Alternative Refrigerant Demonstration Vehicles

DELPHI

SAE Alternate Refrigerant Systems Symposium

July 17, 2007

Alternate Refrigerants

Agenda

- Introduction
- Scope and Objectives
- Testing Protocol
- Secondary Loop R-152a Vehicle
- Global Alternate Refrigerant (GAR) Vehicles
- Fuel Consumption
- Summary / Conclusions

Alternate Refrigerants

Presenters

- James Baker – Delphi
- Mahmoud Ghodbane – Delphi
- John Rugh – National Renewable Energy Laboratory (NREL)
- William Hill – General Motors

Alternate Refrigerants

Program Scope

- Assess The Applicability Of Select Alternative Refrigerants With Respect To Cooling And Energy Performance

- Refrigerants Evaluated
  - R-134a Baseline
  - DuPont (DP-1)*
  - Ineos Fluor (AC-1)*
  - R-152a*

* Hereafter referred to as GAR Refrigerants

Alternate Refrigerants

Objective

- Replace R-134a in current MAC systems with selected refrigerants and demonstrate equivalent cooling and energy performance with minimum component changes
- It is recognized that additional improvements in cooling and energy performance beyond the R-134a baseline may be possible and would be the subject of future activities

Alternate Refrigerants

Cooperative Efforts

Delphi

- Designed & Built All Refrigerant Systems
- Engineered Refrigerant Controls for Each System
- Vehicle Wind Tunnel Tested Cooling & Energy Performance
- Collaborated with NREL for Secondary Loop Fuel Use Analysis

General Motors

- Provided Vehicles For All Testing
- Collaborated With Delphi On A/C System Architectures
- Road Tested Vehicle Cooling Performance for Each Refrigerant
- Measured Fuel Usage Of Each Refrigerant System

US Environmental Protection Agency

- Organized And Sponsored The Secondary Loop R-152a Project

Alternate Refrigerants

Testing & Analysis Protocol

A) Vehicle Testing in Climatic Wind Tunnel

- **Soak & Cool-down, Stable Points, and Extended Idles at 40°C x 40% R.H.**
  - **Cooling Performance**
    - ✓ Average cabin temperature
    - ✓ Average A/C vent temperature
  - **Thermal COP comparison to R-134a baseline at stable points**

Note: Each vehicle served as its own R-134a baseline to limit variation

Alternate Refrigerants

Testing & Analysis Protocol

B) Vehicle Testing in Climatic Wind Tunnel

- City Traffic Schedule at 46 ^{0}C x 15% R.H.
  (Similar to Phoenix conditions)
  - Cooling Performance
    - ✓ Average cabin temperature
    - ✓ Average A/C vent temperature

C) SC03 & Highway Drive Cycles

- Assess Fuel Usage at Selected Ambients

Note: Each vehicle served as its own R-134a baseline to limit variation

Alternate Refrigerants

Demonstration Vehicles

2007 Opel Astra (Courtesy of General Motors)

- 1.6 Liter Gasoline Engine
- Manual Transmission
- Manual A/C System
- Variable Displacement Compressor
- Thermal Expansion Device (TXV)
- Plate-type Evaporator
- Tube & Center Integral R/D Condenser

Note: Each vehicle served as its own R-134a baseline to limit variation

Alternate Refrigerants

Secondary Loop R-152a Air Conditioning System

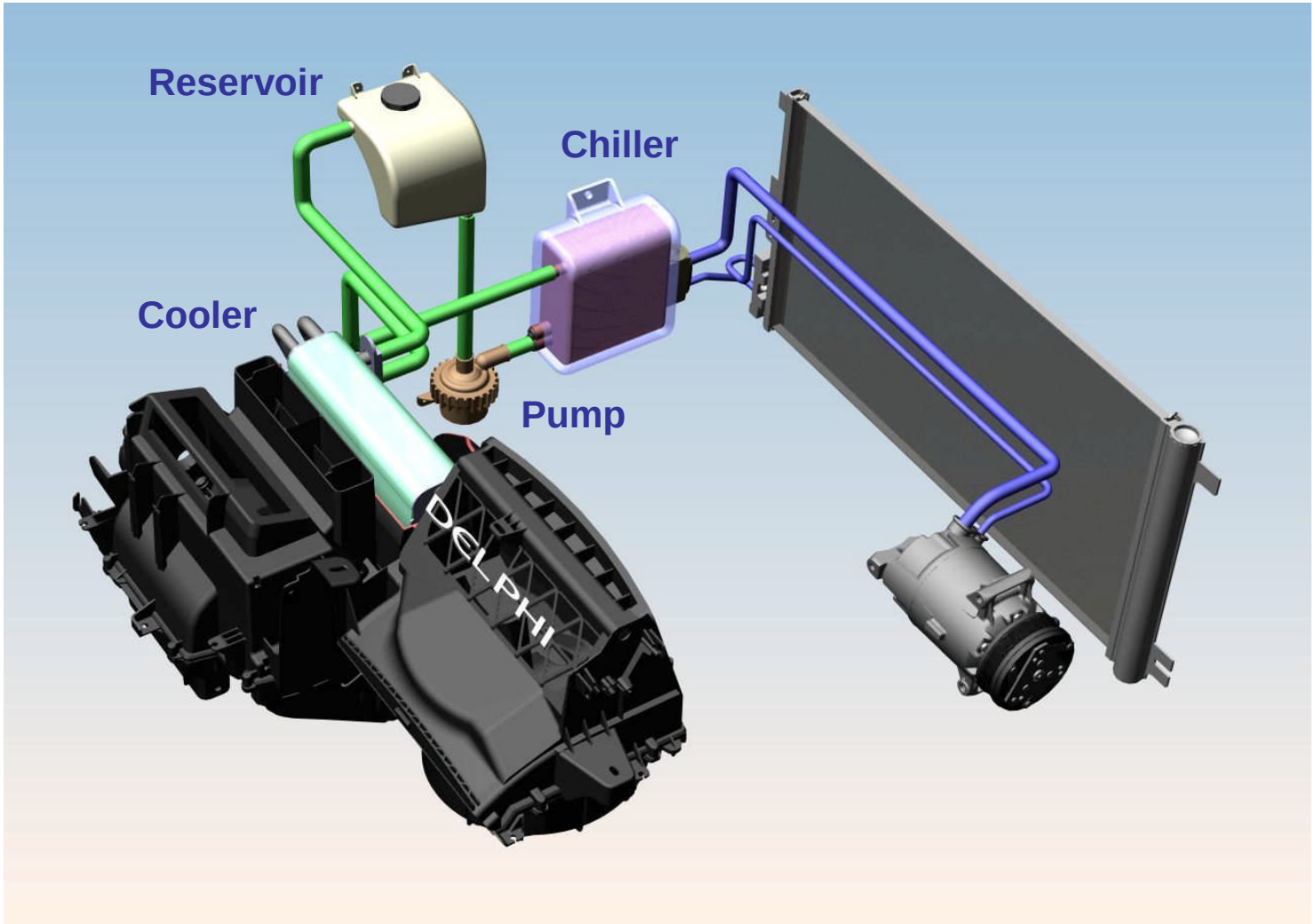
Alternate Refrigerants

Objectives – US EPA Sponsored Program

- **To Build, Test And Demonstrate A Commercially-viable, Energy-efficient, Secondary Loop R-152a Mobile Air Conditioning System.**
  - **Commercially-viable**
    - **No Barriers To Production Readiness For 2011**
  - **Energy-efficient**
    - **At Least Equal Energy Performance To The Current R-134a System With Potential For Improvement**

Alternate Refrigerants

R-152a Secondary Loop System



Alternate Refrigerants

Why Secondary Loop ?

- **Allows safe use of mildly flammable or toxic refrigerants**
- **Requires less refrigerant than a direct expansion system further reducing greenhouse gas emissions potential**
- **Minimizes customer complaints of A/C system noise**
- **Potentially lower cost replacement for dual evaporator systems**
- **Cold storage:**
  - **Allows A/C comfort during idle-stop (e.g. enabling longer off times in mild hybrids)**
  - **Reduces compressor load during accelerations while maintaining comfort for improved drivability and fuel economy**

**** Additional mass, cost, and packaging space are challenges ****

Alternate Refrigerants

R-152a Project “Kick-Off” Meeting

Collaboration Team

- Steve Andersen (EPA)
- Kristen Taddonio (EPA)
- Ward Atkinson (SAE)
- Harry Eustice (GM)
- Bill Hill (GM)
- Steve Lepper (Ford)
- Hans Fernqvist (Volvo)
- Roberto Montforte (Fiat)
- Stefano Mola (CRF)
- John Rugh (NREL)
- Jim Baker (Delphi)
- Tim Craig (Delphi)
- Mahmoud Ghodbane (Delphi)

Alternate Refrigerants

Secondary Loop R-152a Project

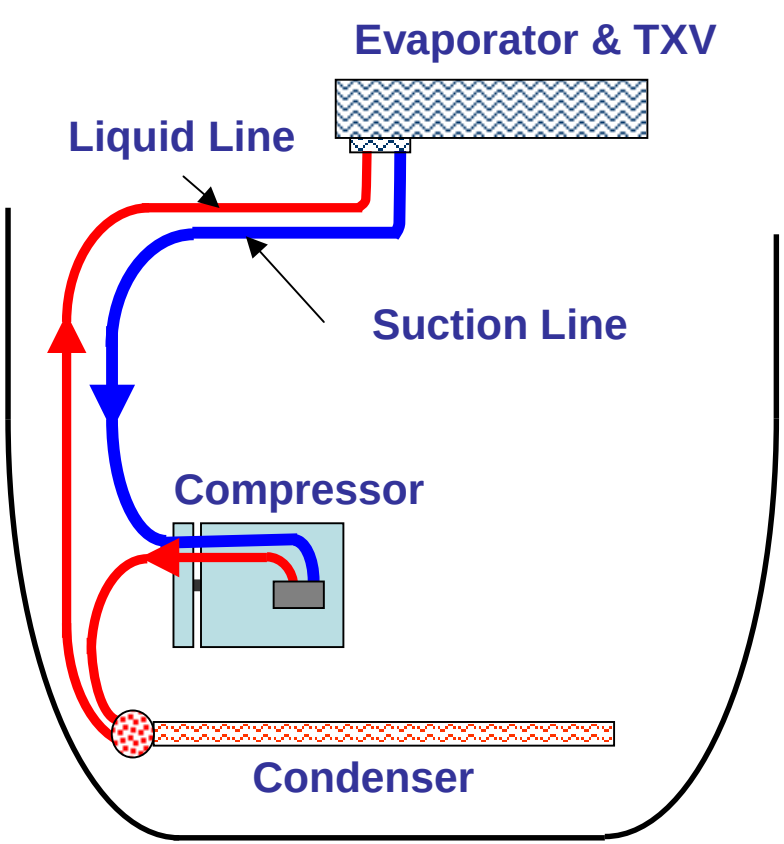
Mahmoud Ghodbane, Ph.D.
Senior Staff Research Scientist
Delphi Thermal Systems

Alternate Refrigerants

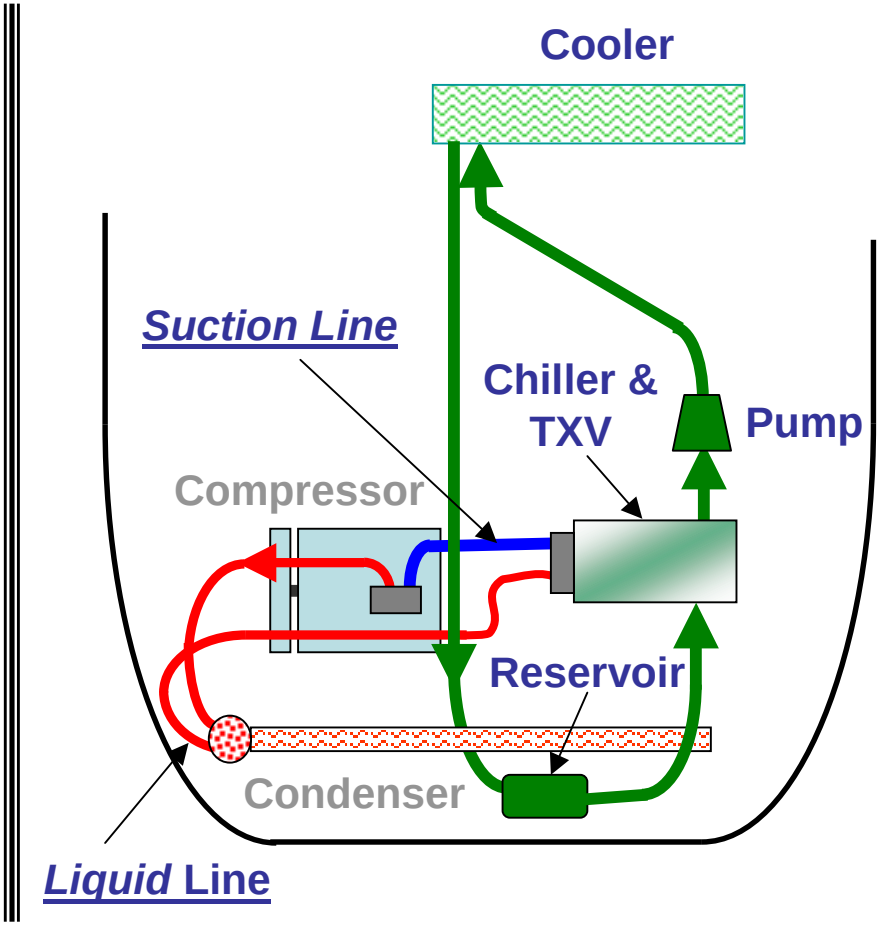
Secondary Loop Layout

R-152a Secondary Loop

Baseline



Secondary Loop



Alternate Refrigerants

System Content

R-152a Secondary Loop

Description	Secondary Loop
Evaporator / Cooler	Tube & Center (Reduced Depth)
Compressor	Increased Displacement
Condenser	Base
Refrigerant Control	TXV Adjustment
Suction Line	Shorter than Base
Refrigerant	40% less charge
Refrigerant Oil	Base PAG
Desiccant	XH-9 Replacing Base XH-7
Fan / Shroud	OEM / Prototype Shroud with Base Fan / Motor
Added Components	Chiller, pump, hoses, & reservoir
Coolant	30 % Glycol Water Mixture
Additional Mass	5.45 kg (12 lbs)

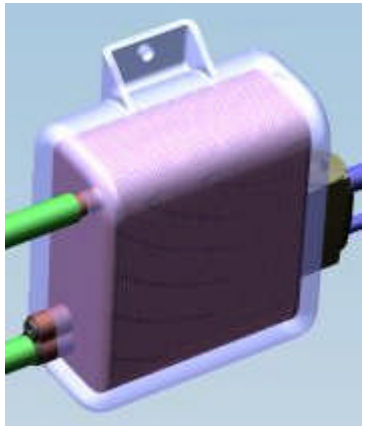
Alternate Refrigerants

System Content

R-152a Secondary Loop

Chiller - Chills the Secondary Fluid with Refrigerant

- Aluminum Construction
- Brazed Plate -Type
- Enhanced Heat Transfer Surfaces
- Currently at Prototype Stage
- Mass *(w / fittings)* = 1.8 kg (4 lbs)
- Existing Technology
- No Barriers to Production



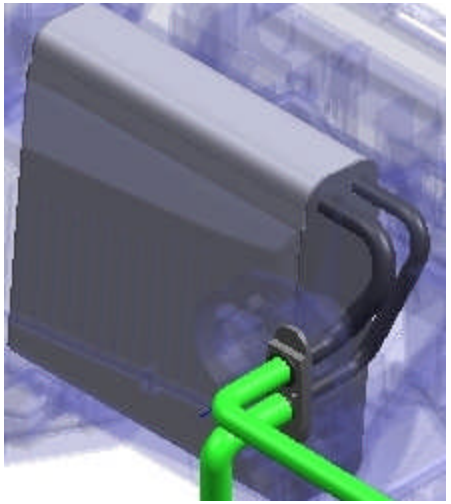
Alternate Refrigerants

System Content

R-152a Secondary Loop

Cooler - Cools Passenger Compartment Air

- Performs Evaporator Function
- Aluminum Construction
- Tube with Water-Shedding Centers
- Enhanced Heat Transfer Surfaces
- Currently at Prototype Stage
- Mass Equivalent to Evaporator
- Existing Technology
- No Barriers to Production



Alternate Refrigerants

System Content

R-152a Secondary Loop

Coolant Pump

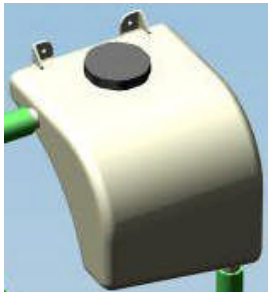
- Brushless, Variable Speed, Centrifugal
- Plastic Housing & Impellers
- Mass = 0.434 kg (0.96 lbs)
- Low Amperage (2 - 4 Amps, depending on load)
  - Most load conditions (Ambient below 38 ^{0}C x 40%R.H.) can be satisfied with (2 Amps)

Alternate Refrigerants

System Content

R-152a Secondary Loop

- **Coolant Reservoir**
  - Volume depends on need for thermal storage
    - Current system volume optimized for equivalent pull down performance and minimum coolant mass

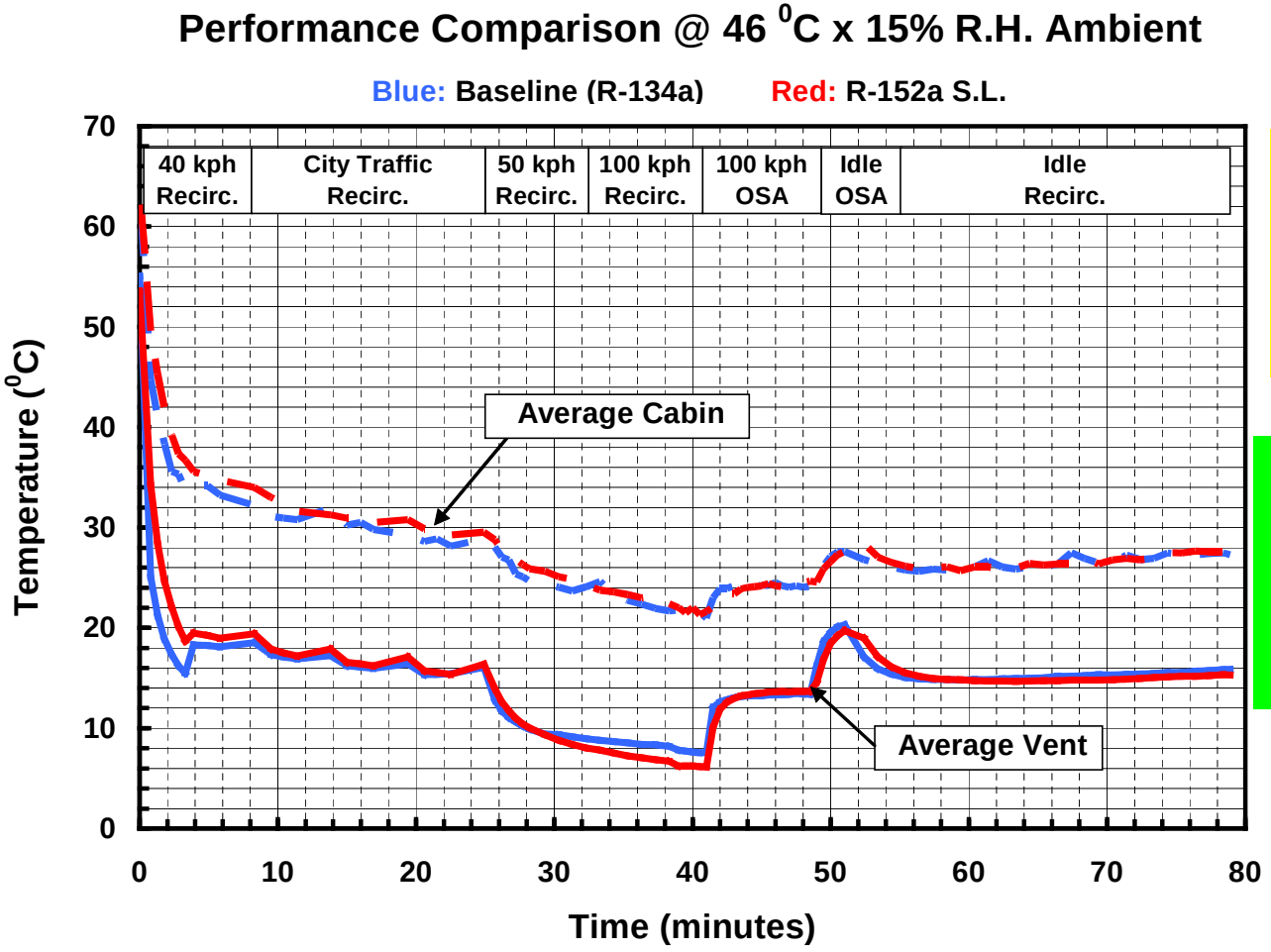


- **Coolant Type & Flow Controls**
  - Coolant is 30% Ethylene Glycol - 70% Water
    - Optimum heat transfer with freeze and burst protection to - 50 ^{0}C
  - Total coolant volume ~ 2.8 l (0.75 gallon); 2.8 kg (6.2 lbs)
  - Capacity Controlled by Coolant Flow Rate to Limit Overcooling

Alternate Refrigerants

Wind Tunnel Cooling Performance

R-152a Secondary Loop



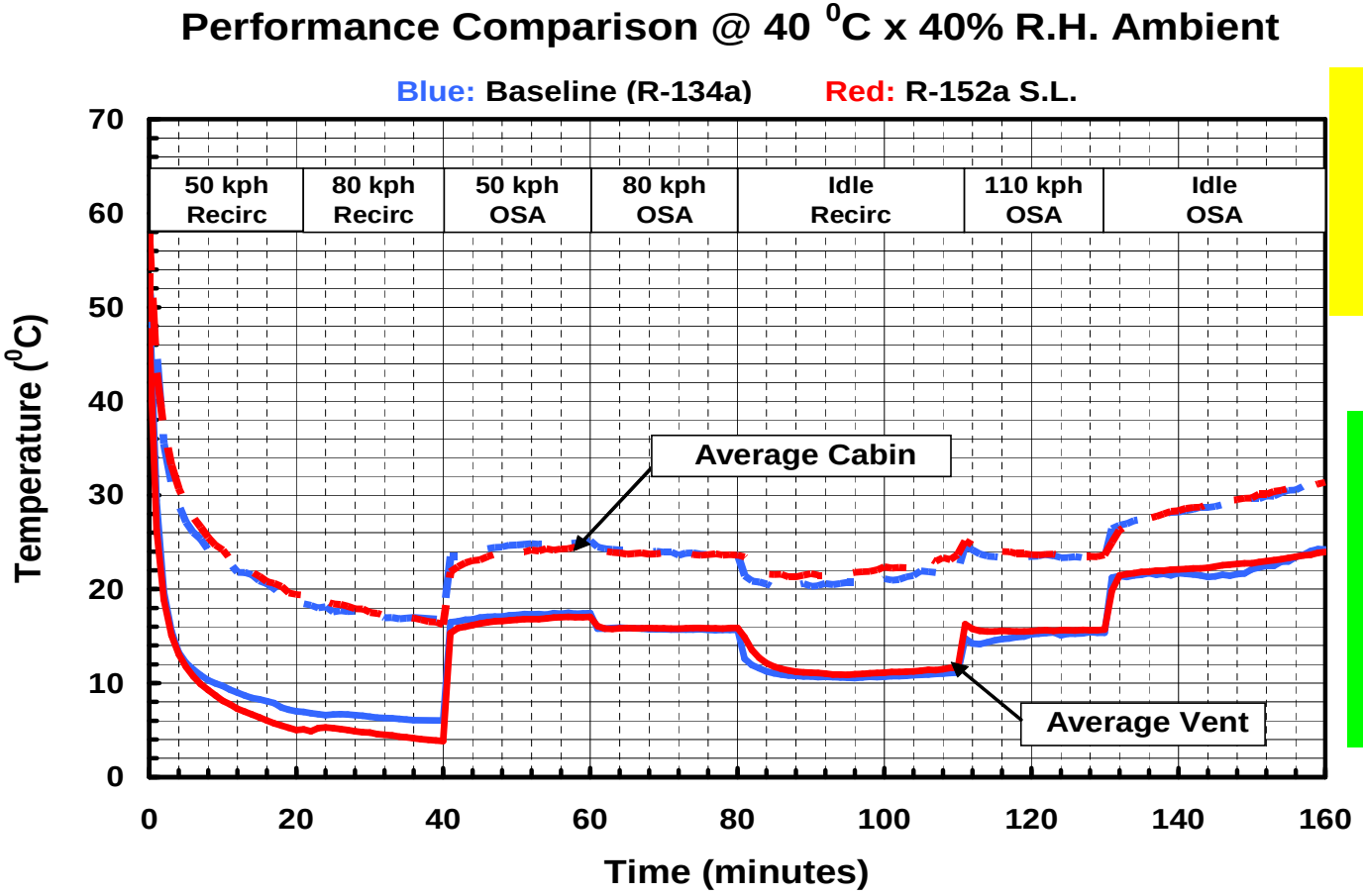
Equivalent Cooling Performance to Baseline

Note: Each vehicle served as its own R-134a baseline to limit variation

Alternate Refrigerants

Wind Tunnel Cooling Performance

R-152a Secondary Loop



Equivalent Cooling Performance to Baseline

Note: Each vehicle served as its own R-134a baseline to limit variation

Alternate Refrigerants

Thermal Coefficient of Performance (COP)

$$COP = \frac{h_{out}\,(\text{Heat Exchanger}) - h_{in}\,(\text{Heat Exchanger})}{h_{out}\,(\text{Compressor}) - h_{in}\,(\text{Compressor})}$$

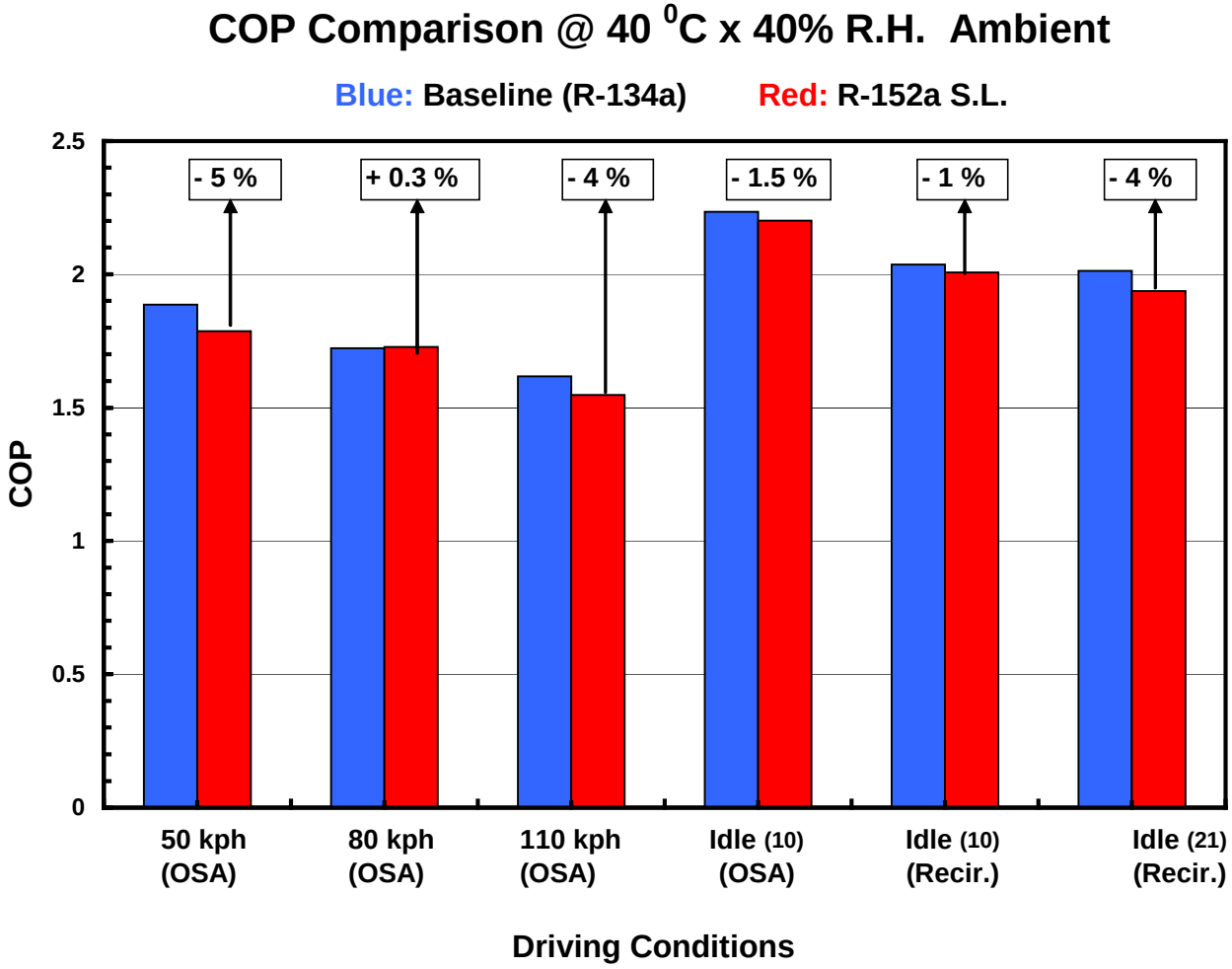
Where

- Heat Exchanger represent the evaporator and chiller for baseline and secondary loop respectively
- h is the refrigerant enthalpy (kJ/kg) calculated at measured inlet and outlet pressure & temperature of each component

Note: Each vehicle served as its own R-134a baseline

Alternate Refrigerants

Thermal Energy Performance R-152a Secondary Loop



On Average

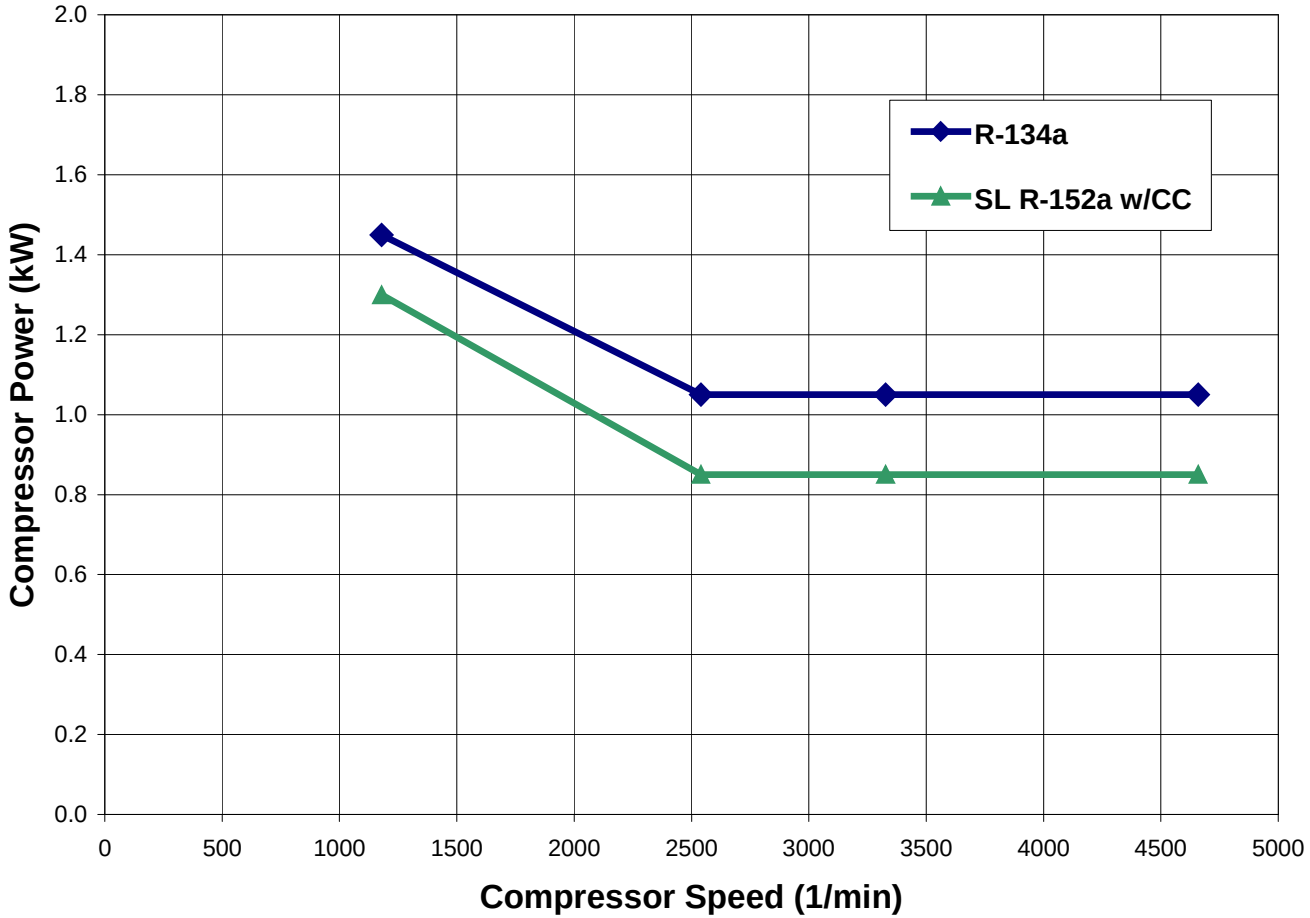
Lower COP (~2.5%) than Baseline

Note: Each vehicle served as its own R-134a baseline to limit variation

Alternate Refrigerants

Vehicle A/C Data – 27 ºC x 60 % RH

Compressor Power vs. Compressor Speed



Alternate Refrigerants

NREL Secondary Loop Fuel Usage Analysis

John Rugh

Senior Engineer

National Renewable Energy Laboratory

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Alternate Refrigerants

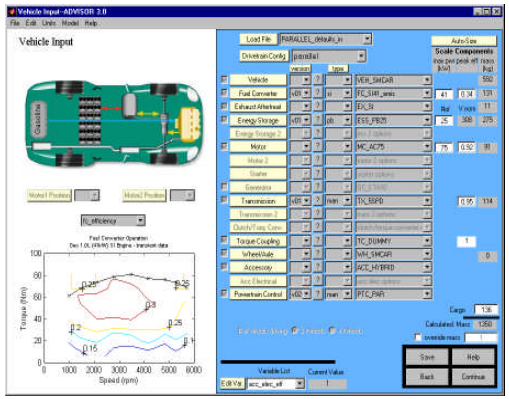
Objective

- **Estimate the A/C fuel use of a baseline R134a and a secondary loop R152a system for various driving cycles**
  - **New European Driving Cycle (NEDC)**
  - **Speed Correction 03 (SC03)**
  - **Highway Fuel Economy Test (HWFET)**

Alternate Refrigerants

Methodology

- **Input Data**
  - **Vehicle and Engine**
  - **A/C systems**
- **Build vehicle model using ADVISOR software**
- **Run vehicle over drive cycles with A/C off/on**
  - **SCO3**
  - **NEDC**
  - **HWFET**



Alternate Refrigerants

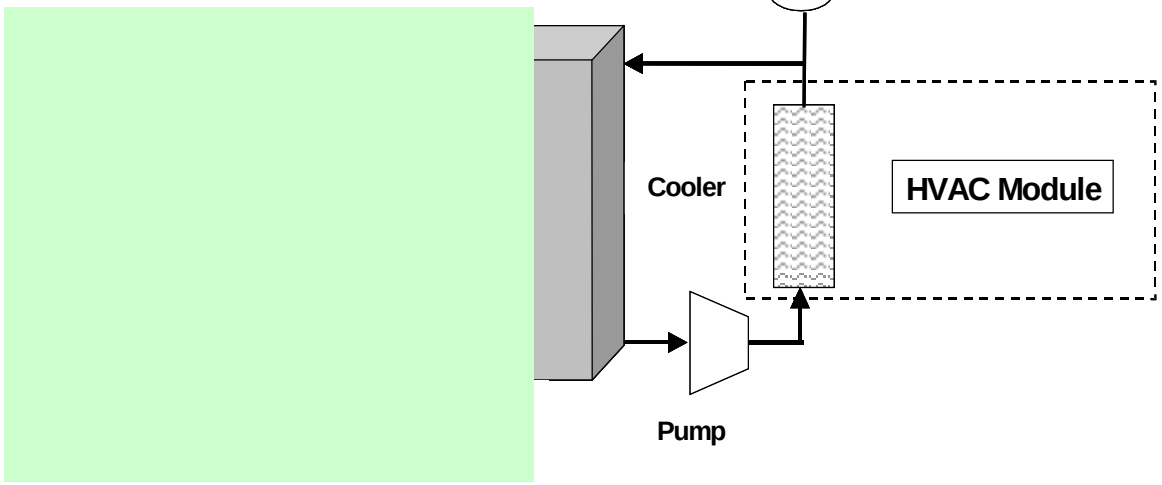
Vehicle Input Data

- Coefficient Of Drag: 0.32
- Frontal Area: 2.11 m^2 (22.7 ft^2)
- Mass:
  - 1263 kg (2784 lbm), A/C Off, R134a
  - 1270 kg (2799 lbm), SL152a
- A/C Off Mechanical Accessory Load = 500 W
- Rolling Resistance Coefficient = 0.009
- Engine – 63 kW 1.9 L Saturn Engine Scaled To 75 kW

Alternate Refrigerants

A/C Data - 27 ºC x 60 % RH (cont.)

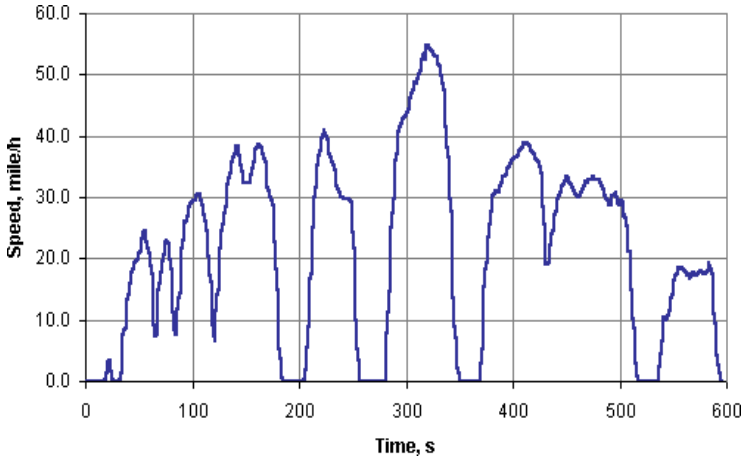
- SL fluid pump = 15 W electrical load included
- Blower power not included
- A/C mode
  - Blower setting 2 (M2, ~ 6V)
  - Outside air
  - Full cold
  - Panel vents



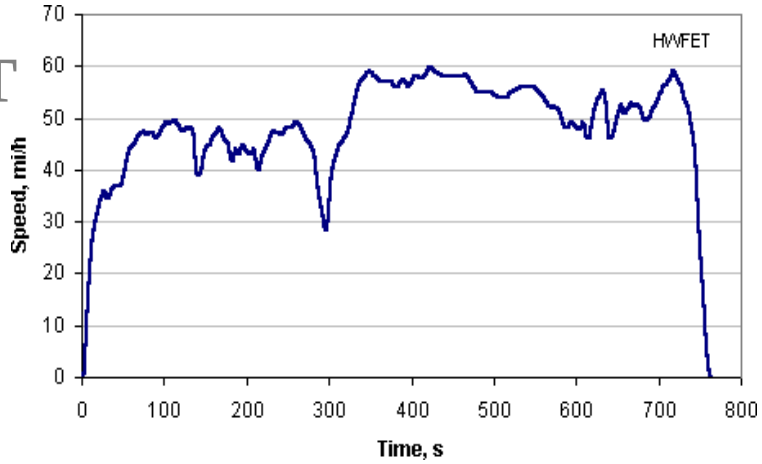
Alternate Refrigerants

Drive Cycles

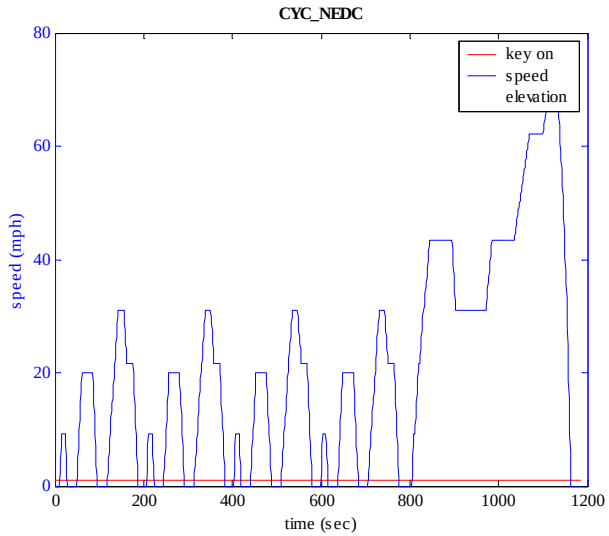
SCO3



HWFET

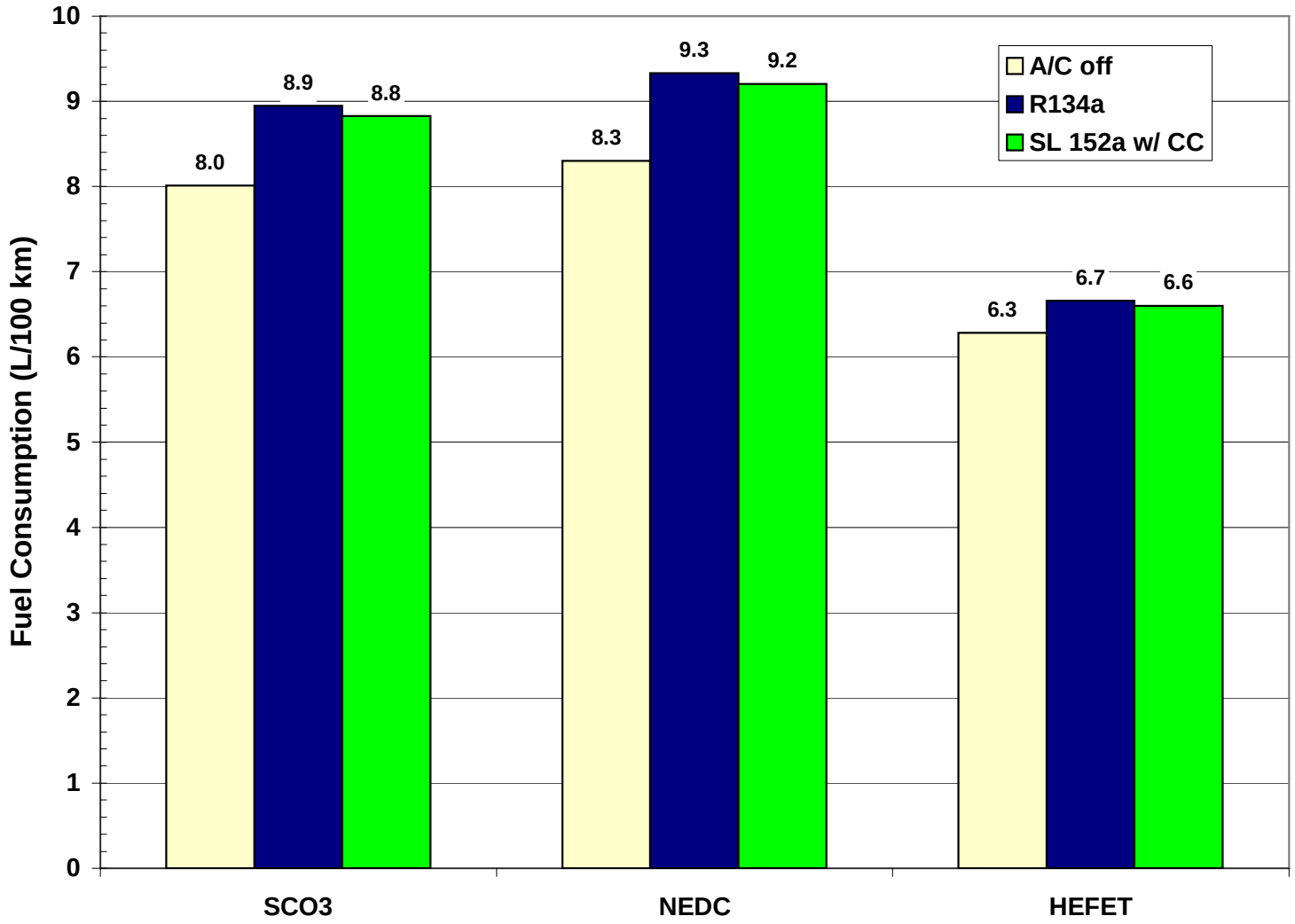


NEDC



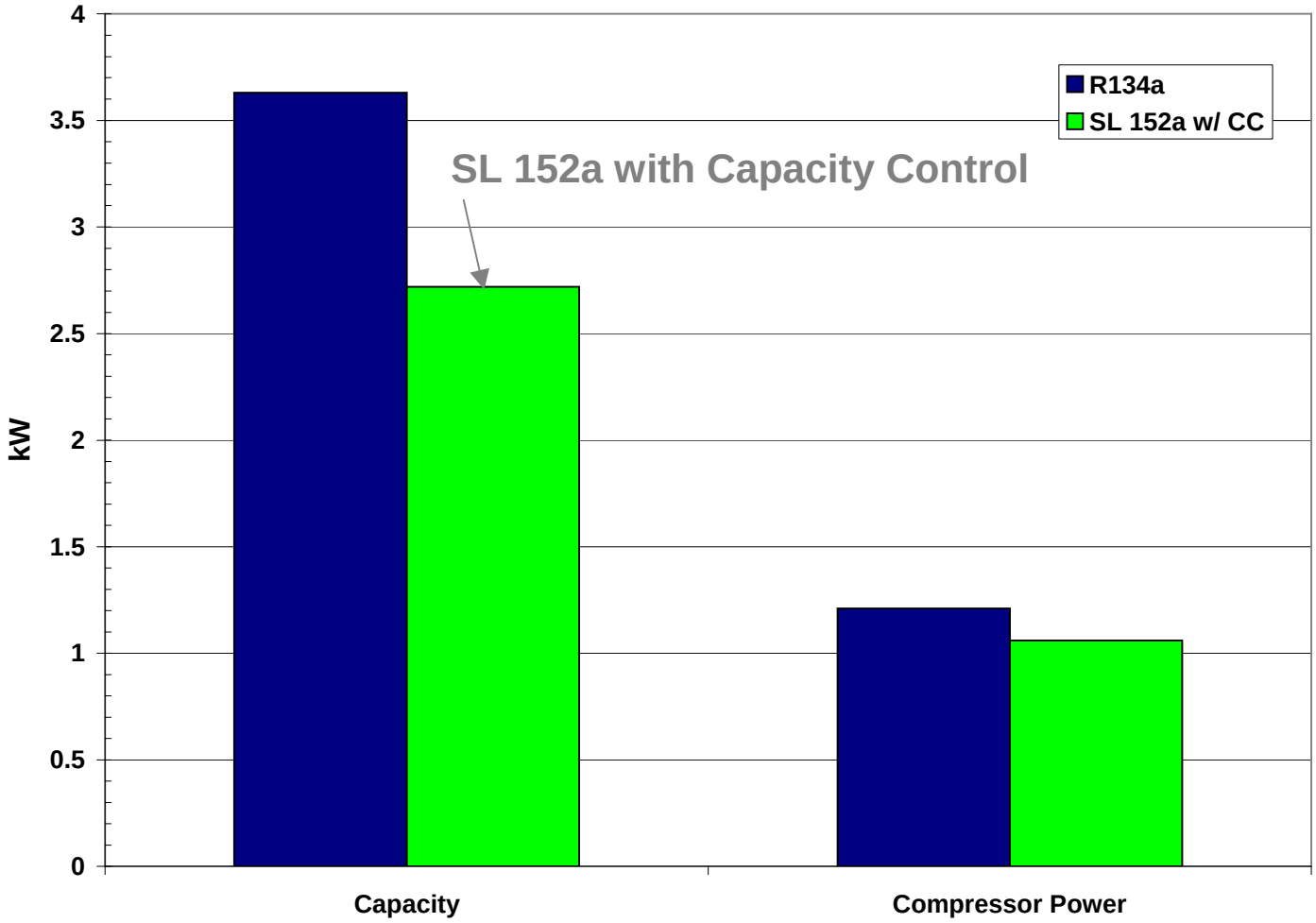
Alternate Refrigerants

Overall Vehicle Fuel Use (L/100km)



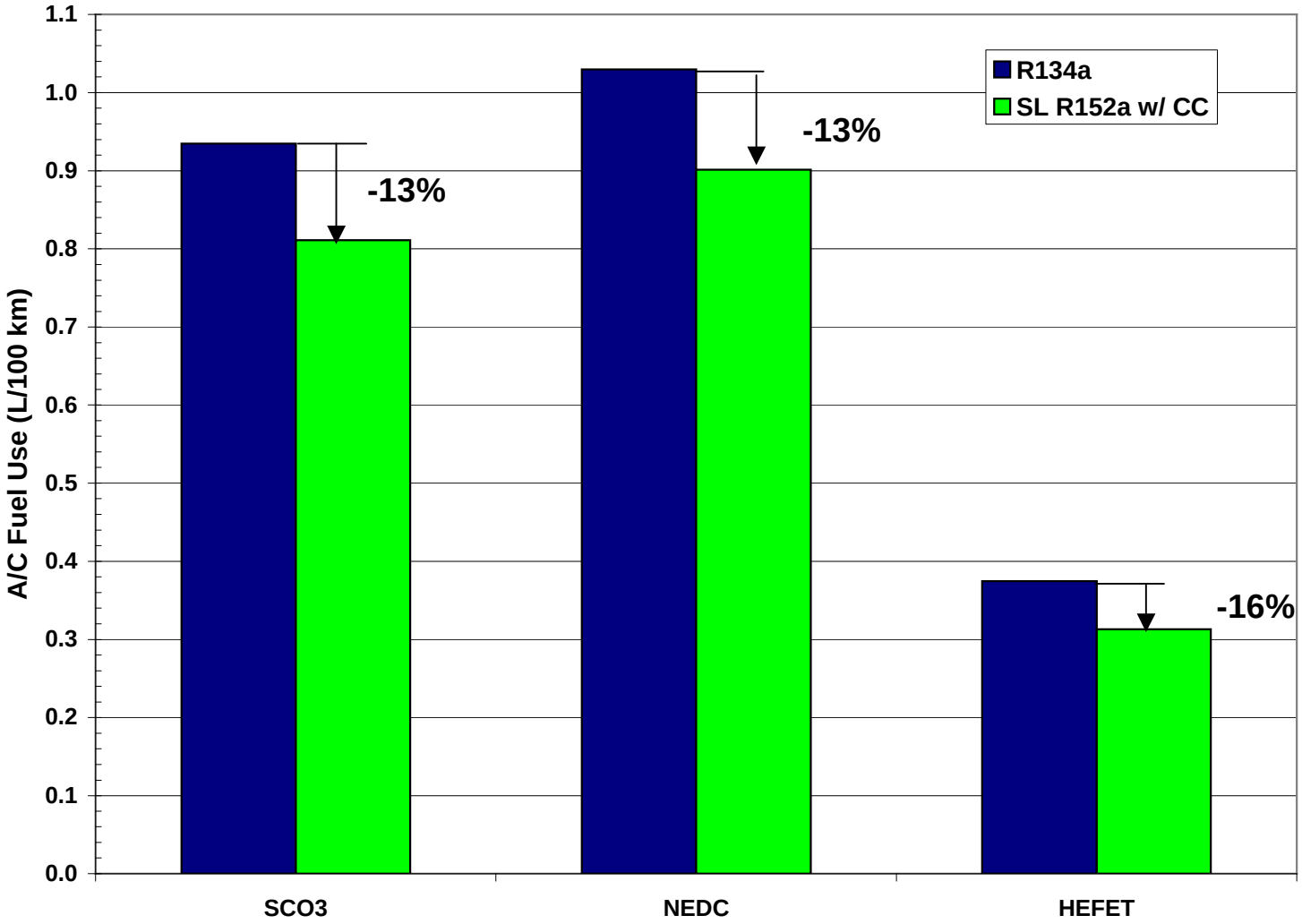
Alternate Refrigerants

SC03 Average Power and Capacity



Alternate Refrigerants

A/C Fuel Use (L/100 km)



Alternate Refrigerants

Analysis Summary

- **Application Of Delphi's Capacity Control Strategy Can Provide An Energy Savings Vs. The R-134a Baseline (13% – 16%)**

- **Further Energy Savings Are Possible Under Control Conditions With An Optimized Compressor Control Valve Setting**

Alternate Refrigerants

Summary

R-152a Secondary Loop

- **Cooling Performance**
  - Cooling Equivalent to R-134a Baseline
- **Environmental Benefit**
  - Global Warming Benefit:
    - Refrigerant GWP Reduced from 1430 to 124
    - 40% Less Charge Further Reduces Climate Impact of the Vehicle
  - Energy Consumption Equivalent to Baseline
- **Health & Safety**
  - No Toxicity Concerns with R-152a for Mobile A/C
  - Mild Flammability Concerns Mitigated

Alternate Refrigerants

Summary

- **Technology Readiness**
  - No Technical Barriers to Production for 2011 Model Year
  - Available Global Supply of R-152a
    - » Approximately 34,000 MT Production Capacity in China
    - » Additional Production in Germany, Japan and USA
- **System Improvement Potential**
  - Mass and Packaging Optimization
  - Optimized Engine Loading by Interaction of Engine Management System (EMS) with Secondary Loop Coolant Buffer
  - Provide Idle-Stop Comfort with Cold Storage

Other GAR Refrigerants

William Hill

Technical Fellow, General Motors

Alternate Refrigerants

Systems

- **GAR A System**
  - **Content**
  - **Performance**
- **GAR B System**
  - **Content**
  - **Performance**

Alternate Refrigerants

System Content

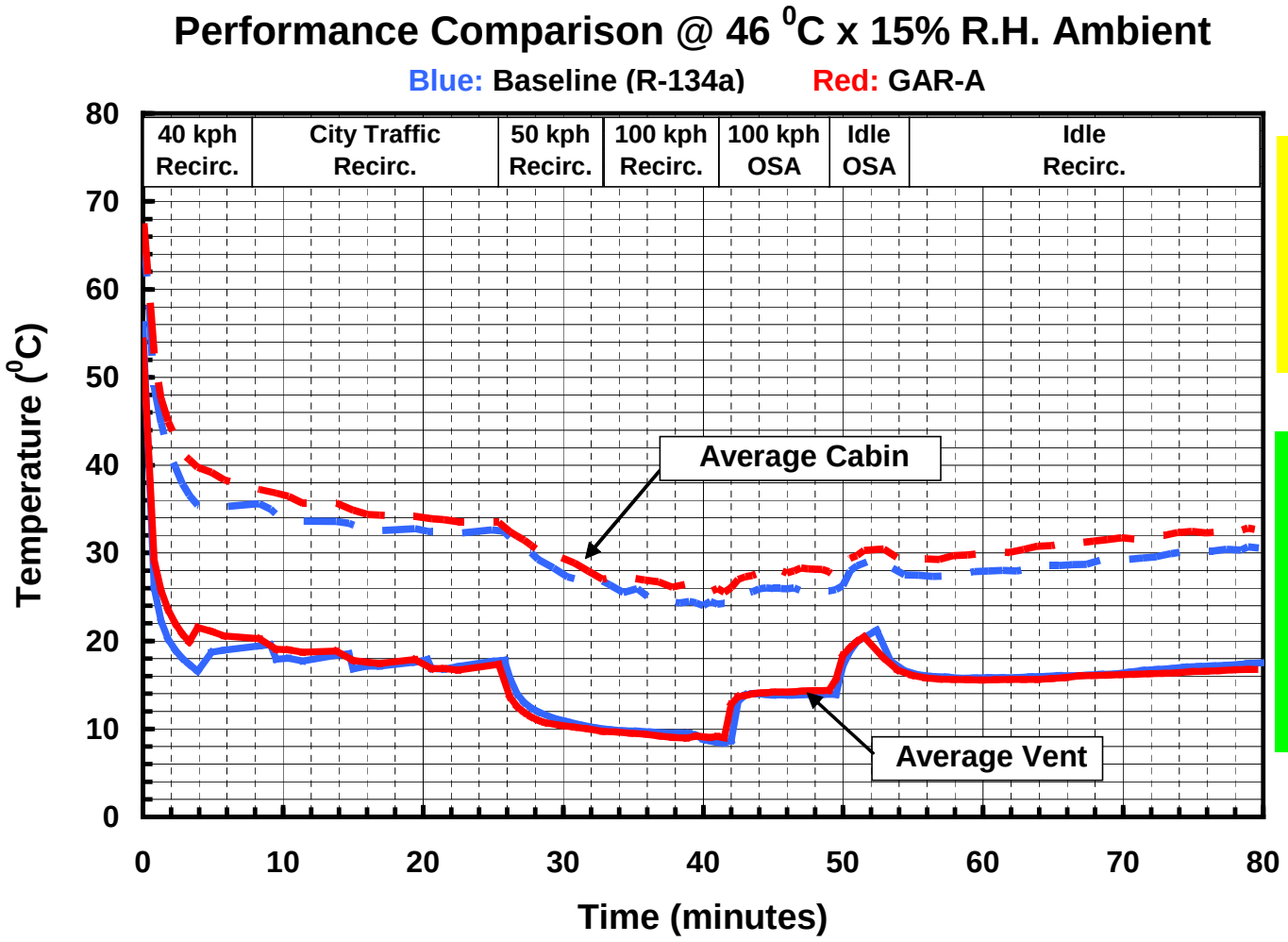
GAR-A System

Description	GAR-A
Evaporator	Plate (Modified Pass Arrangement)
Compressor	Increased Displacemnt
Condenser	Base
Refrigerant Control	TXV Adjustment
Suction Line	Optimized
Refrigerant	10 to 20% more charge
Refrigerant Oil	Base
Desiccant	Base
Fan / Shroud	Base

Alternate Refrigerants

Wind Tunnel Cooling Performance

GAR-A System

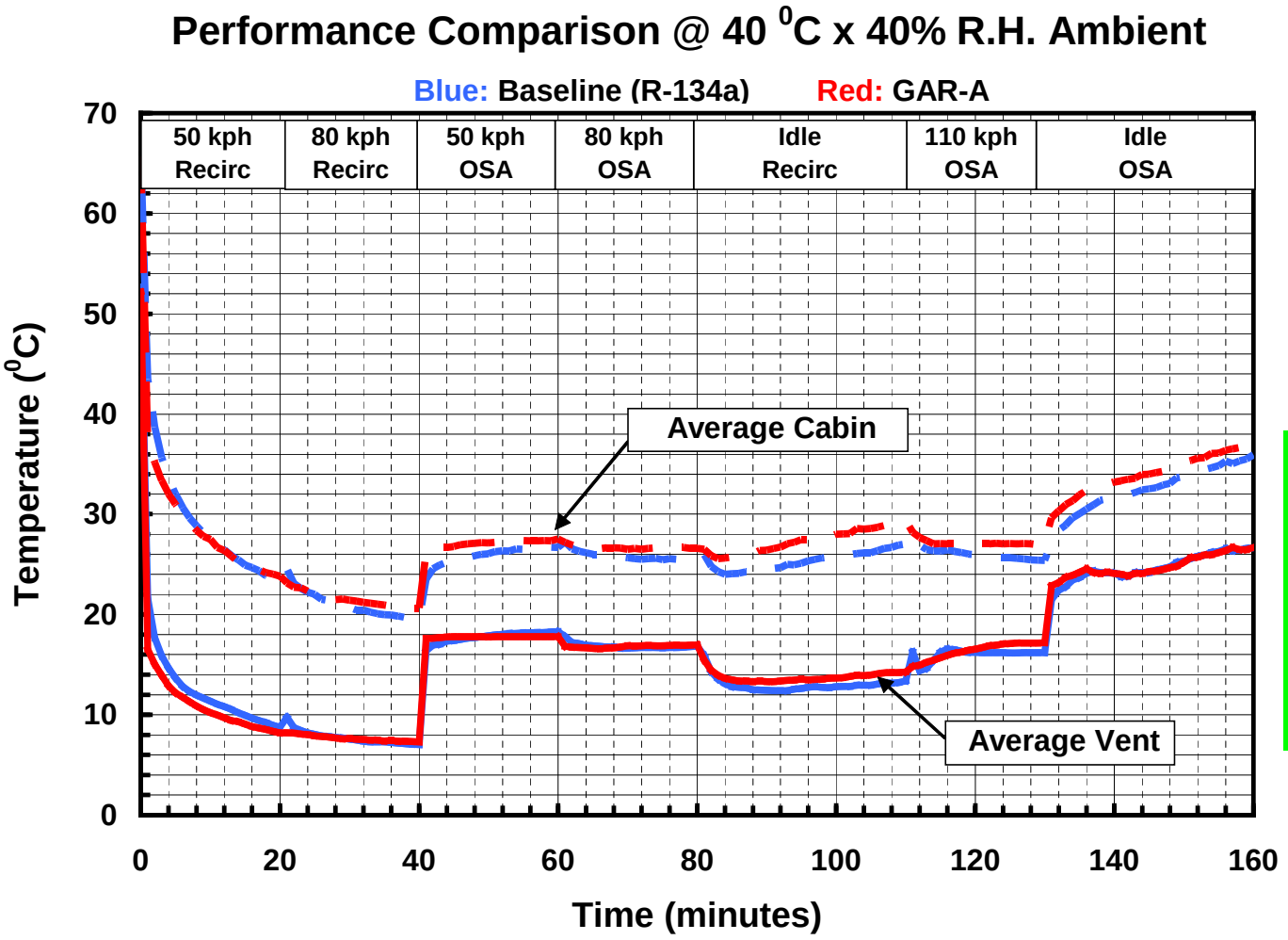


Equivalent Cooling Performance to Baseline

Note: Each vehicle served as its own R-134a baseline to limit variation

Alternate Refrigerants

Wind Tunnel Cooling Performance — GAR-A System



Equivalent Cooling Performance to Baseline

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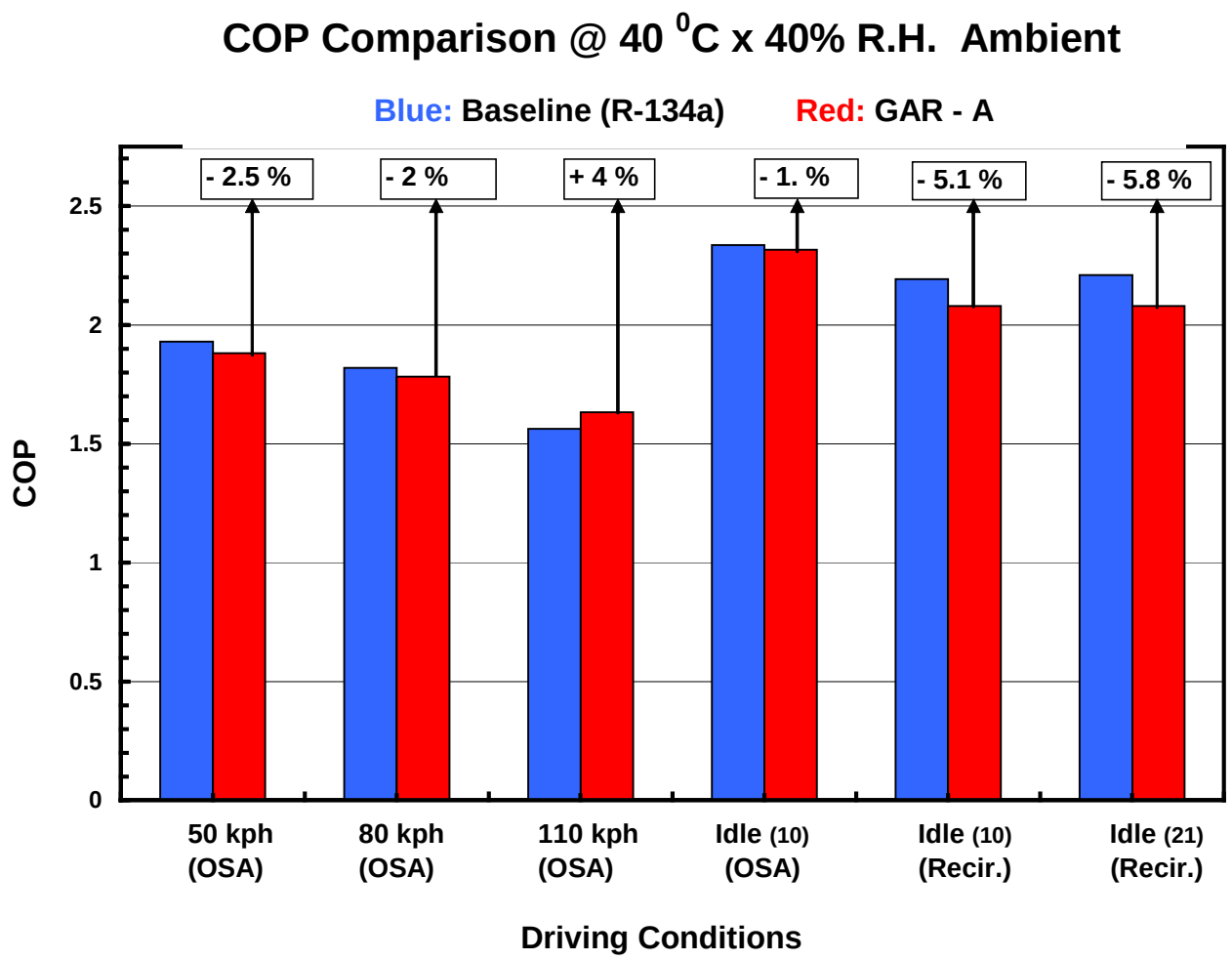
Alternate Refrigerants

Thermal Energy Performance

GAR-A System



On Average

Lower COP (~3%) than Baseline

Note: Each vehicle served as its own R-134a baseline to limit variation

Alternate Refrigerants

Systems

- GAR A System
  - Content
  - Performance
- **GAR B System**
  - **Content**
  - **Performance**

Alternate Refrigerants

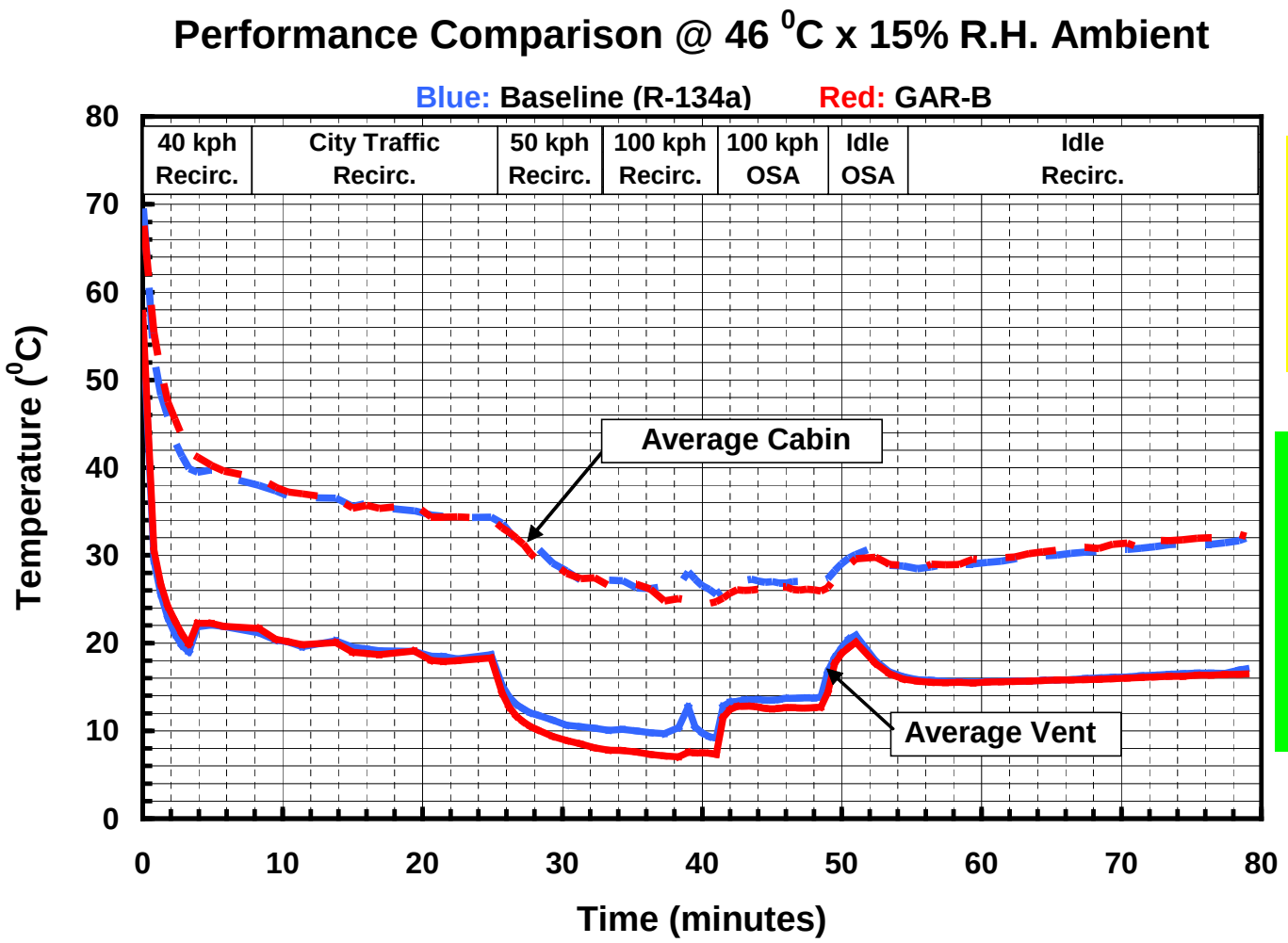
System Content

GAR-B System

Description	GAR-B
Evaporator	Plate (Modified Pass Arrangement)
Compressor	Increased Displacemnt
Condenser	Base
Refrigerant Control	TXV Adjustment
Suction Line	Optimized
Refrigerant	10 to 20% more charge
Refrigerant Oil	Base
Desiccant	Base
Fan / Shroud	Base

Alternate Refrigerants

Wind Tunnel Cooling Performance — GAR-B System



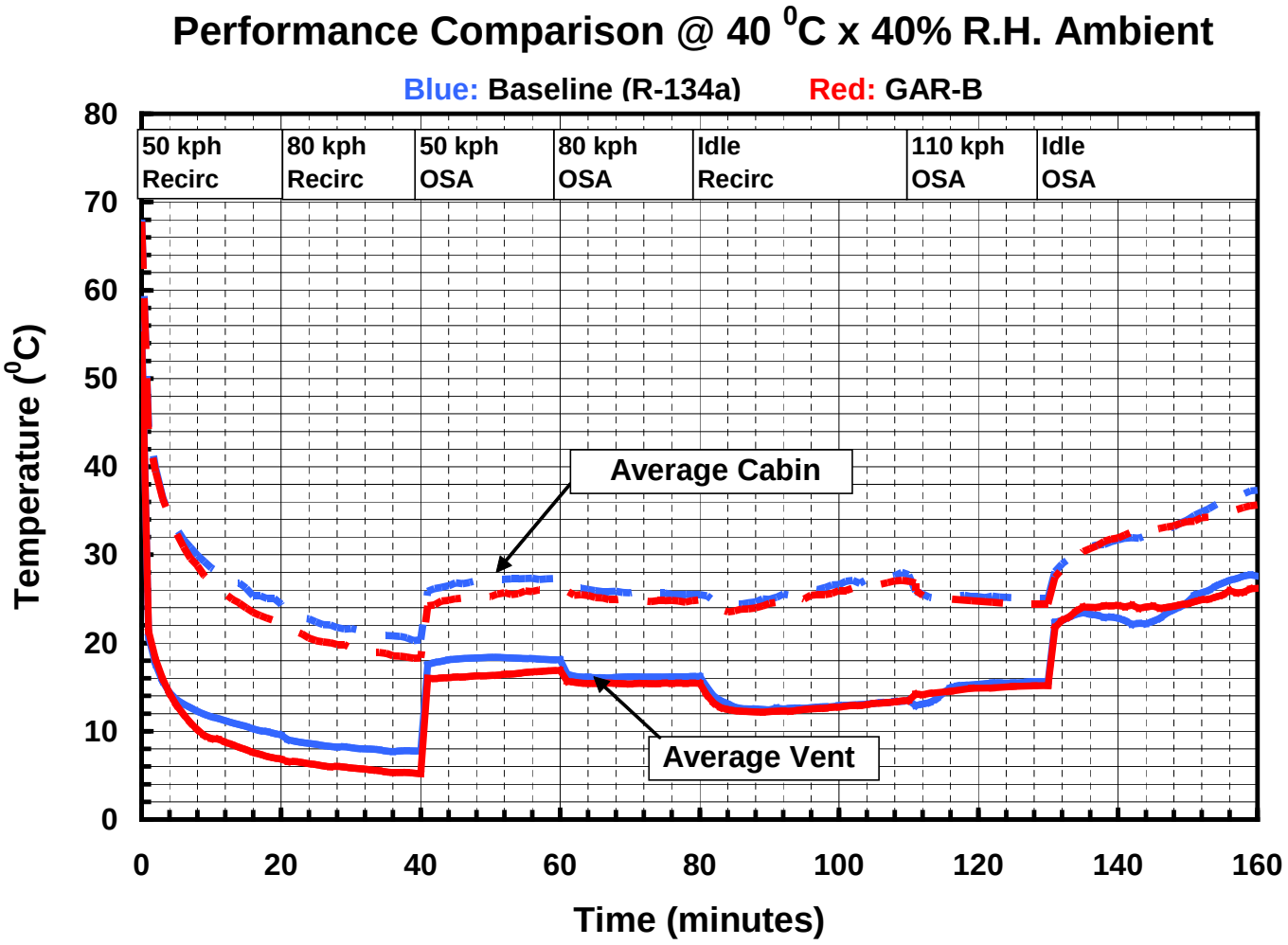
Equivalent Cooling Performance to Baseline

Note: Each vehicle served as its own R-134a baseline to limit variation

Alternate Refrigerants

Wind Tunnel Cooling Performance

GAR-B System



Equivalent Cooling Performance to Baseline

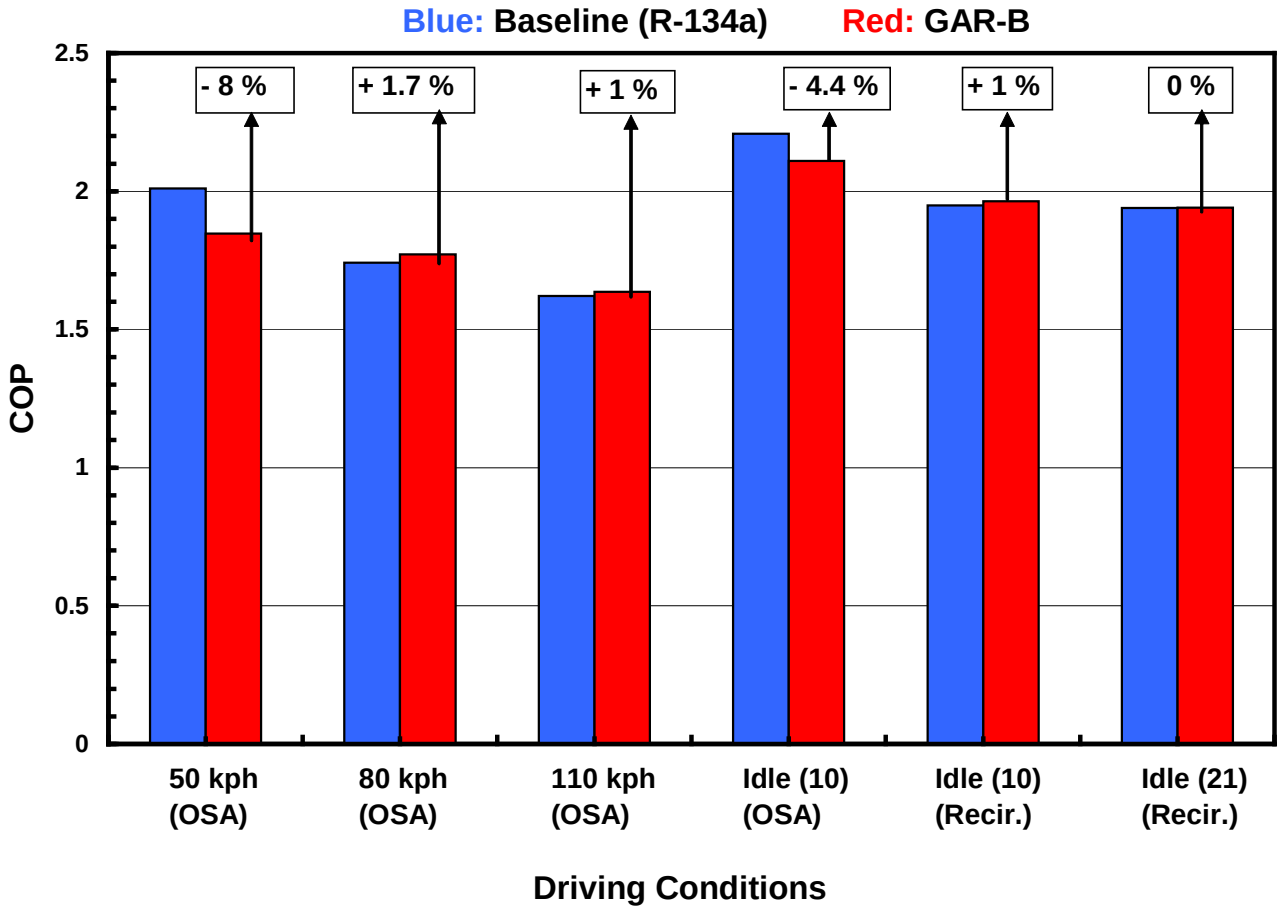
Note: Each vehicle served as its own R-134a baseline to limit variation

Alternate Refrigerants

Thermal Energy Performance

GAR-B System

COP Comparison @ 40 ^{0}C x 40% R.H. Ambient



On Average Lower COP (~2%) than Baseline

Note: Each vehicle served as its own R-134a baseline to limit variation

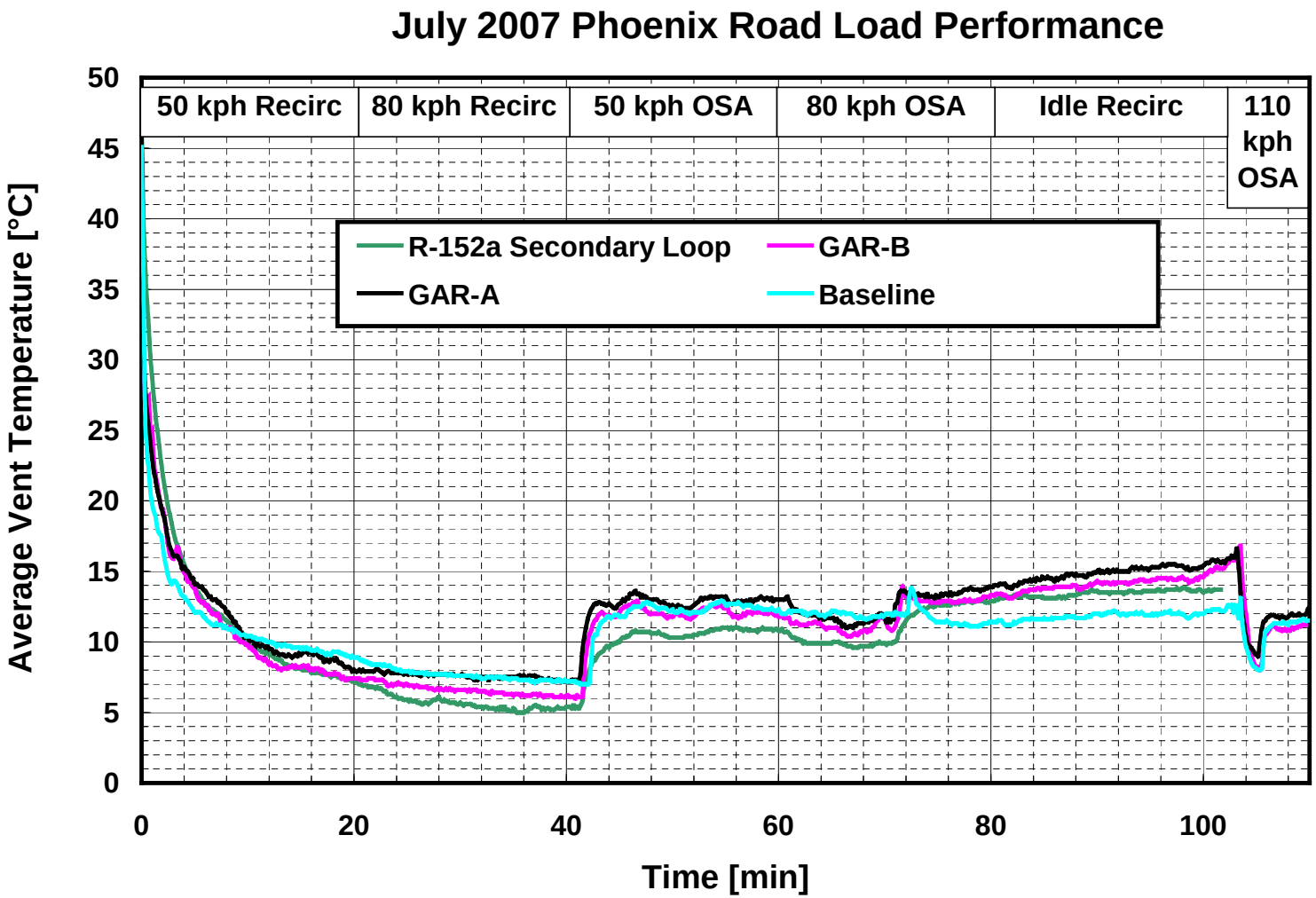
Alternate Refrigerants

Road Test Performance and Fuel Economy

- **Vehicle Road Testing in Phoenix**
- **Each Vehicle Fuel Economy Measured at General Motors Test Facilities**

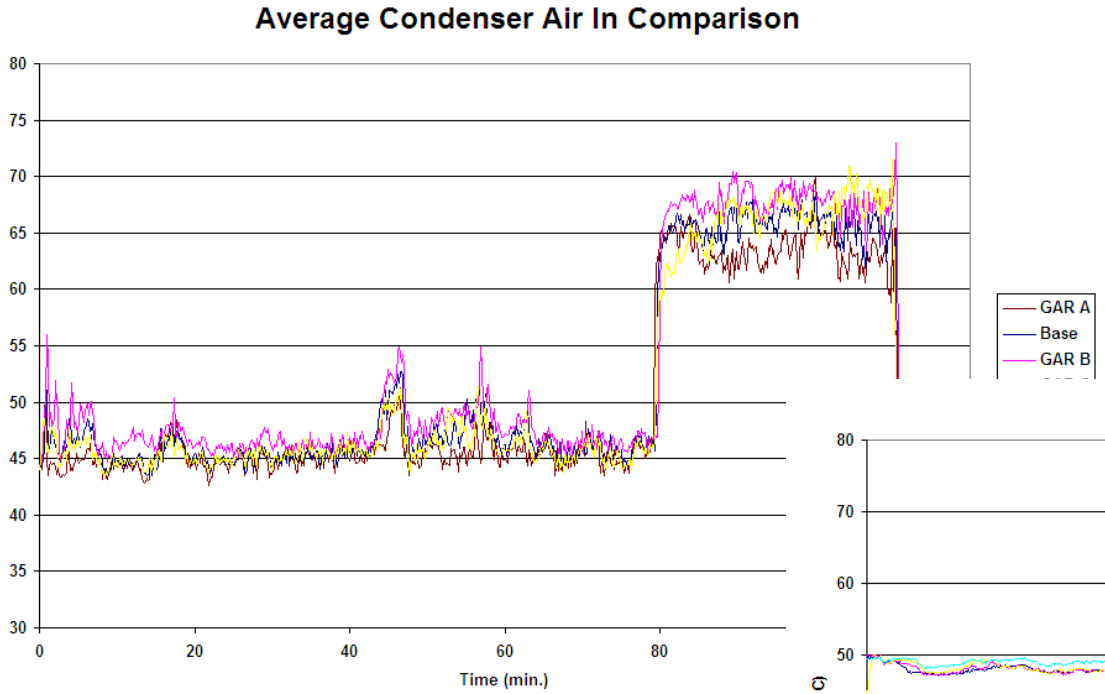
Alternate Refrigerants

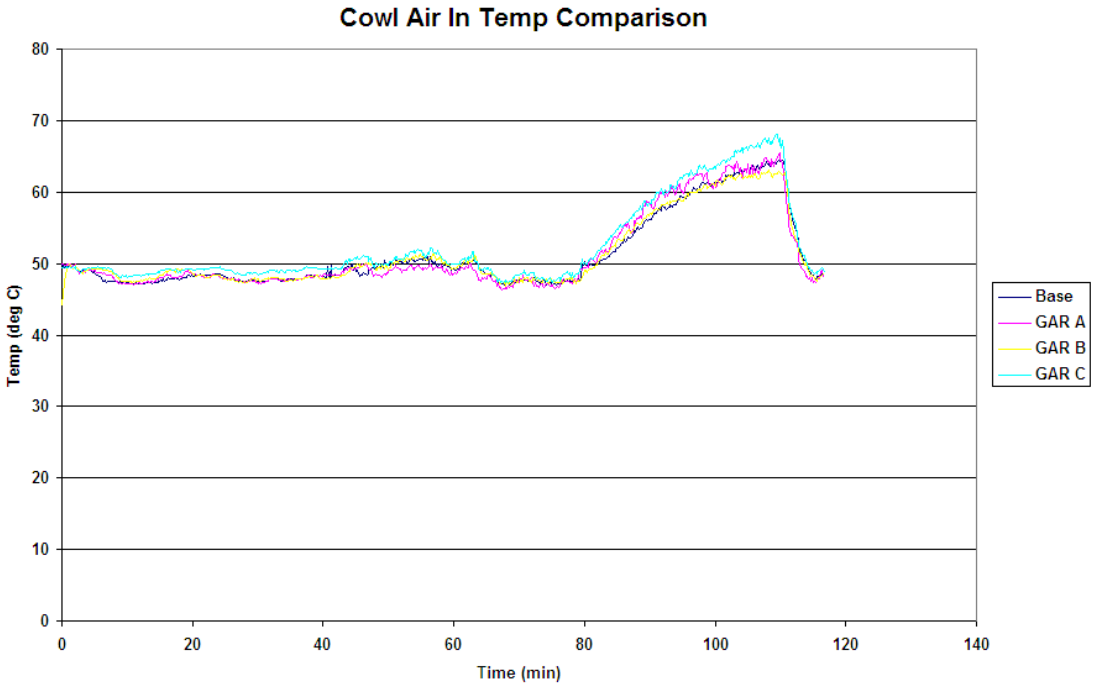
Road Test Performance Summary of All Systems



Alternate Refrigerants

Conditions During Road Test

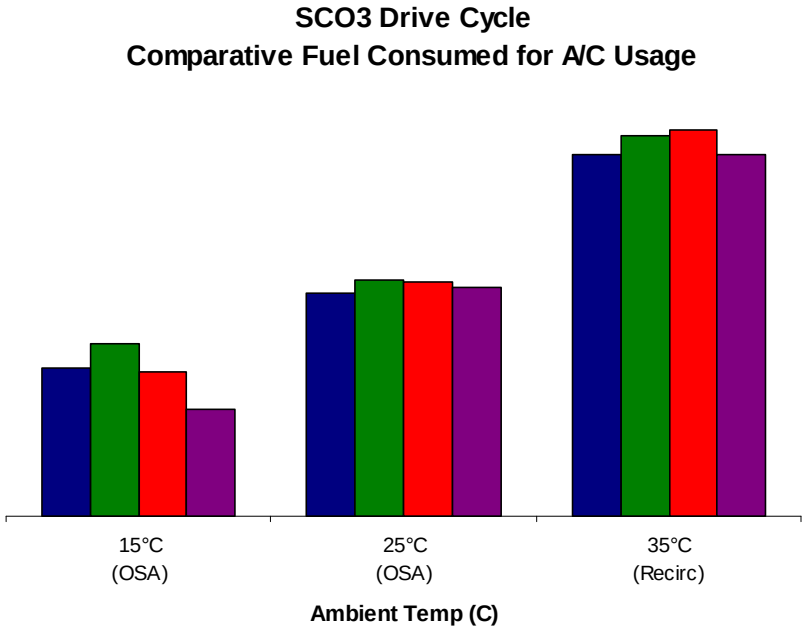


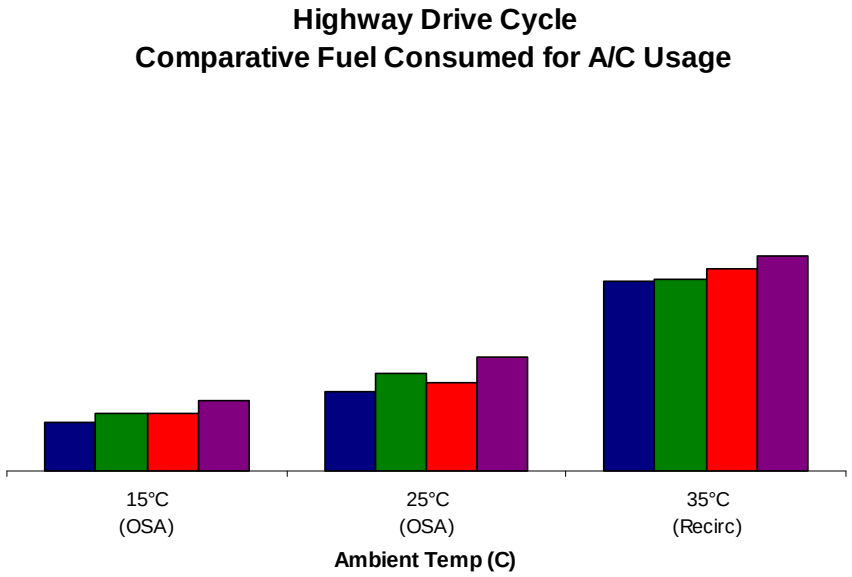


Vehicles have similar boundary operating conditions on the road

Alternate Refrigerants

Wind Tunnel Fuel Economy





Fuel Use Does Change with Drive Cycle and Test Condition but is Essentially Equivalent

Note: Delphi Capacity Control Algorithm Active in Secondary Loop Vehicle

Alternate Refrigerants

Summary

Objective Was Achieved to Replace R-134a with Selected Alternative Refrigerants with Minimum Content Changes while Maintaining Equivalent Cooling and Energy Performance

Thank You

Alternate Refrigerants

Q & A