Fuel Consumption and Associated CO_2 Emissions due to MACs

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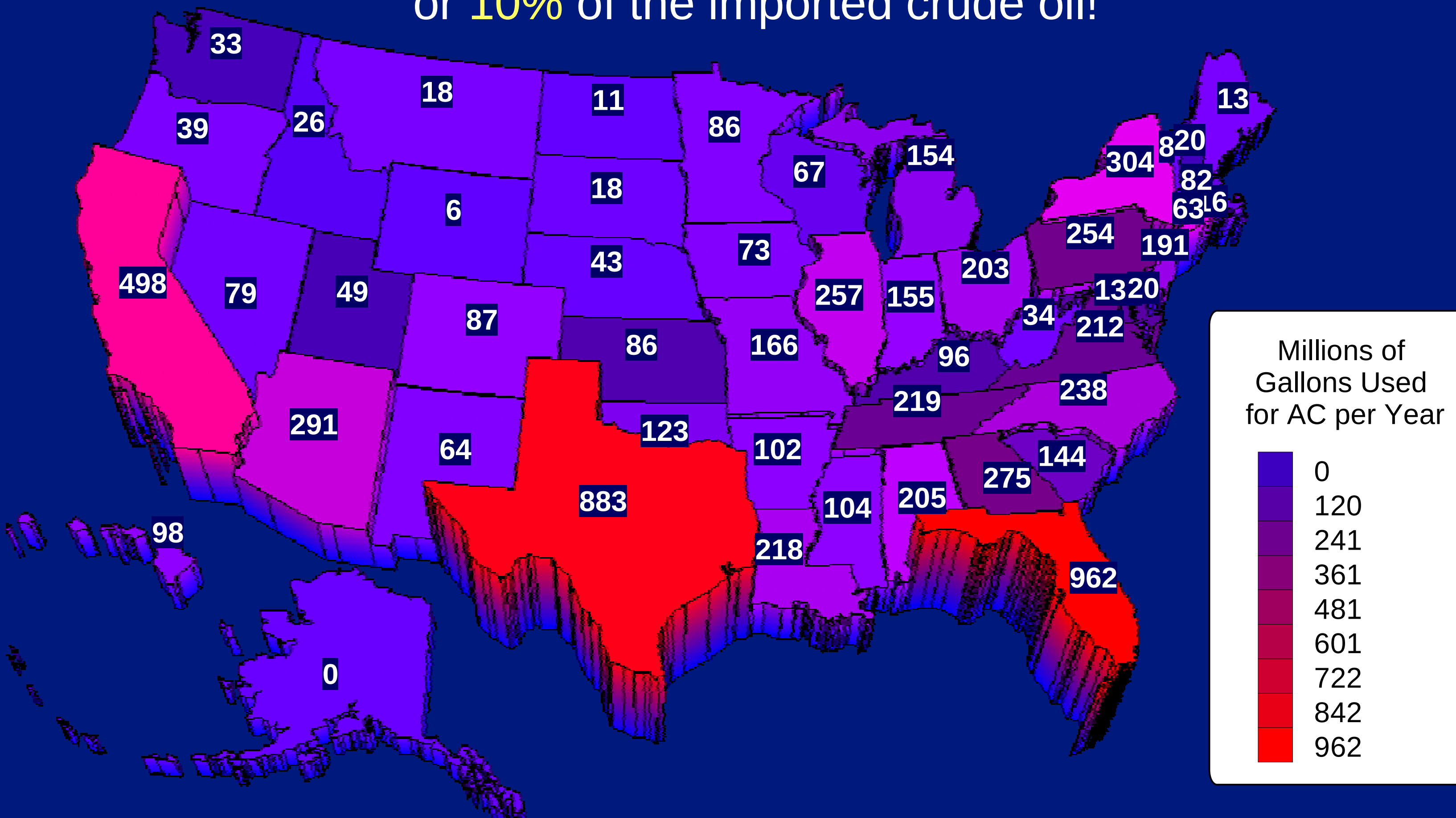
United States AC Fuel Use

27 billion liters (7.1 billion gallons) used for air conditioning annually

Equivalent to 6% of the national fuel use,

or 10% of the imported crude oil!



Why So Much Fuel for A/C?

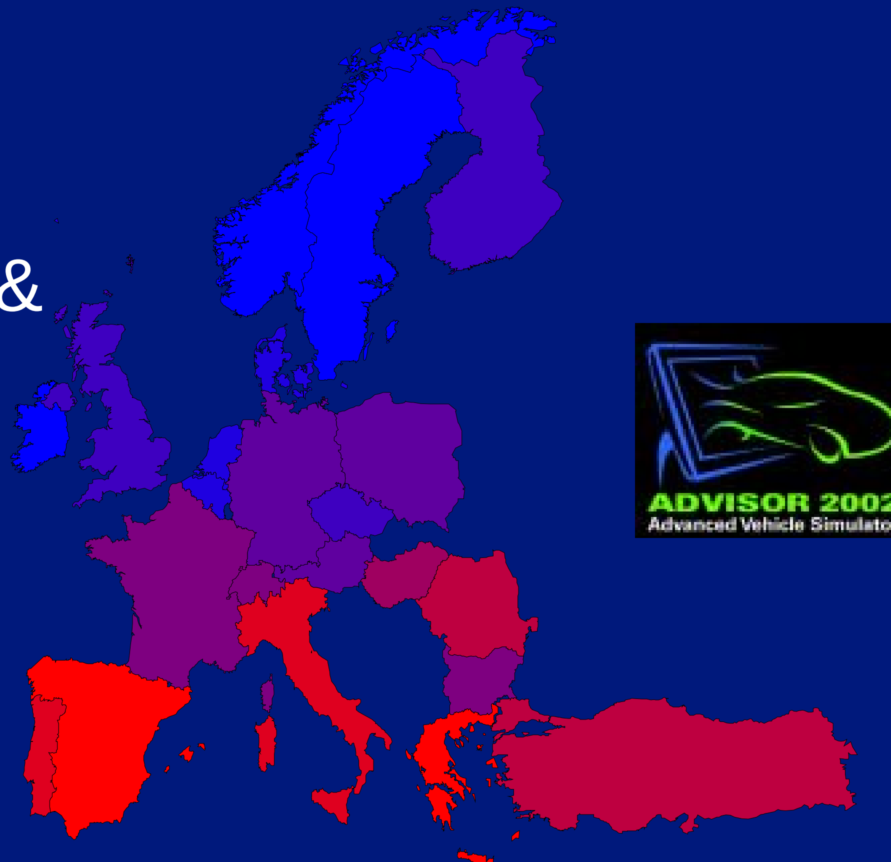
Metabolic Heat Generation

150 Watts

A/C Cooling
3-6 kW_{th}!

Outline

- Important parameters impacting MAC fuel use & CO_2 emissions



- Modeling approach

- Modeling results

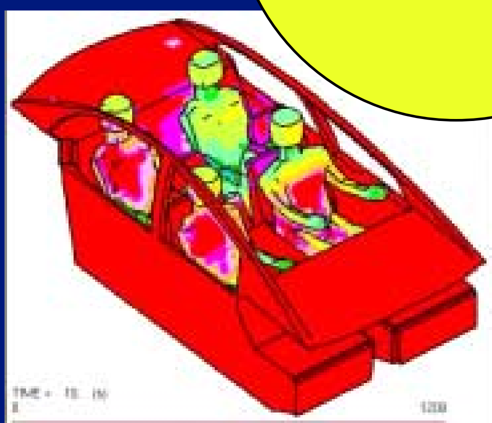
- Solutions to reduce MAC fuel use & CO_2 emissions

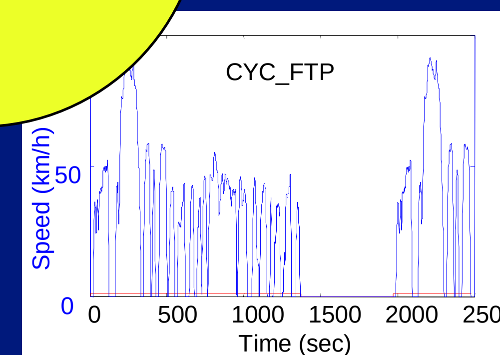
Important Parameters for AC Fuel Use

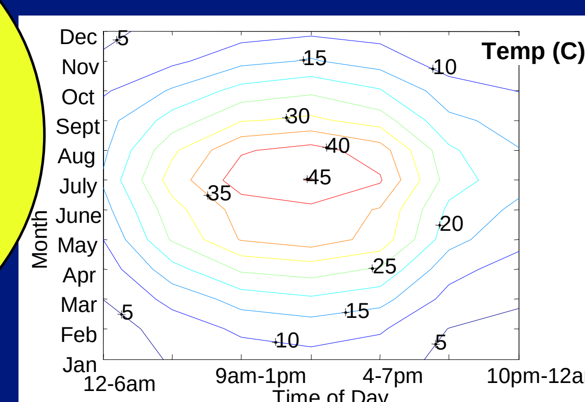
Vehicle Design

Vehicle Use

Environ-ment







Factors Impacting MACS Fuel Consumption and Associated CO_2 Emissions

Vehicle Design

Style

- Glazing
  - Area
  - Slope
- Vehicle mass
- Cabin size and mass
- Instrument panel size
- Engine type, displacement
- Frontal area and geometry
- Vehicle exterior/interior color
- Vehicle drag, rolling resistance

Thermal

- Optical Properties
  - Paint
  - Glass
  - Instrument Panel
- Cabin
  - Mass
  - Insulation
  - Air leakage
  - Thermal properties
- Parked Car Ventilation

AC System

- Controls
  - Cabin temp
  - Recirculation
  - Compressor
  - Solar compensation
- Exhausters
- Air distribution
- System weight
- Refrigerant type
- Compressor
  - Fixed displacement
  - Variable displacement

Factors Impacting MACS Fuel Consumption and Associated CO_2 Emissions

Vehicle Use

Driver/Occupant

- Driving style
- Vehicle maintenance
- Windows open/closed
- Interface with A/C Control
- A/C use
    - Comfort
    - Defogging/dehumidification
    - Noise/allergen reduction
    - Pollution/dust reduction

Drive Cycle

- Regulatory
- Real world
- City vs. Highway
- Idle time (engine off/on)
- Vehicle speed impacts
    - Engine speed
    - Condenser airflow
    - Cabin heat loss/gain

Parked

- In sun
- In shade
- Vehicle orientation
- Sunroof closed/open
- Windows closed/open

Factors Impacting MACS Fuel Consumption and Associated CO_2 Emissions

Environment

Climatic

- Wind
- Humidity
- Solar radiation
- Air temperature
- Air density (altitude)

Thermal Comfort

- Perspiration
- Cabin humidity
- Cabin temperature
- Air velocity on body
- Thermal asymmetry
- Solar radiation on body
- Mean radiant temperature
- Thermal comfort model (Fanger)

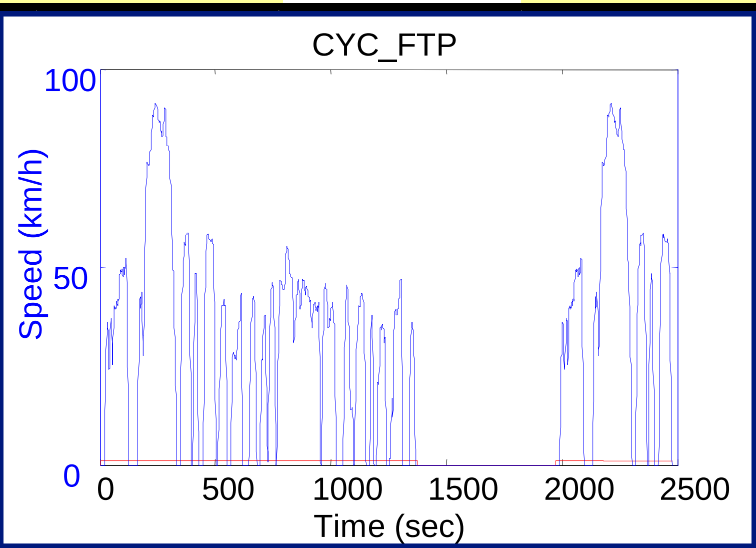
Occupant

- Metabolic rate
- Recent environment
- Occupant preferences
- Clothing type and level
  - Heat/moisture transfer
  - Thermal capacitance
  - Moisture capacitance

Many Drive Cycles: US, Europe, Japan

Drive Cycle	Time sec	Distance km	Max Spd km/h	Avg Spd km/h	Idle Time sec	Max Accel m/s^2
US06	600	13	129	77	45	3.8
SC03	600	6	88	35	117	2.3
FTP	2477	17.8	91	26	360	1.5
NEDC (Urban + ExtraUrban)	1184	11	120	33	298	1.1
J-1015	660	4	70	23	215	0.8

- U.S. SFTP test procedure now includes AC operation for regulated emissions only (SC03)
- Many other drive cycles



Impact of Drive Cycle and Compressor Type

Fuel and CO_2 Impacts of Using AC

Vehicle: 180 g CO2/km (7.7 liters/100km, 30.4 mpg)						
	FTP	US06	SC03	NEDC	J-1015	Range
Fixed Disp	125%	112%	124%	126%	130%	112-130%
Variable Disp	116%	107%	116%	116%	119%	107-119%
Fixed - Variable	9%	5%	9%	10%	10%	5-10%

For example, SC03 drive cycle used in U.S. SFTP shows 24% and 16% over-consumption for fixed and variable displacement compressors

Modeled Impact May Be Conservative

Modeled Fuel Impacts of Using AC	Experimental Fuel Impacts (5 vehicles, 28C, 50% RH) Centro Ricerche Fiat
7 – 30%	32 – 51%

MAC Fuel Consumption Varies with Climate

- Compressor power consumption varies with strongly with climate, vehicle speed, engine speed, blower speed, recirculation
- AC usage varies with thermal comfort
- AC load is a function of cabin soak temperature and demisting needs

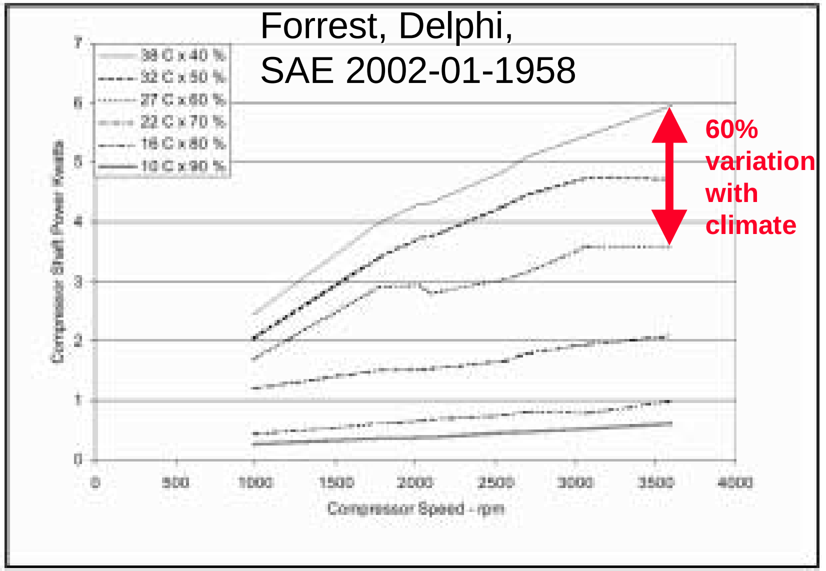
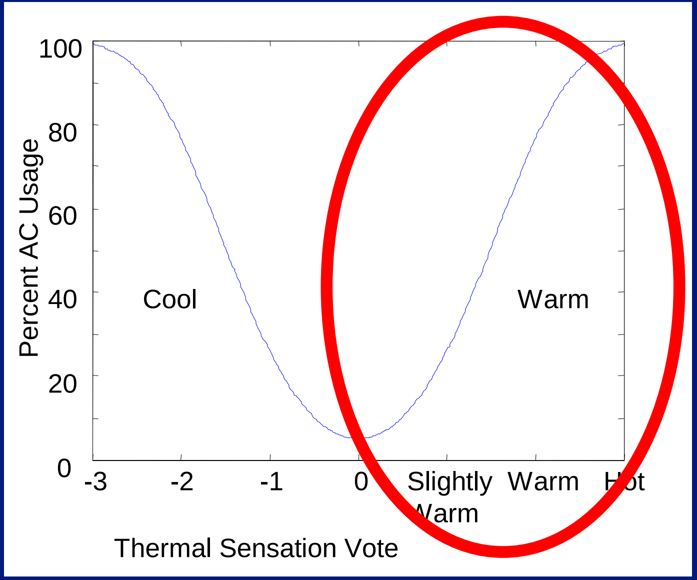


Figure 1 Compressor Shaft Power for a Large Fixed Displacement Compressor at Various Air Conditioning Loads



AC Usage

Methodology: Predicted Percent Thermally Dissatisfied by City

When are people thermally uncomfortable?

Environmental Variables

(T_{air}, Humidity, Q_{solar}; t)

Parked Car (M.R.T.)

Sun or Shade

Occupant Variables

Clothing, Metabolic Rate

Predicted Percent Dissatisfied Any Time of Day or Year

Distance Traveled with A/C

Predicted Percent Dissatisfied Any Time of Day or Year X Time-of-Day and Time-of-Year Travel = % of Time AC on for Each City

% of Time AC on X Annual Distance Traveled = Vehicle Distance Traveled with A/C

Methodology: AC Fuel Used

Vehicle Distance Traveled with A/C

→ Vehicle Fuel Economy with A/C → Vehicle Fuel Used with A/C

→ Vehicle Fuel Economy if no A/C → Vehicle Fuel Used if no A/C

Vehicle Fuel Used with A/C — Vehicle Fuel Used if no A/C = Vehicle Fuel Used for A/C

Weight City Results by Population and Use Country Vehicle Registrations to Get Fuel Used for AC by Country

Countries Used in Study

Austria
Belgium
Bulgaria
Czech Republic
Denmark
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Netherlands
Norway
Poland
Portugal
Romania
Spain
Sweden
Switzerland
Turkey
United Kingdom

Cities Used to Predict Percent of Time AC On

Country	City
Austria	Graz
	Innsbruck
	Linz
	Salzburg
	Vienna
Belgium	Brussels
Bulgaria	Plovdiv
	Sofia
	Varna
Switzerland	Geneva
Czech Republic	Ostrava
	Prague
Germany	Berlin
	Bremen
	Dusseldorf
	Frankfurt
	Hamburg
	Koln
	Mannheim
	Munich
	Stuttgart
Denmark	Copenhagen
Spain	Barcelona
	Madrid
	Palma
	Santander
	Sevilla
	Valencia

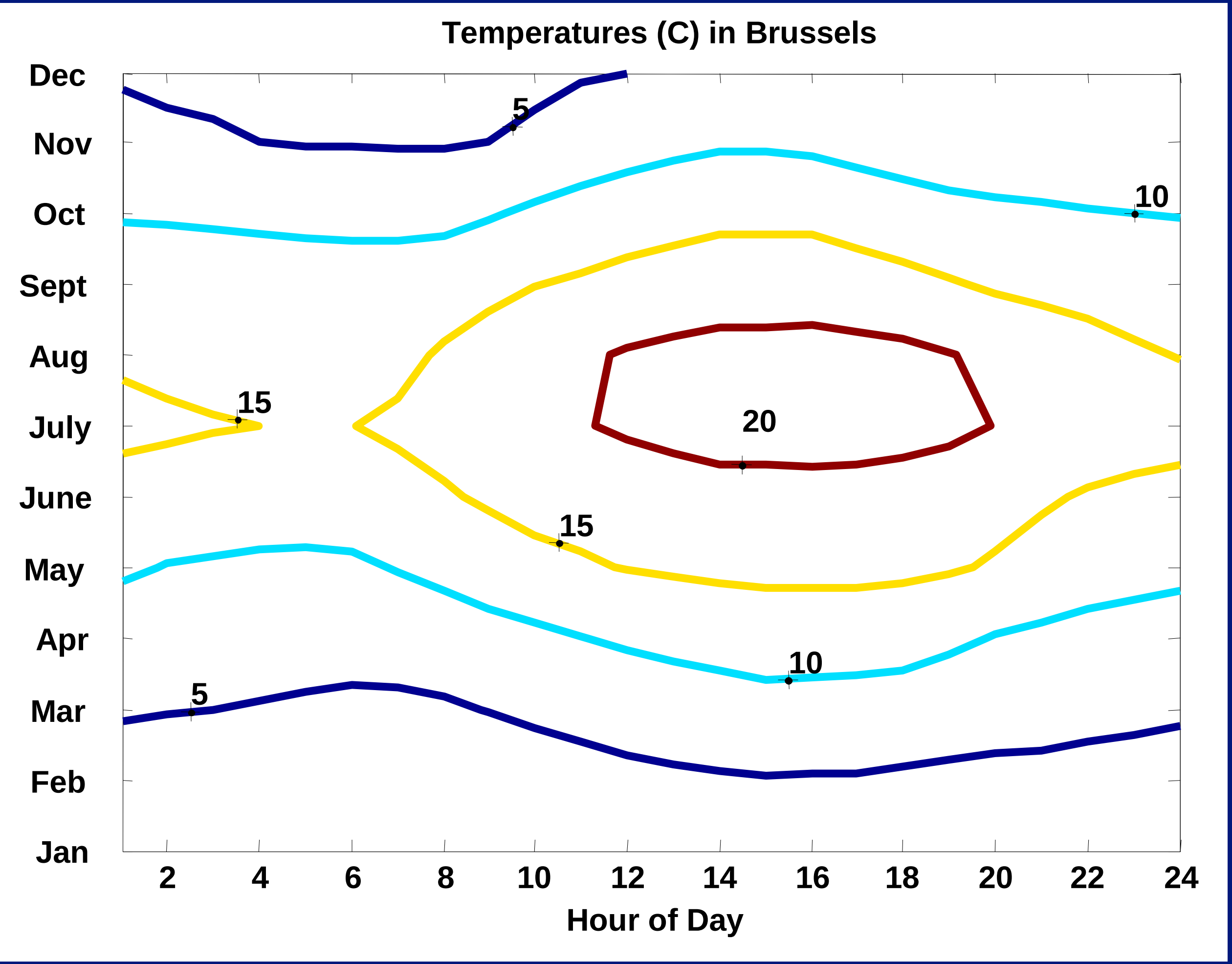
Country	City
Finland	Helsinki
	Tampere
France	Bordeaux
	Brest
	Clermont
	Dijon
	Lyon
	Marseille
	Montpellier
	Nancy
	Nantes
	Nice
	Paris
	Strasbourg
United Kingdom	Aberdeen
	Belfast
	Birmingham
	London
Greece	Andravida
	Athens
	Thessaloniki
Hungary	Debrecen
	Szombathely
Ireland	Birr
	Dublin
	Kilkenny

Country	City
Italy	Brindisi
	Genova
	Messina
	Milan
	Naples
	Palermo
	Pisa
	Rome
	Torino
	Venice
Netherlands	Amsterdam
	Groningen
Norway	Bergen
	Oslo
Poland	Kolobrzeg
	Krakow
	Poznan
	Warsaw

Country	City
Portugal	Braganca
	Coimbra
	Evora
	Faro
	Porto
Romania	Bucharest
	Clujnapoca
	Constanta
	Craiova
	Galati
	Timisoara
Sweden	Goteborg
	Karlstad
	Kiruna
	Ostersund
	Stockholm
Turkey	Ankara
	Istanbul
	Izmir

Local Climatic Data by City

Temperature, humidity, solar radiation

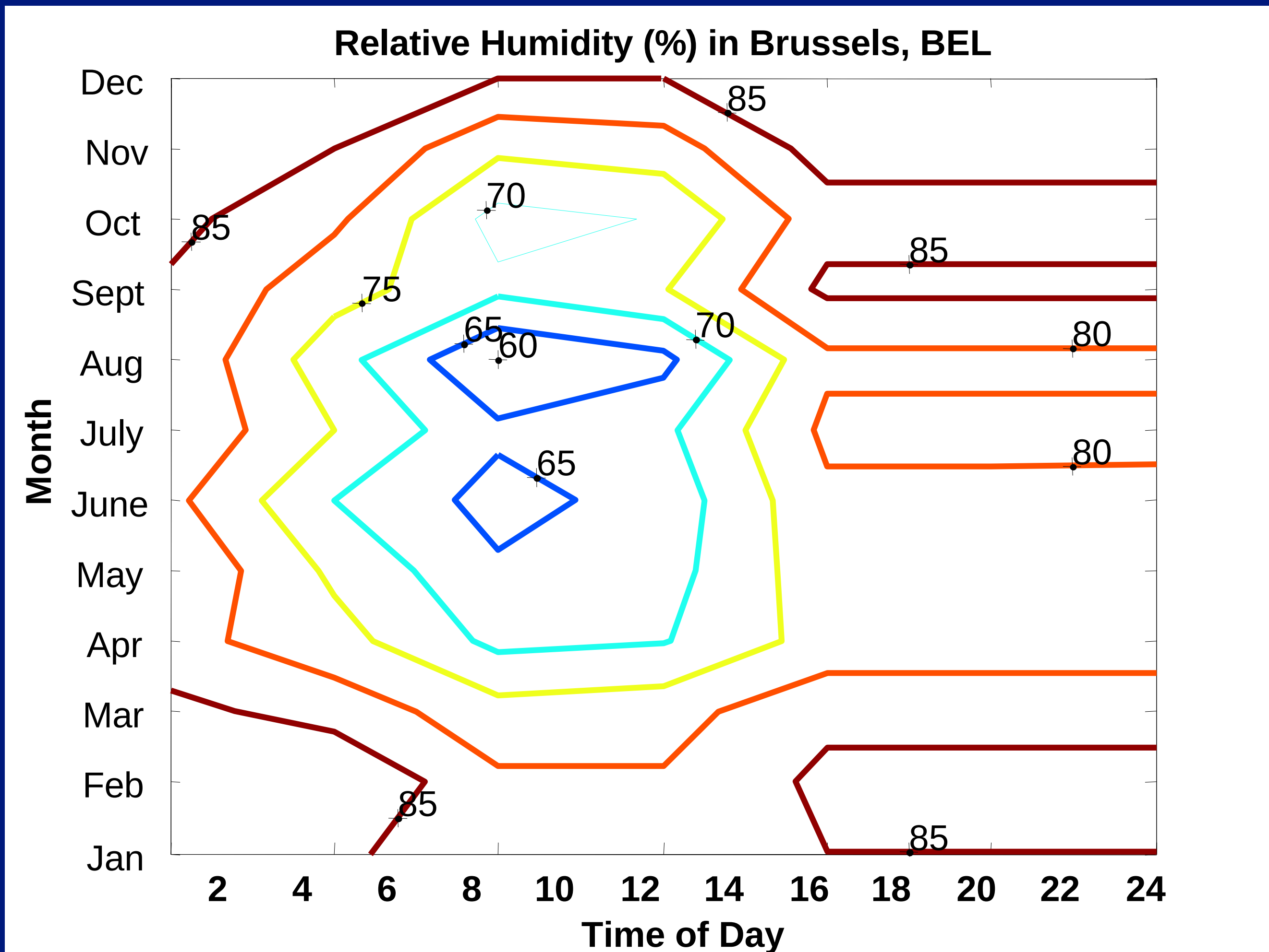


Source: Department of Energy Energy Plus TMY Calculations

http://www.eren.doe.gov/buildings/energy_tools/energyplus/cfm/weatherdata_int.cfm

Local Climatic Data by City

Temperature, humidity, solar radiation



Source: Department of Energy Energy Plus TMY Calculations

http://www.eren.doe.gov/buildings/energy_tools/energyplus/cfm/weatherdata_int.cfm

Thermal Comfort Model Inputs & Outputs

Inputs

Air Temperature
(from data)

Mean Radiant Temperature
(from model & data)

Humidity Ratio
(from data)

Air Velocity
(assume 0.1 m/s)

Activity (met)
(1.5 met driving)

Clothing (clo)
(assume 0.6 clo: trousers, long-sleeve shirt)

Thermal Comfort Model

Energy Balance:

- **Internal heat production**
- **Water vapor diffusion through skin heat loss**
- **Sweating heat loss**
- **Respiration latent and dry heat loss**
- **Convection heat loss**
- **Radiation heat loss**

Outputs

Predicted Mean Vote (PMV)

Predicted Percent Dissatisfied (PPD)

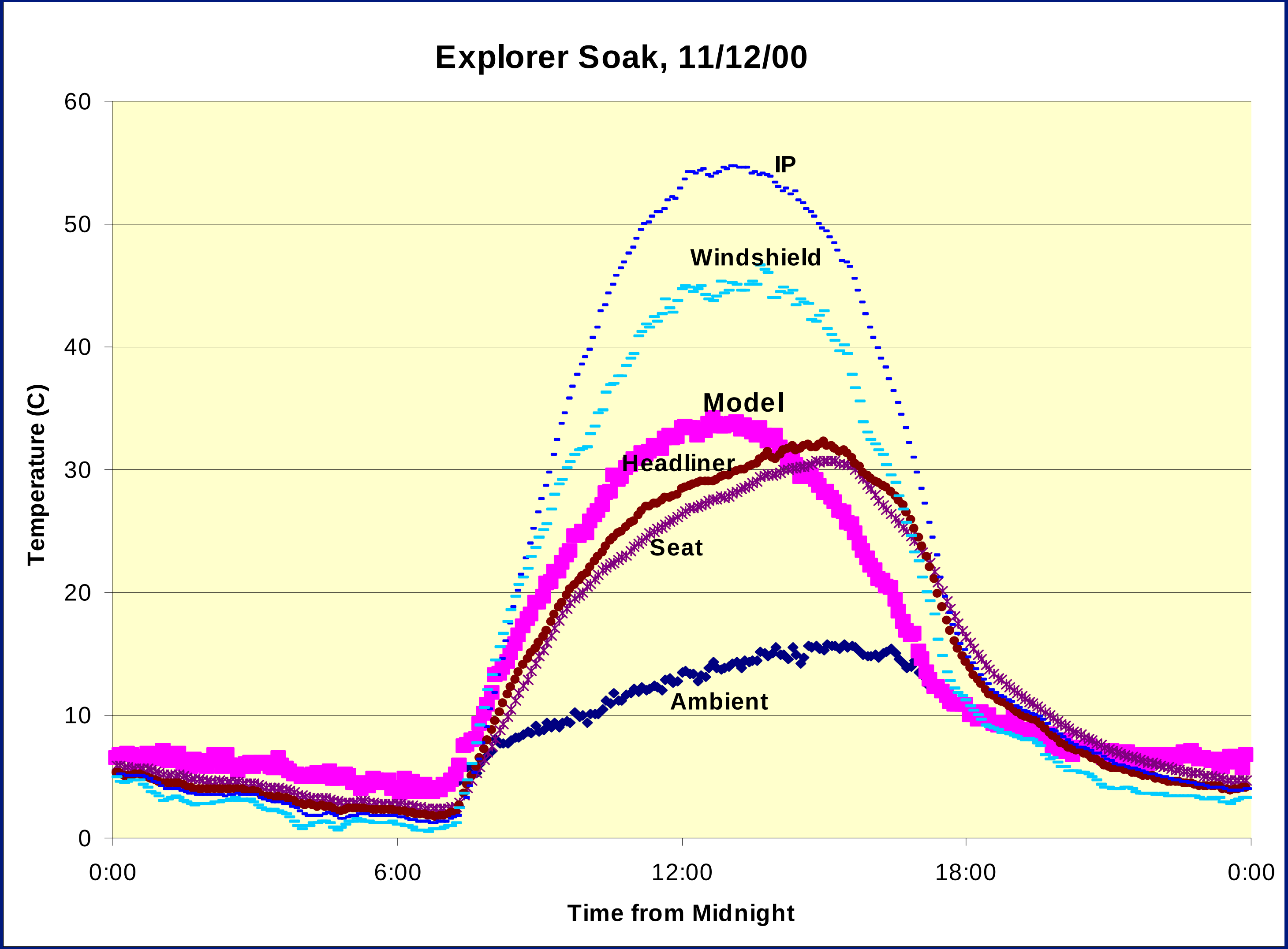
Source: International Standards Organization (ISO) 7730 "Moderate thermal environments—Determination of the PMV and PPD indices and specification of the conditions for thermal comfort"

Conservative Estimate for Fuel Used for AC

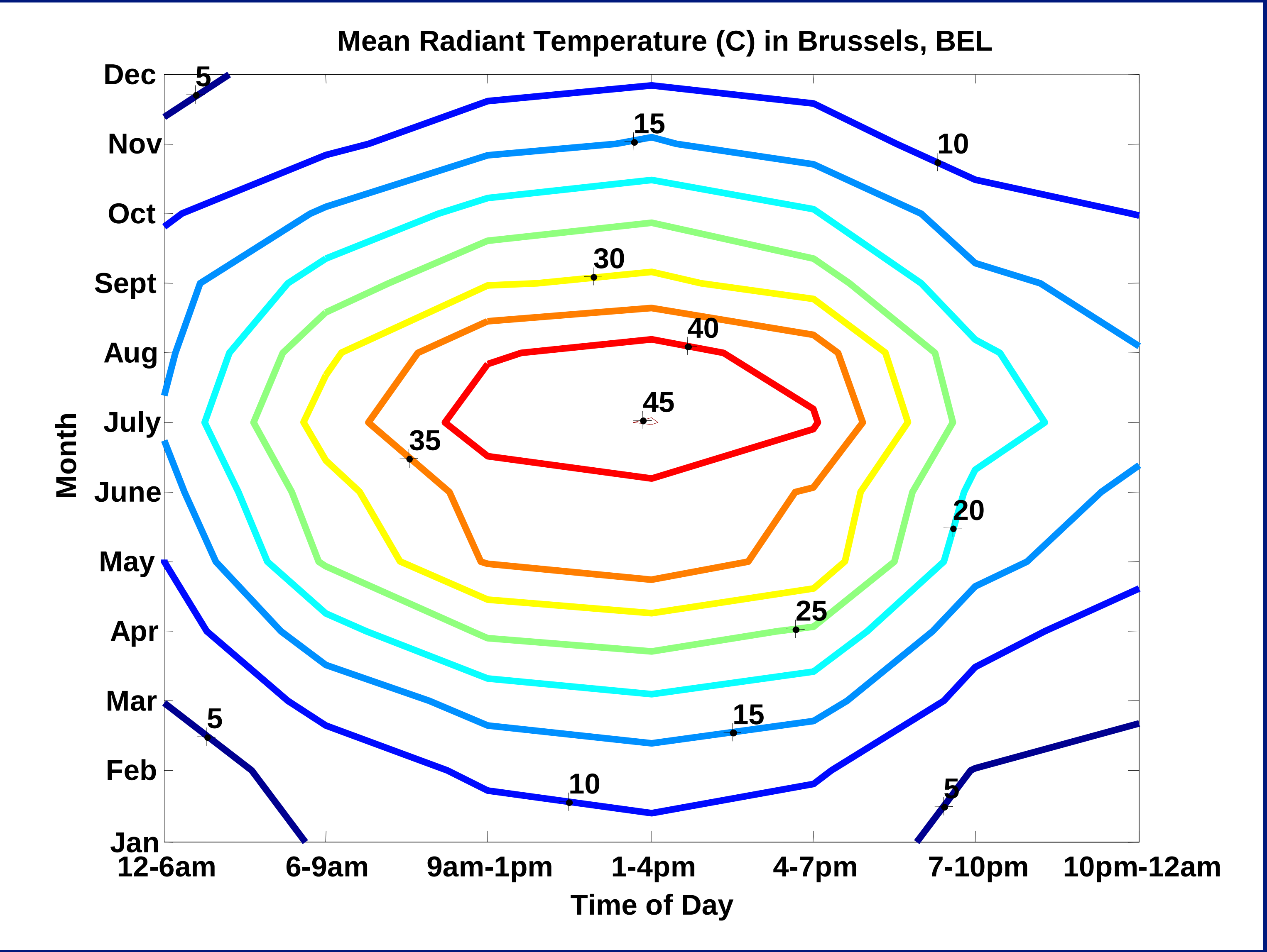
- Fanger's thermal comfort model excludes:
  - Sun hitting a driver
  - Thermal asymmetry
  - Sitting on a hot seat
  - High humidity impacts
- Model excludes AC use due to
  - Automatic Temperature Control
  - Windows closed for noise, dust, allergen, or pollution reduction
- Cabin soak temperature may be higher than modeled

Mean Radiant Temperature Model

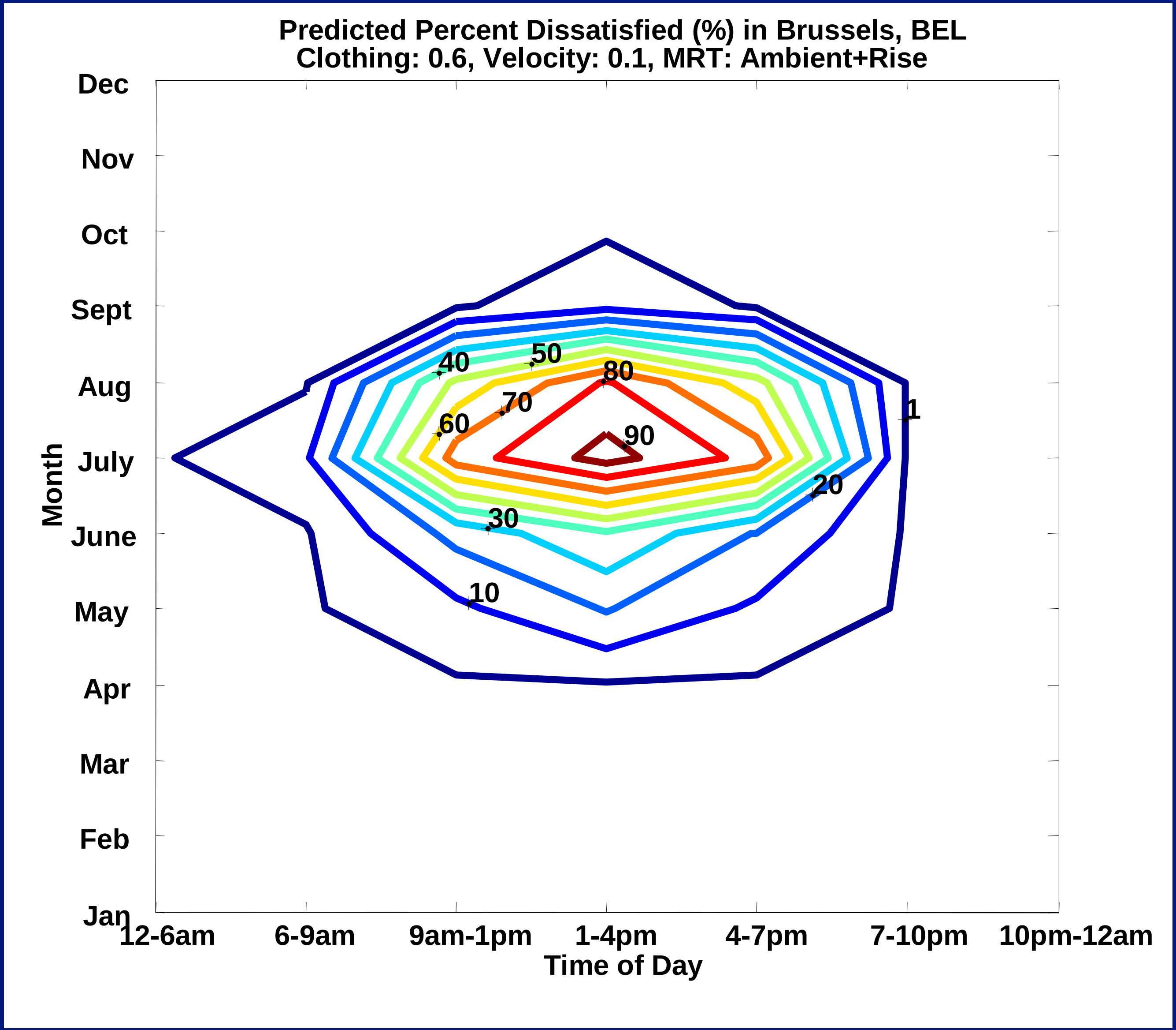
MRT(time) = 20°C * NormalizedRadiation(t) * AvgRad / 4713Wh/m^2



Calculated MRT in Brussels



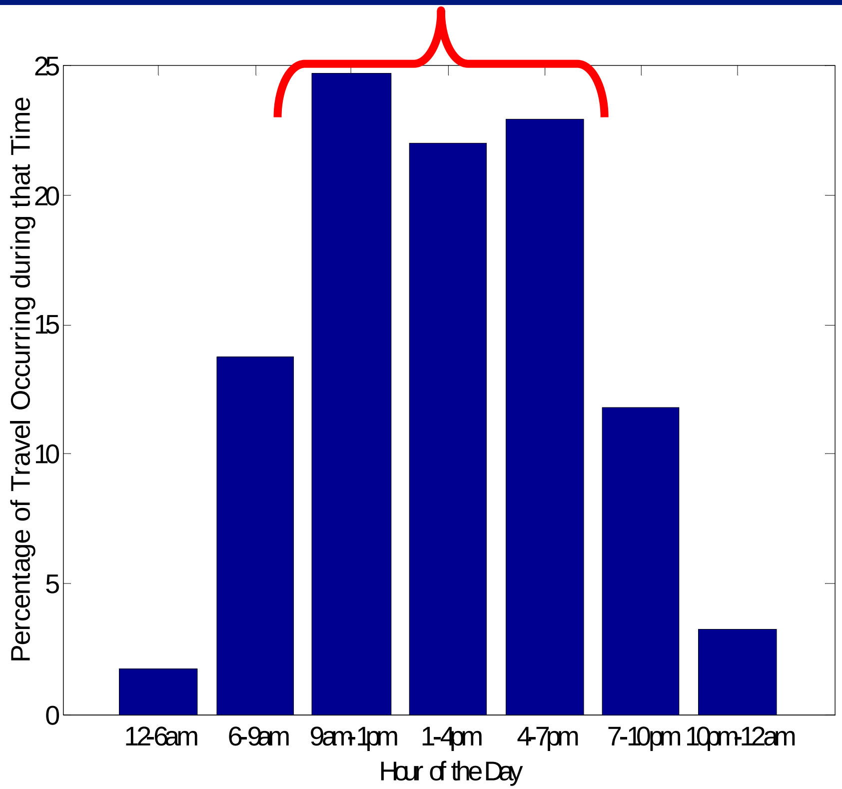
Predicted AC Usage for Cooling in Brussels

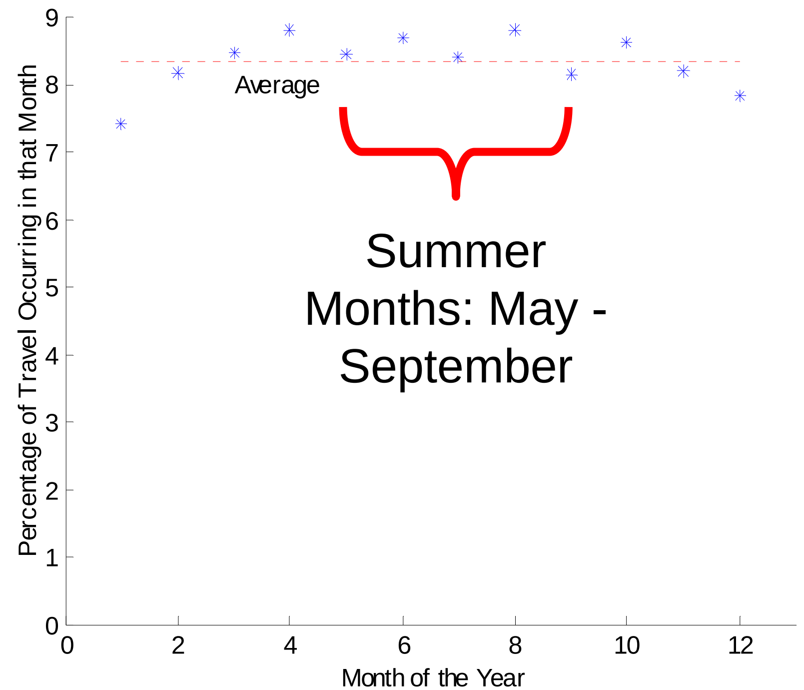


Vehicle Travel Patterns

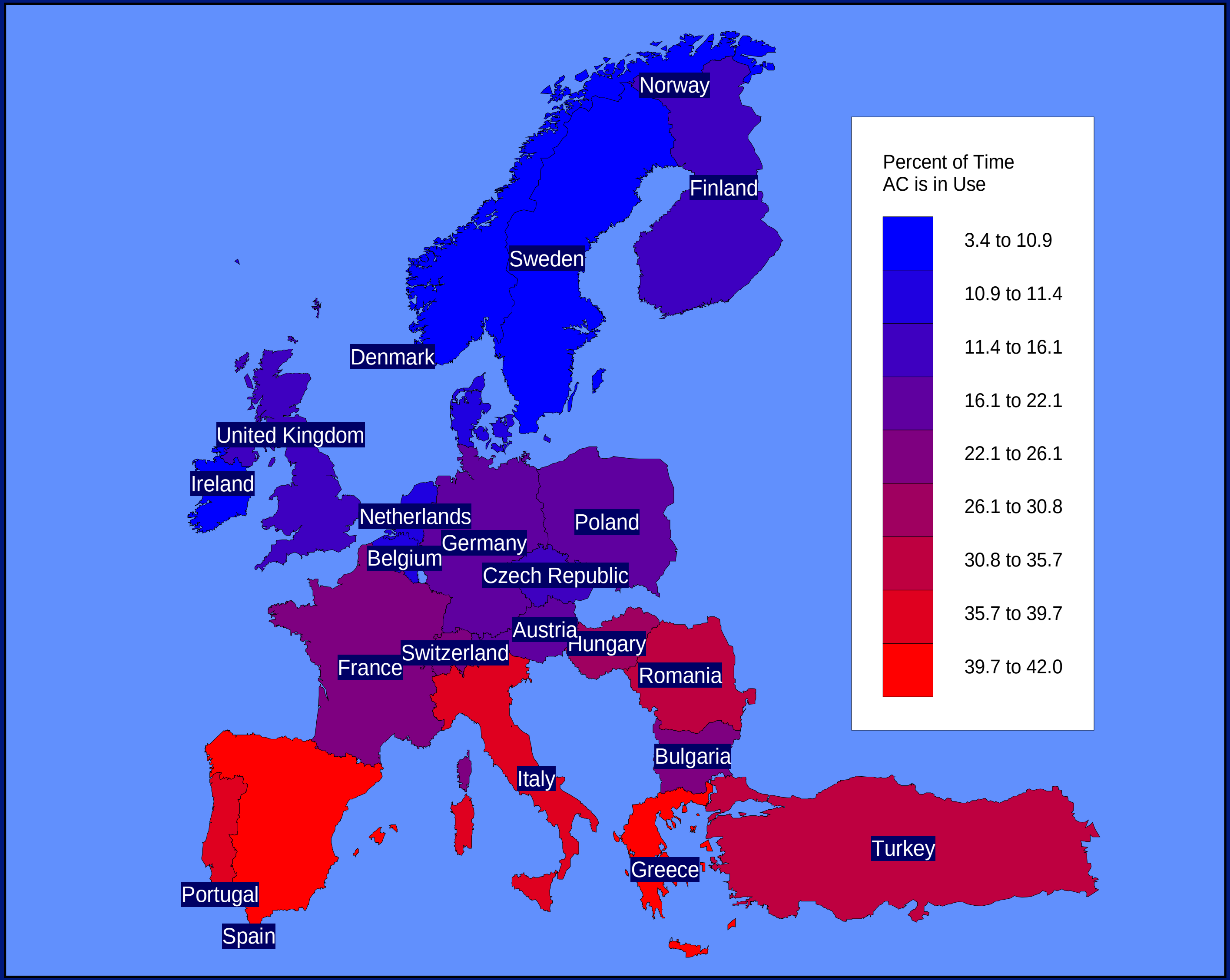
- Assume same travel patterns as U.S.
- Source: 1995 National Personal Transportation Survey

70% Daily Travel

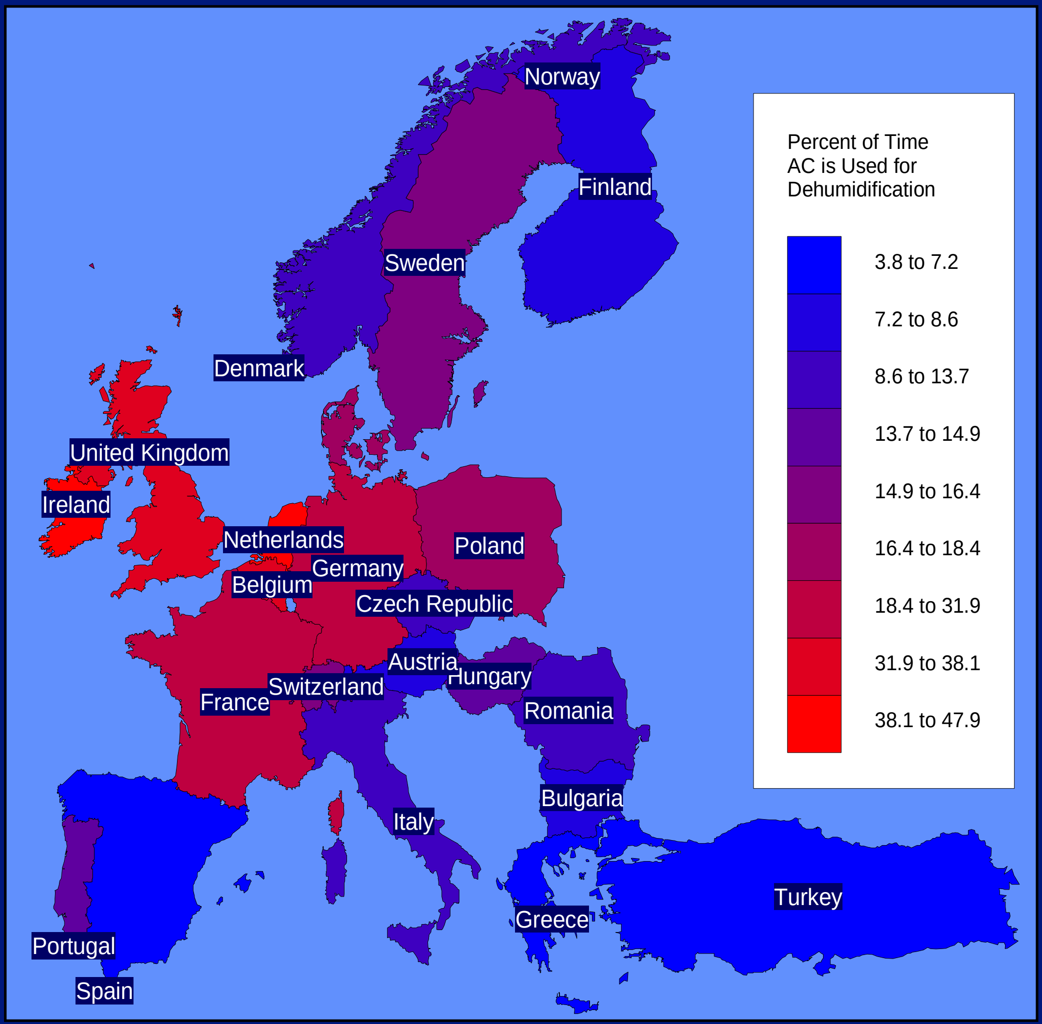




Percent of Time AC is Used for Cooling

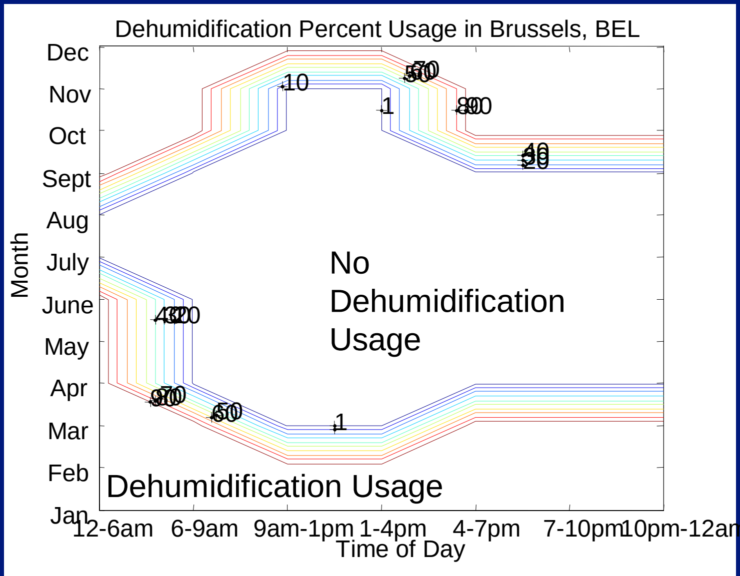


Percent of Time AC is Used for Dehumidification

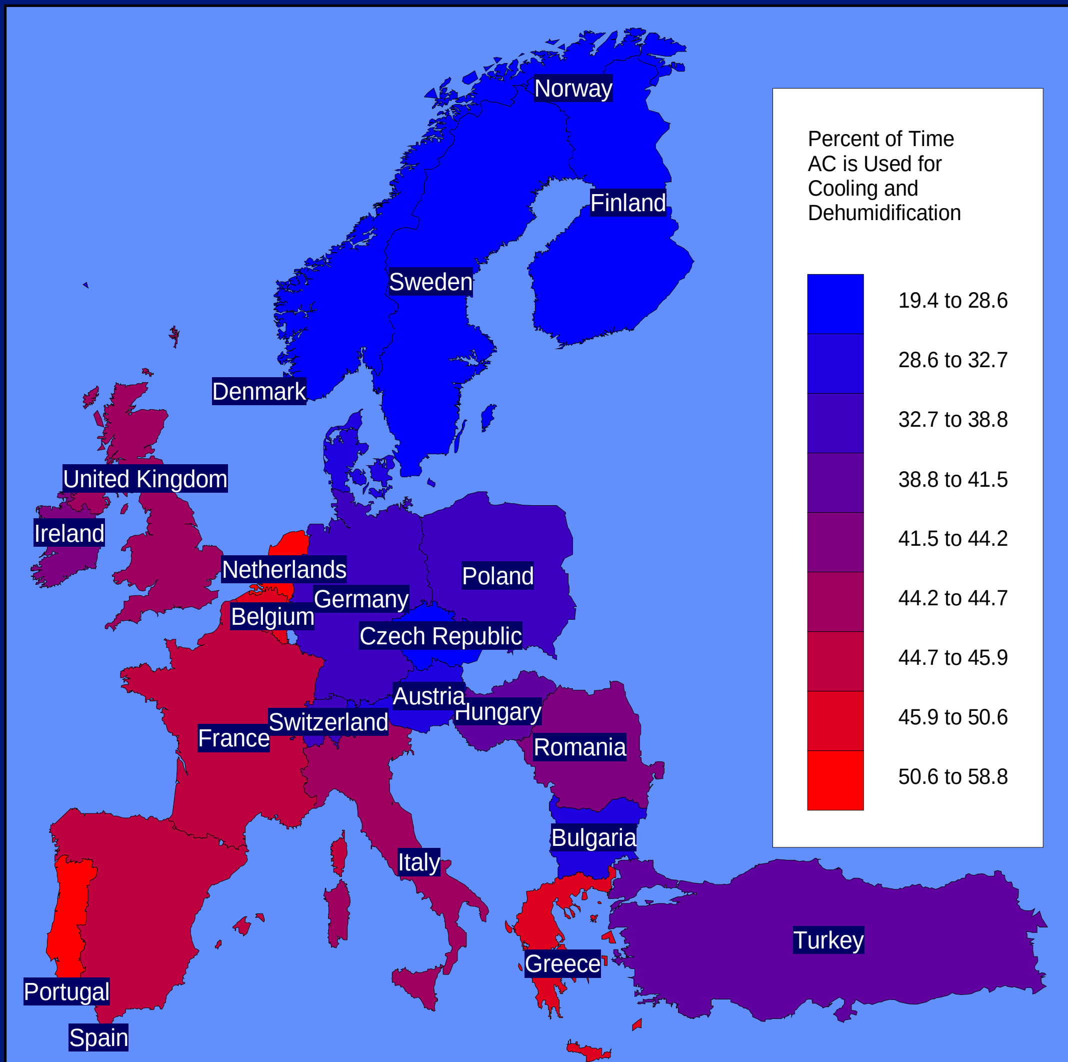


AC used for dehumidification if:

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



Percent of Time AC is Used for Cooling Plus Dehumidification



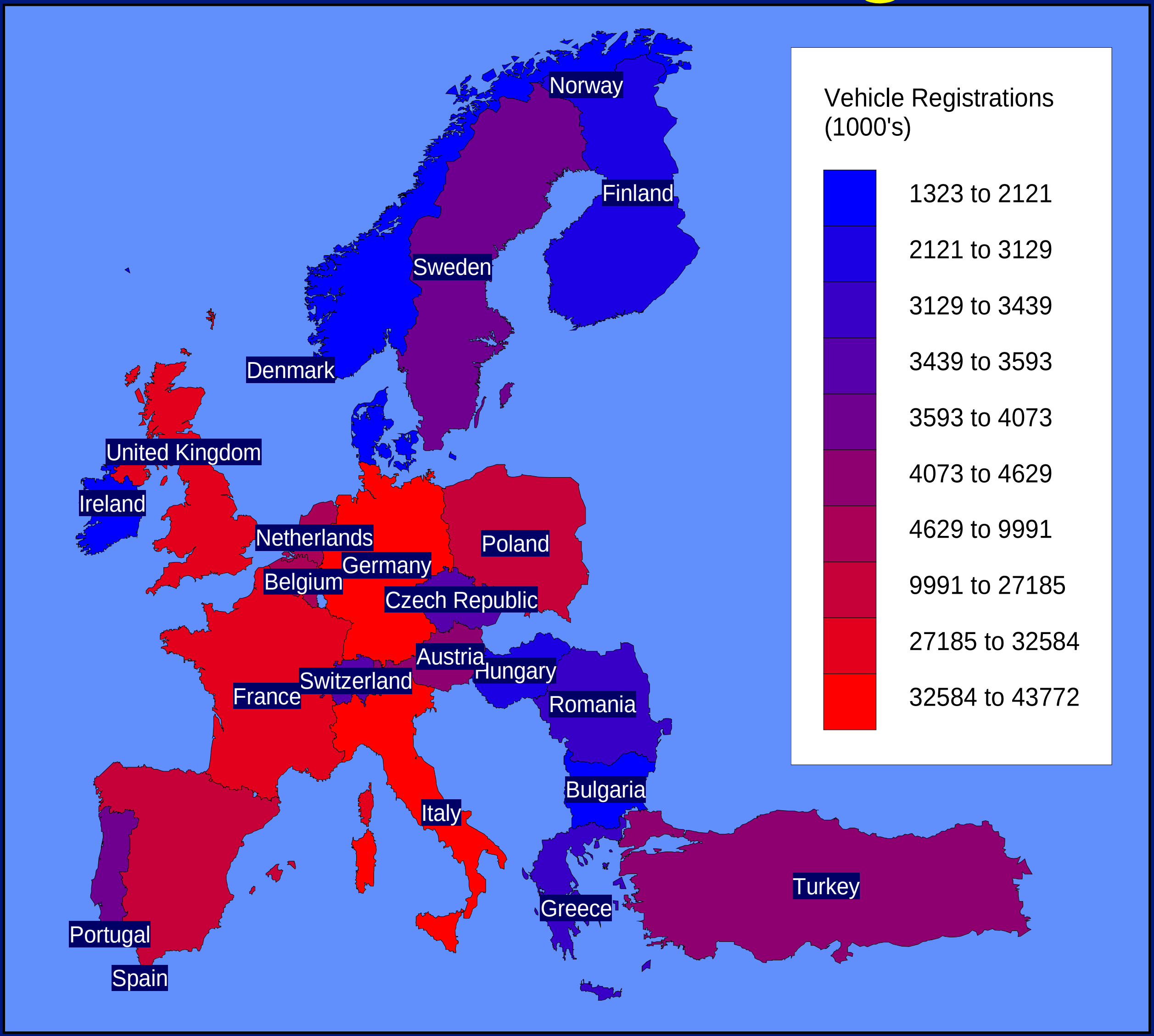
Centro Ricerche Fiat

Annual travelled distance	➔	18000 km
Northern Region	➔	7500 km with MAC ON
Southern Region	➔	11590 km with MAC ON

Comparison to Centro Ricerche Fiat's estimation: we may under predict usage

	This study	Centro Recerche Fiat
North Italy		41.7%
South Italy		64.4%
Avg Italy Cooling	35.7%	53.0%
Cooling + Dehumid	44.2%	

Vehicle Registrations



Sources:

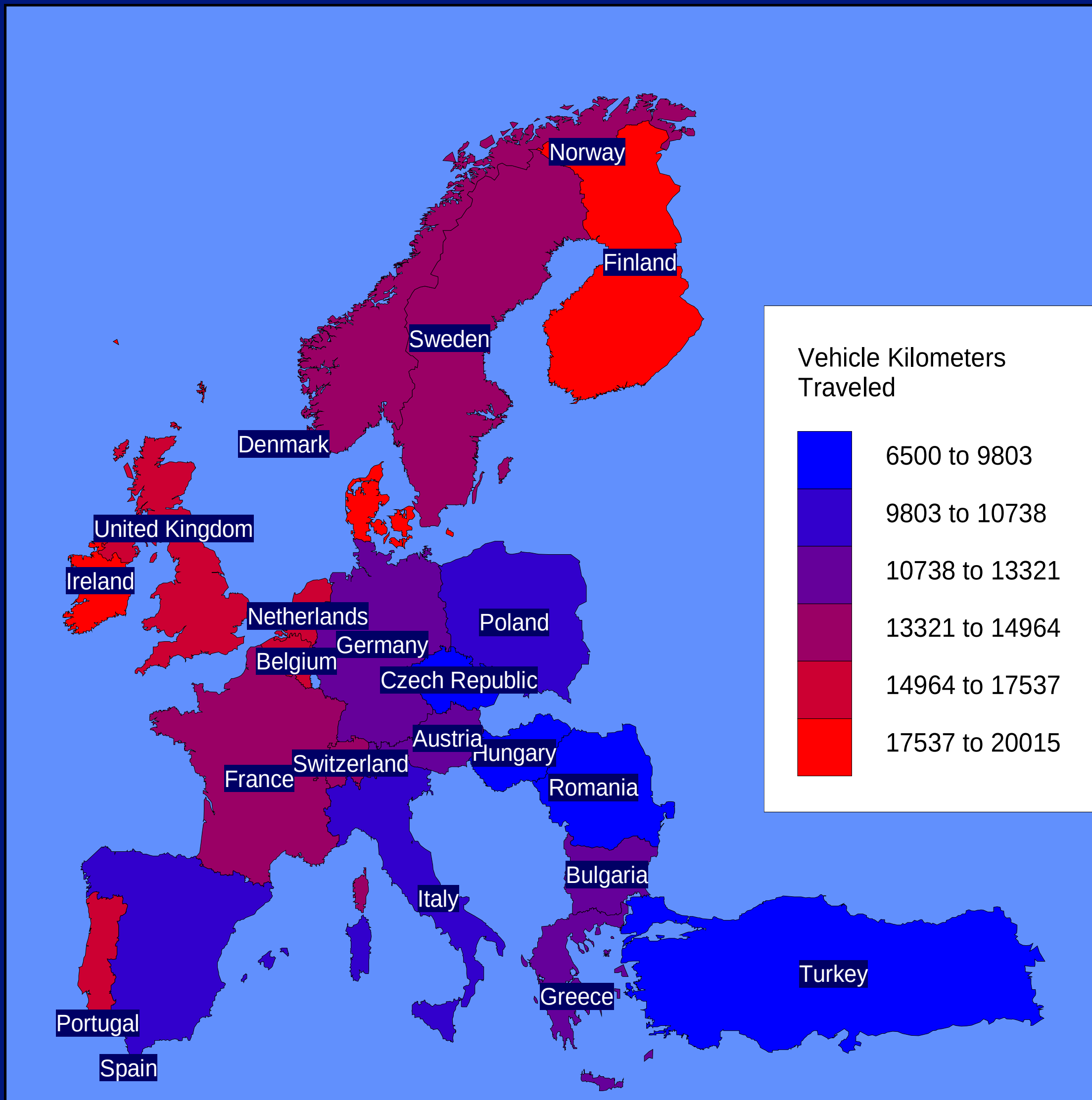
- 2002 World Road Statistics from the International Road Federation
- ACEA European Automobile Manufacturers Association
  - http://www.acea.be/ACEA/Car_Parc_1991-2000.pdf

Total	Million Vehicles
EU	210.8
Japan	62.4

How Many Are 211 Million Vehicles?

Enough to Circle the Globe ~25 Times

Distance Traveled per Year

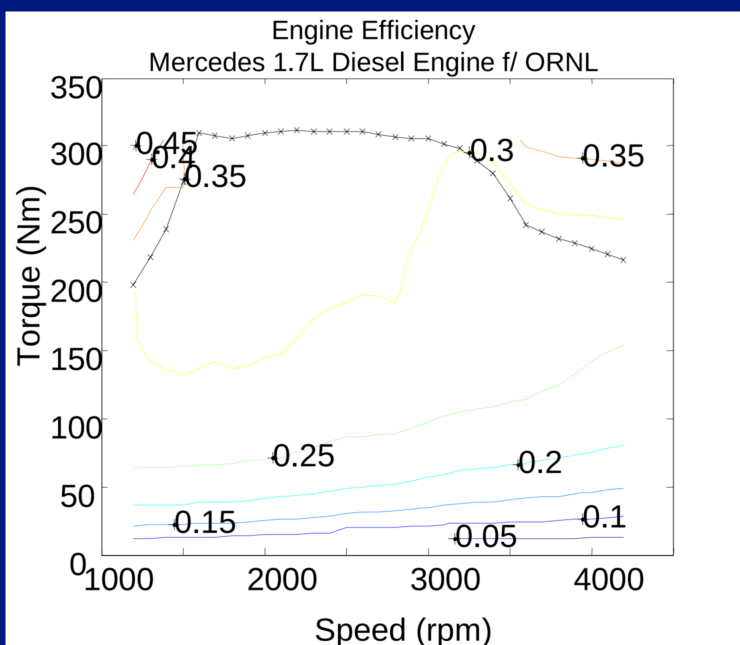


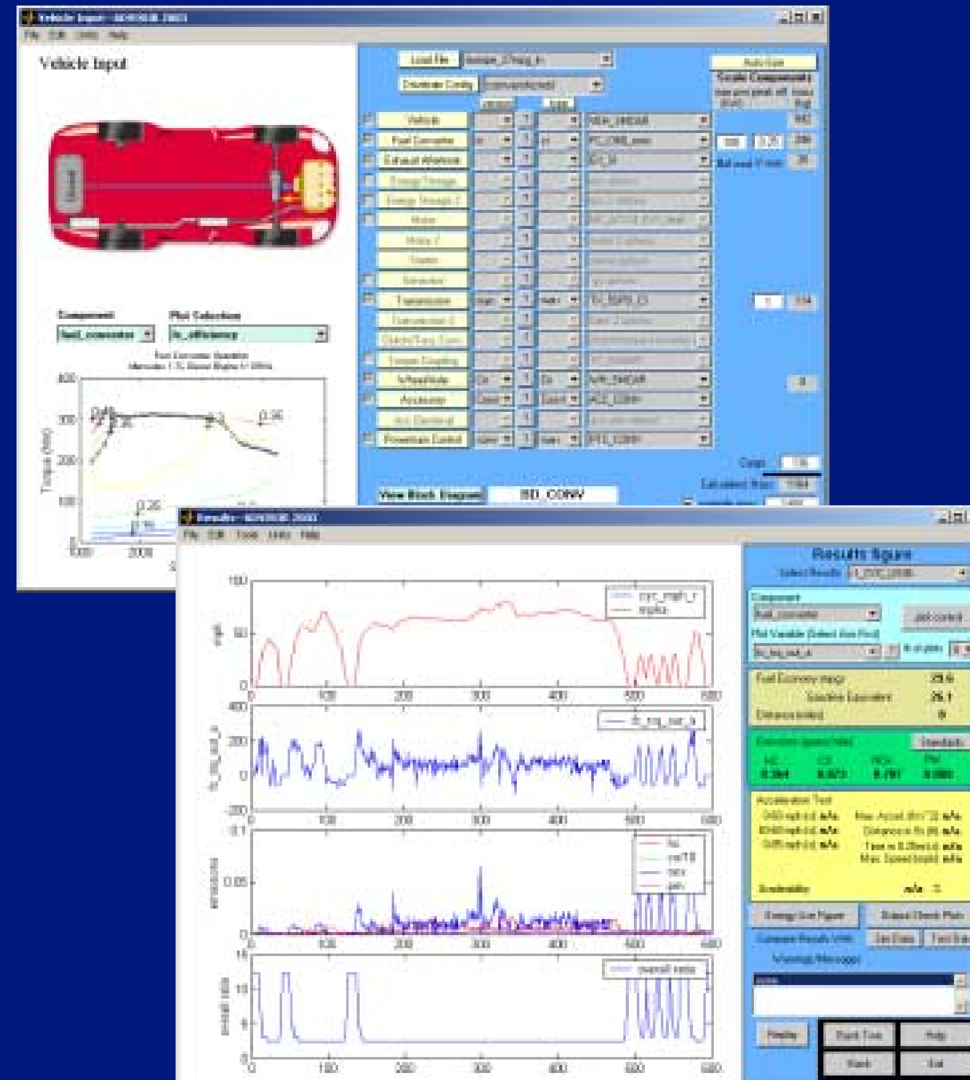
Sources:

- 2002 World Road Statistics from the International Road Federation
- International Road Traffic and Accident Database

Vehicle Modeling in ADVISOR

- Using a Mercedes 1.7 liter compression ignition diesel
- Fuel economy expressed in gasoline equivalent fuel consumption



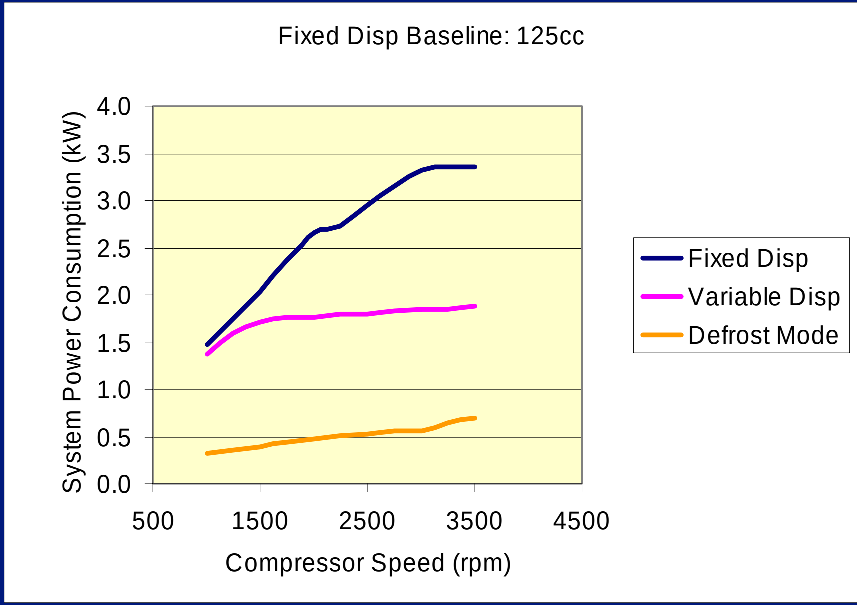


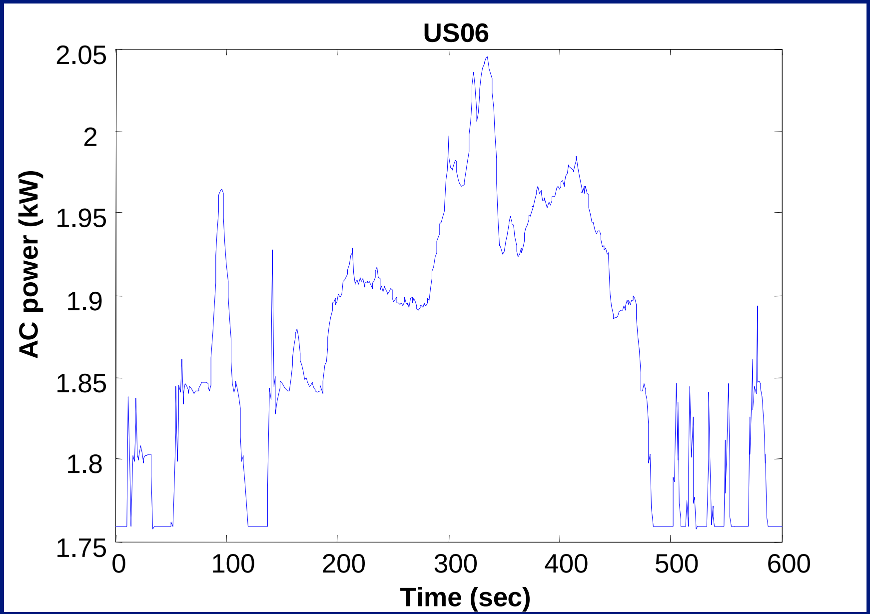
Vehicle Assumptions

- 100-200 g CO_2/km corresponds to
  - 4.3-8.6 liters/100km
  - 55-27 mpg
- Modeled 180 g CO_2/km vehicle (2000)
  - 7.7 liters/100km, 30.4 mpg on FTP cycle, hot initial conditions
- Vehicle parameters
  - Cd*A = 0.33*2 m^2
  - Vehicle mass = 1220 kg, includes mass of AC system
  - Engine max power = 91 kW
  - Engine max efficiency = 36%
- Other parameters use ADVISOR defaults
- CO_2 emissions determined from fuel consumption
  - 2.33 kg CO_2/liter fuel

AC Modeling

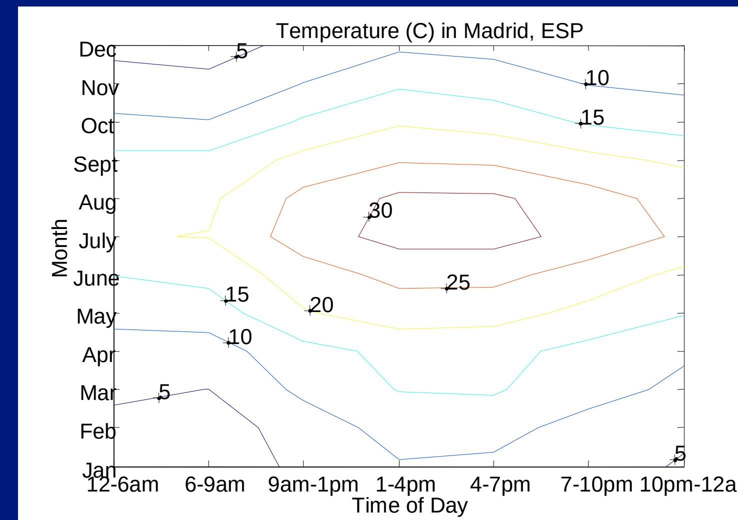
- AC system: 125 cc variable displacement, HFC-134a
  - Power consumption based on Delphi compressor curves
  - 3-4 kW_{th} cooling
    - 125 cc displacement piston
    - Scale fixed disp power consumption of Delphi curves by 125/210 and COP ratios
  - Total power = $P_{compressor}$ /0.85

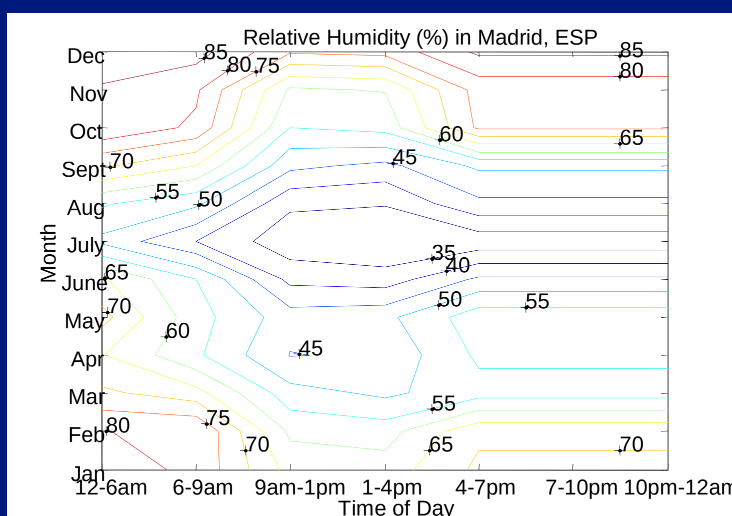


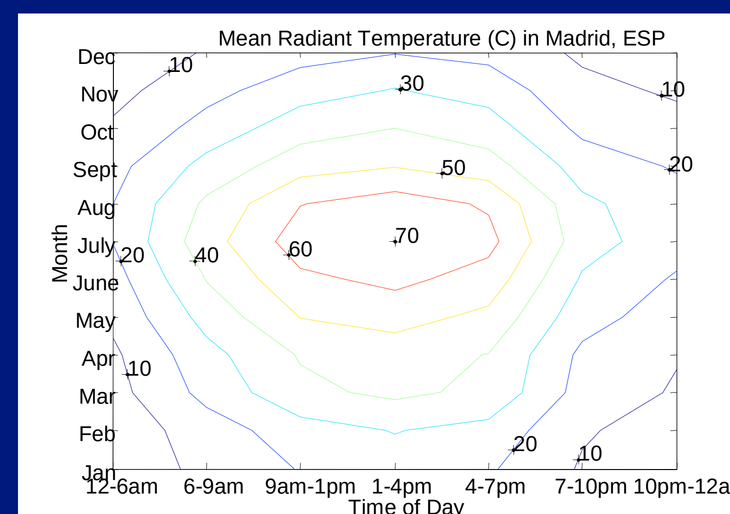


AC Power Consumption Modeling, cont.

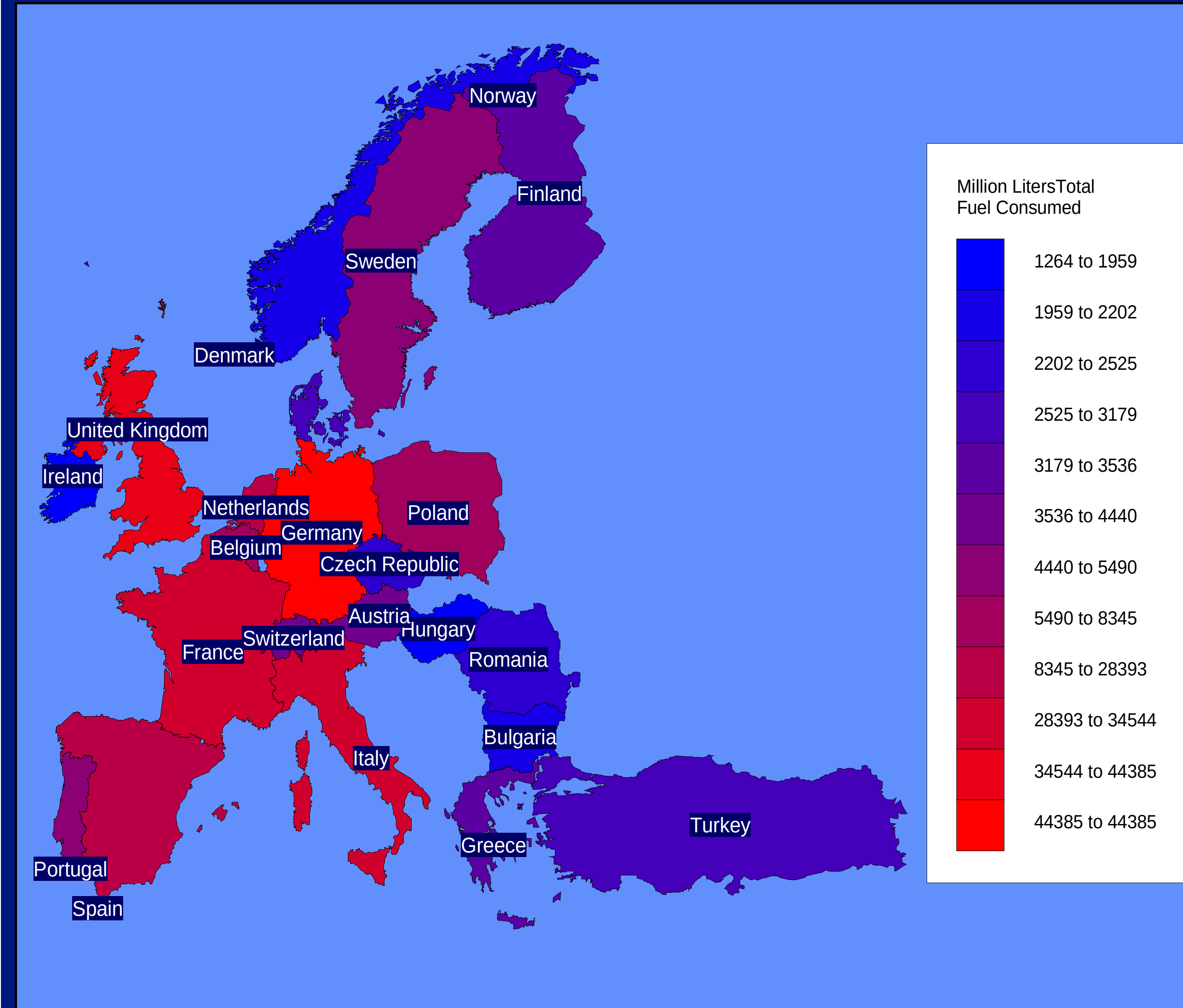
- AC system
  - Assume 32°C, 50% RH
  - Defrost mode: 16°C, 80% RH
  - Engine speed/compressor speed ratio = 0.64 [Forrest, Delphi]







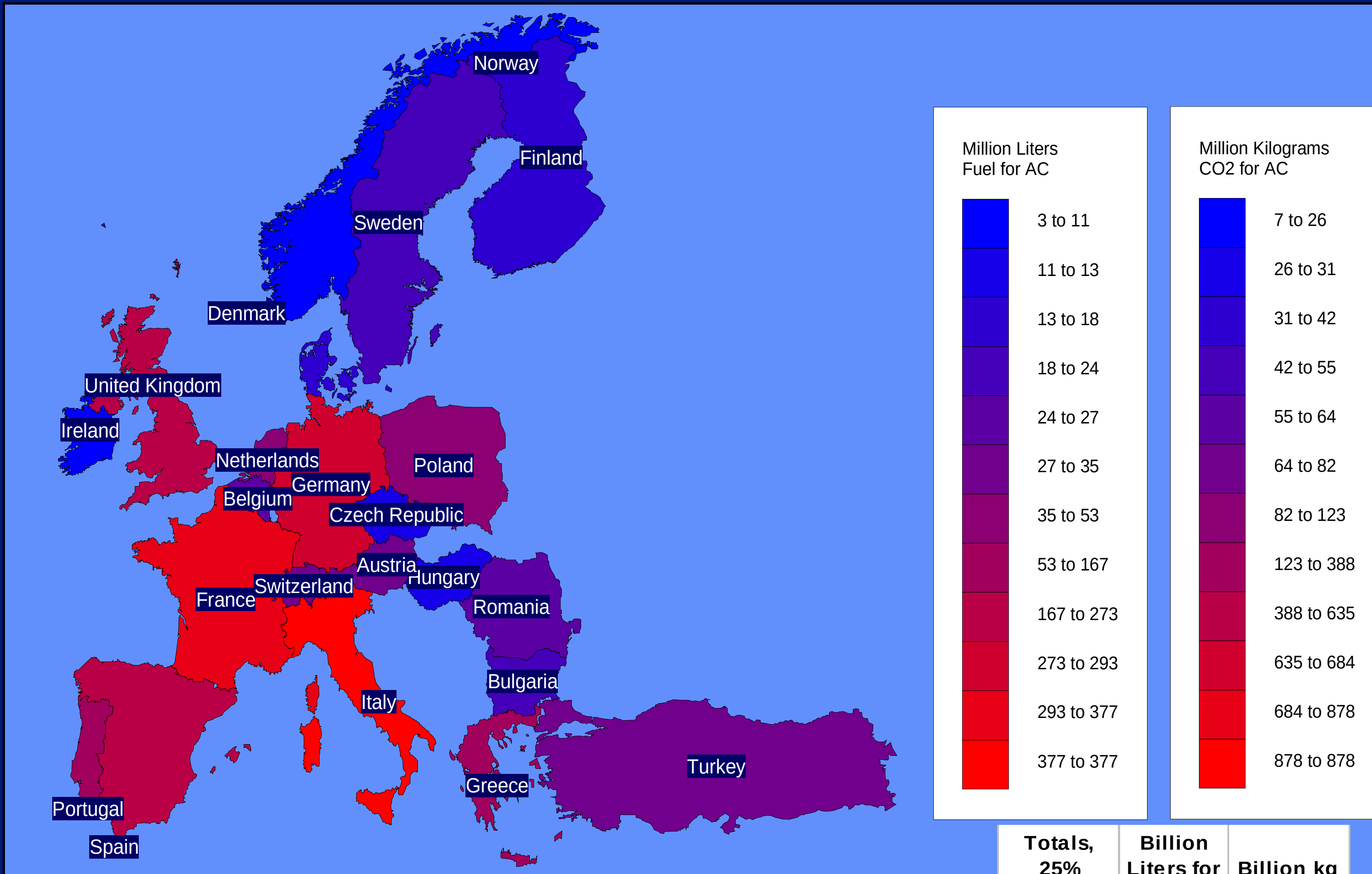
Total Vehicle Fuel Consumption



Totals	Billion Liters Total	Billion kg CO2 Total
EU	216.4	504.1
Japan	50.0	116.5

Fuel Consumption of MACs for Cooling

25% Market Penetration of AC Systems

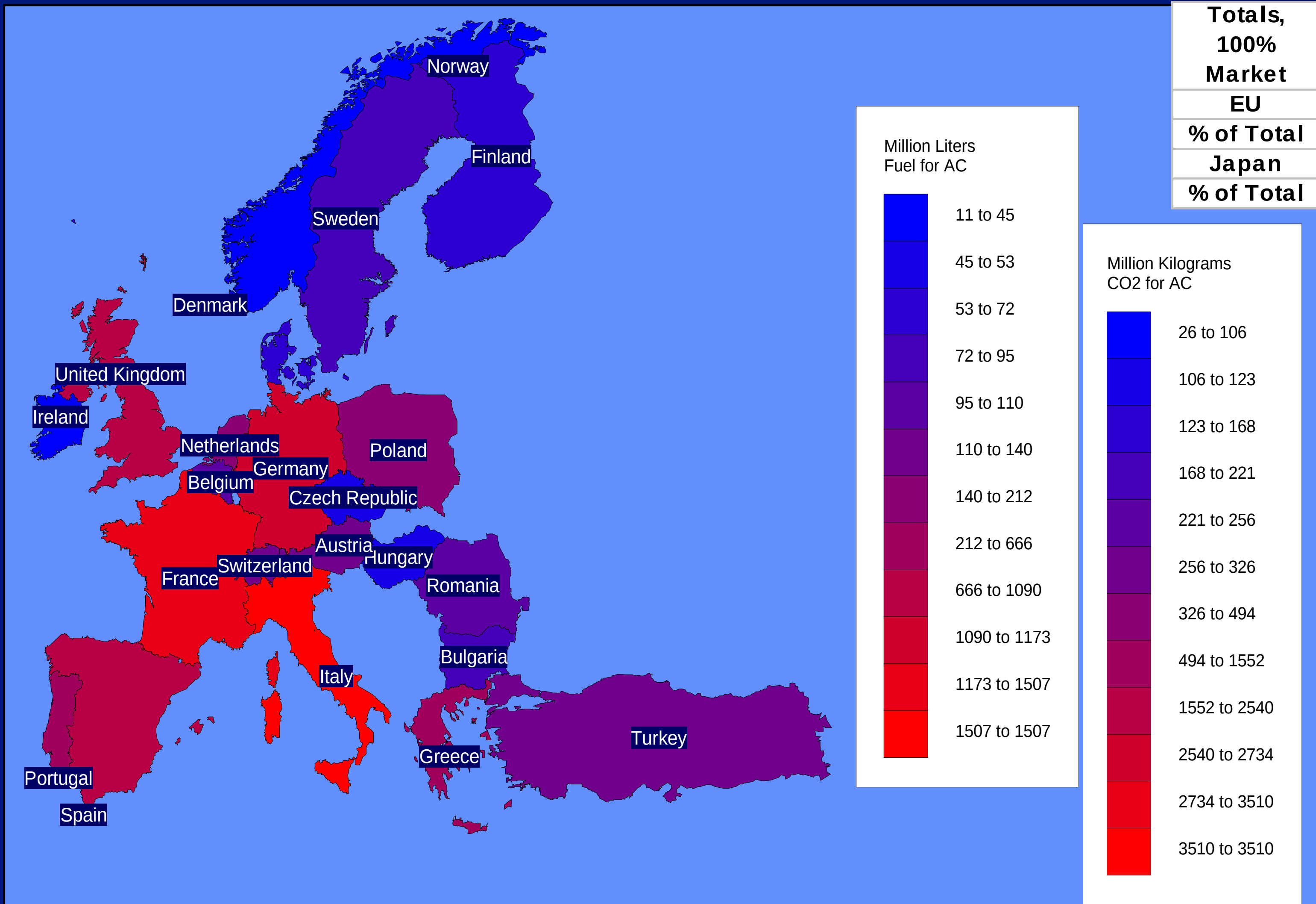


Totals, 25% Market	Billion Liters for AC	Billion kg CO_2
EU	1.8	4.1
% of Total	0.81%	

Fuel Consumption of MACs for Cooling

100% Market Penetration of AC Systems

Totals, 100% Market	Billion Liters for AC	Billion kg CO2
EU	7.0	16.4
% of Total	3.25%	
Japan	2.3	5.3
% of Total	4.57%	



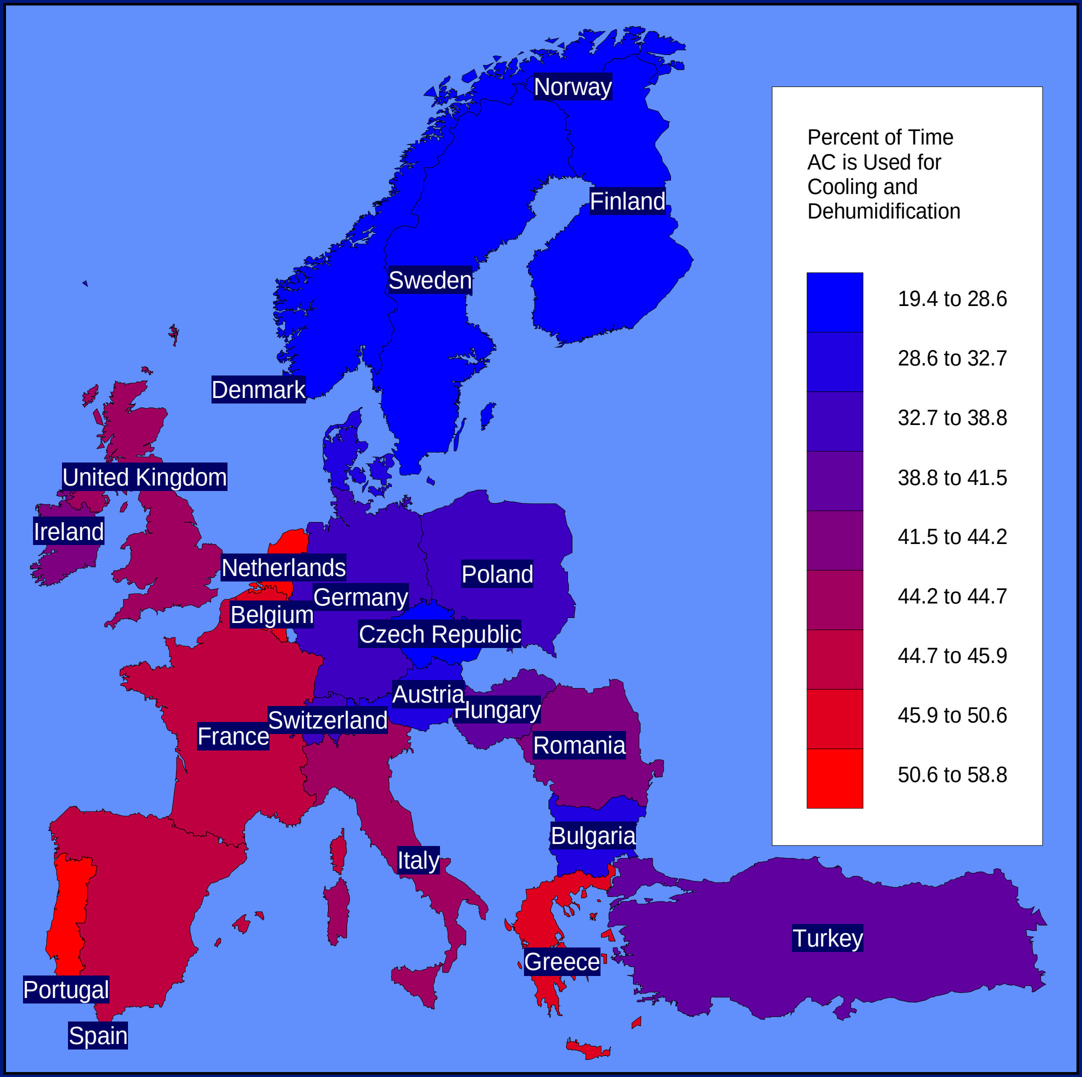
Fuel Consumption of MACs for Demisting

Totals, EU	Billion Liters for Demist	Billion kg CO_2	Percent of Total
25% Market	0.4	1.0	0.19%
100% Market	1.7	3.9	0.76%

AC used for demist if:

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

Percent of Time AC is Used for Cooling Plus Dehumidification

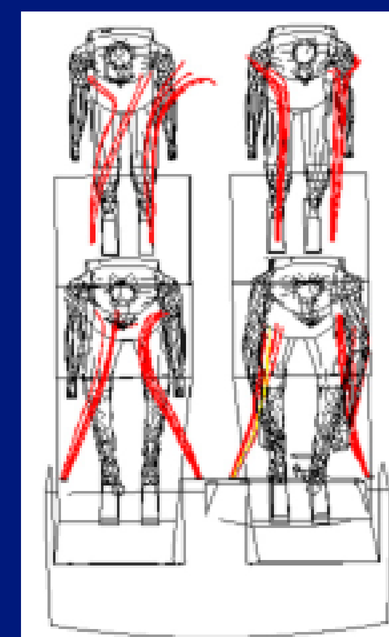


Total Fuel Use for AC
for Cooling and Demisting

Totals Dehumid + Cooling, EU	Billion Liters	Billion kg CO2	Percent of Total Consumption
25% Market	2.2	5.1	1.0%
100% Market	8.7	20.2	4.0%

Solutions to Reduce Fuel Use by MACs
Vehicle Design

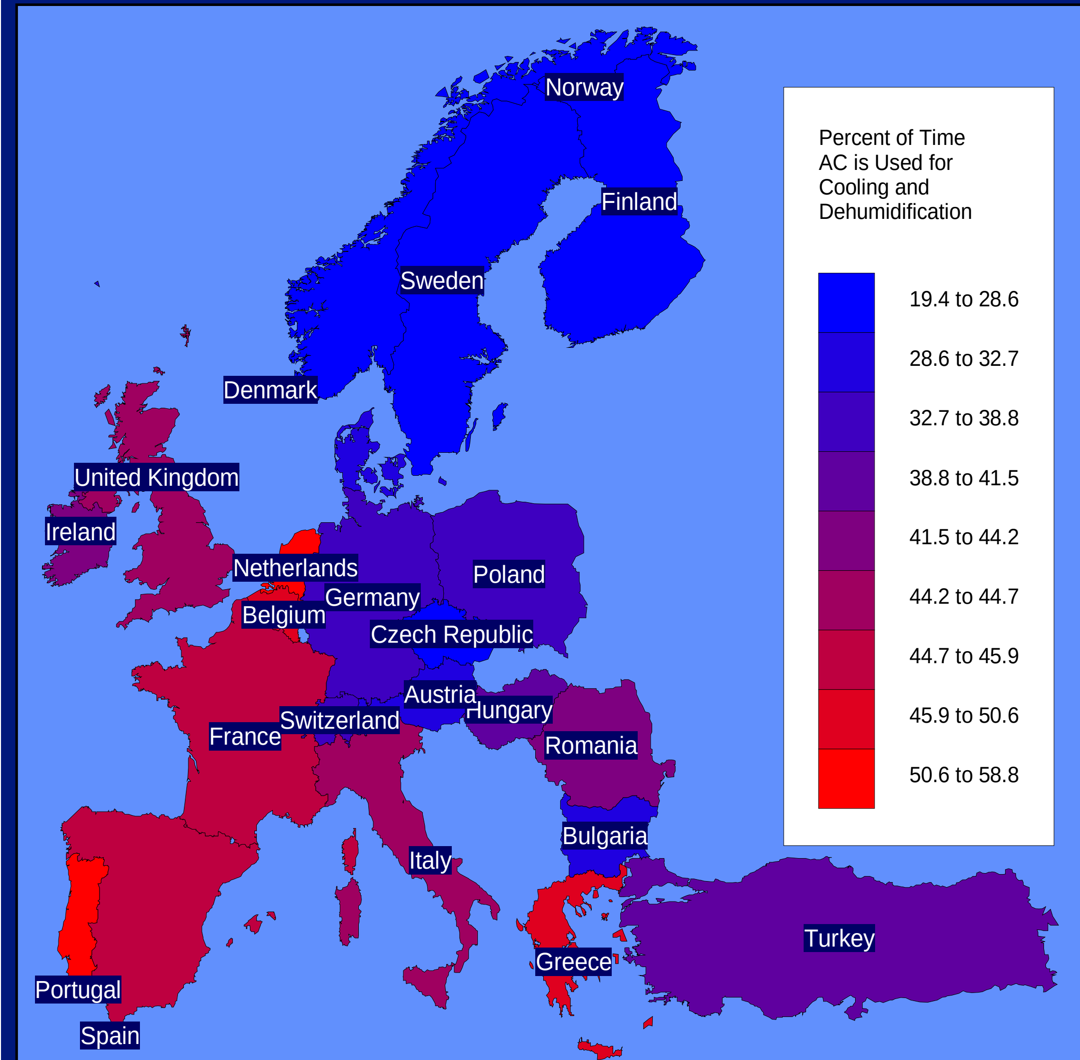
- Reduce the load (e.g. cabin soak temperature)
    - Infrared reflective glazings
        - Cabin soak temperature reduced up to 9°C compared with stock windshield [Farrington, NREL]
    - Increase cabin thermal insulation
    - Ventilation using a 50 W blower lowered temp 16°C [Atkinson, SAE 2000-01-1273]
    - Reflective body material
    - Reduce glazing and IP areas
- Improve distribution of cooling (e.g. direct occupant cooling)



Solutions to Reduce Fuel Use by MACs
Improve AC Equipment

- More efficient equipment
  - Compressors, heat exchangers, expansion devices
  - AC controls
  - Cabin controls (cool occupants not cabin)
- Reduce
  - Outside air to be treated
  - Reheating of overcooled air
- Improve air distribution (e.g. climate control seats)
- Distributed HVAC systems
- Reduce overall AC system weight
- Alternative refrigerants

Conclusions



Fuel Used for Cooling and Dehumidification

Totals Dehumid + Cooling, EU	Billion Liters	Billion kg CO2	Percent of Total Consumption
25% Market	2.2	5.1	1.0%
100% Market	8.7	20.2	4.0%

On average in Europe, about 4% of annual vehicle fuel goes for cooling and dehumidification – this is a strong function of location

Cabin cooling uses 81% of AC fuel

Currently (25% market penetration), 1% of fuel consumed across EU is used for running AC system

In the future (100% market penetration), 4% of fuel consumed across EU will be used for running AC system, unless AC system power is reduced

Conclusions, cont.

- MAC fuel use & CO_2 emissions are strong functions of:
  - Vehicle design
  - Vehicle use
  - Environment
- Solutions to reduce fuel consumed by MACs
  - Reduce the load – improve vehicle design
  - Improve delivery – design for occupant thermal comfort
  - Improve equipment
  - Educate consumers on impacts of driver behavior on MAC fuel use

What's Needed Next?

- Improve model assumptions presented here
  - Verify usage patterns of vehicle AC with Real World Usage Study (blower speed, mode, temp…)
  - Initiate vehicle usage survey similar to U.S.'s National Personal Transportation Survey (trip length, trip distance, time of day travel …)
- Validate thermal comfort criteria to predict AC system usage
- Improve accuracy of power consumption models, to better value technologies (cost-benefit analyses)
- Use model to develop/continually update standardized tests
  - Standardized tests assumptions (drive cycle, operating temperatures, etc) will greatly impact fuel consumption

Thank You!