Incorporating Automobile Climate Control into the Teaching of Thermal Environmental Engineering

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Introduction

There are many mechanical engineering students that are very interested in the automobile and automotive engineering. It has been our experience that students with this interest can be a challenge to motivate in a course on thermal environmental engineering. This challenge has been tackled by using the automobile interior as the HVAC application. A project approach has been used in two senior level thermal design courses at two different institutions (ME 416 at Michigan State University and ME 436 at the University of Portland) that focuses on automobile climate control. Companion lectures are then used to provide the students with the fundamentals of HVAC design and analysis.

In-house computer software is used that performs the simple calculations associated with the design and cost analysis for the heating and air conditioning systems for an automobile interior. The program allows the students to explore the climate control design over a wide range of variables, including location, commute time, type of car, gasoline price, and cool down time. The students work in project teams of two and are asked to determine the best combination of window transmissivity and air conditioner coefficient of performance for an application (primarily, car type and location) of their choosing. Once a design has been identified, they are asked to take their design and two other competitive designs and conduct several robustness studies to explore the impact of parameters such as gasoline costs, design day, and interest rate on their design decision. The students submit a detailed technical memorandum that documents their design analysis.

While working on their projects, students are introduced to the basic technical background of thermal environmental engineering through lectures and problem sets. Standard topics such as convection/conduction heat transfer through walls and ceilings, infiltration affects, and internal heating/cooling loads are presented and predicted models of these processes are demonstrated. Some of the processes fundamental to automotive climate control are given special attention, including solar loading through windows and thermal transients that occur during heating up or cooling down of the interior.

This paper continues with a discussion of the technical background provided to the students followed by a presentation of the software used. Next a description of the project is provided and the paper concludes with student feedback and recommendations.

Technical Background

There are two aspects of thermal environmental engineering that are special to automotive climate control. The first is inclusion of the solar load through the windows. This analysis begins with a calculation of the solar insolation, q_{sun} , based on location, time of day, and time of year. The process behind this standard HVAC calculation is provided in lecture. With the solar insolation known, the solar load to the automotive interior is then calculated from

$$Q_{\text{solar}} = \tau_{\text{wind}} A_{\text{wind}} q_{\text{sun}} \quad (1)$$

where τ_{wind} is the solar transmissivity of the car windows and A_{wind} is the window area of the car.

The second aspect of note is the cool down process that is a major customer concern in climate control. The focus of this calculation is to determine the air conditioner size required to cool the automobile interior to a target temperature within a specified time. To begin this analysis, the maximum interior temperature is estimated. This temperature is determined by assuming that the car is parked outside in the sun and reaches a steady state interior temperature. An energy balance on the car interior will give

$$Q_{\text{solar}} = Q_{\text{ext}} \quad (2)$$

The solar load is given in Eq. (1), while the external heat loss, Q_{ext} , is calculated through the use of the thermal circuit analogy for the roof, doors, and windows of the car. It is assumed that natural convection occurs on all the surfaces. This simply model provides a fairly realistic internal temperature. For example, the maximum inside temperature of a Taurus sedan in Chicago on July 4 is calculated from this model to be 165°F.

The next step is to determine the air conditioner size required to cool the car interior to a comfort temperature within a specified time. For simplicity, the interior is treated as only the air present. Seats, dashboard, etc. are ignored in this analysis as inclusion would require extensive knowledge of these interior components. With this assumption the transient cooling load, Q_{AC} , is given by

$$Q_{\text{AC}} = [\text{air density}] \times [\text{air specific heat}] \times [\text{interior volume}] \times [T_{\text{max}} - T_{\text{int}}] \div [\text{specified cool down time}] \quad (3)$$

For the example given above, this calculation yields an air conditioner size of 1.75 tons for a five minute cool down time. It is interesting to compare this to an air conditioner size for the steady state cooling load of 0.5 tons.

The more standard calculations of thermal environmental engineering, e.g., wall and ceiling cooling loads, occupant loads, and electronic loads, are also provided to the students in lecture in the context of the automotive application.

CC Auto Program

CC_Auto (Climate Control **A**utomobile) is an interactive DOS program that allows for the optimization of window tint, heater core type, and air conditioner type in the thermal environmental engineering design for an automobile interior. The software has proved to be very useful to teach the basic principles of HVAC design within the context of a realistic problem. The program utilizes weather data for ten different U.S. cities and allows the user to select from five vehicle types, to vary the number of passengers, and the speed of the car. These values are then used in the heating and cooling load calculations performed by the program. Heating and cooling loads, as well as the design/cost analysis, are performed on a daily basis for a specified period of driving. The student may choose an air conditioner size for steady state operation or a size that will provide cooling to reduce the interior temperature to a target value within a specified time period. The economic analysis allows for an appropriate selection of design parameters to be explored by the students, including the interaction among these selections. Figure 1 shows an interactive run of the program. A user's guide for the program is provided in Appendix A. The program is downloadable from the ME 416 web site at Michigan State University, which has the URL

<http://www.egr.msu.edu/classes/me416/>

Figure 1 Interactive Run of CC-Auto

```
*****
|                                     |
|   *****   *****   *   *   *****   *****   |
|   *         *   *   *   *   *   *   *   *   *   *   |
|   *         *   *   *   *   *   *   *   *   *   *   |
|   *         *   *   *   *   *   *   *   *   *   *   |
|   *****   *****   *   *   *****   *   *****   |
|                                     |
|           CC_AUTO: Climate Control AUTOmobile         |
|                   Version 2.0                           |
|           Copyright 1997 Dan Lewis                      |
|                   Craig W. Somerton                     |
|                   Laura J. Genik                        |
|*****|
|
| BEGIN BY CHOOSING A DESIGN STUDY
|   1. SINGLE DAY AIR CONDITIONING
|   2. SINGLE DAY HEATING
| INPUT A CHOICE (1-2): 1
|
| INPUT THE REQUIRED INTERIOR TEMPERATURE (in F)
| FOR AIR CONDITIONING: 72
|
| SELECT A CITY
|   1. NEW YORK CITY           6. MIAMI
|   2. DETROIT                 7. SALT LAKE CITY
|   3. CHICAGO                 8. SEATTLE
|   4. LOS ANGELES             9. PHOENIX
|   5. INTERNATIONAL FALLS    10. PORTLAND
| INPUT A CHOICE (1-10): 4
```

Figure 1 (continued)

```
SELECT A VEHICLE (1-5)
  1. Aerostar (1 - 8 PEOPLE)
  2. Taurus Sedan (1 - 5 PEOPLE)
  3. Mustang GT (1 - 4 PEOPLE)
  4. Ranger (1 - 4 PEOPLE)
  5. Your Car (1-whatever people)
INPUT A CHOICE (1-5): 2

FOR VENTILATION PURPOSES:
  ENTER PERCENT (in decimal form) OF FRESH AIR: 0
  ENTER AIR EXCHANGE RATE (INTERIORS/HOUR): .35

FOR INFILTRATION PURPOSES:
  ENTER VOLUME CHANGE PER HOUR: .2

HOW MANY PEOPLE IN THE CAR: 2

ENTER VEHICLE SPEED (mph): 70

ENTER THE DAY TO BE USED IN THE DESIGN ANALYSIS
  ENTER MONTH (1-12): 7
  ENTER THE DAY OF THE MONTH: 4

SELECT A DESIGN TEMPERATURE (1-4)
  1.RECORD HIGH
  2.NORMAL HIGH
  3.NORMAL LOW
  4.RECORD LOW
INPUT A CHOICE (1-4): 2

ENTER BEGINING HOUR (IN MILITARY TIME): 12

ENTER BEGINING MINUTE: 00

ENTER ENDING HOUR (IN MILITARY TIME): 14

ENTER ENDING MINUTE: 00

SELECT AN AIR CONDITIONER (1-4)
  1. COP OF 2
  2. COP OF 3
  3. COP OF 4
  4. COP OF 5
INPUT A CHOICE (1-4): 2

ENTER TRANSMISSIVITY OF GLASS: .5

**** SUMMARY OF INPUT ****
CITY:                      LOS ANGELES
VEHICLE:                   Taurus Sedan
DESIGN DAY:                7- 4
THE TIME OF DAY:          12: 0 TO 14: 0
INTERIOR TEMPERATURE:    72.0
PERCENT OF FRESH AIR:    .00
AIR EXCHANGE RATE:       .35
INFILTRATION RATE:       .20
OCCUPANTS:               2
VEHICLE SPEED:           70.
A/C COP:                 3.0
WINDOW TRANSMISSIVITY    .50
```

Pause - Please enter a blank line (to continue) or a DOS command.

Figure 1 (continued)

```
**** RESULTS OF THERMAL LOAD ANALYSIS ****

      OPERATING CONDITIONS
      OUTSIDE TEMPERATURE (F):      8.136E+01
      INSIDE TEMPERATURE (F):       7.200E+01
      SOLAR FLUX (BTU/HR/FT^2):     2.996E+02

      LOAD CALCULATIONS
      TOTAL LOAD (BTU/HR):          4.683E+03
      INSTRUMENT LOAD (BTU/HR):     2.000E+02
      OCCUPANT LOAD (BTU/HR):       9.500E+02
      SOLAR LOAD (BTU/HR):          2.847E+03
      CONVECTIVE LOAD (BTU/HR):     8.418E+01
      INFILTRATION LOAD (BTU/HR):   3.402E+01
      VENTILATION LOAD (BTU/HR):    0.000E+00
      CONDUCTION LOAD (BTU/HR):     5.679E+02
      MAX. INSIDE TEMPERATURE (F):  1.474E+02
      COOL DOWN TIME (MIN):         1.370E+01
      AC SIZE (TONS):               5.000E-01

      IS THE COOL DOWN TIME ACCEPTABLE? (YES OR NO) n

      INPUT A COOL DOWN TIME IN MINUTES: 5

**** RESULTS OF THERMAL LOAD ANALYSIS ****

      OPERATING CONDITIONS
      OUTSIDE TEMPERATURE (F):      8.136E+01
      INSIDE TEMPERATURE (F):       7.200E+01
      SOLAR FLUX (BTU/HR/FT^2):     2.996E+02

      LOAD CALCULATIONS
      TOTAL LOAD (BTU/HR):          1.644E+04
      INSTRUMENT LOAD (BTU/HR):     2.000E+02
      OCCUPANT LOAD (BTU/HR):       9.500E+02
      SOLAR LOAD (BTU/HR):          2.847E+03
      CONVECTIVE LOAD (BTU/HR):     8.418E+01
      INFILTRATION LOAD (BTU/HR):   3.402E+01
      VENTILATION LOAD (BTU/HR):    0.000E+00
      CONDUCTION LOAD (BTU/HR):     5.679E+02
      MAX. INSIDE TEMPERATURE (F):  1.474E+02
      COOL DOWN TIME (MIN):         4.567E+00
      AC SIZE (TONS):               1.500E+00

      IS THE COOL DOWN TIME ACCEPTABLE? (YES OR NO) y

Pause - Please enter a blank line (to continue) or a DOS command.

      WOULD YOU LIKE TO CONDUCT AN ECONOMIC ANALYSIS? (YES OR NO): y

      INPUT INTEREST RATE (in decimal form): .04
      INPUT NUMBER OF YEARS: 4
      INPUT FUEL COST ($/GAL): 2.05

**** RESULTS OF COST ANALYSIS ****

      TOTAL PRESENT VALUE COST:    $    856.67
      FUEL COST:                   $      2.05 PER GALLON
      CAPITAL COST OF TINTING:     $    321.00
      CAPITAL COST OF A/C:         $    437.50
      ANNUAL A/C OPERATING COST:  $     27.04
      CAPITAL COST OF HEATER:      $      .00
      ANNUAL HC OPERATING COST:    $      .00
      INTEREST RATE:               $      .04
      NUMBER OF YEARS:             $      4.00
      P/A FACTOR:                  $      3.63
      COOLING DAYS:                $    207.00
      HEATING DAYS:                $      .00
```

Project Description

The first step in assigning this project is forming the teams. The teams are assigned by the instructor using the data collected through the form shown in Fig. 2. In pairing students, experience has shown that teams are most effective when the students have similar work habits, i.e., they are both procrastinators or both like to jump right on an assignment. With respect to technical background, it appears that teams work best when the members are close in their expertise. That is, a student with poor heat transfer background will work better and learn more with another weak heat transfer student than a strong heat transfer student. With the teams assign, the team is presented with the project description.

The project statement provided is in Appendix B. The project is framed within the activity of an engineering firm. This makes the project more realistic to the students. The overall goal of the project is for the team to identify the best climate control design for the application. The best design is defined to be the window transmissivity – air conditioner coefficient of performance (COP) that produces the lowest present cost over a wide range of conditions. The students begin by identifying the application or base conditions for their design. This includes setting the following parameters:

- Type of automobile
- Location of automobile
- Day of the year for which the outside conditions will be taken (design day)
- Number of occupants
- Commute time
- Average automobile speed

Several other design parameters are set for the students. These include:

- Interior temperature of 72°F
- Zero percent for fresh air for ventilation.
- Ventilation rate of 0.35 volumes per hour.
- Infiltration rate of 0.2 volumes per hour.
- Normal high temperature is used for the design temperature
- Cool down time of five (5) minutes.
- Interest rate of 0.04.
- Car lifetime of 4 years.
- Fuel cost of \$2.05 per gallon.

For the first set of parameters the student team is asked to complete a matrix, so that a 3-D graph of cost versus transmissivity and COP. An example of such a graph is shown in Fig. 3. This type of analysis is done for two different conditions of the parameters shown in the first list above (except for the design day), so that six such 3-D graphs are produced. From these results the team decides upon their best design and two competing designs.

Figure 2 Team Survey

NAME: _____ Student Number: _____

Please complete this survey by circling an appropriate response.

Work Habits

I have to jump right on an assignment

I am pretty flexible in working with people

I am a big time procrastinator

Heat Transfer

Hot (Good)

Lukewarm (Fair)

Cold (Poor or None)

I am currently taking ME 410: YES _____ NO _____

Fluid Mechanics

Dr. Foss loves me (Good) I'm a little wet behind the ears (Fair) I'm drowning (Poor or None)

Thermodynamics

I'm a god (Good)

I'm OK (Fair)

Isn't steam an ideal gas? (Poor or None)

Computers and Programming

I'm a jockey (Good)

I can pound the keyboard (Fair)

No! No! Not them! (Poor or None)

Please indicate on a 1-5 scale, with 5 being the best, your abilities working with the following software:

Microsoft Excel _____

MATLAB _____

Please indicate people you may want to work with on Projects 4 and 5, so I will try not to team you for Projects 2 and 3.

Figure 3 3-D Graph of Cost Function

Using the three designs identified in the base design studies, the team then conducts a robust study to see how their best design stands up to the two competitors as some of the parameters in the second list above are varied. The following parameters are varied one at a time in the robustness study:

- Design day
- Record or normal high temperature
- Cool down time
- Interest rate
- Car lifetime
- Fuel cost

The robustness study is done for two different cars. An example of the results of a robustness analysis is shown in Fig. 4. Based upon these results the team makes a final recommendation for the transmissivity – COP combination.

To assist the students in successfully completing the project, they are provided with a succinct list of requirements, shown in Fig. 5. The technical memos are graded with the use of the grading sheet shown in Fig. 6. Finally, a peer review of the team is conducted using the form of Fig. 7.

Figure 4 Example Results from Robustness Study

Student Feedback and Recommendations

Student response to this project and the use of an automotive application to teach the basics of thermal environmental engineering was very positive. The students' learning was enthusiastic. They found the project challenging, but rewarding. It was problematic that most of them had never done a parametric study before, yet they successfully completed the project and many felt that learning how to undertake a parametric study was the most important thing they learned. The students adjusted to the old style interactive nature of the DOS program, but strongly recommended that the program be modified to decrease the difficulty of running multiple cases.

Figure 5 Project Requirements

1. Cost versus transmissivity and COP matrix for two different cars at base design conditions, including appropriate graphs.
2. Bar graph indicating cost breakdown for each of the two matrices from above.
3. Cost versus transmissivity and COP matrix for a second city at base design conditions, including appropriate graphs.
4. Cost versus transmissivity and COP matrix for a second occupant load at base design conditions, including appropriate graphs.
5. Cost versus transmissivity and COP matrix for a second commute time at base design conditions, including appropriate graphs.
6. Cost versus transmissivity and COP matrix for a second vehicle speed at base design conditions, including appropriate graphs.
7. Graph of cost versus design day at both record high temperature and normal high temperature for the optimal base design (COP and τ combination) and some competing designs.
8. Graph of cost versus interest rate for the optimal base design (COP and τ combination) and some competing designs.
9. Graph of cost versus car lifetime for the optimal base design (COP and τ combination) and some competing designs.
10. Graph of cost versus gasoline cost for the optimal base design (COP and τ combination) and some competing designs.
11. Graph of cost versus cool down time for the optimal base design (COP and τ combination) and some competing designs.
12. Discussion on how design parameters affect results and lead to a final recommendation.

Figure 6 Project Grading Form

Student Name: _____

Student Name: _____

Topic	Car #1	Car #2	Total
<i>Base Condition Design</i>			50
Matrix for Base Conditions and cost breakdown			30
Matrix for different cities	XXXXXXXXX XXXXXX		5
Matrix for different number of occupants		XXXXXXXXX XXXXXX	5
Matrix for different commute times	XXXXXXXXX XXXXXX		5
Matrix for different speeds		XXXXXXXXX XXXXXX	5
<i>Robustness Study</i>			40
Design Day and Temperature Choice			10
Interest Rate			6
Car Lifetime			6
Gasoline Cost			6
Cool Down Time			12
<i>Final Recommendation</i>			10
TOTAL			100

Figure 7 Peer Evaluation Form

Please evaluate you and your partner(s) contribution and effort on this project. These responses will be held in confidence.

Your Name: _____ Grade: _____

Partner's Name: _____ Grade: _____

Comments:

Appendix A: CC Auto User's Guide

The software CC_AUTO is an interactive computer program for the design and cost analysis for the heating and cooling of an automobile interior. The software is provided in executable format, and can be run by double clicking on the AC_AUTO icon. The program begins by running through a number of menu options that allow the user to specify the problem conditions. The following menus are provided:

Design Study Menu: User may select to do an air conditioning design at a specified design day, a heating design at a specified design day, or a combined climate control design for an entire year.

Interior Temperature Menu: User will specify the required interior temperature for the air conditioning and/or heating design.

City Menu: User may select any one of nine different U.S. cities. This selection will be used in calculating the outside temperature and solar flux.

Car Menu: User may select any one of four different cars for which the program has data or choose to provide data for their own car. If 'Your Car' is chosen from the menu, the user must be prepared to enter the interior volume in cubic feet, the window area in square feet, the EPA city mpg, and the engine horsepower.

Ventilation Menu: User is asked to specify the percent of fresh air that is use during re-circulation. This should be entered in decimal form (e.g., 0.5 not 50%). Next the user is asked to provide a ventilation rate in number of interiors per hour.

Infiltration Menu: User asked to specify an infiltration (or leakage) rate in terms of volume change per hour.

People and Speed Menu: The user is prompted to indicate the occupancy of the car and its commute speed in mph.

Design Day Menu: The user inputs the month and day of interest.

Design Temperature Menu: The user selects which daily outside temperature the program will use for the cooling load calculations.

Time Menu: The starting and ending times of the commute are inputted in military time.

COP Menu: The type of air conditioner is selected.

Transmissivity Menu: The user inputs the transmissivity of the glass. If its value is greater then 0.8 no tinting is used. The lowest value by law is 0.3.

The program then provides a summary of user inputted specifications. Next the cooling calculations are made and a summary of these results are provided. If the cool down time is not acceptable, then the user is asked to specify a cool down time and the required air conditioner size is calculated. If an economic analysis is desired the interest rate, number of years, and fuel cost must be inputted. The program provides a summary of the economic analysis results and then allows the user to re-specify the COP or transmissivity, run another case, or exit. Output is provided both to the screen and to an output file named CC_AUTO.OUT located on the default drive. All output is appended to the file, so the user may wish to rename it after running a set of cases.

Appendix B: Project Statement

The Rhino Thermal Engineering Company has recently received a contract to provide a major automobile company with a system design and optimization of a automobile air conditioning system. Three of the principals of the company, Dr. Craig W. Somerton, Dr. Laura Genik, and Mr. Dan Lewis, have developed a computer program that can be used to optimize the air conditioner and window tint choices for the cooling of an automobile interior. The goal of the design study is to determine the combination of air conditioner coefficient of performance (COP) and window tinting that will minimize the present value cost. To complete the contract a design team of two students have been assigned. This thermal design/cost analysis should be done for several different situations including:

- (1) at least two different cars
- (2) car pool (3-6 occupants) versus non-car pool (1-2 occupants)
- (3) two different cities
- (4) a short commute time (1-2 hours) versus a long commute (3-5 hours)
- (5) a slow driver (55-70 mph) versus a fast driver (70-90 mph)

It may be assumed that the commute time occurs over one time period around mid-day. The design team should also establish the robustness of the preferred design for the following parameters:

- (1) design day
- (2) design temperature (normal high versus record high)
- (3) gasoline cost
- (4) interest rate
- (5) car lifetime
- (6) cool down time

The team may wish to chose a design day for a certain city based on maximizing the outside temperature, solar flux, or car inside temperature. For ventilation purposes the team may use an air exchange rate of 0.35 and for infiltration calculation a volume change per hour factor of 0.2 can be assumed. An important aspect of automobile air conditioning design is the time it takes to cool the interior from a non-cooling condition (car sitting in the sun) to the comfort temperature. The team should consider costs associated with ignoring this factor compared to costs for specified cooling down times.

Three components are considered in the cost analysis

- (1) capital cost of window tinting (varies with glass transmissivity)
- (2) capital cost of air conditioner (varies with COP and size)
- (3) annual operating cost of air conditioner (depends on nearly all specifications)

The results of your design study should be presented in technical memo format.

CRAIG W. SOMERTON

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