Significant Fuel Savings and Emission Reductions by Improving Vehicle Air Conditioning

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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 CO₂ reductions across California, U.S., EU, and Japan

- 26 billion liters (7 billion gallons)
- 6.9 billion liters (1.8 billion gallons)
- 1.7 billion liters (0.5 billion gallons)
Predicting Fuel Used for AC

• Use Multiple Models/Inputs/Data Sets
  – Environmental Conditions (Temp, RH, W/m²)
  – 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)
Environmental Conditions:
Phoenix, AZ: Temperature

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

\[
\text{MRT(car, time)} = 27^\circ C \times \frac{\text{Radiation}(t)}{1000\text{W/m}^2} + T_{\text{ambient}}(t)
\]

\[
\text{MRT(truck, time)} = 24^\circ C \times \frac{\text{Radiation}(t)}{1000\text{W/m}^2} + T_{\text{ambient}}(t)
\]
Mean Radiant Temperature by City

Mean Radiant Temperature (C) in Phoenix, AZ

Month
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec

Time of Day
12-6am
6-9am
9am-1pm
1-4pm
4-7pm
7-10pm
10pm-12am

10
20
30
40
50
60
20
Thermal Comfort Model:
Percent of People Using AC

Thermal Comfort Model, \( PPD \) from \( PMV \)

<table>
<thead>
<tr>
<th>PMV</th>
<th>Thermal Sensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 3</td>
<td>Hot</td>
</tr>
<tr>
<td>+ 2</td>
<td>Warm</td>
</tr>
<tr>
<td>+ 1</td>
<td>Slightly Warm</td>
</tr>
<tr>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>- 1</td>
<td>Slightly Cool</td>
</tr>
<tr>
<td>- 2</td>
<td>Cool</td>
</tr>
<tr>
<td>- 3</td>
<td>Cold</td>
</tr>
</tbody>
</table>
AC Usage for Cooling

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

100% of People Have AC On

AC Off
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

Month
Dec
Nov
Oct
Sept
Aug
July
June
May
Apr
Mar
Feb
Jan

No Demist Usage

100% Demist Usage

Time of Day
12-6am 6-9am 9am-1pm 1-4pm 4-7pm 7-10pm 10pm-12am
Vehicle Usage with Time of Day, Month

70% Daily Travel

Hour of the Day

Month of the Year

Average

Summer Months: May - September

Day

Month

70% Daily Travel

Hour of the Day

Month of the Year

Average

Summer Months: May - September
Percent of Time AC is On: Cooling + Demist

State A

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

NREL National Renewable Energy Laboratory
Climate during AC Use

Temperature, Humidity

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

U.S. Average: 25°C
## Fuel Economy Impact: Vehicle Simulations

### FTP drive cycle
- Hot initial conditions

### ADVISOR 2002
- Advanced Vehicle Simulator

### Table: Fuel Economy Impact

<table>
<thead>
<tr>
<th></th>
<th>US Car</th>
<th>US Truck</th>
<th>EU Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel Economy no AC</strong></td>
<td>22.0</td>
<td>18.8</td>
<td>30.4</td>
</tr>
<tr>
<td><strong>Fuel Economy with AC</strong></td>
<td>18.0</td>
<td>16.2</td>
<td>27.3</td>
</tr>
<tr>
<td><strong>Fuel Economy defrost</strong></td>
<td>21.1</td>
<td>18.1</td>
<td>29.0</td>
</tr>
</tbody>
</table>

### Table: FE Drop with AC

<table>
<thead>
<tr>
<th></th>
<th>US Car</th>
<th>US Truck</th>
<th>EU Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FE Drop with AC</strong></td>
<td>18%</td>
<td>14%</td>
<td>10%</td>
</tr>
<tr>
<td><strong>FE Drop with defrost</strong></td>
<td>4%</td>
<td>4%</td>
<td>4%</td>
</tr>
</tbody>
</table>

US car and truck based on existing fleet
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

U.S.:
• Car: 11,850 miles (19,070 km)
• Truck: 11,958 miles (19,244 km)
• 7.0 billion gallons used for air conditioning annually
• 5.5% total fuel consumption
• 62 billion kg CO₂
• 9.5% imported crude oil
Total Fuel Use for AC for Cooling and Demisting

<table>
<thead>
<tr>
<th></th>
<th>Totals Dehumid + Cooling</th>
<th>Billion Gallons</th>
<th>Billion Liters</th>
<th>Billion kg CO2</th>
<th>Percent of Total Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU</td>
<td>100% Market</td>
<td>1.8</td>
<td>6.9</td>
<td>16.0</td>
<td>3.2%</td>
</tr>
<tr>
<td>Japan</td>
<td>100% Market</td>
<td>0.45</td>
<td>1.7</td>
<td>4.0</td>
<td>3.5%</td>
</tr>
</tbody>
</table>
U.S. Fuel Saved & CO₂ Reduced by Reducing AC Consumption

AC Power Consumption: Percent of Baseline

Billion Gallons

Billion kg CO₂

65% 70% 75% 80% 85% 90% 95% 100% 105%

AC Consumption

AC Fuel Saved

CO₂ Reduced

Vs. Total Consump.
5.5%
3.6%
Fuel Saved per Vehicle by Climate

30% Reduction in AC Power

Gallons Saved /Vehicle/Year, 30% Reduction in AC Power

- Blue: 0.4 to 6.6
- Light Blue: 6.6 to 7.5
- Purple: 7.5 to 7.9
- Dark Purple: 7.9 to 8.7
- Light Red: 8.7 to 9.4
- Red: 9.4 to 10.1
- Dark Red: 10.1 to 11.9
- Maroon: 11.9 to 13.1
- Medium Maroon: 13.1 to 14.7
- Deep Maroon: 14.7 to 16.6
- Reddish Brown: 16.6 to 21.9
- Brown: 21.9 to 28.2
Per Vehicle Fuel Saved by Reducing AC Consumption

- Car: Baseline Use 33.7 gal/year
- Truck: Baseline Use 26.8 gal/year
- Average: Baseline Use 30.8 gal/year
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
Per Vehicle Savings from an Improved MAC

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
EU Fuel Saved by Reducing AC Power Consumption

- EU AC Consumption
- EU AC Fuel Savings
- Bil kg CO2 Saved

AC Power Consumption: Percent of Baseline

Billion Gallons vs. Total Consump.

3.2%

EU AC Consumption

Billion kg CO2 Saved

65% 70% 75% 80% 85% 90% 95% 100% 105%
Japan Fuel Saved by Reducing AC Power Consumption

AC Power Consumption: Percent of Baseline

- 65%
- 70%
- 75%
- 80%
- 85%
- 90%
- 95%
- 100%
- 105%

Billion Gallons

- 0.14
- 0.11
- 0.09
- 0.07
- 0.05
- 0.02
- 0.005

Billion kg CO2

Vs. Total Consump.

- 3.4%

2.4%

AC Fuel Saved

- CO2 Reduced

Japan AC Consumption

Vs. Total Consump.
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

<table>
<thead>
<tr>
<th></th>
<th>US</th>
<th>EU</th>
<th>Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Fuel Use, Billion Gallons</td>
<td>7.0</td>
<td>1.82</td>
<td>0.45</td>
</tr>
<tr>
<td>AC Fuel Use, Percent of Total Consumption</td>
<td>5.5%</td>
<td>3.2%</td>
<td>3.4%</td>
</tr>
</tbody>
</table>

• Reducing AC fuel use has the potential to greatly benefit the nation
  • Reduce imported oil
  • Reduce CO₂

• Per vehicle savings allow calculation of payback time

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

• Impact of incremental reduction in AC power: states, nations, world
Fuel Savings across the World

Billion Gallons: Savings with 30% Drop in AC Power

2.5

0.56

0.14
CO₂ Reduction across the World

Billion kg CO₂: Reduction with 30% Drop in AC Power
Thank you!

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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

Temperature (C) vs. Time

- Trim
- Seat
- Air
- Glazing
- IP
- Headliner
- Ambient
- Model

Plymouth Breeze
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
- \( \text{CO}_2 \) emissions determined from fuel consumption
  - 2.33 kg \( \text{CO}_2 \)/liter fuel
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 = $P_{\text{compressor}} + P_{\text{blower}}$
    - $P_{\text{blower}} = 120$ 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
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

- 85% of Baseline Power
- 70% of Baseline Power
EU/Japan Per Vehicle Fuel Saved by Reducing AC Consumption

Gallons Saved/Year/Vehicle

Liters Saved/Year/Vehicle

AC Power Consumption: Percent of Baseline

EU Baseline: 8.0 gallons
Japan Baseline: 7.2 gallons

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