Significant Fuel Savings and Emission Reductions by Improving Vehicle Air Conditioning

John Rugh
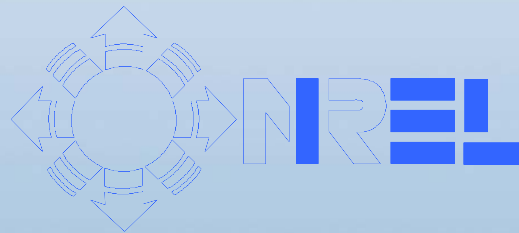
National Renewable Energy Laboratory

Valerie Hovland

Mesoscopic Devices
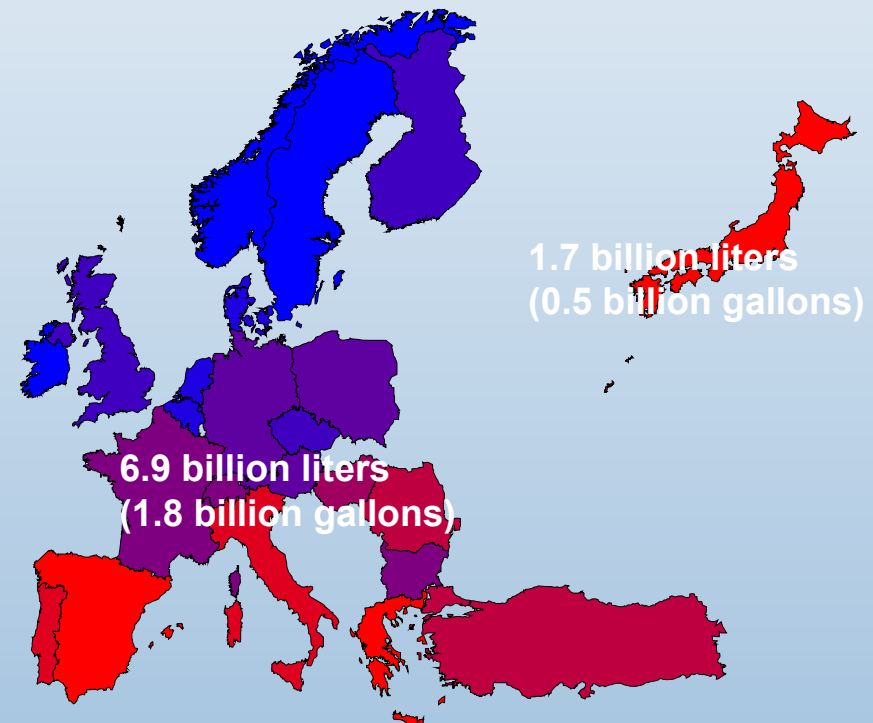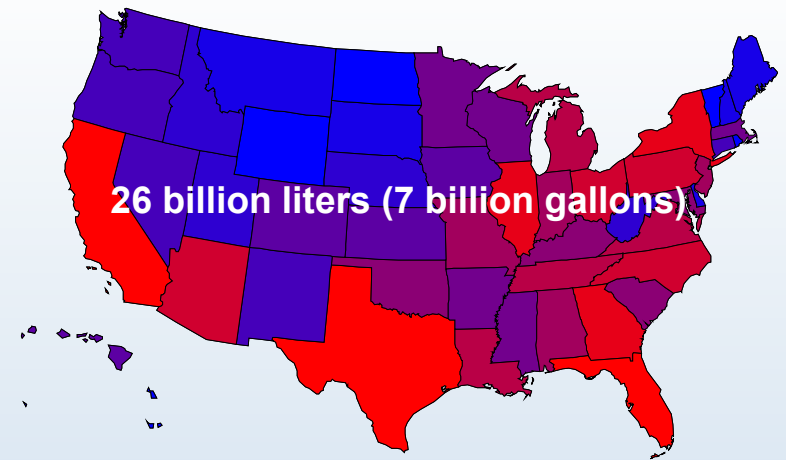
Stephen O. Andersen

U.S. Environmental Protection Agency

15th Annual Earth Technologies Forum and Mobile Air Conditioning Summit

April 15, 2004

Outline

- Modeling approach

  - Thermal comfort-based AC fuel use prediction

  - Model updates

- Fuel saved for *up to 30%* drop in AC power (equal to a 43% increase in COP)

  - Per vehicle (cars, light trucks)

  - By climate

  - Total savings and CO_2 reductions across California, U.S., EU, and Japan

26 billion liters (7 billion gallons)

1.7 billion liters (0.5 billion gallons)

6.9 billion liters (1.8 billion gallons)

Predicting Fuel Used for AC

- Use Multiple Models/Inputs/Data Sets
  - Environmental Conditions (Temp, RH, W/m^2)
  - Thermal Comfort Model
 - Vehicle Simulations (Fuel Economy Reduction with AC)
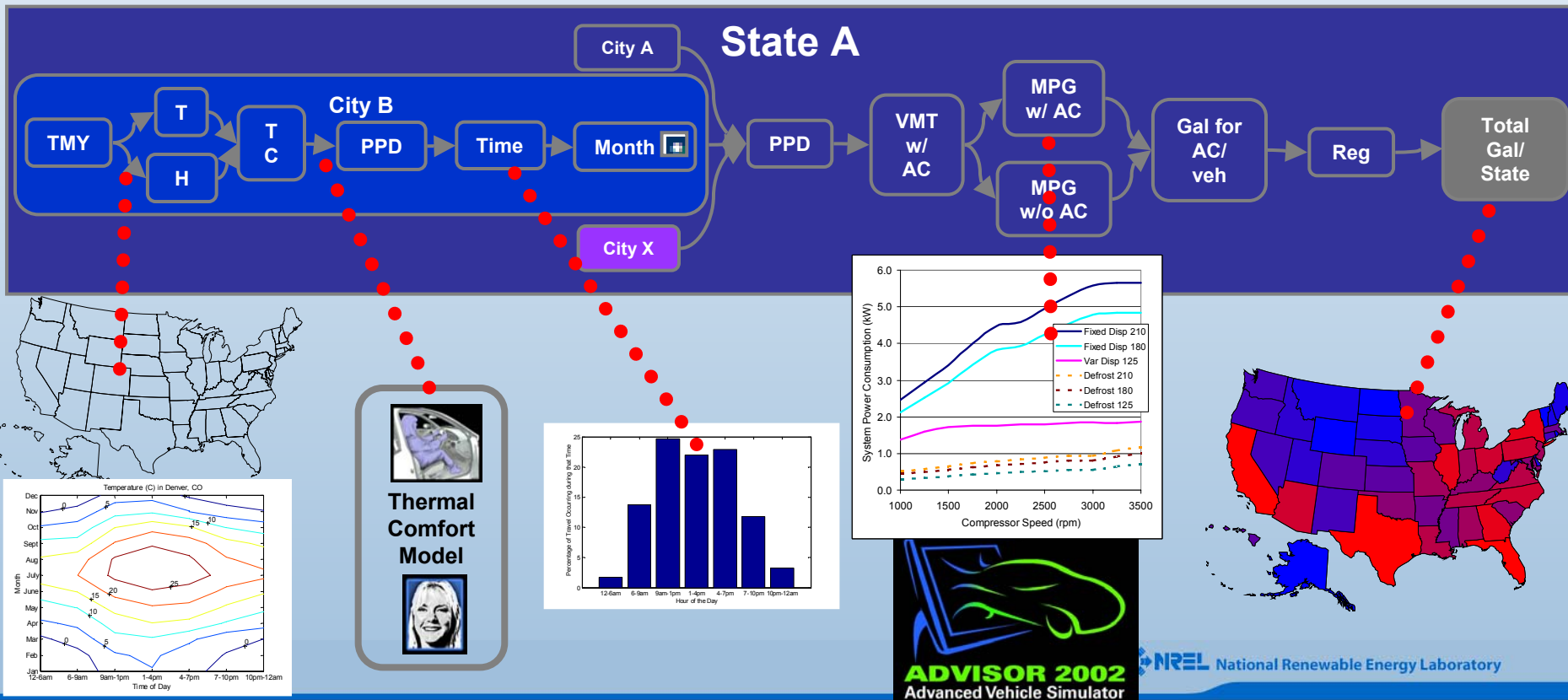
Model Updates

- Updates to U.S. study, Summer 2003
  - Mean Radiant Temperature varies with vehicle type (car, truck)
    - Therefore usage PPD varies with type
  - Thermal comfort: use one assumption for clothing and soak (MRT)
  - Include demisting
  - AC power consumption = f(type, compressor speed)
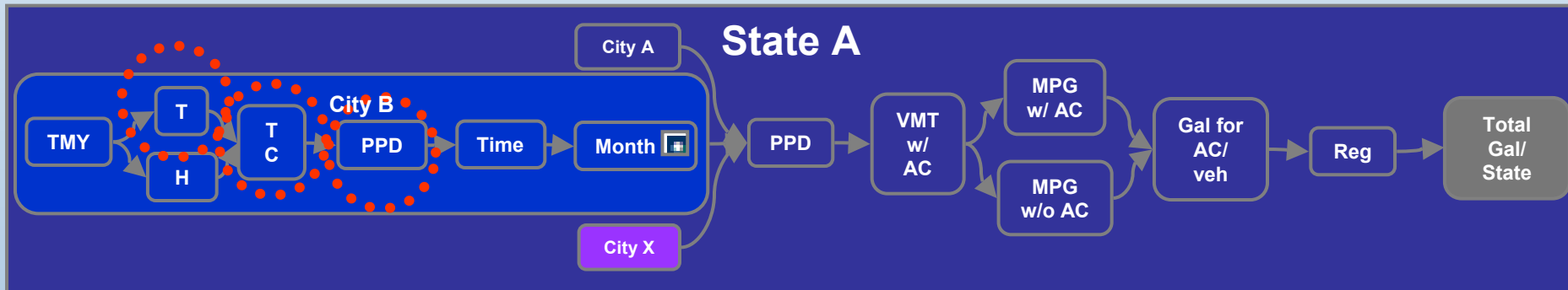
Demist

Environmental Conditions: Phoenix, AZ: Temperature

Temperature (C) in Phoenix, AZ
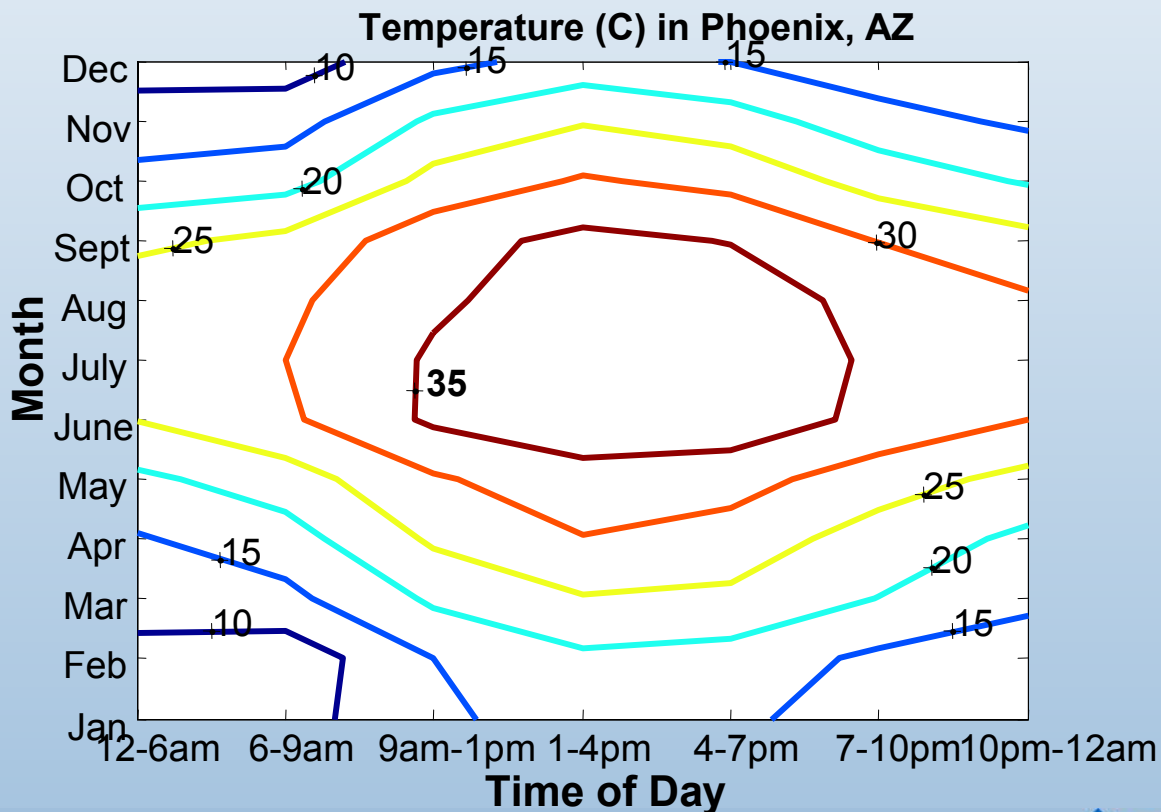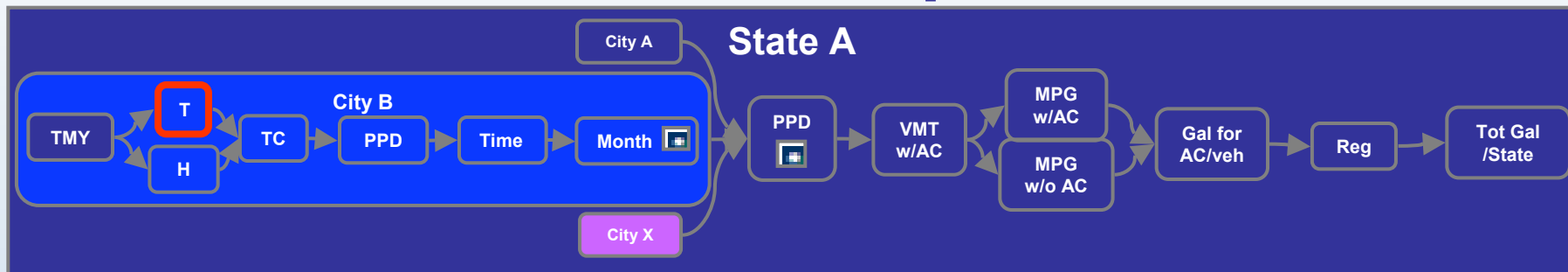
Temperature, humidity, solar radiation
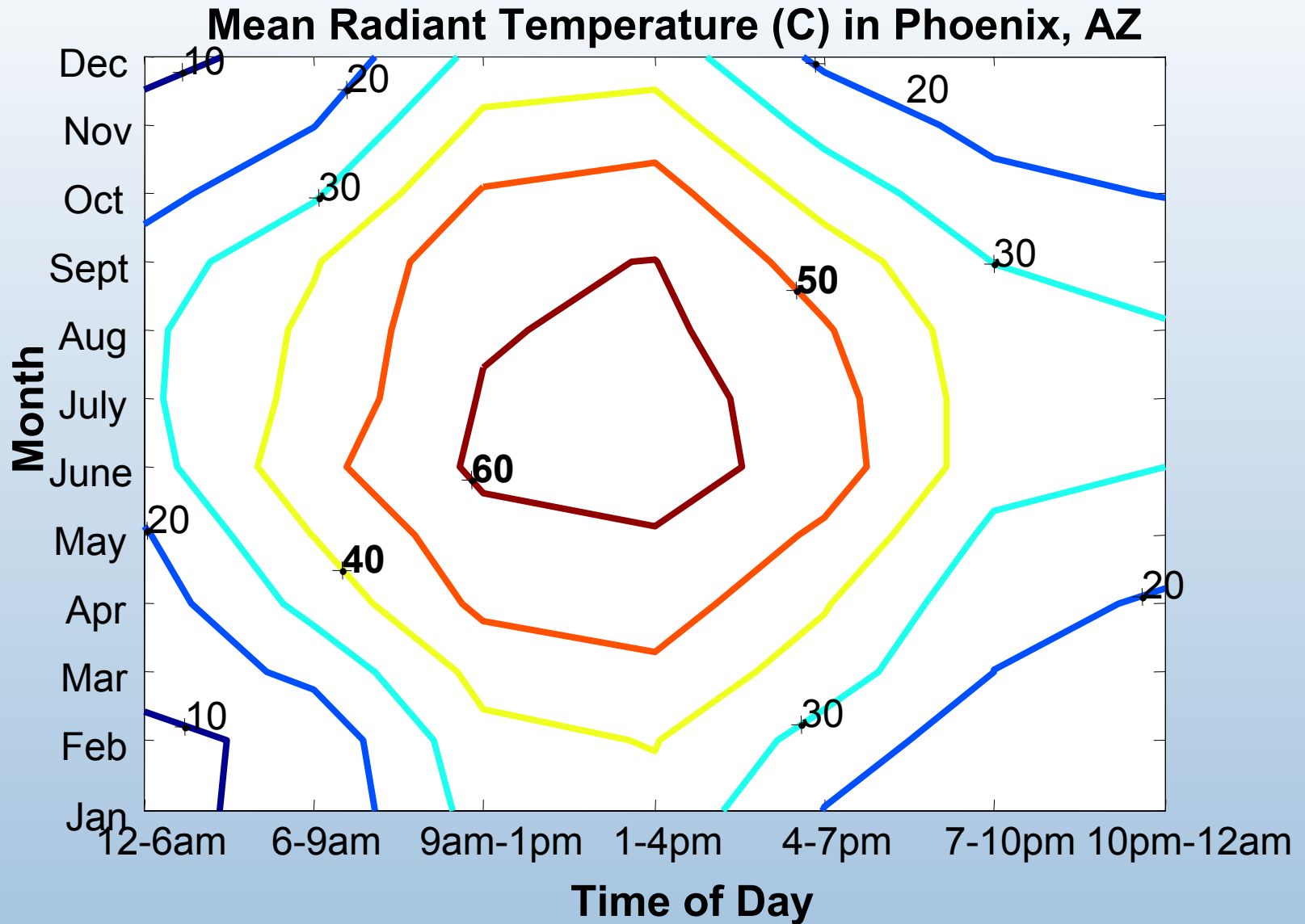
Mean Radiant Temperature Models

- MRT varies with vehicle type (car, truck)

- Vehicle data used to generate models

- Ford Crown Victoria
- Plymouth Breeze
- Jeep Grand Cherokee

- Ford Explorer (White)
- Ford Explorer (Black)
- Lincoln Navigator
- Dodge Grand Caravan

- Ward Atkinson – Phoenix 2002
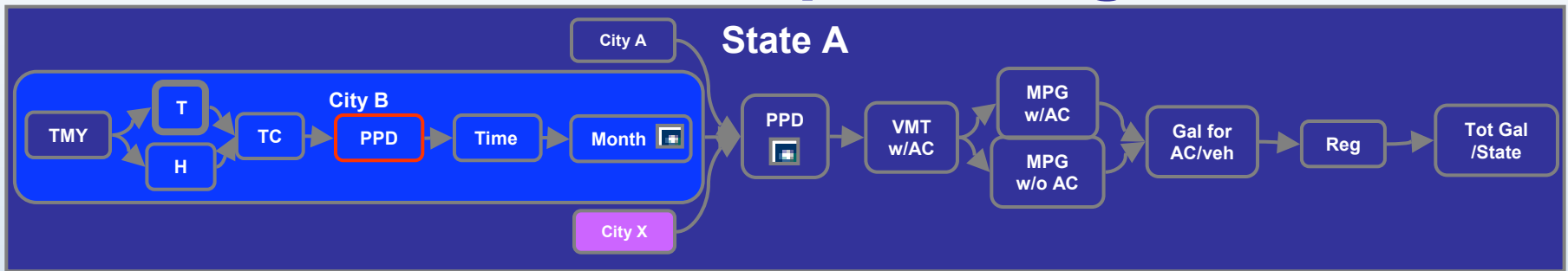- Bill Hill – GM Data

Models

$$\text{MRT(car, time)} = \mathbf{27°C} * \text{Radiation}(t)/1000W/m^2 + T_{ambient}(t)$$

$$\text{MRT(truck, time)} = \mathbf{24°C} * \text{Radiation}(t)/1000W/m^2 + T_{ambient}(t)$$

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Mean Radiant Temperature by City

Mean Radiant Temperature (C) in Phoenix, AZ

Thermal Comfort Model:
Percent of People Using AC

State A

City A — City B — City X

TMY → T, H → TC → **PPD** → Time → Month → PPD → VMT w/AC → MPG w/AC / MPG w/o AC → Gal for AC/veh → Reg → Tot Gal /State
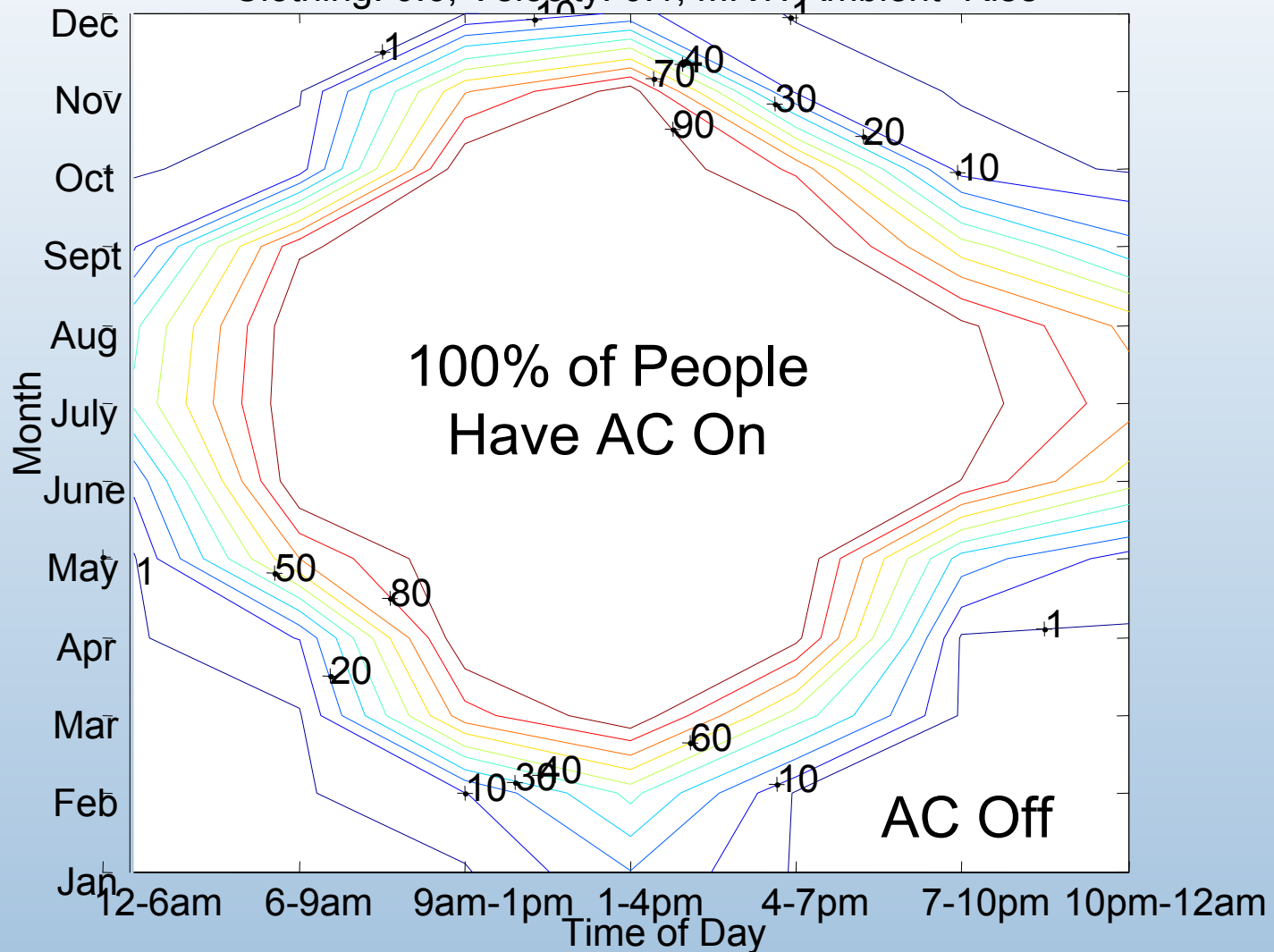
Thermal Comfort Model, *PPD from PMV*

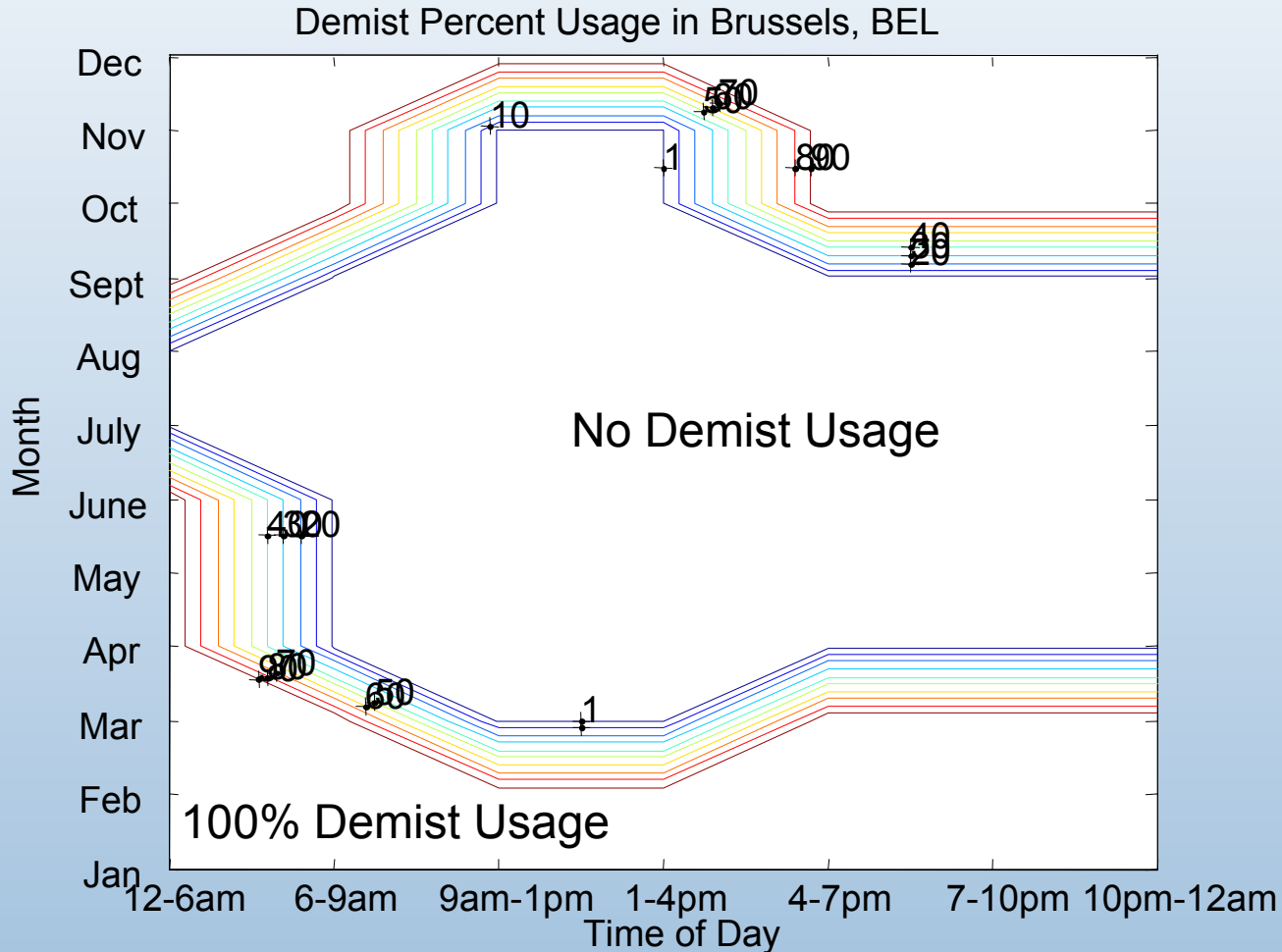| PMV	Thermal Sensation
+ 3	Hot
+ 2	Warm
+ 1	Slightly Warm
0	Neutral
- 1	Slightly Cool
- 2	Cool
- 3	Cold
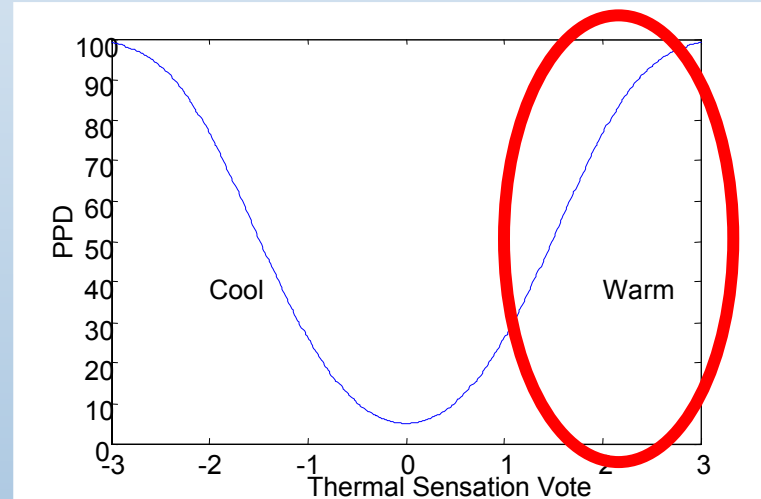
AC Usage for Cooling

Predicted Percent Dissatisfied (%) in Phoenix, AZ
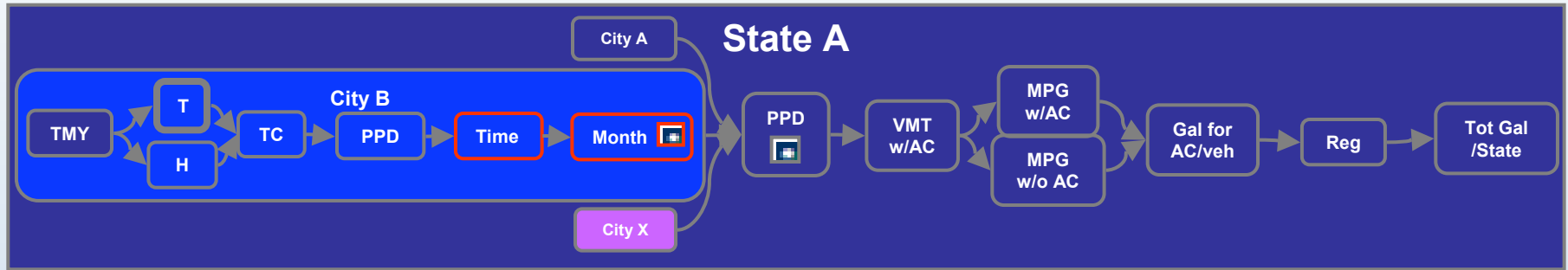Clothing: 0.6, Velocity: 0.1, MRT: Ambient+Rise
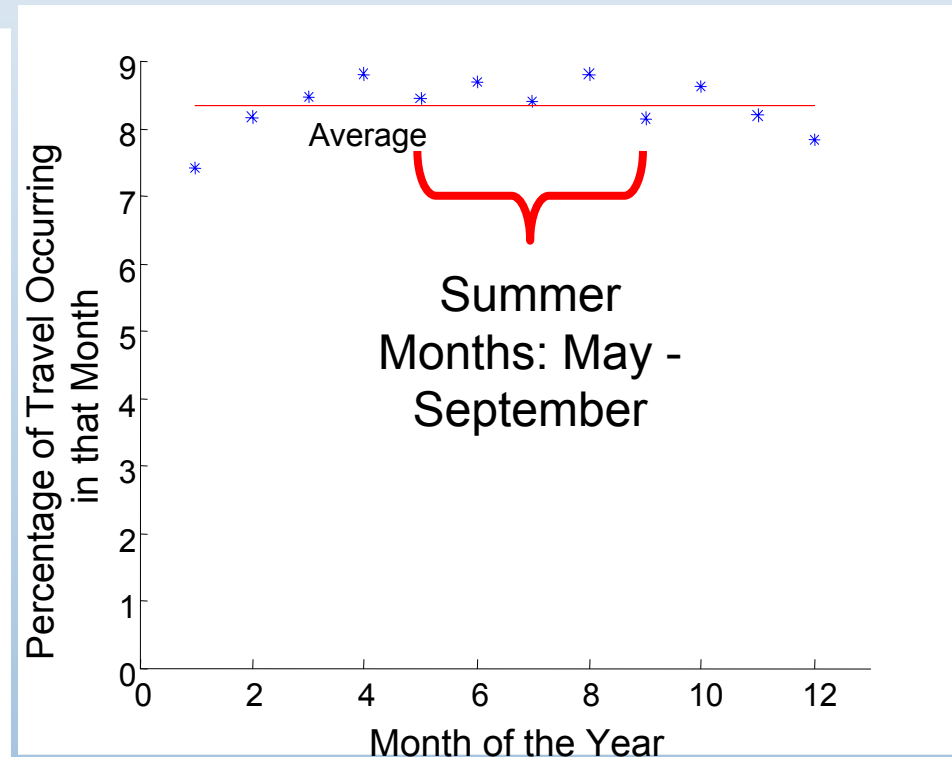
AC Usage for Demisting

AC used for demist if:

Temperature is between 1.7-12.8°C (35-55°F), and Relative Humidity > 80%

Demist Percent Usage in Brussels, BEL

Vehicle Usage with Time of Day, Month
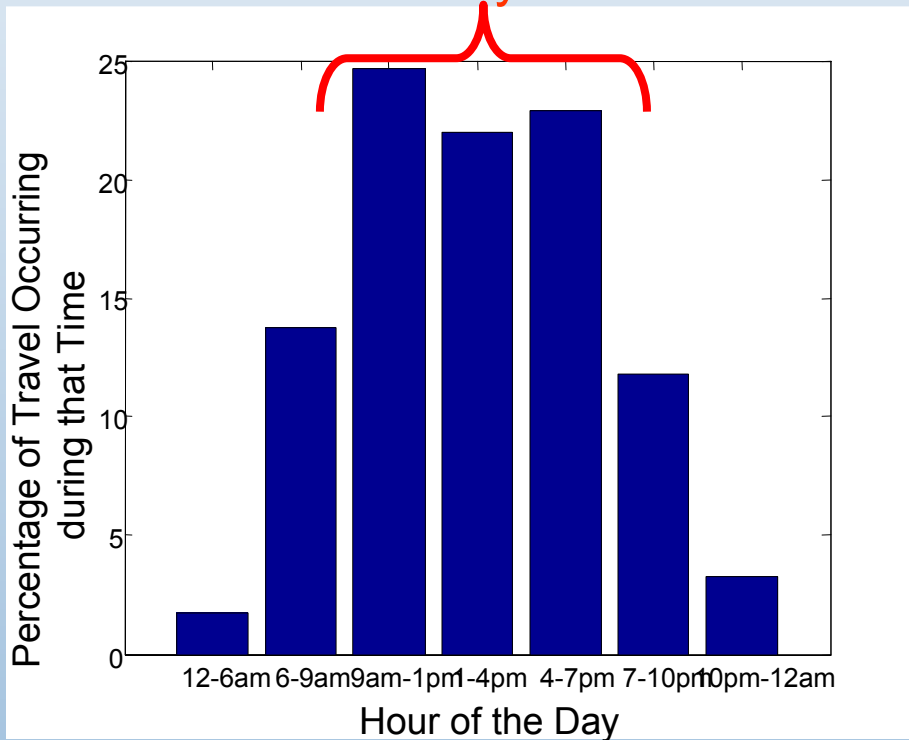
Percent of Time AC is On: Cooling + Demist

Percent of Time AC for Cooling + Dehumidification

- 6.3 to 17.9
- 17.9 to 19.6
- 19.6 to 22.9
- 22.9 to 25.1
- 25.1 to 25.9
- 25.9 to 28.4
- 28.4 to 32.1
- 32.1 to 37.8
- 37.8 to 41.4
- 41.4 to 49.2
- 49.2 to 57.3
- 57.3 to 69.3

Climate during AC Use
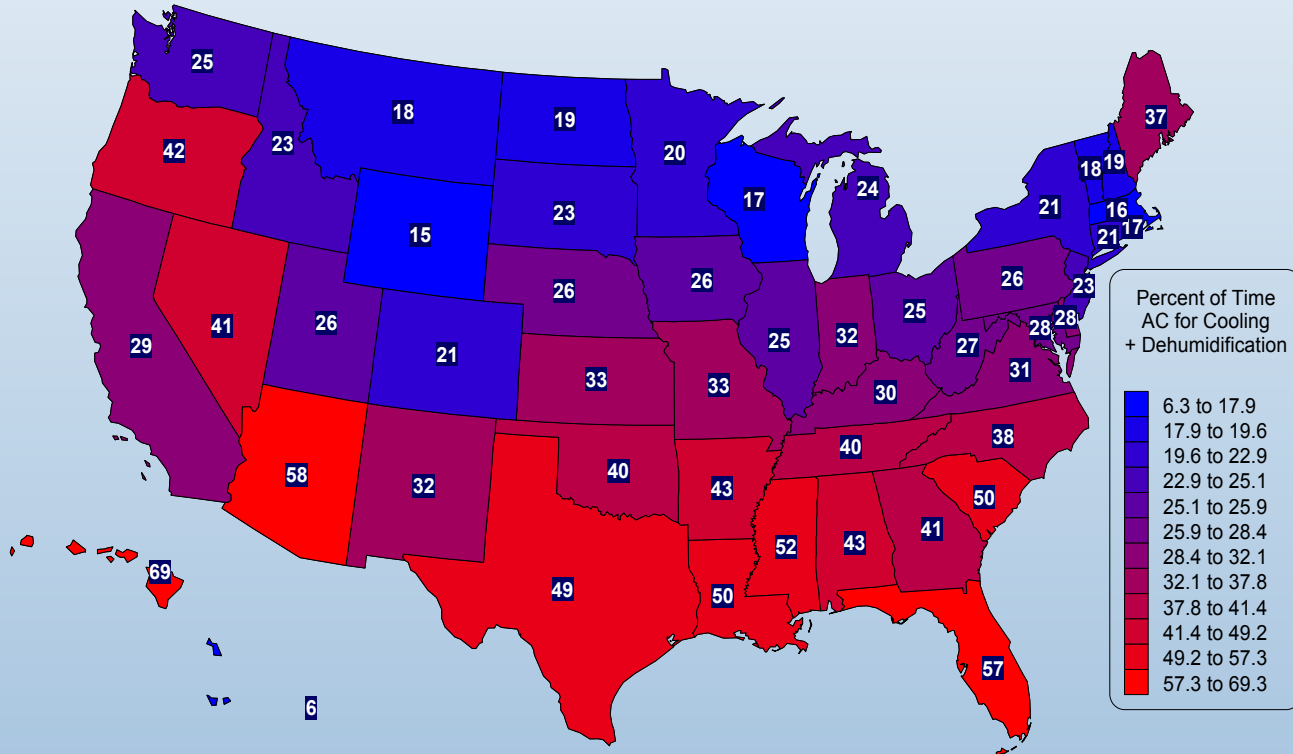## Temperature, Humidity

U.S. Average: 25°C

Average Temperature During AC Use (C)

- 16.9 to 22.8
- 22.8 to 23.5
- 23.5 to 24.1
- 24.1 to 24.6
- 24.6 to 24.9
- 24.9 to 25.1
- 25.1 to 25.5
- 25.5 to 26.2
- 26.2 to 26.7
- 26.7 to 26.7
- 26.7 to 27.3
- 27.3 to 30.2

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Climate during AC Use
Temperature, Humidity

U.S. Average: 66% RH

Average Relative Humidity During AC Use (%)

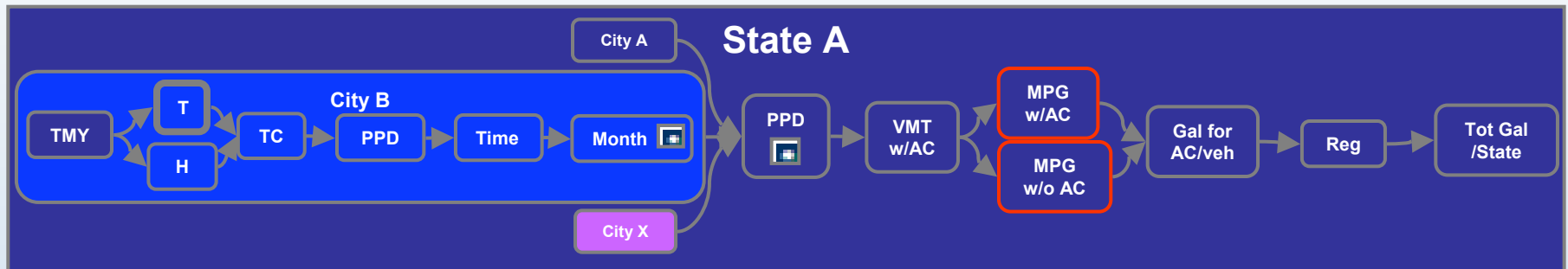| Color	Range
Blue	31 to 47
	47 to 56
	56 to 67
	67 to 69
	69 to 70
	70 to 71
	71 to 72
	72 to 73
	73 to 74
	74 to 76
	76 to 77
Red	77 to 81

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Percent of Time AC in Use Cooling and Demisting
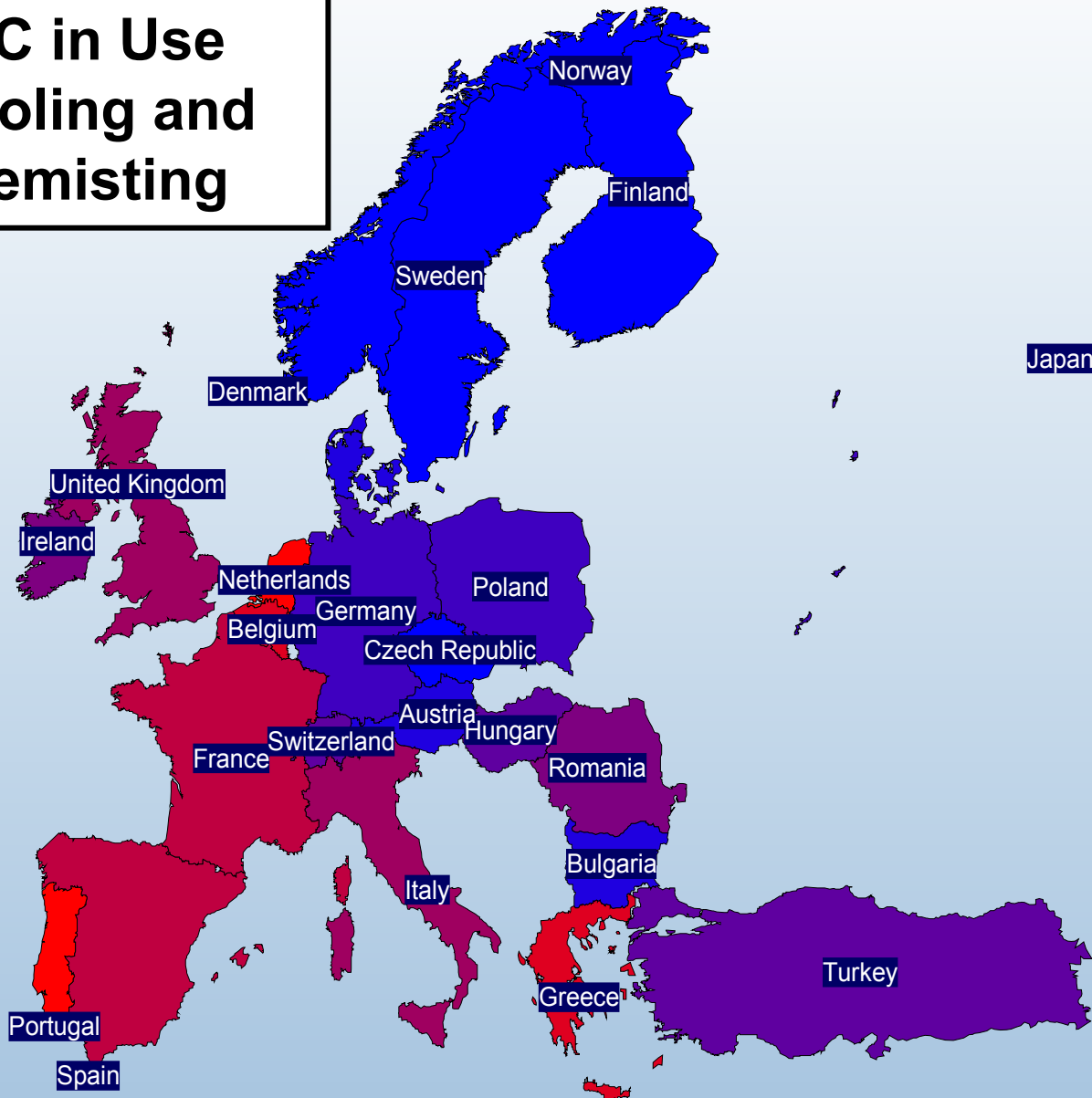
Fuel Economy Impact: Vehicle Simulations

FTP drive cycle
Hot initial conditions

	US Car	US Truck	EU Vehicle
Fuel Economy no AC	22.0	18.8	30.4
Fuel Economy with AC	18.0	16.2	27.3
Fuel Economy defrost	21.1	18.1	29.0

	US Car	US Truck	EU Vehicle
FE Drop with AC	18%	14%	10%
FE Drop with defrost	4%	4%	4%

US car and truck based on existing fleet

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Vehicle Registrations
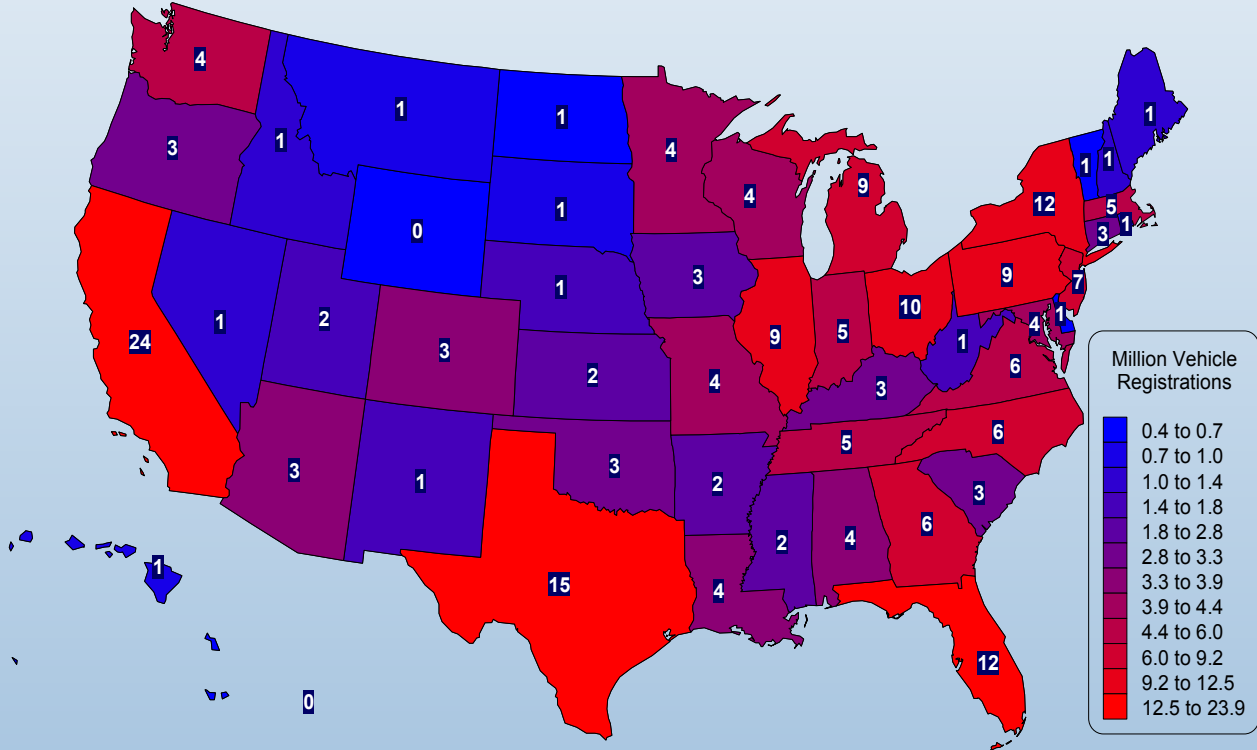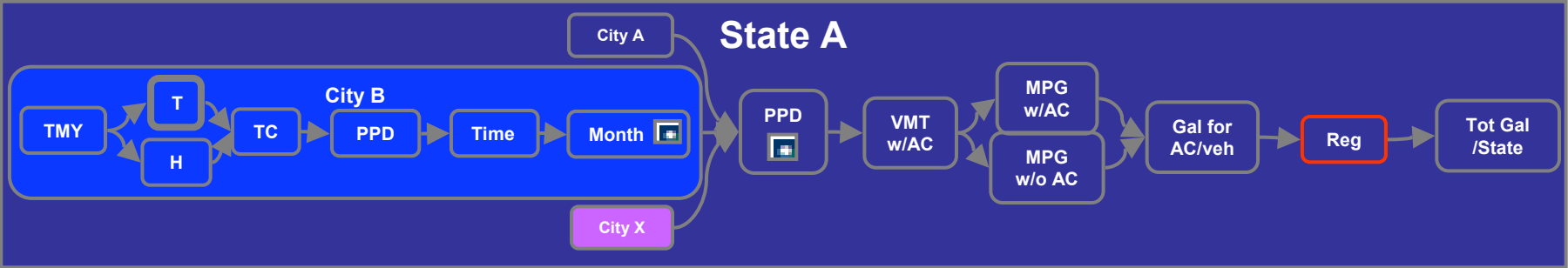
Distance Traveled per Year EU and Japan
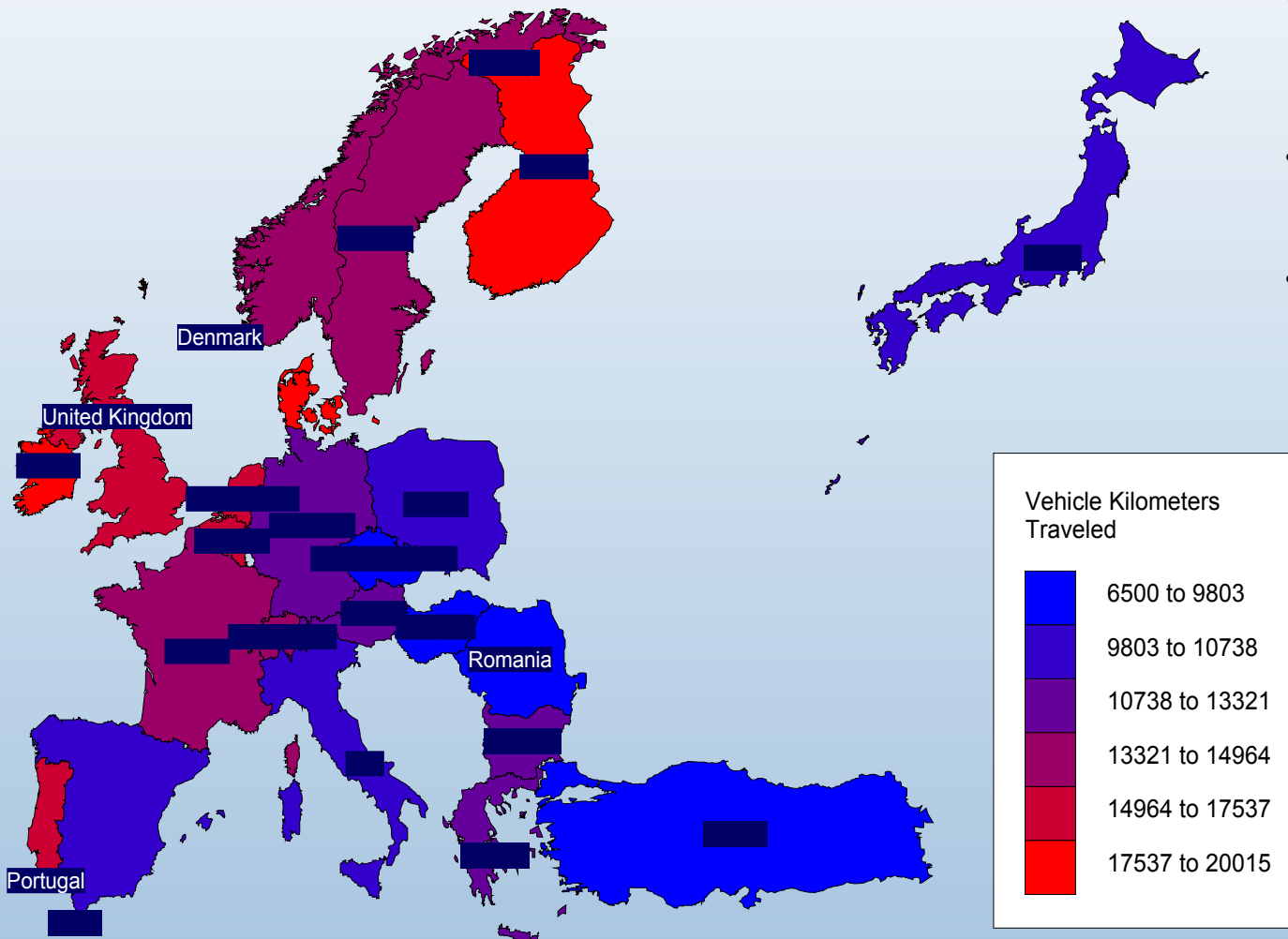
Sources:

- 2002 World Road Statistics from the International Road Federation
- International Road Traffic and Accident Database
- Ward's Automotive Yearbook, 2001

Vehicle Kilometers Traveled

- 6500 to 9803
- 9803 to 10738
- 10738 to 13321
- 13321 to 14964
- 14964 to 17537
- 17537 to 20015

U.S.:

- Car: 11,850 miles (19,070 km)
- Truck: 11,958 miles (19,244 km)

Denmark

United Kingdom

Portugal

Romania

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National Fuel Used for AC

State A

TMY → T / H → TC → City B (PPD → Time → Month) [City A, City X] → PPD → VMT w/AC → MPG w/AC / MPG w/o AC → Gal for AC/veh → Reg → Tot Gal /State
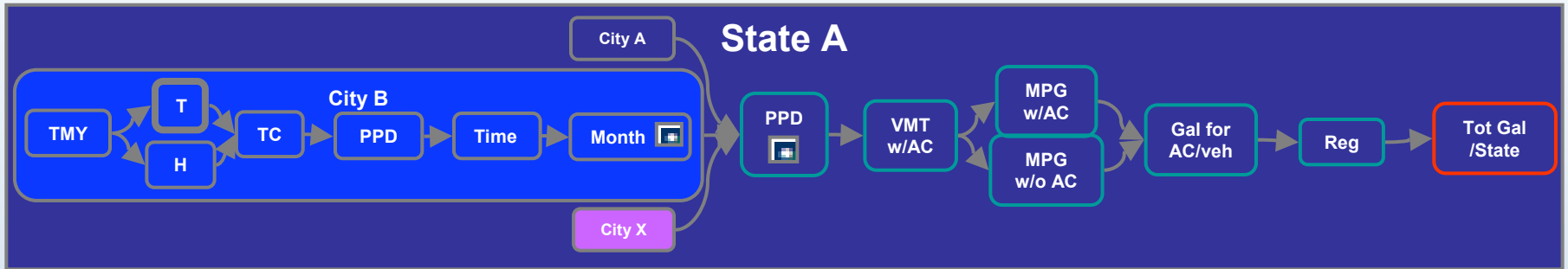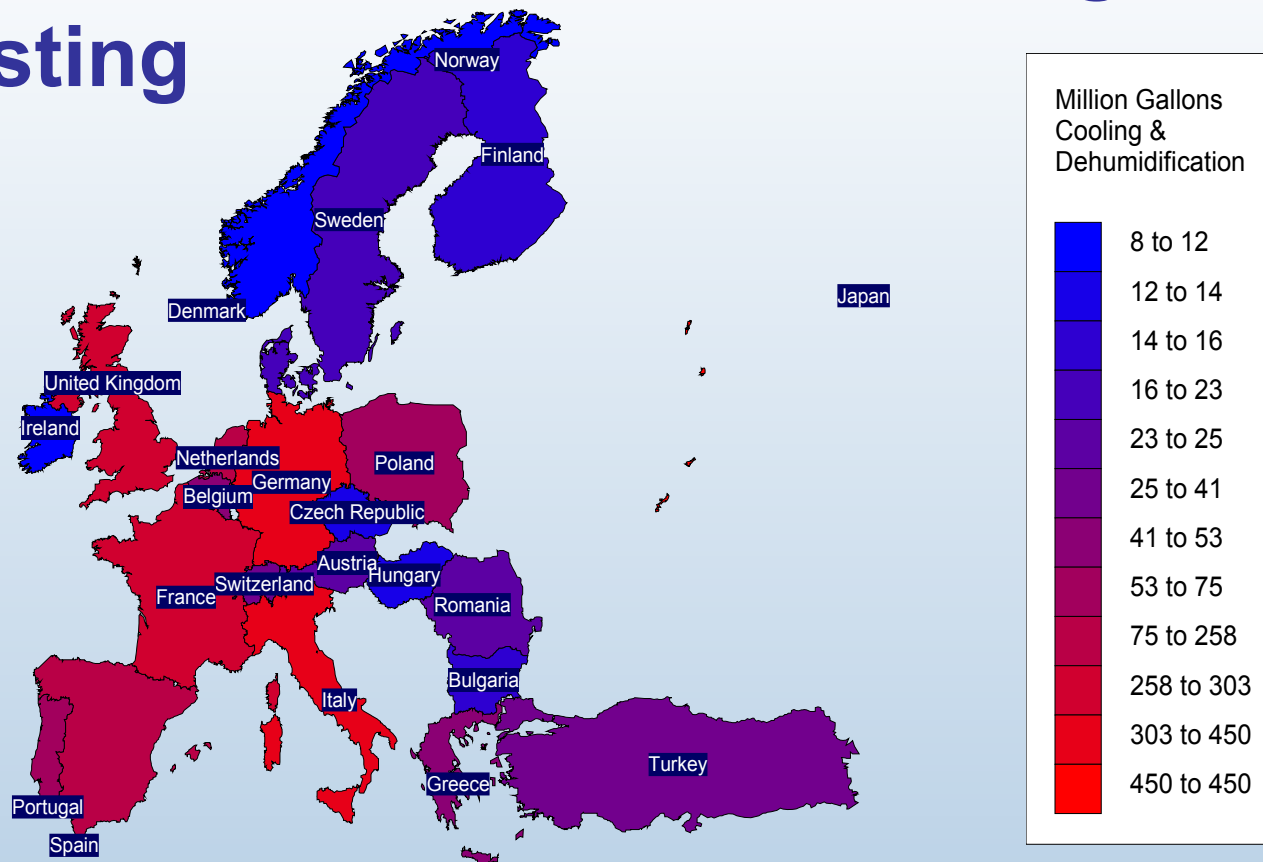
- **7.0** billion gallons used for air conditioning annually
- **5.5%** total fuel consumption
- **62** billion kg CO_2
- **9.5%** imported crude oil

**Million Gallons Cooling & Dehumidification**

- 1 to 17
- 17 to 26
- 26 to 52
- 52 to 68
- 68 to 78
- 78 to 86
- 86 to 142
- 142 to 176
- 176 to 216
- 216 to 242
- 242 to 730
- 730 to 753
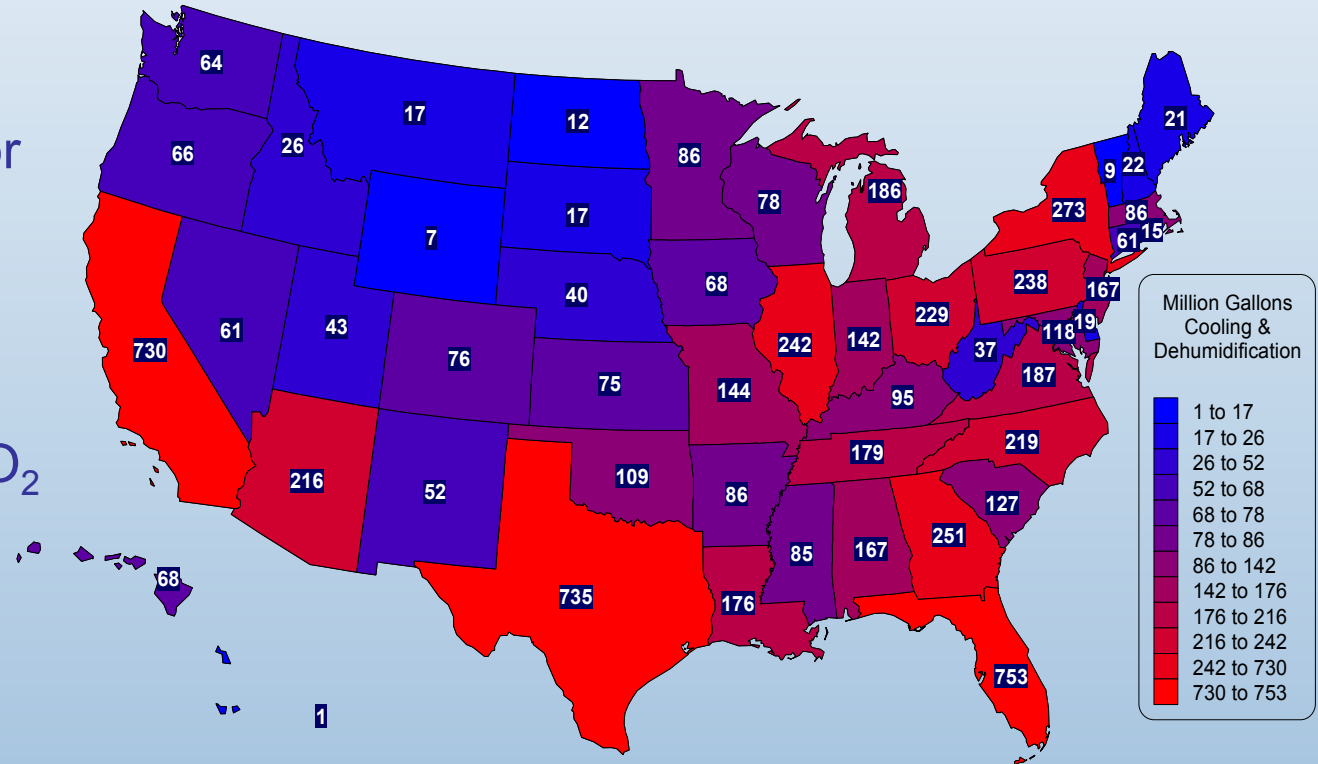
Total Fuel Use for AC for Cooling and Demisting

Million Gallons Cooling & Dehumidification

Color	Range
	8 to 12
	12 to 14
	14 to 16
	16 to 23
	23 to 25
	25 to 41
	41 to 53
	53 to 75
	75 to 258
	258 to 303
	303 to 450
	450 to 450

	Totals Dehumid + Cooling	Billion Gallons	Billion Liters	Billion kg CO2	Percent of Total Consumption
EU	100% Market	1.8	6.9	16.0	3.2%
Japan	100% Market	0.45	1.7	4.0	3.5%

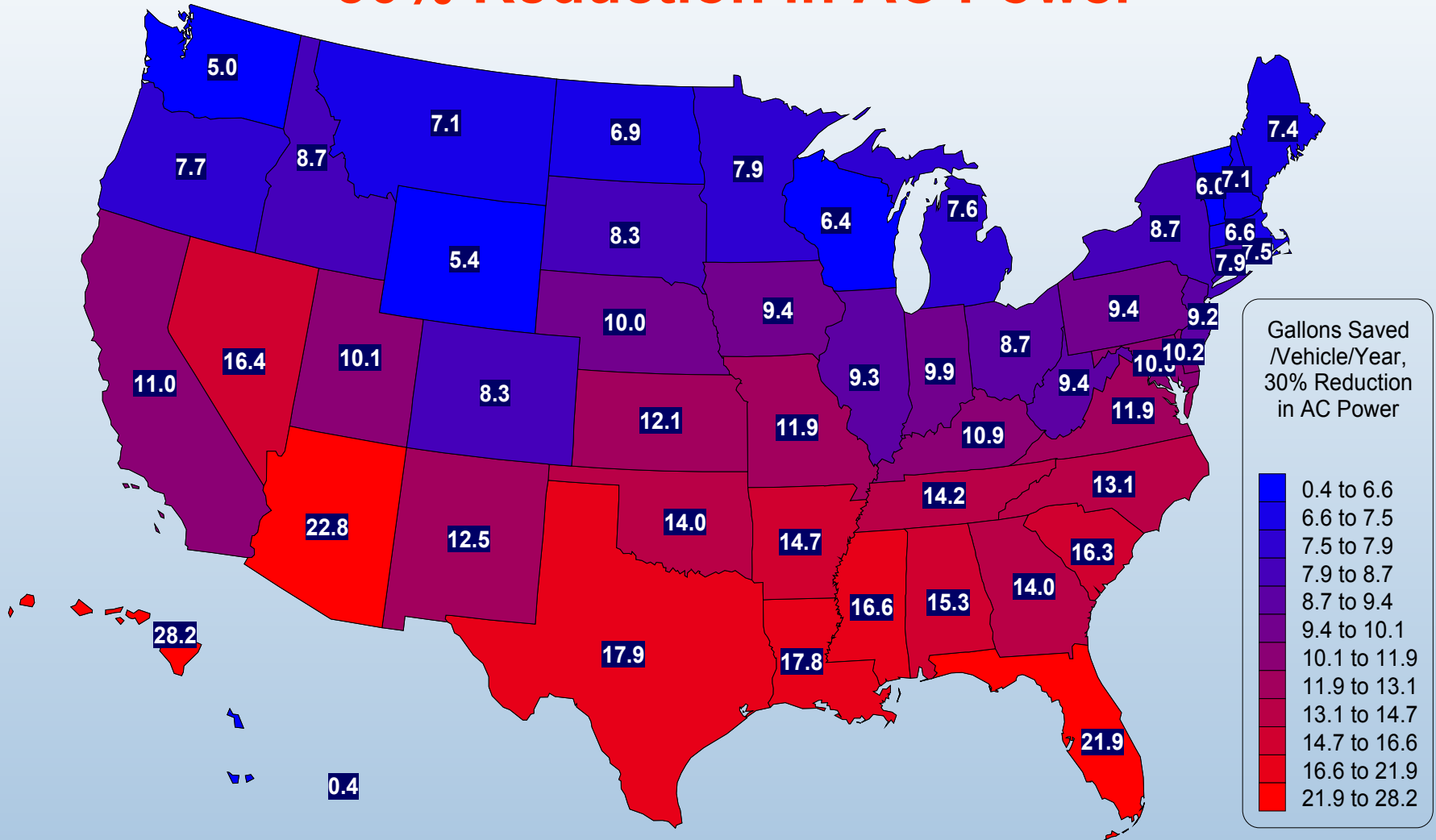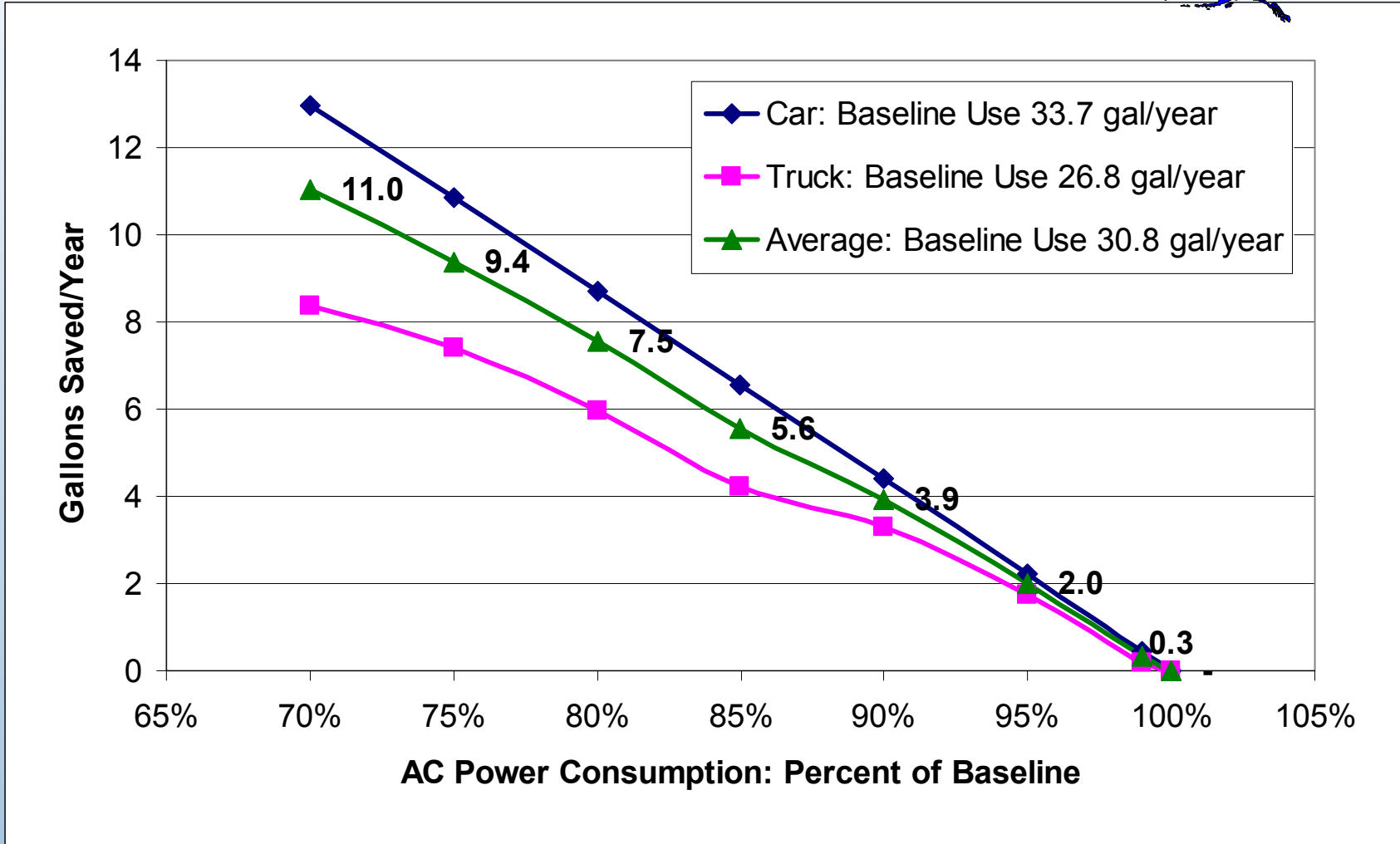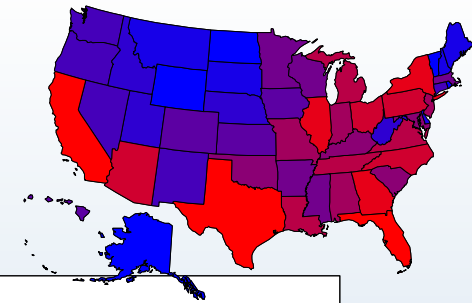# U.S. Fuel Saved & CO$_2$ Reduced by Reducing AC Consumption
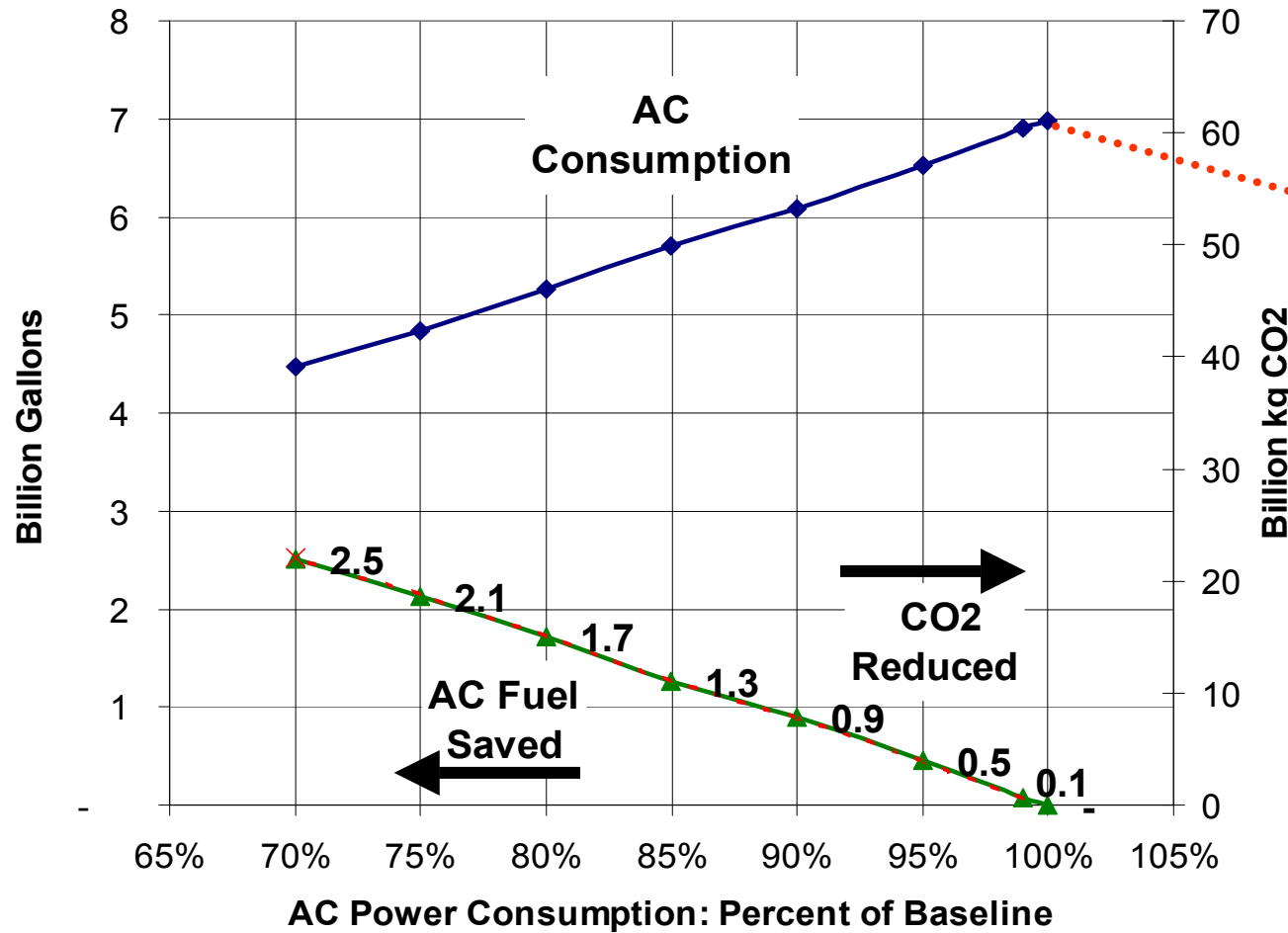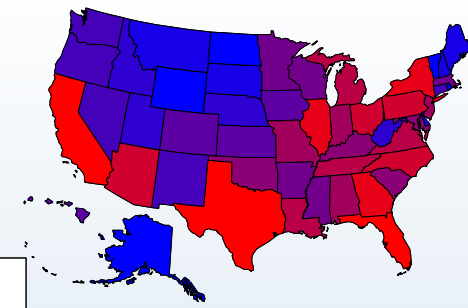
Fuel Saved per Vehicle by Climate
30% Reduction in AC Power

Per Vehicle Fuel Saved by Reducing AC Consumption

Gallons Saved/Year (y-axis)

AC Power Consumption: Percent of Baseline (x-axis)

Legend:
- Car: Baseline Use 33.7 gal/year
- Truck: Baseline Use 26.8 gal/year
- Average: Baseline Use 30.8 gal/year

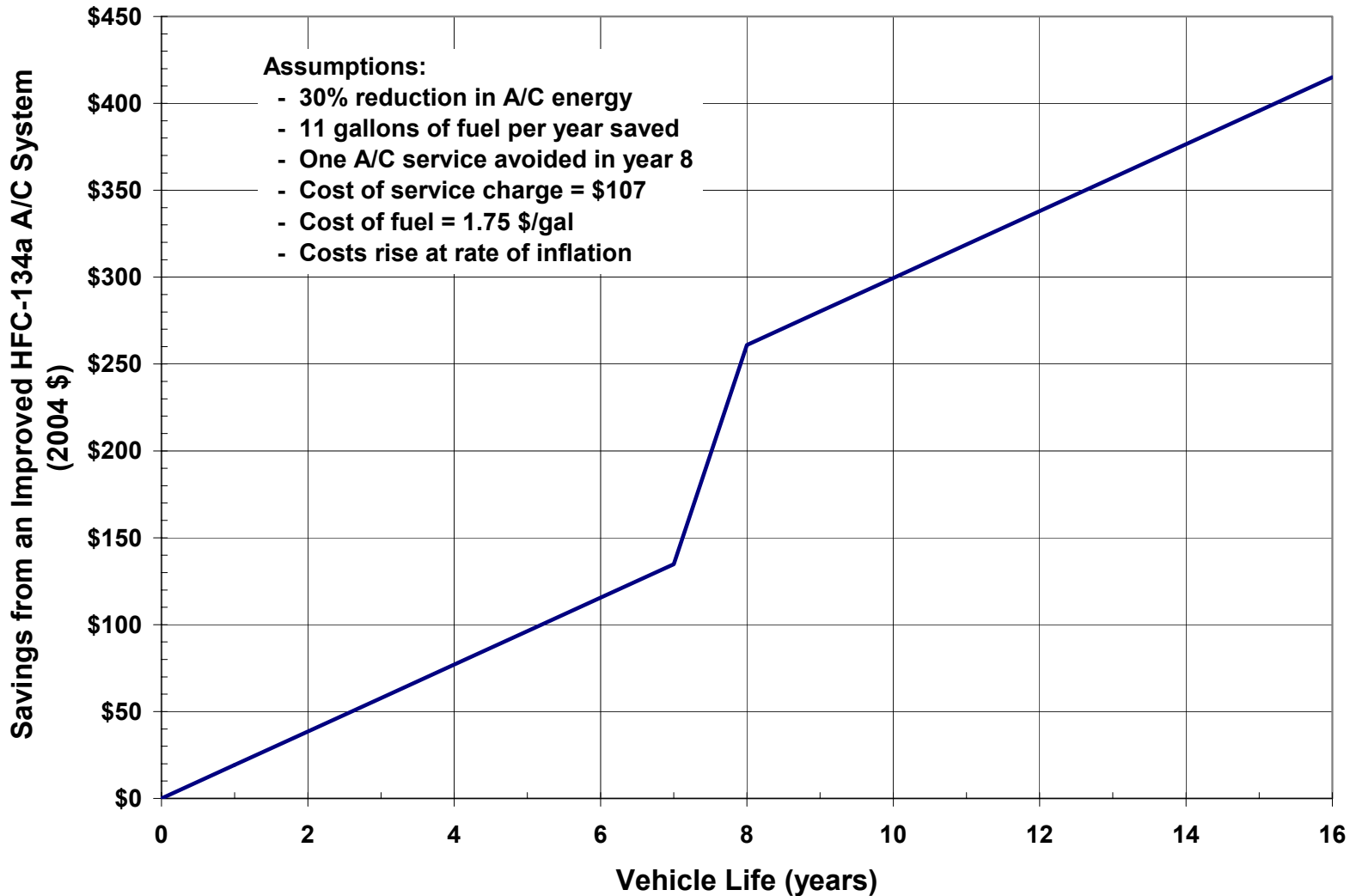Average data labels: 11.0, 9.4, 7.5, 5.6, 3.9, 2.0, 0.3

U.S. Fuel Savings Taking into Account New Technology Penetration
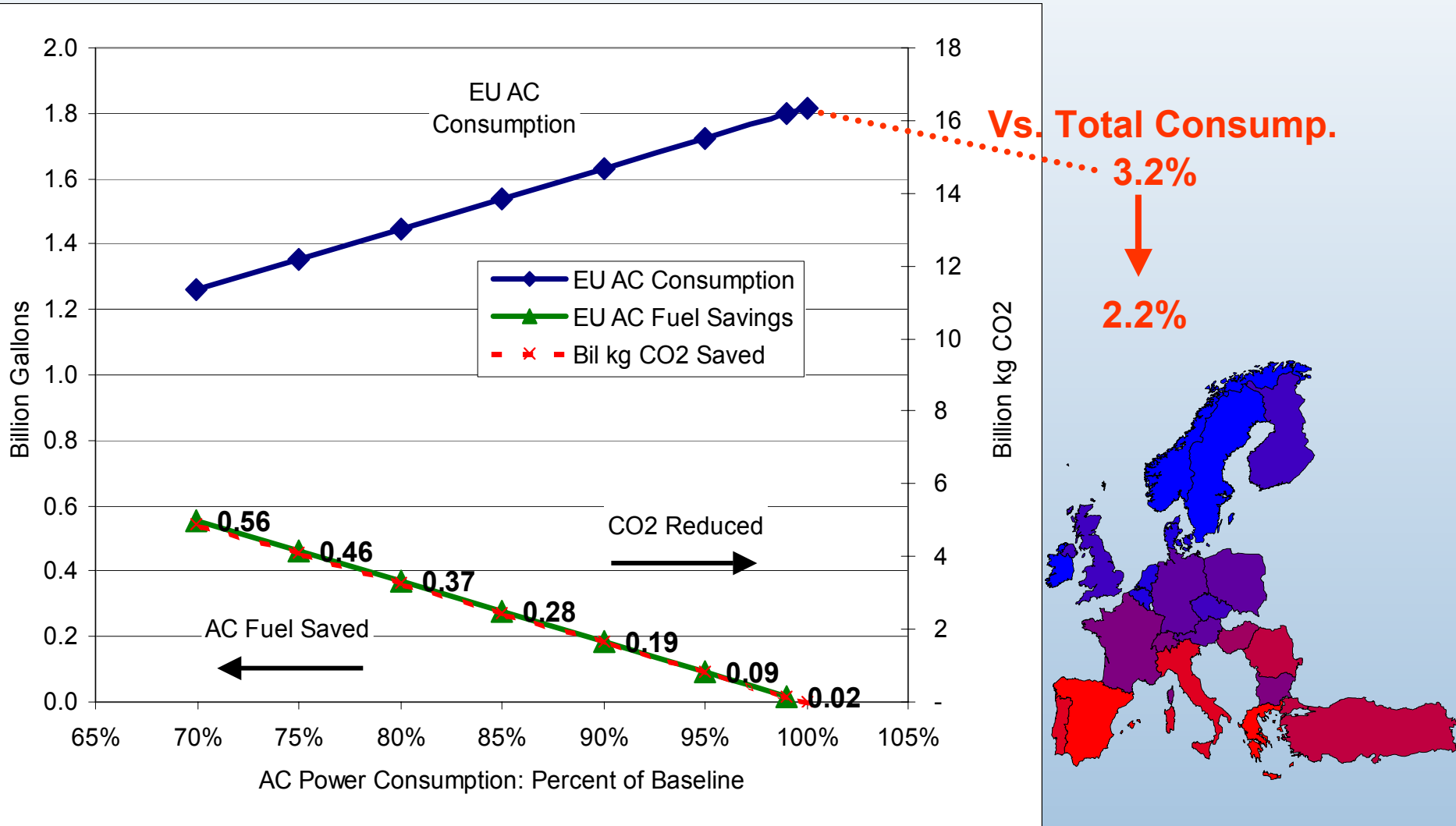
- Assumptions
  - 15% and 30% reductions in AC power
  - Power reductions begin in 2010
  - Fleet grows through time (DOE's Vision model)
    - 234 million in 2010
    - 293 million in 2050
  - Fleet turnover in 16 years
  - VMT increases over time
   - 13,500 miles in 2010
    - 19,950 miles in 2050

30% Reduction in AC Power

3.7 bil gal/yr Saved by 2025

15% Reduction in AC Power

Billion Gallons per Year Saved

Time (year)
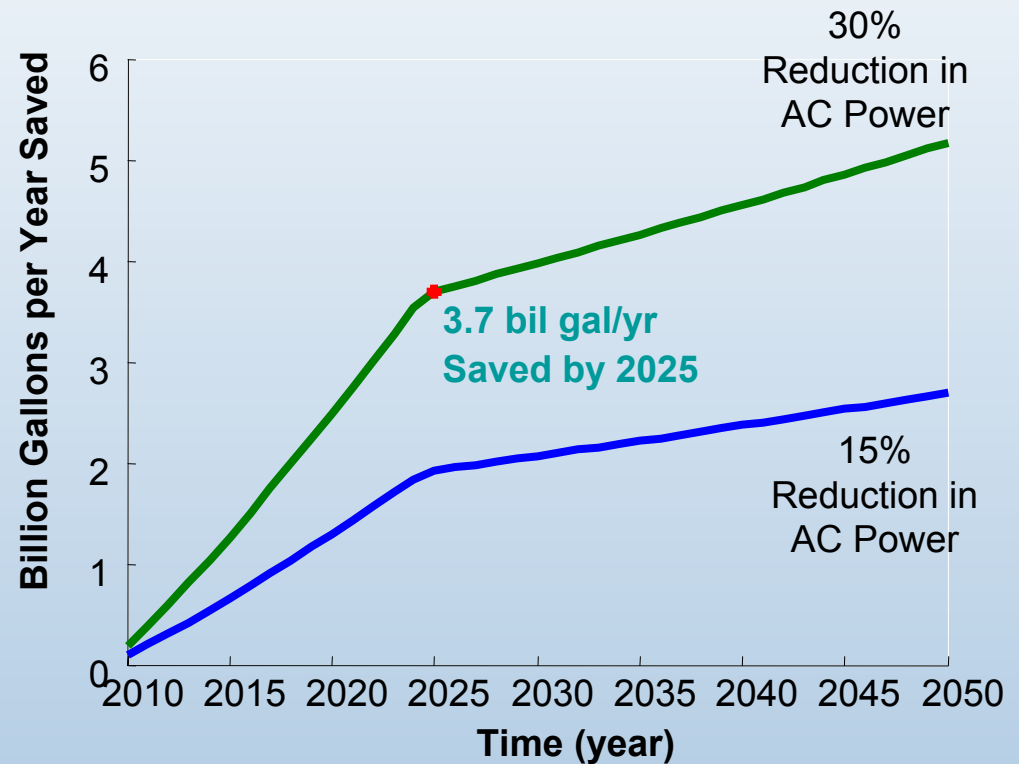
Per Vehicle Savings from an Improved MAC

Savings from an Improved HFC-134a A/C System (2004 $) vs. Vehicle Life (years)

Assumptions:
- 30% reduction in A/C energy
- 11 gallons of fuel per year saved
- One A/C service avoided in year 8
- Cost of service charge = $107
- Cost of fuel = 1.75 $/gal
- Costs rise at rate of inflation

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EU Fuel Saved by Reducing AC Power Consumption

Vs. Total Consump.
3.2%

2.2%

Japan Fuel Saved by Reducing AC Power Consumption
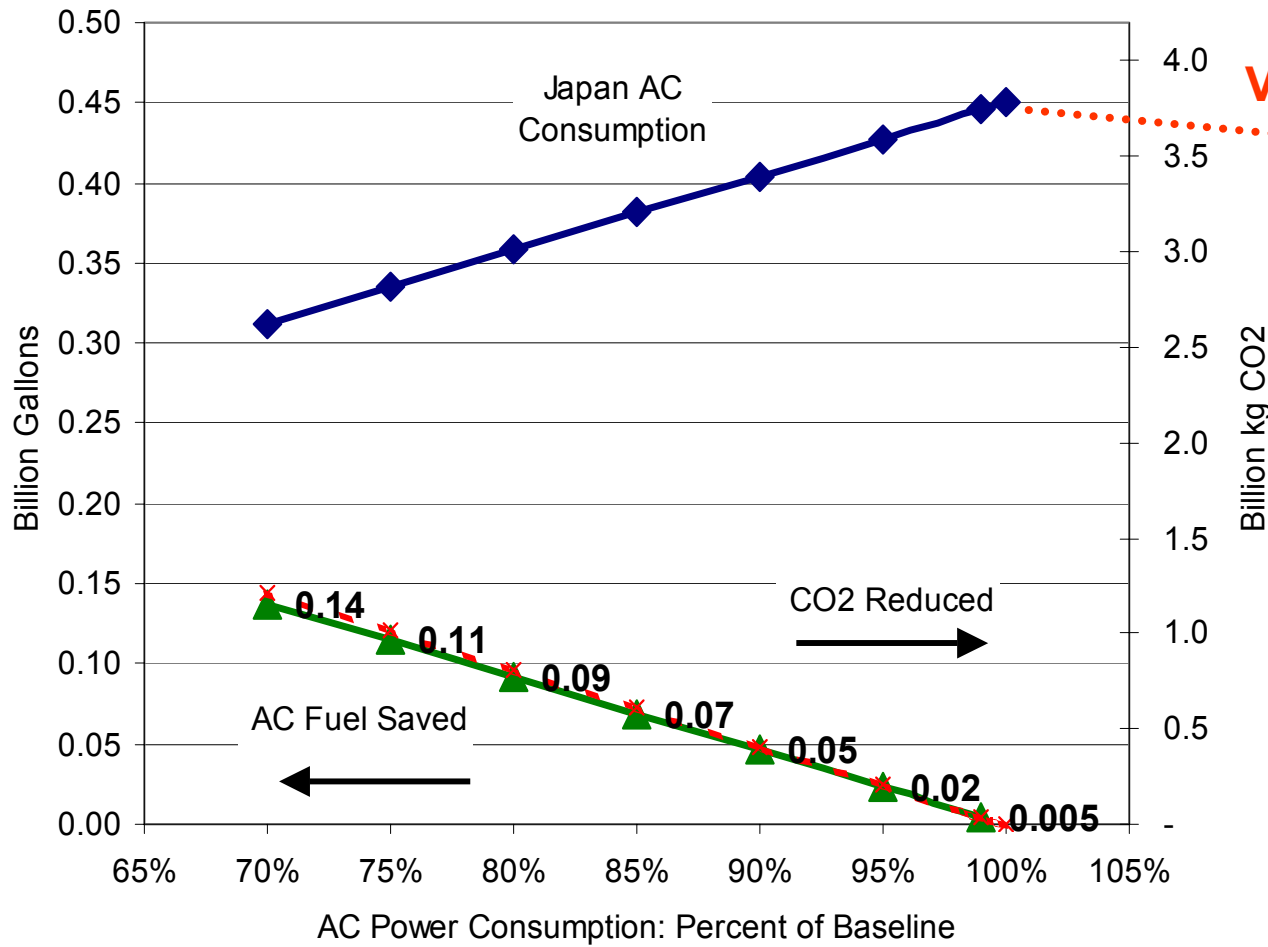
Conclusions

- MAC fuel use & CO2 emissions are strong functions of:
  - Vehicle design
  - Vehicle use
  - Environment

- Solutions to reduce fuel consumed by MACs
  - Reduce the thermal load – improve vehicle design
  - Improve delivery – design for occupant thermal comfort
  - Improve equipment
  - Educate consumers on impacts of driver behavior on MAC fuel use

Conclusions (cont.)

- Thermal comfort-based AC fuel use prediction

|	US	EU	Japan
AC Fuel Use, Billion Gallons	7.0	1.82	0.45
AC Fuel Use, Percent of Total Consumption	5.5%	3.2%	3.4%

- Reducing AC fuel use has the potential to greatly benefit the nation

  - Reduce imported oil

  - Reduce CO_2

- Per vehicle savings allow calculation of payback time

30% Reduction in Power	Units	US	California	EU	Japan
Savings per Vehicle	*gal/year*	**11.0**	**11.0**	**2.5**	**2.2**
Reference Total Consumption	*gal/year*	30.8	30.5	8.0	7.2
Savings of Total Consumption	*%*	2.0%	-	1.0%	1.0%
Fuel Saved	*Bil Gallons*	2.5	0.26	0.56	0.14
Fuel Saved	*Bil Liters*	9.5	1.0	2.1	0.5
Emissions Reduced	*Bil kG CO2*	22.1	2.3	4.9	1.2

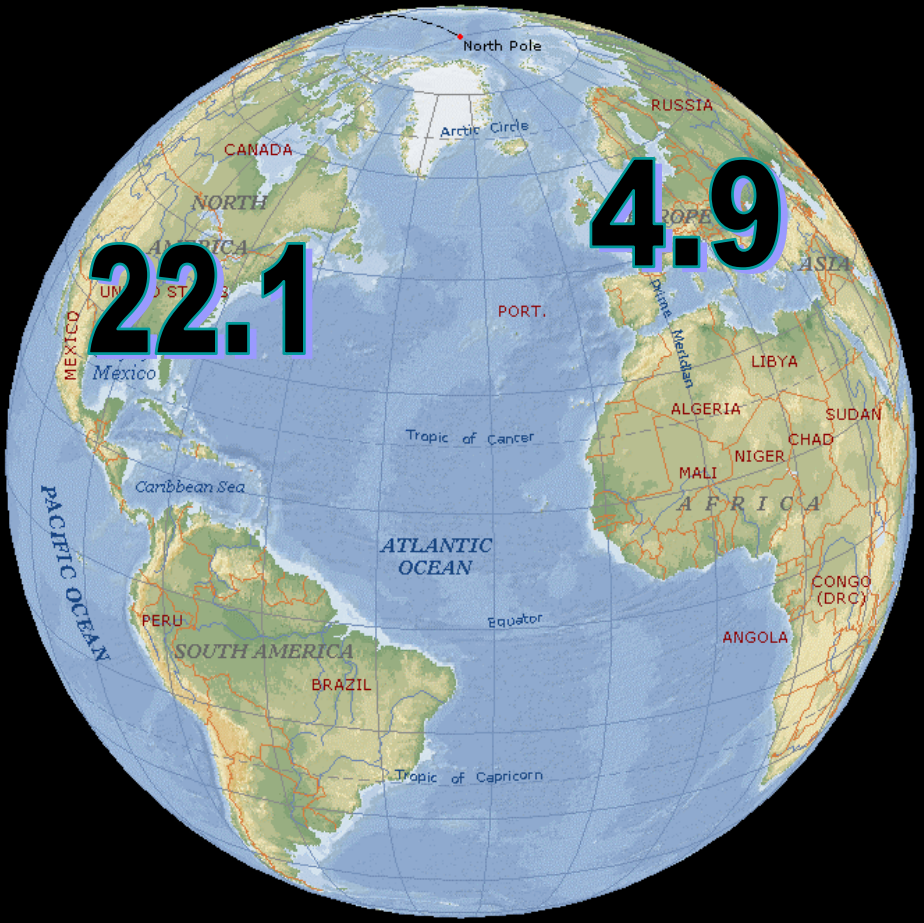- Impact of incremental reduction in AC power: states, nations, world

Fuel Savings across the World

Billion Gallons: Savings with 30% Drop in AC Power

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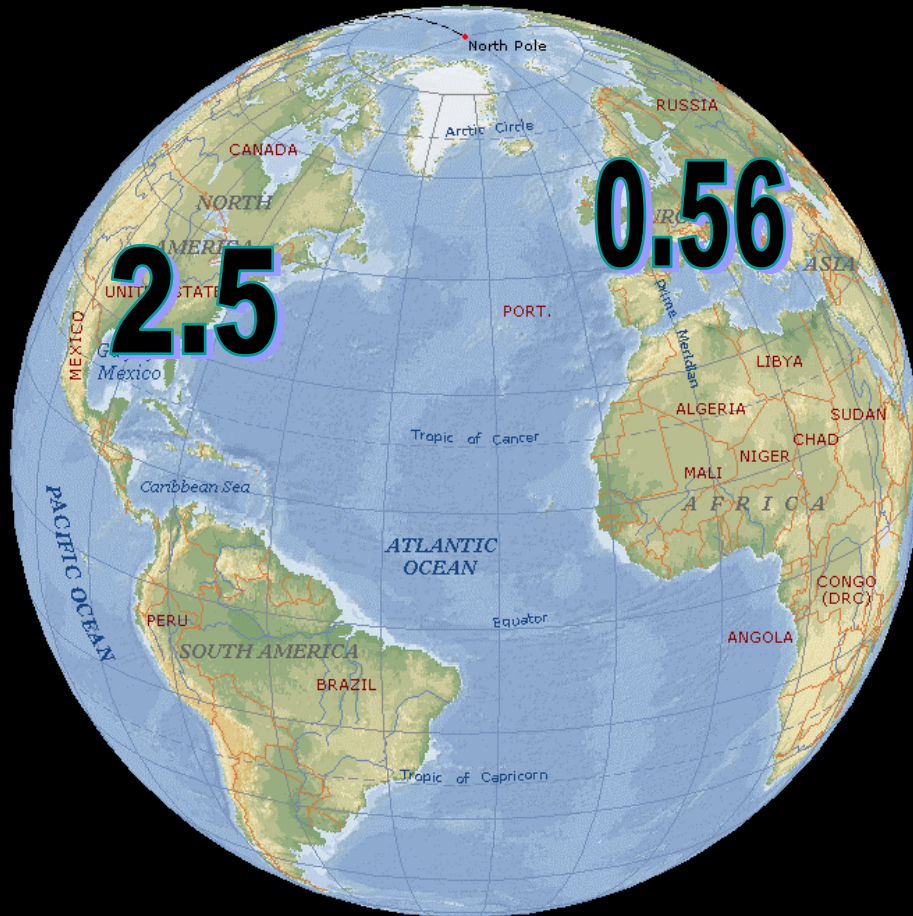
CO$_2$ Reduction across the World

Billion kg CO$_2$: Reduction with 30% Drop in AC Power

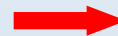

22.1

4.9

1.2

Thank you!

- John Rugh
  - Ph: 303-275-4413
  - Email: john_rugh@nrel.gov
- Valerie Hovland
  - Email: vhovland@mesoscopic.com
- Stephen Andersen
  - Ph: 202-343-9069
  - Email: andersen.stephen@epa.gov
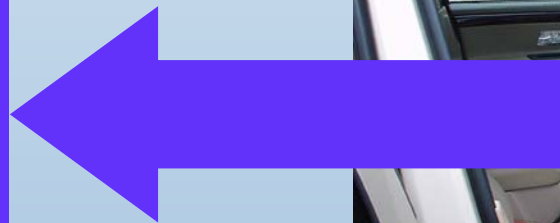
Back Up

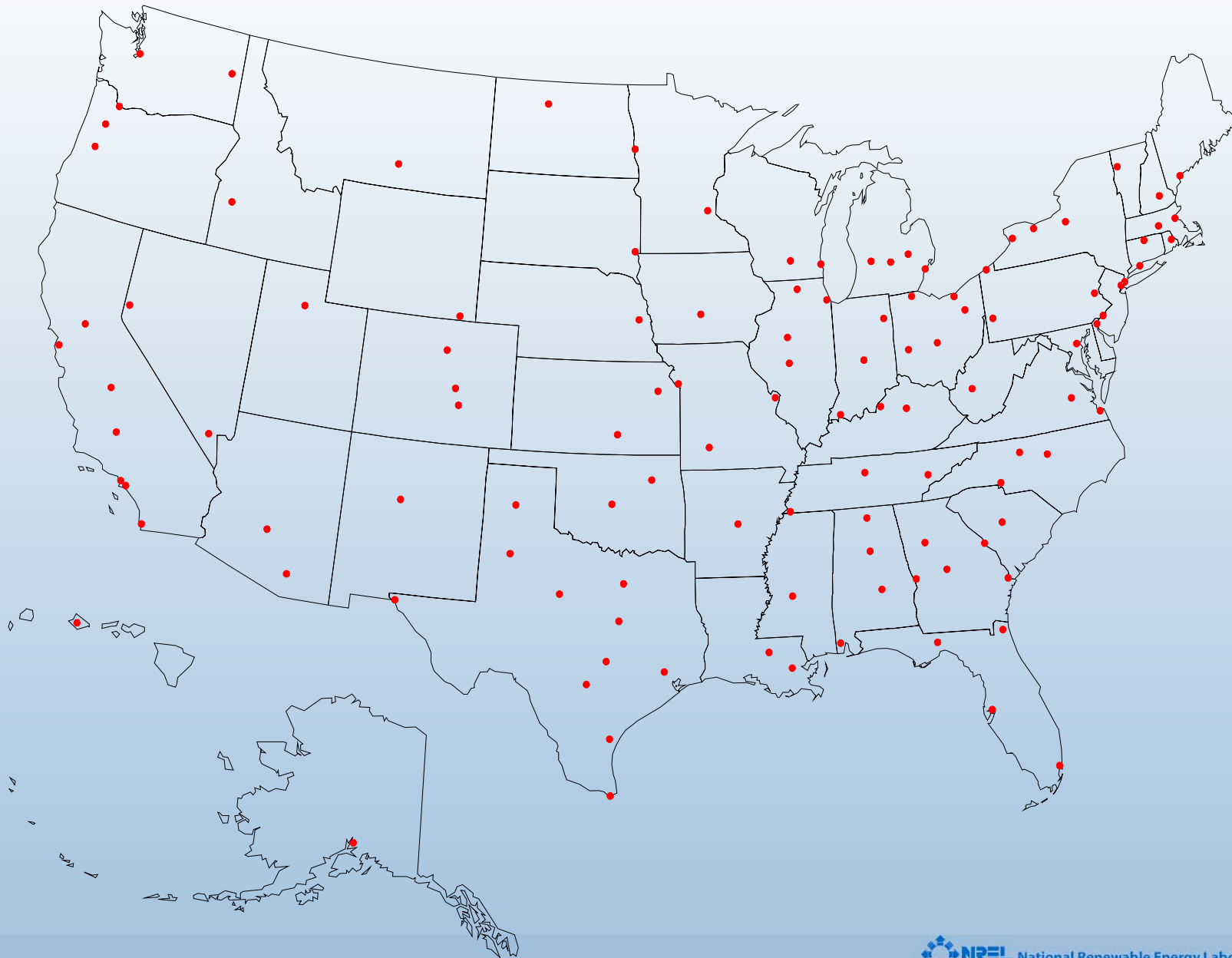# Why So Much Fuel for A/C?

Metabolic Heat Generation

150 Watts

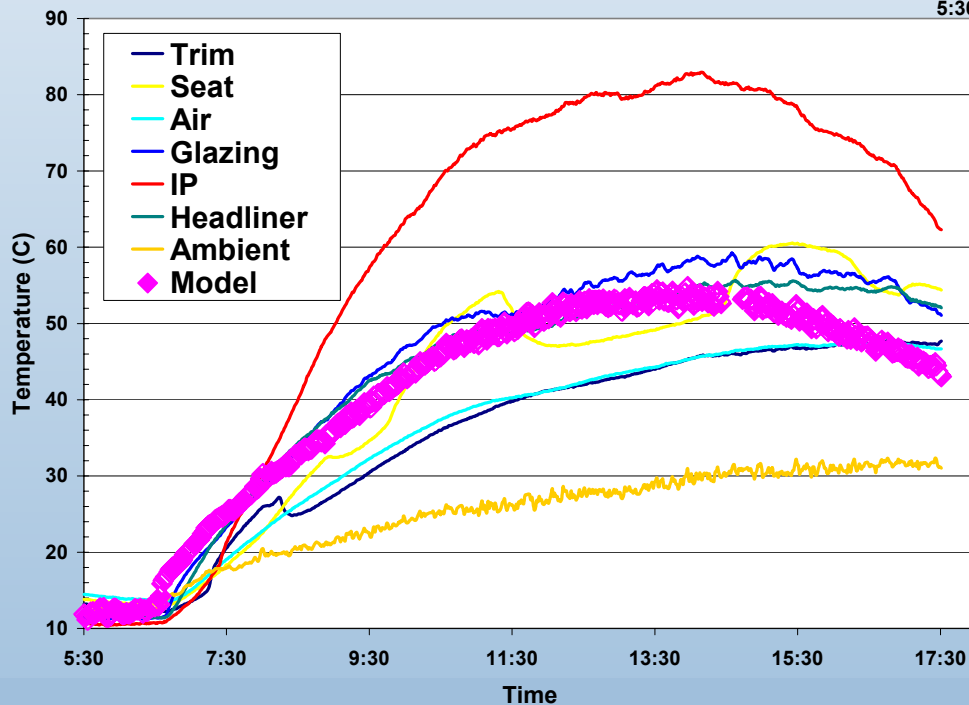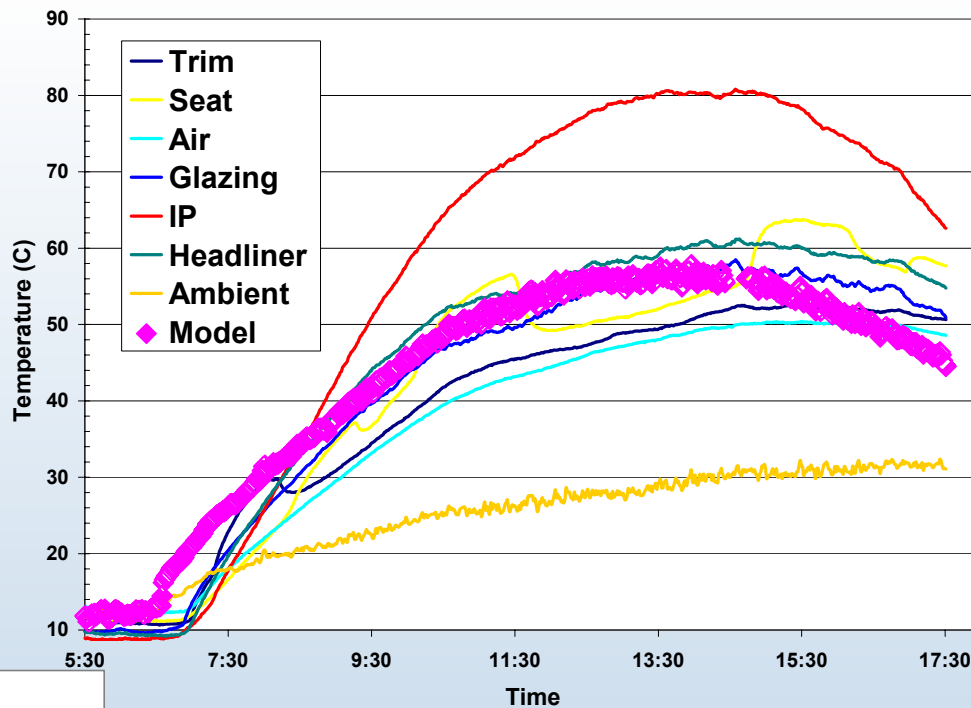A/C Cooling 3-6 kW$_{th}$!

Cities Used from TMY Data Base

Car & Truck MRT

- Plymouth Breeze
- July 12
- Golden, CO

- Jeep Grand Cherokee
- July 12
- Golden, CO

Vehicle Modeling in ADVISOR

- U.S. Car
  - 115 kW SI engine, 1300 kg
- U.S. Truck
  - 144 kW SI, 1924 kg
- EU Vehicle
  - 91 kW compression ignition diesel, 1220 kg
- Fuel economy expressed in gasoline equivalent fuel consumption
- CO_2 emissions determined from fuel consumption
  - 2.33 kg CO_2/liter fuel

Engine Efficiency
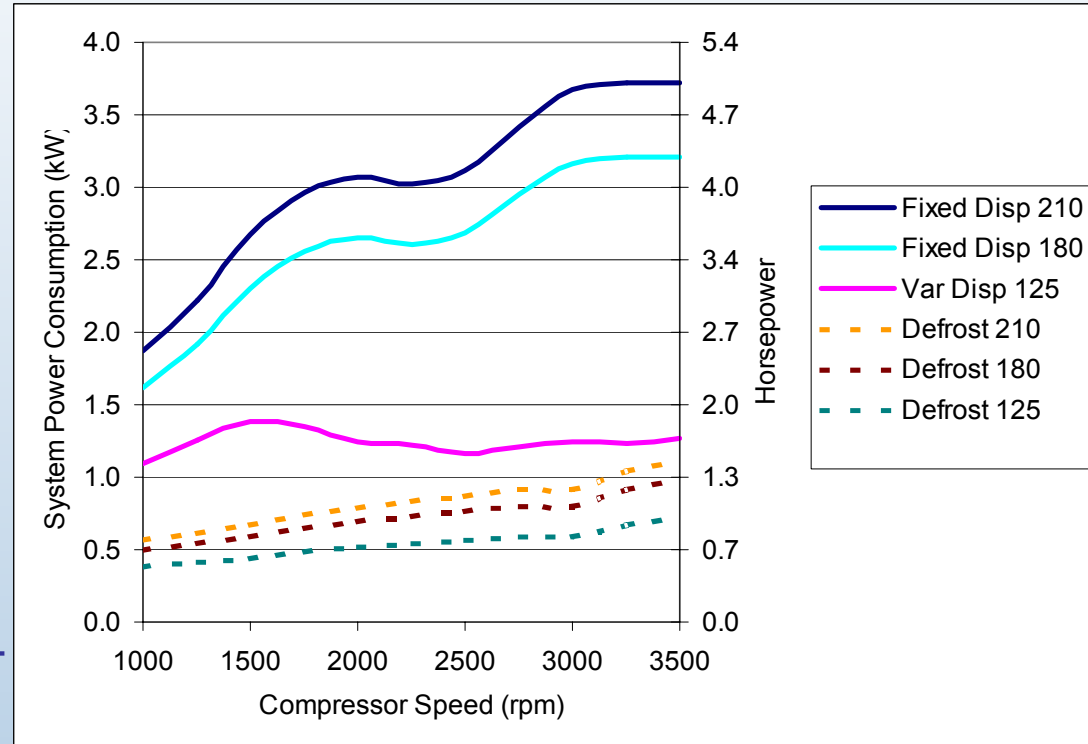Mercedes 1.7L Diesel Engine f/ ORNL
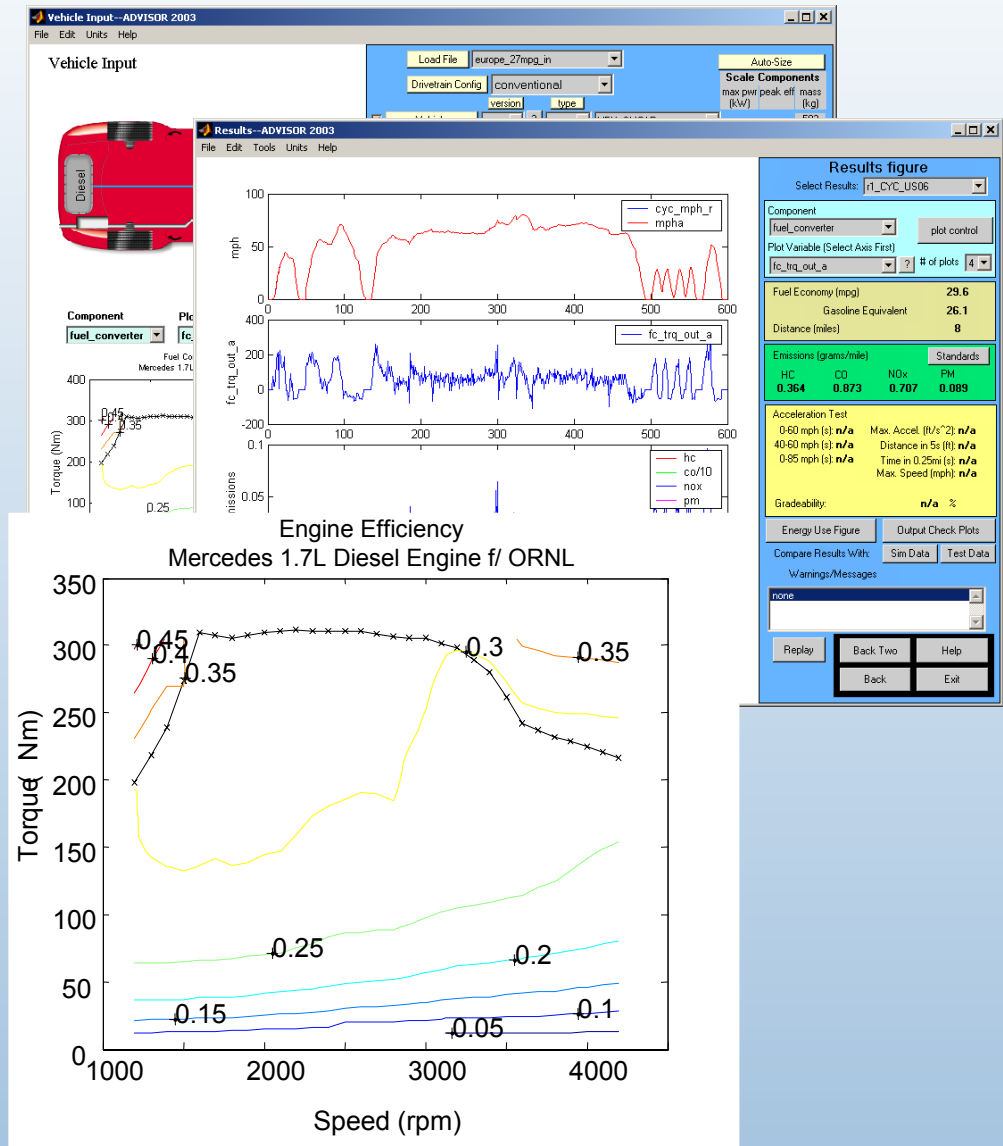
AC Modeling

- HFC-134a

  - U.S. trucks: 210 cc fixed

  - U.S. cars: 180 cc fixed

  - EU vehicle: 125 cc variable displacement

  - Compressor power consumption based on Delphi compressor curves

  - Total power = $P_{compressor}$ + P_{blower}

   - P_{blower} = 120 W

- Engine speed/compressor speed ratio = 0.64

Curves based on work by Forrest at Delphi

- Cooling mode: 27°C, 60% RH
- Demist mode: 16°C, 80% RH

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Conservative Estimate of Fuel Used for AC

- Fanger's thermal comfort model excludes:
  - Sun hitting a driver
  - Thermal asymmetry
  - Sitting on a hot seat
  - High humidity impacts
- Model excludes AC use due to
  - Automatic Temperature Control
- EU compressor power
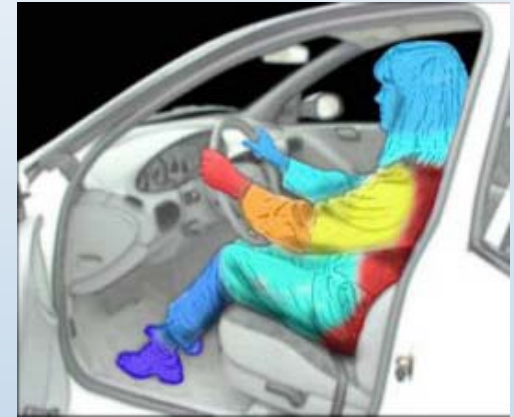
Incremental Reduction in AC Power
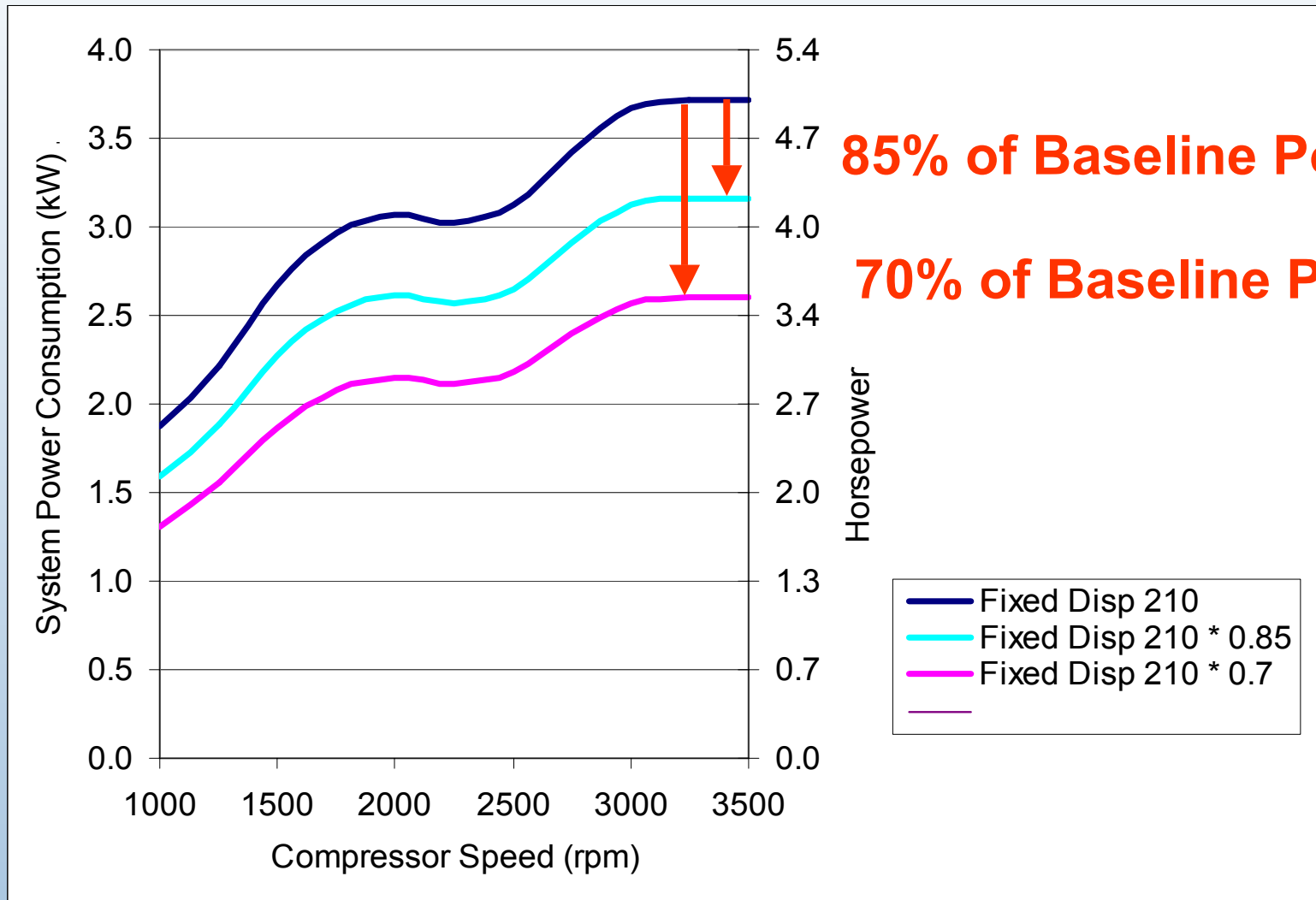
EU/Japan Per Vehicle Fuel Saved by Reducing AC Consumption