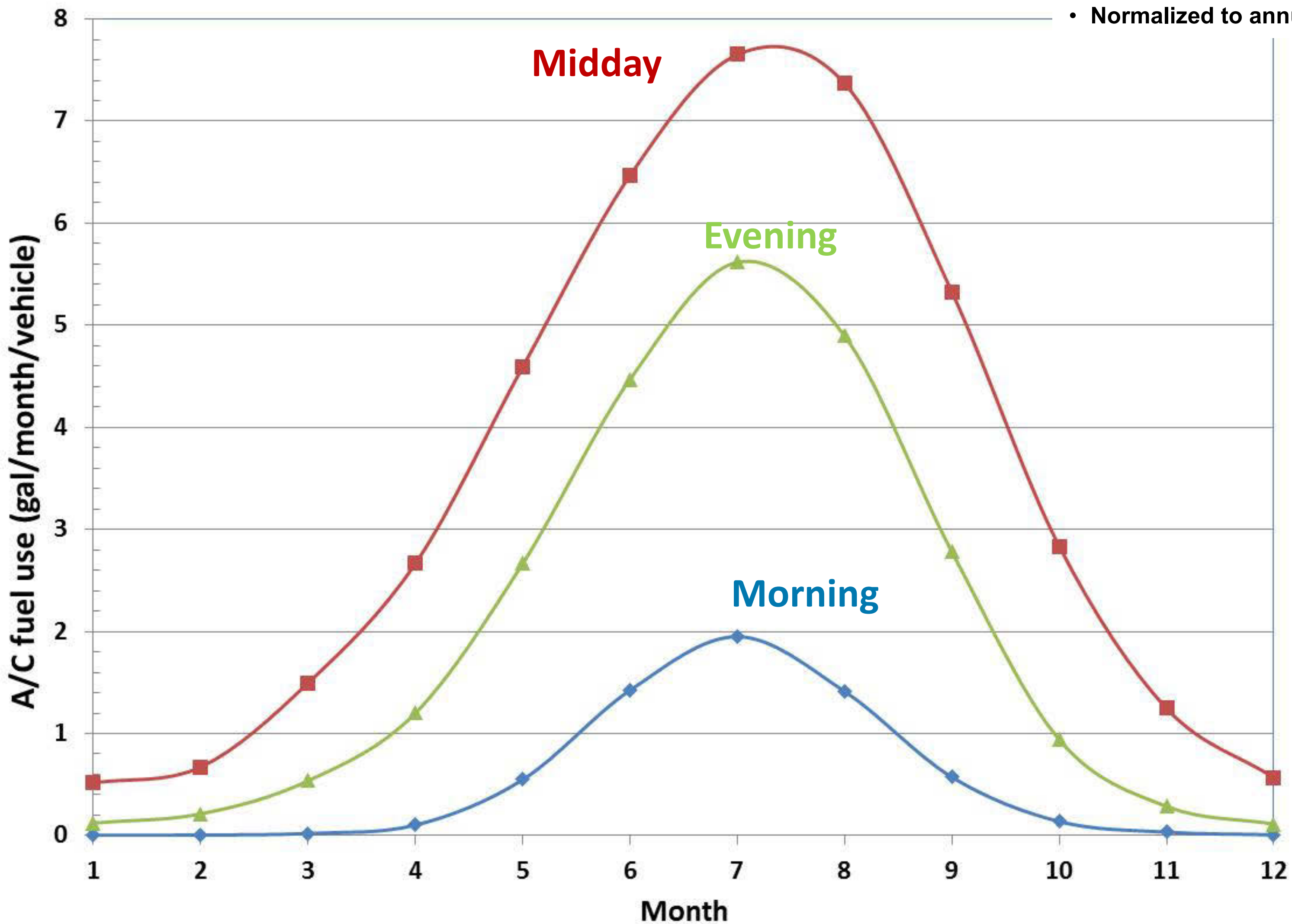


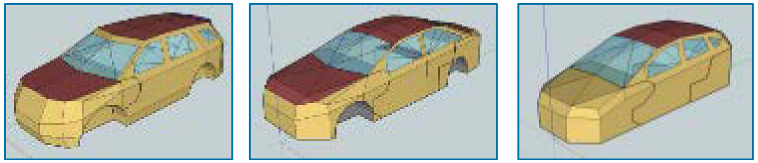
Three Drive Start Times – Midsized Vehicle: Monthly Baseline A/C Fuel Use

- Normalized to annual VMT



Three Representative Vehicle Platforms

Three Representative Vehicle Platforms



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Baseline Vehicle and Modified Vehicle

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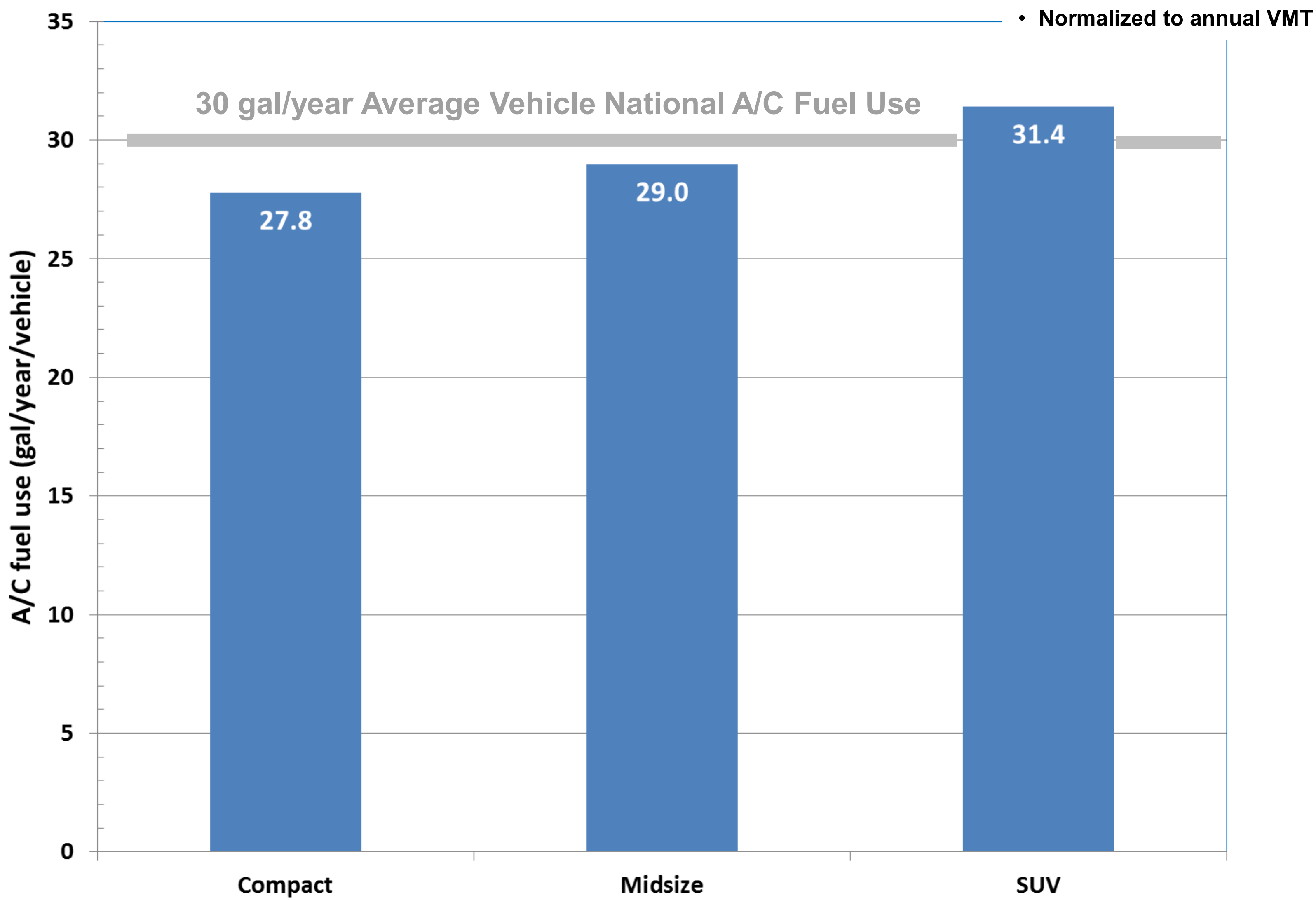
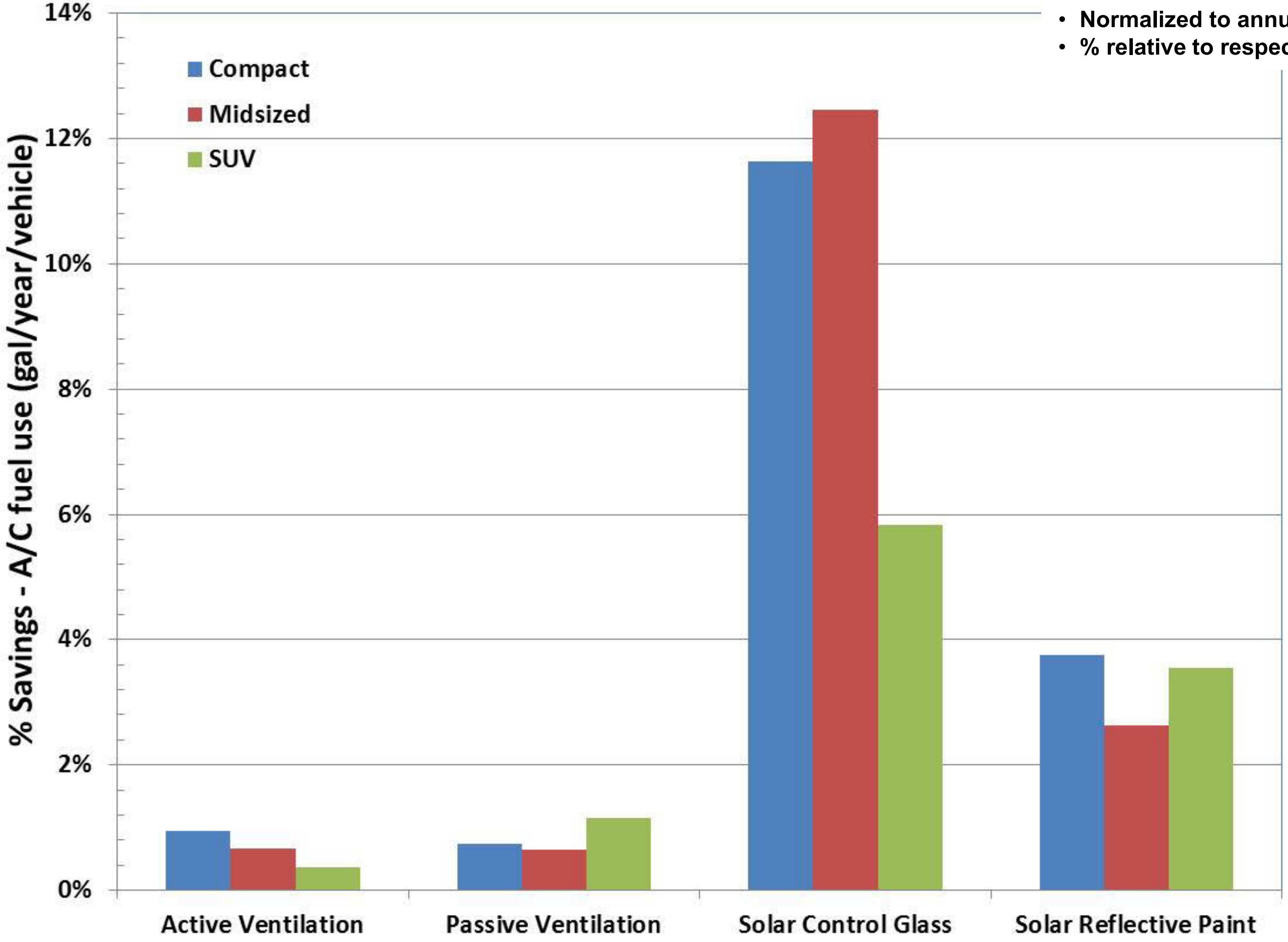
Three Vehicle Platforms – Baseline A/C Fuel Use



Three Vehicle Platforms – % Savings: A/C Fuel Use

- Normalized to annual VMT
- % relative to respective baseline



Discussion of Passive and Active Ventilation Results

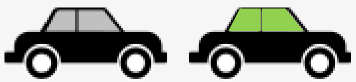
- **Impact of parked car ventilation is lower relative to solar reflective glass/paint technologies and the respective off-cycle credits**
  - Partial soak – 50% of time parked car ventilation is not used
  - Definition of strategy and impact on interior mass temperature
    - Passive – continuous low air flow
    - Active – Just in time (15 minutes prior to drive)
- **Passive ventilation is more effective than active ventilation for the SUV**
  - The difference is small
  - A long-duration low flowrate may remove more heat from the interior mass than a short-duration high flowrate
  - Impact is a function of ventilation strategy employed

Five Vehicle Configurations

Three Representative Vehicle Platforms

Five Vehicle Configurations

Baseline Vehicle and Modified Vehicle



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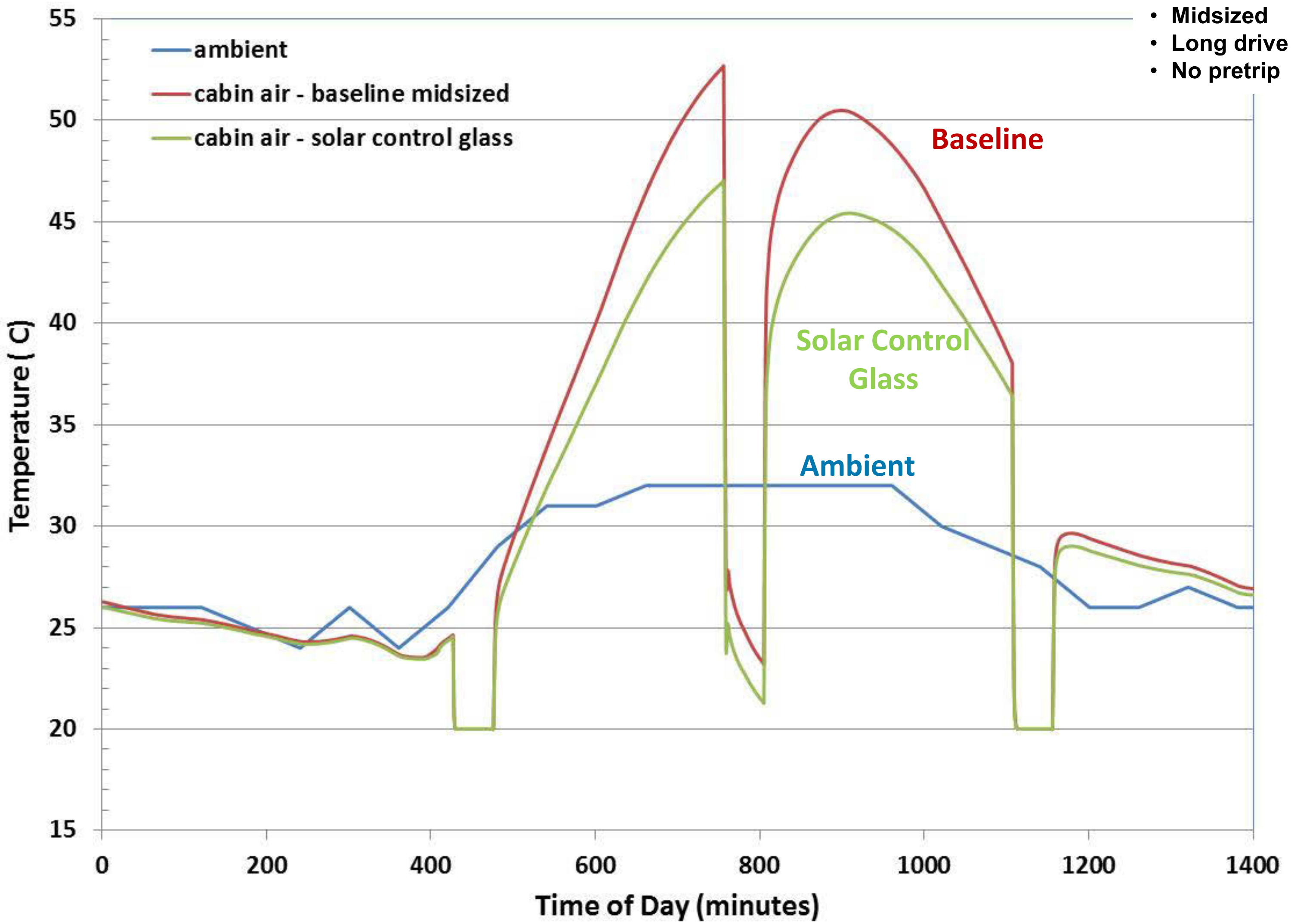
Cabin Air and Ambient Temperature – Miami, September 2
Solar Control Glass & Baseline



- Midsized
- Long drive
- No pretrip

Three Representative Vehicle Platforms

Five Vehicle Configurations

Three Representative Drive Durations

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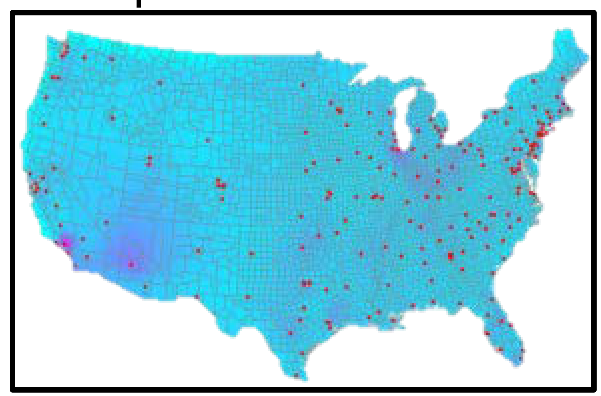

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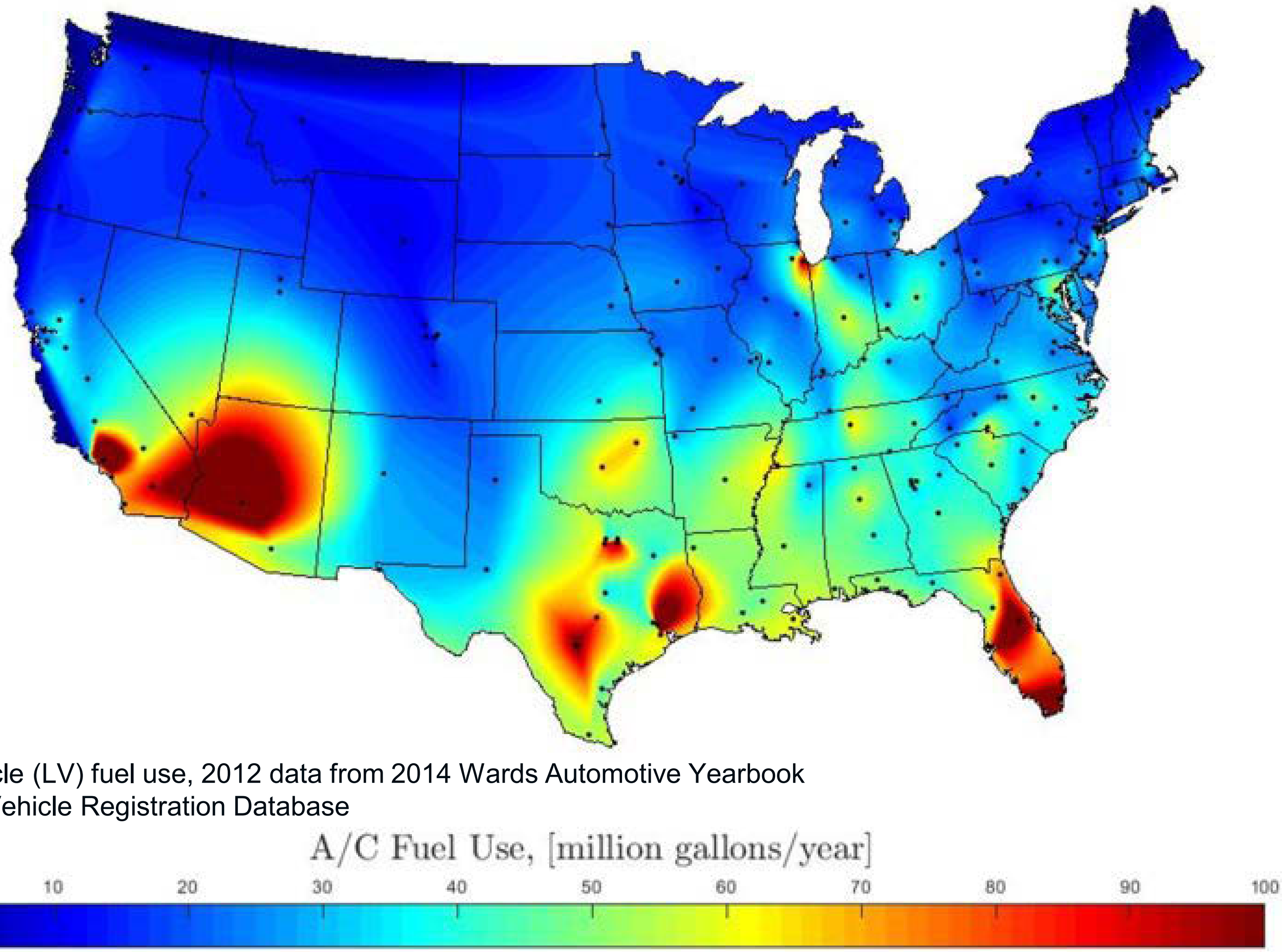
National Level A/C Fuel Use Analysis Results

National Baseline A/C Fuel Use: Vehicle Platform Weighted Average

National A/C Fuel Use [gal/year]	
Baseline	7.6 billion

5.7 % of Total U.S LV Fuel Use*



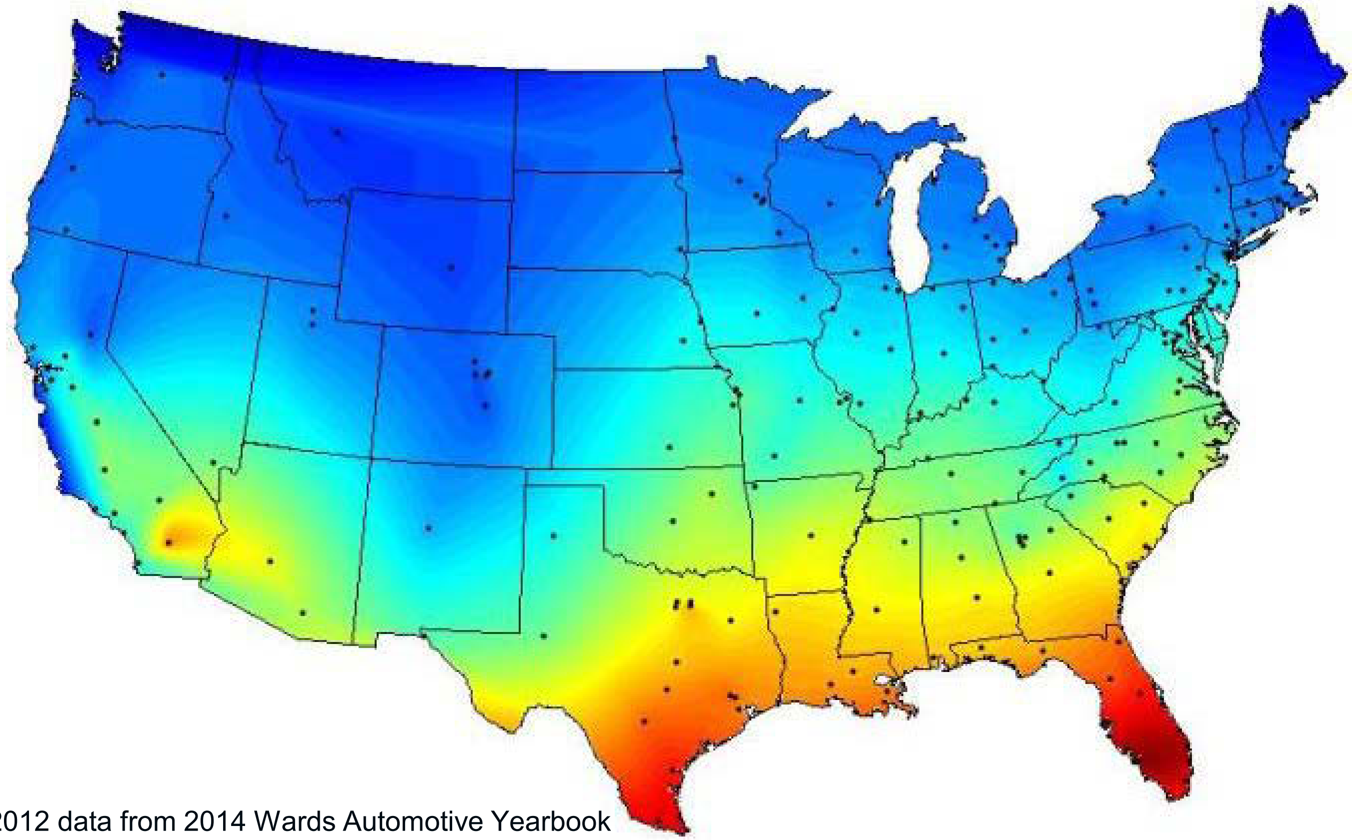
* 213.6 billion gallons total light vehicle (LV) fuel use, 2012 data from 2014 Wards Automotive Yearbook
252.7 million vehicles, 2014 Polk Vehicle Registration Database

National Level A/C Fuel Use Analysis Results

National Baseline A/C Fuel Use Per Vehicle: Vehicle Platform Weighted

National A/C Fuel Use [gal/year]	
Baseline	7.6 billion

30.0 gal/year National Average



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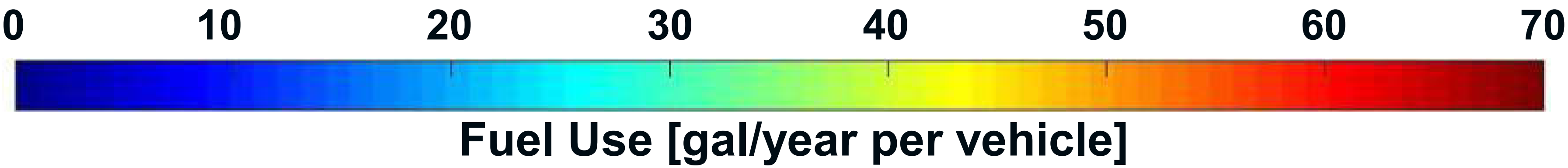

Comparison to Previous Work

	Fuel Use (gal/yr)	CO2 emissions (g/mi)
NREL 2016	30.0	23.5
NREL 2004	30.8	
EPA car		13.8
EPA truck		17.0
NREL 2016 Phoenix	42.2	33.1
LCCP Phoenix (2009)		38.7

Fuel Use – Impact of Solar/Thermal Technologies

	Reductions Due to Solar/Thermal Control Technologies		
Solar/Thermal Control Technology	**U.S. Light-Duty Fleet Savings [Gal/year] ***	**Average Vehicle Savings [Gal/year]**	**Average Vehicle National A/C Fuel Use (gal/year/vehicle)**
Baseline	N/A	N/A	30.0
Active Ventilation	42.2 million	0.17	29.9
Passive Ventilation	71.3 million	0.28	29.7
Solar Control Glass	661 million	2.62	27.4
Solar Reflective Paint	180 million	1.00	29.0

* Based on U.S. light-duty vehicle fleet size of 252,714,871 vehicles [10], individual vehicles traveling 11346 miles/year [18]

CO_2 g/mi – Impact of Solar/Thermal Technologies

Vehicle Configuration	Individual Vehicle A/C CO_2 Emissions * [g/mi]	Individual Vehicle Savings [g/mi]	EPA Car - Baseline Emissions due to A/C and Credit [g/mi]	EPA truck- Baseline Emissions due to A/C and Credit [g/mi]
National Baseline Vehicle	23.5		13.8	17.2
Active Ventilation	23.4	0.1	2.1	2.8
Passive Ventilation	23.3	0.2	1.7	2.3
Solar Control Glass	21.5	2.0	Up to 2.9	Up to 3.9
Solar Reflective Paint	22.7	0.8	0.4	0.5
* Based on 8887 grams of CO_2 per gallon of gasoline [19]				

Summary

- **NREL developed a rigorous national-level A/C fuel use analysis process**
- **A/C fuel use and GHG emissions results compared well to previous NREL and LCCP results**
- **Four thermal load reduction technologies from the solar/thermal off-cycle credit menu were assessed**
  - Solar reflective glazing and paint had a reasonable comparison to the off-cycle credits
  - Active and passive parked car ventilation were lower than the off-cycle credits

- **Next steps**
  - Journal article
  - DOE approval
  - Industry review
  - Potentially refine analysis

Acknowledgements and Contacts

Special thanks to:

David Anderson
Lee Slezak
Vehicle Technologies Office

For more information:

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National Renewable Energy Laboratory
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Team Members:

Jason Lustbader, Jeff Tomerlin
Cory Kreutzer, Gene Titov

Photo Credits

Slide 3

- Windshield and road: John Rugh, NREL
- Exhaust pipe: John Rugh, NREL

Slide 5 & 15

- Red vehicle: Cory Kreutzer, NREL
- Blue vehicle: Matthew Jeffers, NREL
- Black vehicle: John Rugh, NREL

Slide 8

- Dennis Schroeder, NREL image gallery # 35357

Slide 50 (acknowledgements)

- Cory Kreutzer, NREL