

# **An Assessment of Alternative Refrigerants for Automotive Applications based on Environmental Impact**

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## **ABSTRACT**

It is evident that societies around the globe are demonstrating growing interest and concern for the environment. This trend has manifested itself in demand for products that meet societies' expectations for environmental friendliness. Automakers, globally, have rallied to devise better designs and solutions that meet these expectations. In the area of automotive air-conditioning systems, the technology has evolved to a reliance on HFC-134a as a stable non-corrosive, non-toxic refrigerant that avoids adverse impact on the ozone layer. More recently, the industry has been involved in assessment of refrigerants other than HFC-134a, motivated primarily by efforts to minimize greenhouse gas emissions. Typical candidates include carbon-dioxide as well as members of the hydrocarbon group (usually, propane and iso-butane).

The present study was undertaken to assess the relative advantages of these alternative refrigerants, with specific emphasis on carbon-dioxide systems. To do so, the study employs the Total Environmental Warming Impact (TEWI) index as a holistic measure of the system. The analysis was undertaken with carefully defined conditions involving two standard production vehicles representing small and mid-size cars. The simulations were run to represent vehicle and air-conditioning use in six cities around the globe using standard vehicle operation cycles. Key assumptions such as refrigerant emission were made using a range of values cited in references. In the case of CO<sub>2</sub> systems, given lack of adequate on-road measurements, the effect of approach temperature was also evaluated with a range of values.

The results reveal that when the total picture is considered, HFC-134a systems demonstrate advantages compared to carbon-dioxide and hydrocarbon systems on the TEWI scale. Looking ahead, there is opportunity for further reduction of TEWI values for HFC-134a systems if their emission rates can be reduced. The advantage for HFC-134a systems is pronounced in the warmer regions around the globe. The advantages derive mainly from the fact that the HFC-134a systems offer better cycle efficiencies at high ambient temperature. For some of the cooler regions, carbon-dioxide systems may offer better TEWI performance. This advantage may be eroded if further progress is made to reduce lifetime emission for HFC-134a systems. Also, the hydrocarbon systems are broadly comparable to carbon-dioxide systems on the TEWI scale for the conditions evaluated.

To maximize beneficial impact on the environment, it may be necessary to analyze the distribution of global vehicle population densities and the efficacy of any technical solution.

## 1. INTRODUCTION

The Montreal Protocol was signed in 1987 amidst growing concern about ozone depletion effects of various refrigerants used in air-conditioning systems. Chlorofluorocarbons (CFCs) which were extensively used at that time in air-conditioning systems were identified as contributing to ozone depletion. The potential dangers of ozone-producing materials, such as CFC's, which affect the earth's stratosphere, have been documented in various publications [1-6]. Since the signing of the Montreal Protocol, a broad search was undertaken for alternatives that would replace CFCs. Among the several groups of alternatives the hydrochlorofluorocarbons (HCFCs) and the hydrofluorocarbons (HFC's) were considered to be the most obvious. The choices were motivated by the urge to develop safe (non-toxic, non-flammable) refrigerants that would be efficient for the intended air-conditioning cycle. It should be noted, however, that HCFCs, unlike HFCs, contain chlorine and therefore are still ozone depleting materials. Consequently, the automotive industry made the switch to HFCs from CFCs as a long-term solution to this environmental issue [5-7].

More recently, the Kyoto Protocol (1997) has caused environmental focus to shift from *ozone depletion* to *global warming* and equivalent emission of carbon dioxide into the atmosphere. All emissions, attributable to automobiles and their effect on global warming were identified and this, in the area of refrigerants, led to the inclusion of HFC-134a among the "basket" of gases monitored by the Kyoto Protocol.

As a gas, HFC-134a has a significantly larger global warming potential (GWP=1300) than non-halocarbon working fluids. This means that emission of HFC-134a causes a significantly larger effect on global warming, compared to an equivalent amount of carbon dioxide (GWP=1 by definition). However, it is also important to study the problem in its larger context. The total effect of mobile refrigeration systems on global

warming is more accurately described by the Total Environmental Warming Impact (TEWI) [5,7]. The TEWI concept takes into account the contributions to global warming of:

- 1) the overall efficiency of the air-conditioning system which directly affects fuel burned to power the system and thereby, the  $\text{CO}_2$  from that related combustion,
- 2) the emission of  $\text{CO}_2$  from burning fuel to transport the (mass of the) air-conditioning system;
- 3) the result of refrigerant being released to the atmosphere due to leakage, servicing and accidents.

The TEWI concept has gained favor as the preferred method for considering, in a holistic manner, the multiple environmental effects of alternative refrigerants in mobile air-conditioning systems.

Focus on the effect of refrigerant emission has triggered a move to advocate use of working fluids like carbon dioxide. Indeed,  $\text{CO}_2$  and hydrocarbons (HCs) are viable refrigerants that, solely from an emission perspective, offer advantages compared to HFC-134a. Furthermore, carbon dioxide being a non-flammable, enjoys popular preference over hydrocarbons.

The present study was undertaken to investigate the relative advantages of these alternative refrigerants employing the TEWI index. The analysis was undertaken with carefully defined conditions involving two standard production vehicles representing small and mid-size cars. The simulations were run to represent vehicle and air-conditioning use in six cities around the globe using standard vehicle operation cycles.

## **2. ANALYSIS TOOL**

Measured compressor performance data were used with a commercial software package called EES (developed by F-Chart Inc.) [8] to evaluate system coefficient of performance (COP) for the different air-conditioning cycles. The basic function provided by EES is the numerical solution of a set of algebraic equations. The EES software was used in conjunction with REFPROP6 [8] from the National Institute of Standards and Technology (NIST) in order to calculate refrigerant thermodynamic and thermophysical properties. REFPROP6 computes high accuracy properties for many pure and mixtures of liquids and gases. Laboratory and wind tunnel measurements were used to specify optimal high side pressure of the  $\text{CO}_2$  systems [9-11] and condensing pressure for the other systems.

In addition to the EES program an Excel spreadsheet was developed to calculate TEWI values in each case. This spreadsheet takes into account many factors:

- annual vehicle driving hours and distance
- annual air-conditioning usage, the vehicle driving cycle (regional driving schedules), the average lifetime of the vehicle
- refrigerant emission values

- incremental (vehicle) fuel consumption
- refrigerant type
- vehicle electrical requirements to operate the A/C system (blower) for the different regions
- other factors

For HFC134a systems, the variable displacement compressor information was obtained from the manufacturer and uses measured data. For CO<sub>2</sub> systems, data was provided by sources cited in the list of references [9, 10].

### **3. VEHICLES MODELED AND CONDITIONS**

The analysis was performed for two standard production vehicles representing small and mid-size cars. The vehicle and the engine specifications as well as the important parameters adopted in the present study are summarized in Table 1.

The performance comparisons for different refrigerants (HFC-134a, CO<sub>2</sub>, and HCs) were made under identical conditions. Air temperature and the air flow leaving the evaporator core were set at 55 °F and 250 CFM, respectively.

### **4. ANALYSIS CONDITIONS AND ASSUMPTIONS**

#### **4.1 Ambient Temperature and Relative Humidity Distributions**

The simulations were run to represent vehicle and air-conditioning use in six cities around the globe using standard vehicle operation cycles as well as different vehicle characteristics. The six cities that were selected represent diverse climates around the globe. For example, European climates (Frankfurt) tend to be cooler, with air-conditioning usage at lower energy consumption, while Pacific Rim, and tropical climates (Miami) are warmer and more humid, with more frequent air-conditioning usage at higher consumption. Typical meteorological weather information was used for the different cities around the globe [12]. Figure 1 shows the ambient temperature and the corresponding relative humidity distributions for the regions (six cities) considered in our investigation. For each region these meteorological data, in conjunction with the assumed comfort levels, were used to obtain the required cooling loads for calculation of the system COP.

#### **4.2 Vehicle Operational Cycles**

For cities in the US the Environmental Protection Agency (EPA) driving cycle was adopted to determine the air-conditioning compressor usage profile and consequently the TEWI index for running the air-conditioning system. Similarly, for Europe the calculations involved the European ECE 93/116 driving schedule (Figure 2a). For Tokyo a driving cycle shown in Figure 2b was used in the analysis [13].

A variable displacement compressor model was used for the HFC-134a system. The power input to the compressor was a function of ambient temperature. Also, the compressor was turned on at and above 40 °F with cooling output and power input changing to meet the load.

### **4.3 HFC-134a Cycle Systems**

Figure 3 depicts the schematic of the HFC-134a compression used in the present study. The subcritical systems were evaluated using calculated refrigerant properties at: the compressor inlet, the compressor exit, the condenser exit, the evaporator inlet, and saturated vapor leaving the evaporator.

#### 4.3.1 Emission Assumption for HFC-134a System

Refrigerant emissions from leakage, servicing, end-of-life procedures and accidents are critical components for HFC-134a air conditioning systems. An estimate in automobile air-conditioning system has been given by [14,15]. To address this issue, four different emission rates were used for the HFC-134a refrigerant system. Henceforth these four emission rates will be referred to as: E1, E2, E3 and E4 refrigerant emissions. The values for HFC-134a systems in different cars are described in Table 2. The E3 and E4 values for each vehicle are based on 1.5 and 2 recharges (for refrigerant) during the operating lifetime of the air-conditioning system (11 years), each requiring refrigerant addition at 40% of the original charge [14]. The range of values for refrigerant emission, used in this study, spans values used by other studies [3, 14-16].

### **4.4 Carbon Dioxide (CO<sub>2</sub>) Cycle**

Figure 4 illustrates the schematic of the CO<sub>2</sub> cycle for the two vehicles. For the CO<sub>2</sub> cycle, the analysis of the supercritical refrigerant includes the use of calculated refrigerant properties at the evaporator inlet, saturated vapor at the evaporator exit, the inlet and exits of a suction line heat exchanger, compressor suction and discharge ports, and the gas cooler exit. Refrigerant temperature leaving the gas cooler is determined from the ambient temperature and the approach temperature.

#### 4.4.1 Approach Temperature Assumptions for CO<sub>2</sub> System

It is convenient to compute TEWI using cooling loads and efficiencies as they vary with ambient temperature, since that is how climate data are organized. The performance of CO<sub>2</sub> systems, however, depends heavily on the temperature of the air entering the gas cooler. At idle conditions or low vehicle speeds the air temperature (air entering the gas cooler) can be significantly higher than the ambient temperature due to the entrainment of engine heat. The temperature of the refrigerant leaving the gas cooler will be hotter than the air entering the gas cooler. The temperature difference across

the gas cooler can be very small depending on the design conditions (3 to 5 °K) for a well-built gas cooler but it varies with heat exchanger loading. These two temperature differences ( $\Delta T$ s) and the gas cooler approach temperature are illustrated in Figure 5.

The approach temperatures used in this analysis are based on the various re-entrainment modes for the CO<sub>2</sub> systems (Figure 6a). These values are used in conjunction with the vehicle operation cycles. Experimental measurements conducted in a climatic wind tunnel confirmed this behavior, both as a function of vehicle speed and ambient temperatures (Figure 6b).

#### 4.4.2 Emission Assumptions for CO<sub>2</sub> System

Emission rates for CO<sub>2</sub> air-conditioning systems are not readily available compared to that of HFC-134a systems. However, gases such as CO<sub>2</sub> and hydrocarbons have extremely low global warming effects and thus the impact of CO<sub>2</sub> leakage on TEWI is insignificant.

### **4.5 Hydrocarbon systems**

The refrigeration cycles adopted for propane and iso-butane are shown in Figure 7 schematically. This system adopts a secondary loop, compared to HFC-134a systems. TEWI evaluations for the hydrocarbons were performed only for the mid-size car. The secondary loop pump power (for the secondary loop) is assumed to be 200 W coincident with the compressor operation and there is an assumed temperature difference across the secondary heat exchanger.

## **5. TEWI CALCULATIONS**

Figure 8 summarizes the steps that are taken to generate TEWI values in each analysis. For each vehicle, the regional climates (Figure 1) and the required passenger compartment comfort levels were used as inputs to the EES program. This step generated the COP and the cooling load required for each air-conditioning system for the respective vehicle and the region. The COP and the cooling load were then fed into an Excel spreadsheet utilizing the various usage profile assumptions, which in turn resulted in a TEWI index.

In this analysis the equivalent CO<sub>2</sub> emission due to the transportation of the weight of the air conditioning system is computed using 57 liters/100 kg/10,000 km for incremental fuel use for weight increases [7]. A lifetime fuel consumption was then computed by using the vehicle usage time for the different regions (cities) and the air-conditioning lifetime. This lifetime fuel consumption for the weight of the air-conditioning was converted to an equivalent CO<sub>2</sub> emission using 2.32 kg CO<sub>2</sub>/liter of fuel [3,7,14].

## 6. RESULTS

In each section, results are shown as bar charts. Each bar consists of TEWI contributions from the energy input to the compressor, the fuel consumption for transporting the weight of the air-conditioning system, and the direct global warming effect of refrigerant emissions.

### 6.1 Effect of Different Emission Rates on TEWI for the HFC-134a System

Figure 9 illustrates the effect of the emission rates on TEWI index for the mid-size car in all six cities for the HFC-134a system. It is evident from this figure that the TEWI contribution from refrigerant emission is the dominant portion of the total TEWI in the cooler climates while the power consumption for the air-conditioning system is dominant in other regions. The following table compares the contributions of the various components that comprise the total TEWI values for Phoenix and Frankfurt for the mid-size vehicle. These values are based on the E2 emission level (55 g/year).

City	A/C compressor power consumption	fuel consumption for transporting the weight of the air-conditioning system	Direct Emission
Phoenix	72%	8%	20%
Frankfurt	22%	15%	63%

Similar results were observed for the small car (not shown here).

As expected the TEWI values increase as the emission rate increases. Also shown in the figure are significant variations of total TEWI for different regions. This result is consistent with the previous published investigations [3,7].

### 6.2 Effect of Approach Temperature on TEWI for CO<sub>2</sub> System

As discussed earlier, three different approach temperatures (Figure 6) were used for the CO<sub>2</sub> system. These approach temperatures represent:

- A1 re-entrainment,
- A2 re-entrainment and
- A3 re-entrainment modes, respectively.

Figure 10 shows the variation of TEWI index as a function of approach temperature in different climates. It is apparent from the figure that the approach temperature significantly affects the TEWI index particularly at higher hot air re-entrainment modes during idle. This will impact performance of CO<sub>2</sub> system significantly while the vehicle is

stationary in the warmer regions. The direct emission (leakage) effects are so small for the CO<sub>2</sub> system that they are not visible in the figure.

### **6.3 TEWI Comparisons for Vehicle and Refrigerant Types in Different Climates**

As described in the previous sections, TEWI values for HFC-134a systems vary significantly, depending on the assumptions of emissions from such systems. Likewise, for CO<sub>2</sub> systems, assumptions of approach temperature can strongly influence TEWI values. This section will depict these variations as a range, using the values described above.

Figures 11 and 12 show the TEWI variations as a function of vehicles (small and mid size cars) and refrigerant types (HFC-134a and CO<sub>2</sub>) in different climates (six cities). In these figures for CO<sub>2</sub> systems, the third segment is labeled as “approach temperature uncertainty” which represents emissions from re-entrainment ranging from A1 to A3 re-entrainment values. For the HFC-134a system the last segment (in the bar chart) is the uncertainties due to direct emission levels (E2-E4 emissions).

It appears that the HFC-134a system is superior to the CO<sub>2</sub> system, particularly in hot and humid regions (Phoenix and Miami.). In cooler climates, like Frankfurt, however, CO<sub>2</sub> systems reveal an advantage in terms of TEWI index.

Also, comparing Figures 11 and 12, it is evident that the value of TEWI (for both HFC-134a and CO<sub>2</sub> systems) increases with vehicle size while maintaining the same level of occupant comfort. This is also understandable in the sense that the larger vehicle requires greater cooling capacity.

Figure13 illustrates the variation of TEWI index for propane and iso-butane in different cities. Similar to the CO<sub>2</sub> systems, the emission effects of the hydrocarbons are very small (third segment almost zero). It should be noted that the effect of re-entrained approach temperature was not performed for the hydrocarbon systems.

## **7. CONCLUSIONS**

In summary, it is evident that the total environmental impact of a mobile refrigeration system derives from several factors in addition to refrigerant GWP. Any assessment based solely on the GWP of the refrigerant is therefore incomplete. The TEWI index appears to comprehend these additional factors successfully. Furthermore, calculating the TEWI index depends on several key assumptions of local climate, vehicle use, system performance and, etc. Our data reveals that it is possible to arrive at different conclusions depending upon particular choice of assumptions. To achieve robust conclusions, it was necessary to evaluate the TEWI index for a selection of vehicles, in

different global cities using standard reference values for local climates, driving cycles, vehicle use, etc.

From the set of calculations performed for this study, it appears that HFC-134a systems enjoy an advantage (over CO<sub>2</sub> systems) in the warmer regions around the globe. The advantages derive mainly from the fact that the HFC-134a systems offer better cycle efficiencies emissions when actual heat exchanger air temperatures are considered. For some of the cooler regions, CO<sub>2</sub> systems may offer better TEWI performance. As was observed in the results, for cooler climates, TEWI contributions are often dominated by emission of refrigerant.

This advantage, for CO<sub>2</sub> systems in the cooler climates, may be eroded if further progress is made to reduce lifetime emissions for HFC-134a systems. This may be impacted by local (technical) improvements to fittings, system sealing, etc. as well as procedural changes for recovery and recycling during service and at end-of-life.

Likewise, it is possible to arrive at very different conclusions on the TEWI performance of CO<sub>2</sub> systems depending on how one accounts for re-entrainment of engine and pavement heat and for gas-cooler approach temperatures. Given limited test data for this effect, it is an important area for further study. Current experience reveals that CO<sub>2</sub> systems suffer significant performance degradation when the temperature of the air passing through the gas cooler is elevated. This translates to much higher values of TEWI under these conditions.

Finally, this study briefly examined the TEWI performance of hydrocarbon systems. Overall, they offered a comparable level of TEWI performance as HFC-134a systems for the assumptions chosen regarding secondary loop performance and pumping power. Additional work is underway to study this system in more detail.

To maximize beneficial impact on the environment, it may be necessary to analyze the distribution of global vehicle population densities and the efficacy of any technical solution.

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## REFERENCES

1. M. J. Molina and F. S. Rowland, "Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom-Catalyzed Destruction of Ozone," *Nature*, Vol. 249, pp. 810 – 812, 1974.
2. M. J. Molina, "Polar Ozone Depletion," 1995 Nobel Lecture, *Angewandte Chemie*, Vol. 35, No. 16, International English Edition, pp. 1778 – 1777, September 6, 1996.
3. M. S. Bahatti, "A Critical Look at R-744 and R-134a Mobile Air Conditioning Systems," SAE paper no. 970527, February 1997.
4. P. A. Newman, "Preserving Earth's Stratosphere," *Mechanical Engineering*, October 1998, pp. 88 – 91.
5. S. Gopalnarayanan, "Choosing the Right Refrigerant," *Mechanical Engineering*, October 1998, pp. 92 – 95.
6. Y. Hwang, M. Ohadi, and R. Radermacher, "Natural Refrigerants," *Mechanical Engineering*, October 1998, pp. 96 – 99.
7. S. K. Fischer and J. R. Sand, "Total Environmental Warming Impact (TEWI) Calculations for Alternative Automotive Air-Conditioning Systems," SAE paper no. 970526, February 1997.
8. EES (Engineering Equation Solver), User Manual, F-Chart Software, Middleton, Wisconsin.
9. R. P. McEnaney, Y. C. Park, J. M. Yin, and P. S. Hrnjak, "Performance of the Prototype of a Transcritical R744 Mobile A/C System," SAE paper no. 990872, 1999.
10. D. Boewe, J. Yin, Y. C. Park, C. W. Bullard, and P. S. Hrnjak, "The Role of the Suction Line Heat Exchanger in Transcritical R744 Mobile A/C Systems," SAE paper no. 990583, 1999.

11. R. P. McEnaney, D. E. Boewe, Yin, J. M., Y. C. Park, C. W. Bullard, and P. S. Hrnjak, "Experimental comparison of mobile a/c systems when operated with transcritical CO<sub>2</sub> versus conventional R134a", Purdue conference Proceedings, pp. 145-150, 1998.
12. Engineering Weather data, AFM 88-29, TM 5-785, NAVFAC P-89, Department of the Air Force, the Army and the Navy, July 1978.
13. T. Hirata, Private communication to S. Fischer of Oak Ridge National Laboratory, 1997.
14. J. R. Sand, S. K. Fischer and V. D. Baxter, "Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies," Oak Ridge National Laboratory, 1997.
15. James A. Baker, "Mobile Air Conditioning: HFC-134a Emissions and Emission Reduction Strategies" Joint IPCC/TEAP Expert Meeting on Options for the Limitation of Emissions of HFCs and PFCs", Energieonderzoek Centrum Nederland (ECN), Petten, The Netherlands, May 26-28, 1999.
16. J. M. Yin, J. Pettersen, R. McEnaney, and A. Beaver, "TEWI Comparison of R744 and R134a Systems for Mobile Air Conditioning", SAE paper no. 990582, 1999.

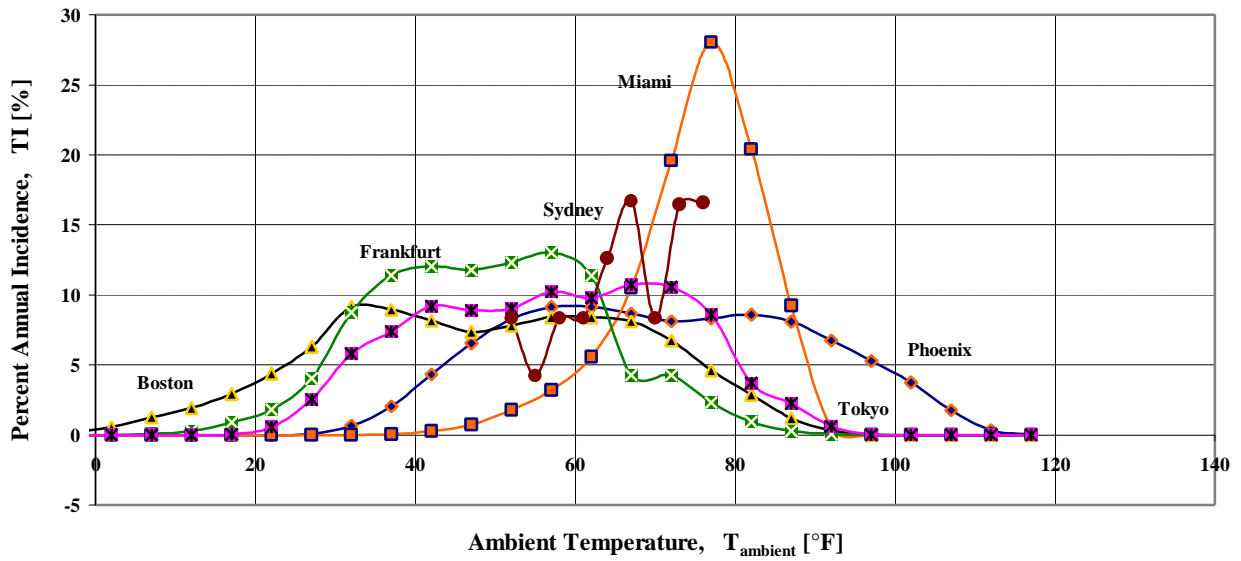
**Table 1. Vehicles and A/C system information**

<b>Small Car</b>	<b>Mid-size Car</b>
2.4L 4-Cylinder Engine	3.8L V6 Engine
Automatic Transmission	Automatic Transmission
Refrigerant Charge = 682 g (24 oz) HFC-134a	Refrigerant Charge = 964 g (34 oz) HFC-134a
Compressor = Variable displacement, Mfr. data	Compressor = Variable displacement, Mfr. data

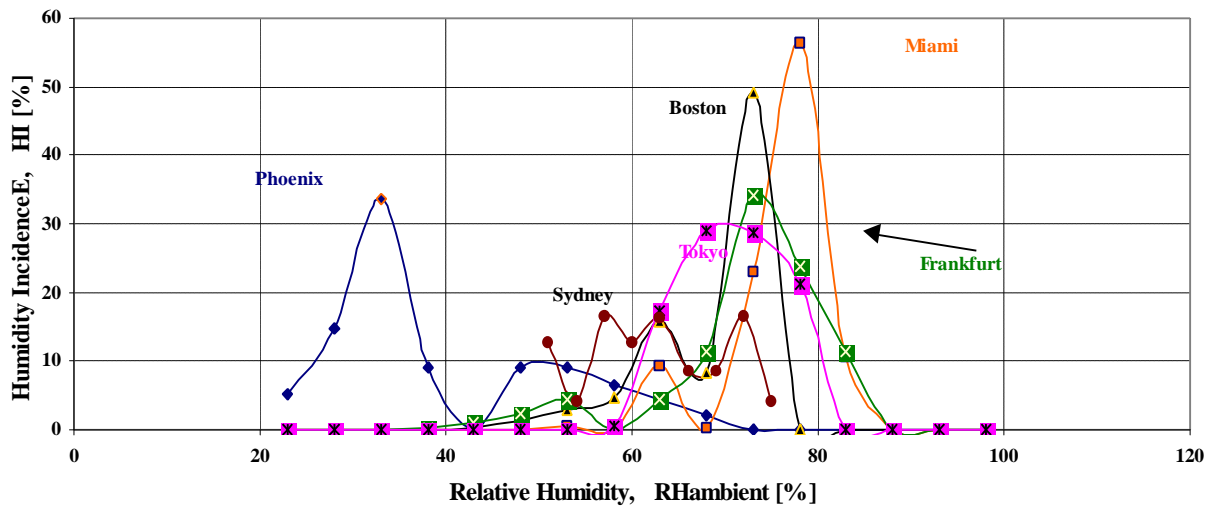
**Table 2. Refrigerant emissions assumptions for HFC-134a systems**

<b>Small Car</b>	<b>E1</b>	<b>E2</b>	<b>E3</b>	<b>E4</b>
Vehicle lifetime (years)	11	11	11	11
Full initial charge (g)	682	682	682	682
Recharges over lifetime	0.5	1	1.5	2
EOL residual charge (g)	450	450	450	450
EOL emission (g)	45	45	45	45
Recovery at EOL (%)	90	90	90	90
<b>Effective emissions per year</b>	<b>25</b>	<b>40</b>	<b>55</b>	<b>70</b>

<b>Mid-size Car</b>	<b>E1</b>	<b>E2</b>	<b>E3</b>	<b>E4</b>
Vehicle lifetime (years)	11	11	11	11
Full initial charge (g)	964	964	964	964
Recharges over lifetime	0.5	1	1.5	2
EOL residual charge (g)	630	630	630	630
EOL emissions (g)	63	63	63	63
Recovery at EOL (%)	90	90	90	90
<b>Effective emissions per year</b>	<b>35</b>	<b>55</b>	<b>78</b>	<b>98</b>

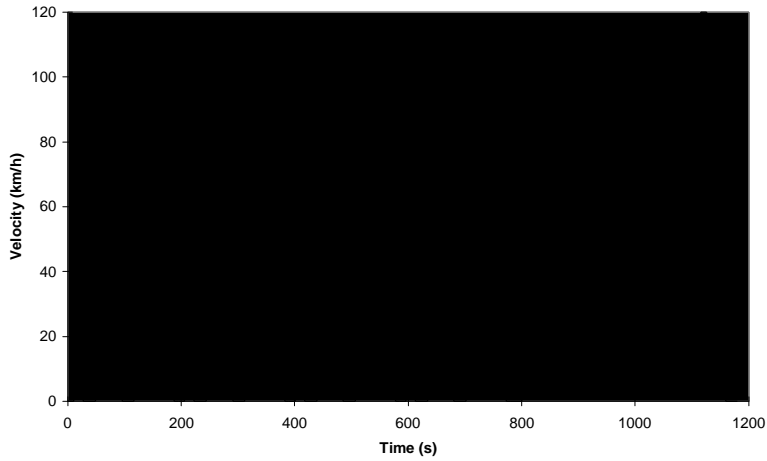


(a) Temperature Distributions



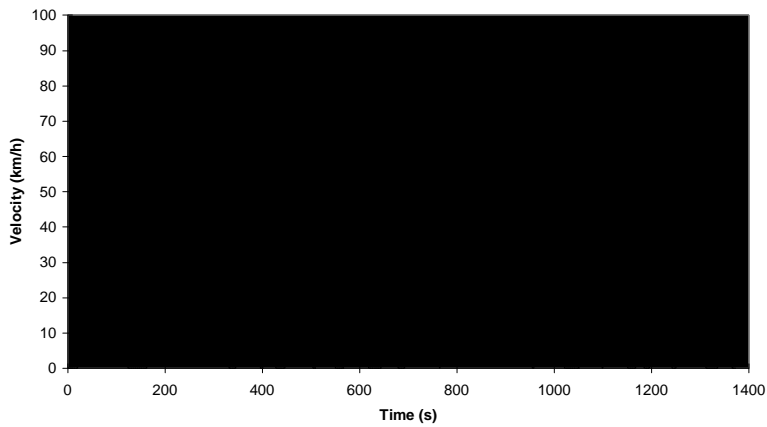
(b) Relative humidity distributions

Figure 1. Regional temperature and relative humidity distributions [12].



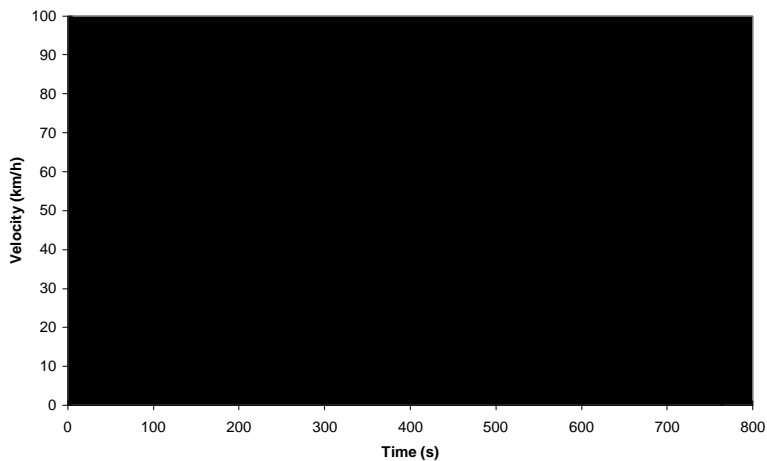
Driving cycle for European Union (93/116)

Length: 11.007 km  
 Total duration: 1220 s  
 Max. speed: 120 km/h  
 Average speed: 33.6 km/h



US Federal Test Procedure (EPA) City Cycle

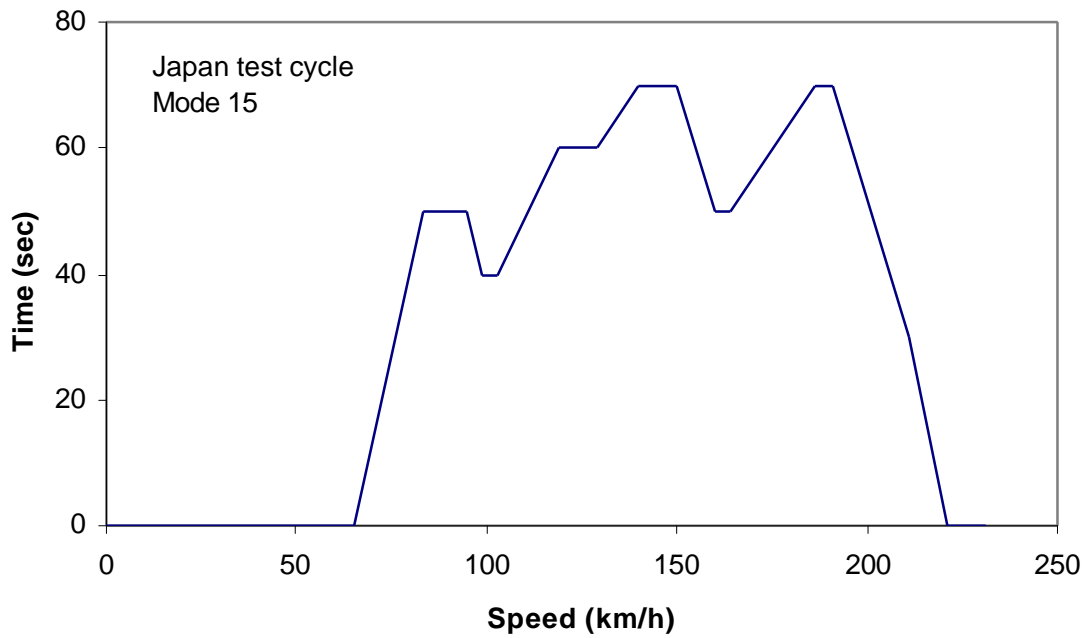
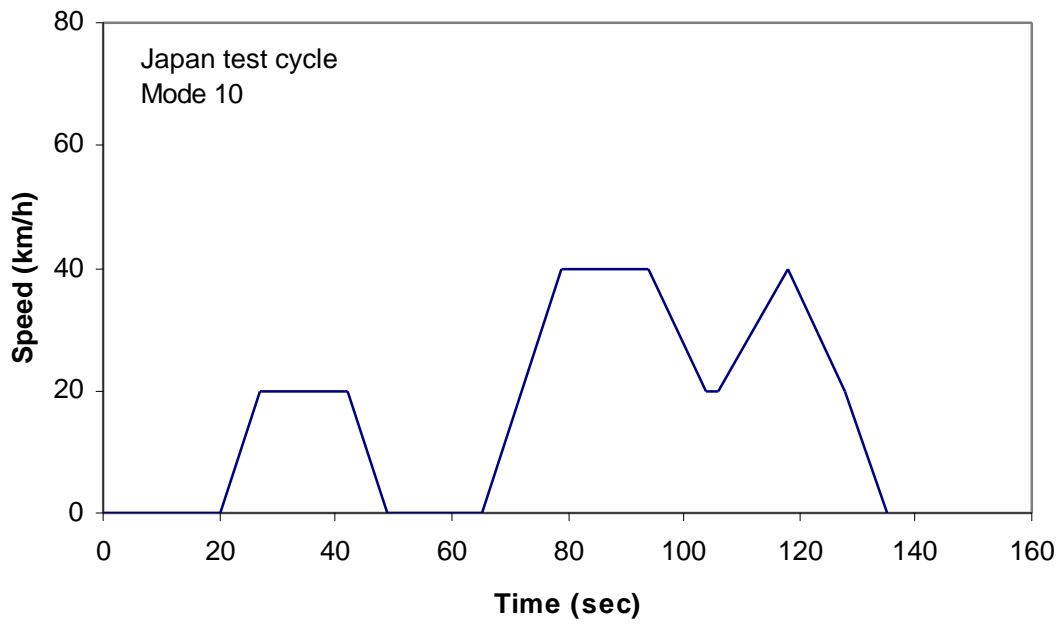
Length: 17.8 km  
 Total duration: 1877 s  
 Max. speed: 91.2 km/h  
 Average speed: 34.1 km/h



US Federal Test Procedure (EPA) Highway Cycle

Length: 16.5 km  
 Total duration: 77.4  
 Max. speed: 96.4 km/h  
 Average speed: 77.4 km/h

**Figure 2a: Vehicle test cycles used for evaluation of refrigerants**



**Figure 2b. Vehicle test cycle for Japan [13]**

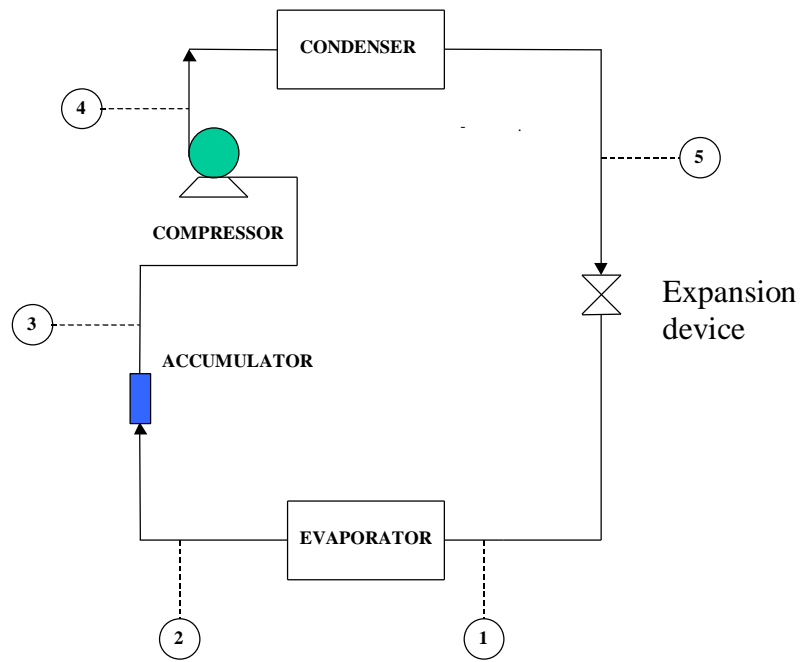


Figure 3. Schematic of the HFC-134a cycle.

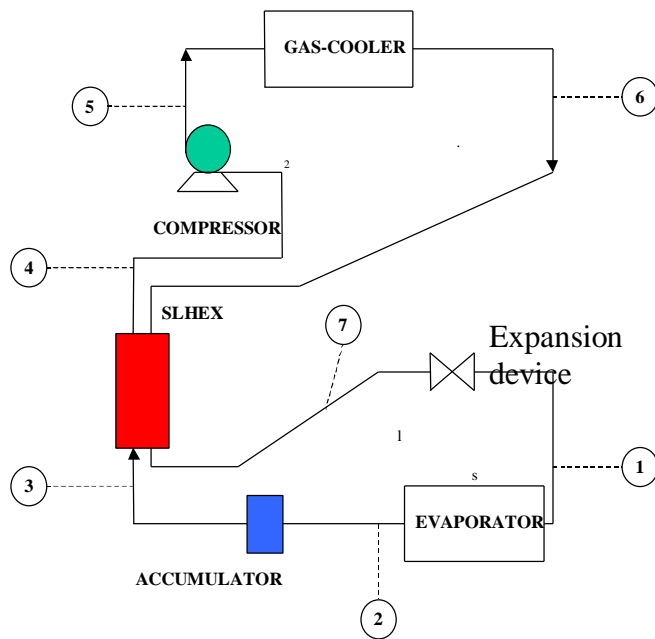
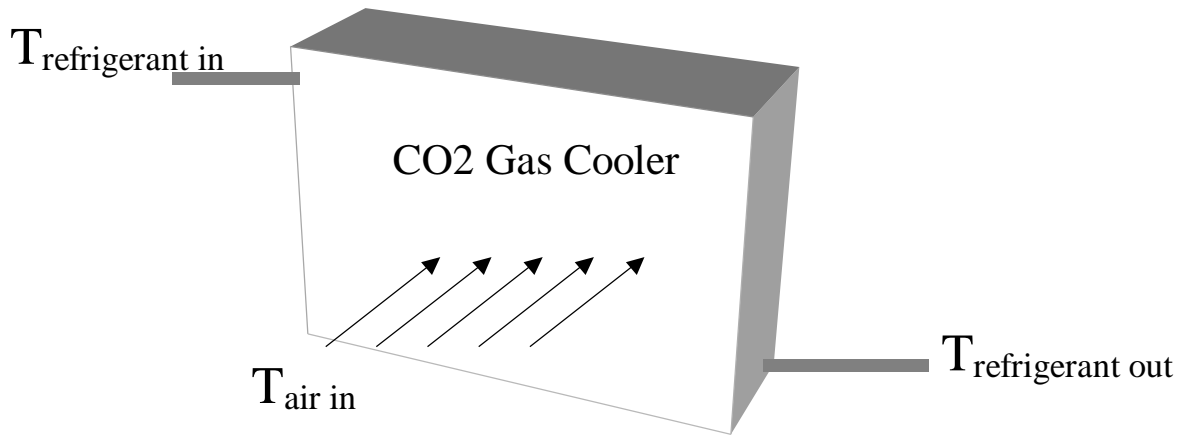


Figure 4. Schematic of the CO2 cycle.



$T_{\text{air ambient}}$



Hot-air re-entrainment

$$\Delta T_{\text{approach}} = \Delta T_{\text{re-entrainment}} + \Delta T_{\text{gas cooler}}$$

where,  $\Delta T_{\text{re-entrainment}} = T_{\text{air in}} - T_{\text{air ambient}}$

$$\Delta T_{\text{gas cooler}} = T_{\text{refrigerant out}} - T_{\text{air in}}$$

**Figure 5. Schematic of a CO<sub>2</sub> gas cooler and the approach temperature definition.**

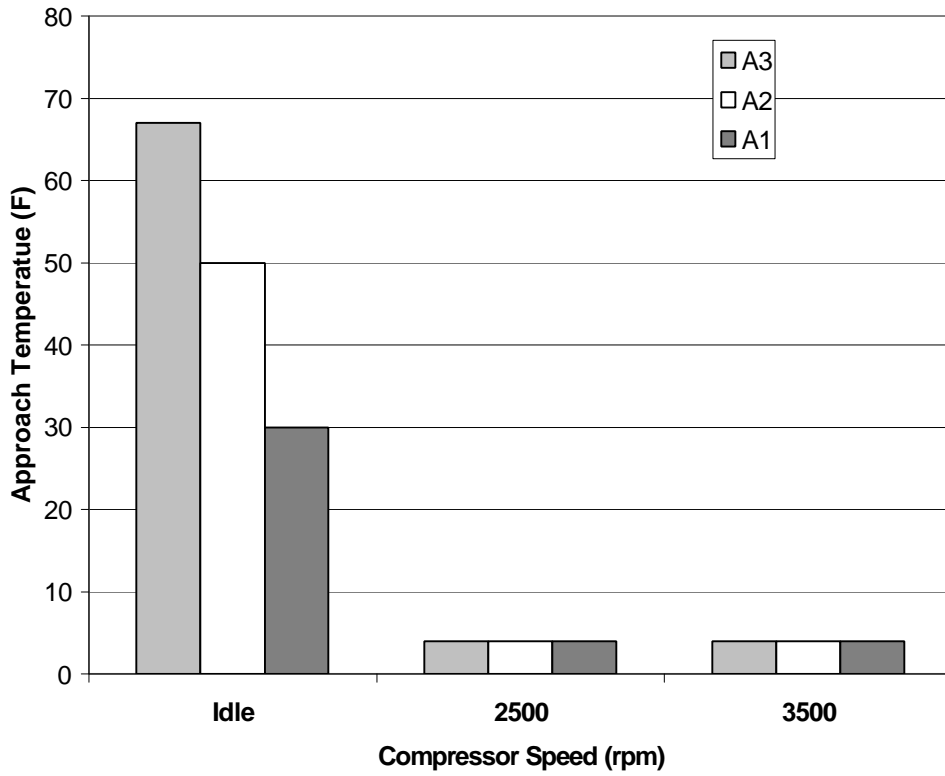


Figure 6a. Three approach temperature distributions used for the CO<sub>2</sub> cycle.

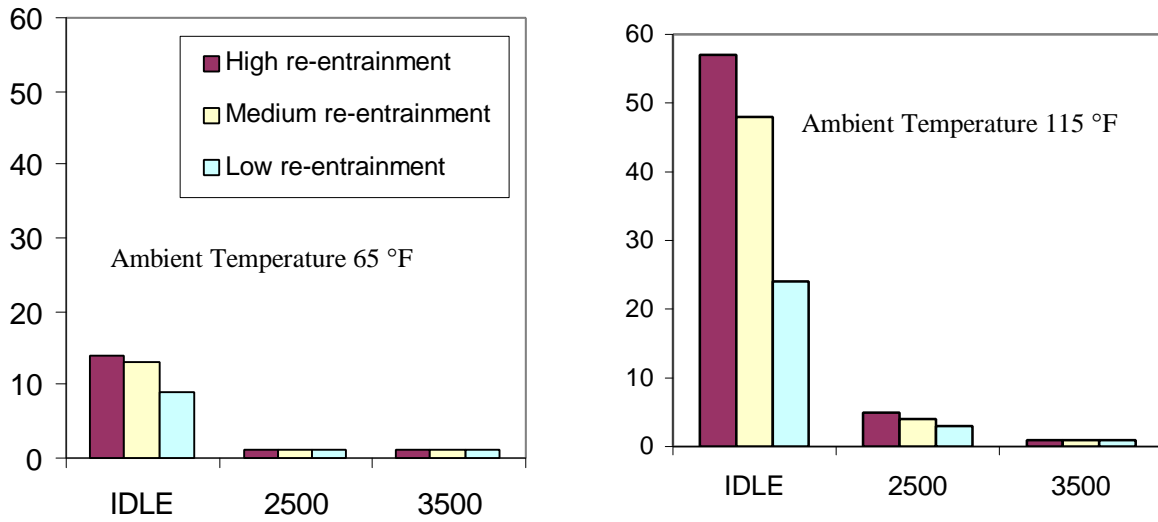


Figure 6b. Wind tunnel data

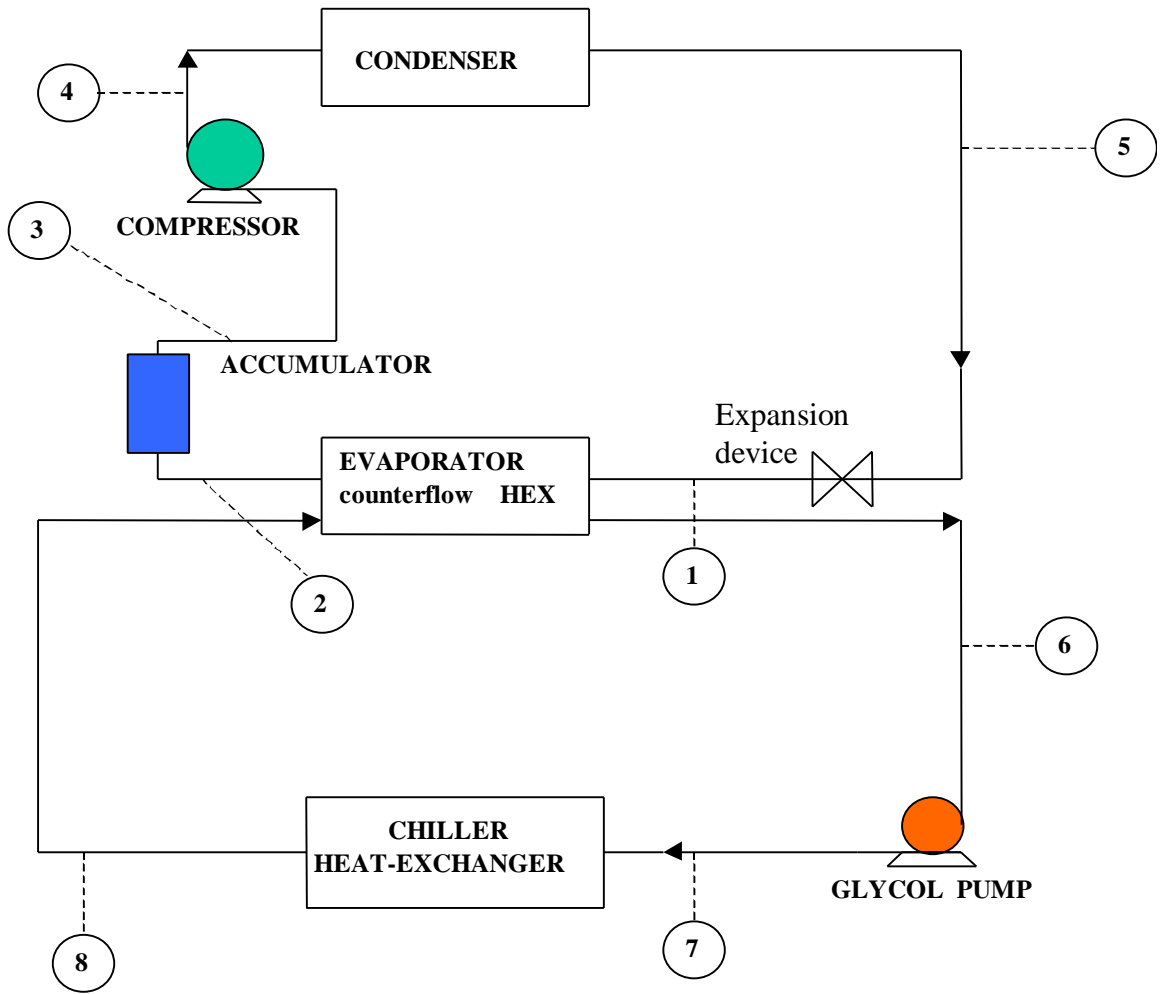


Figure 7. Schematic of a typical hydrocarbon cycle for the Mid-size car.

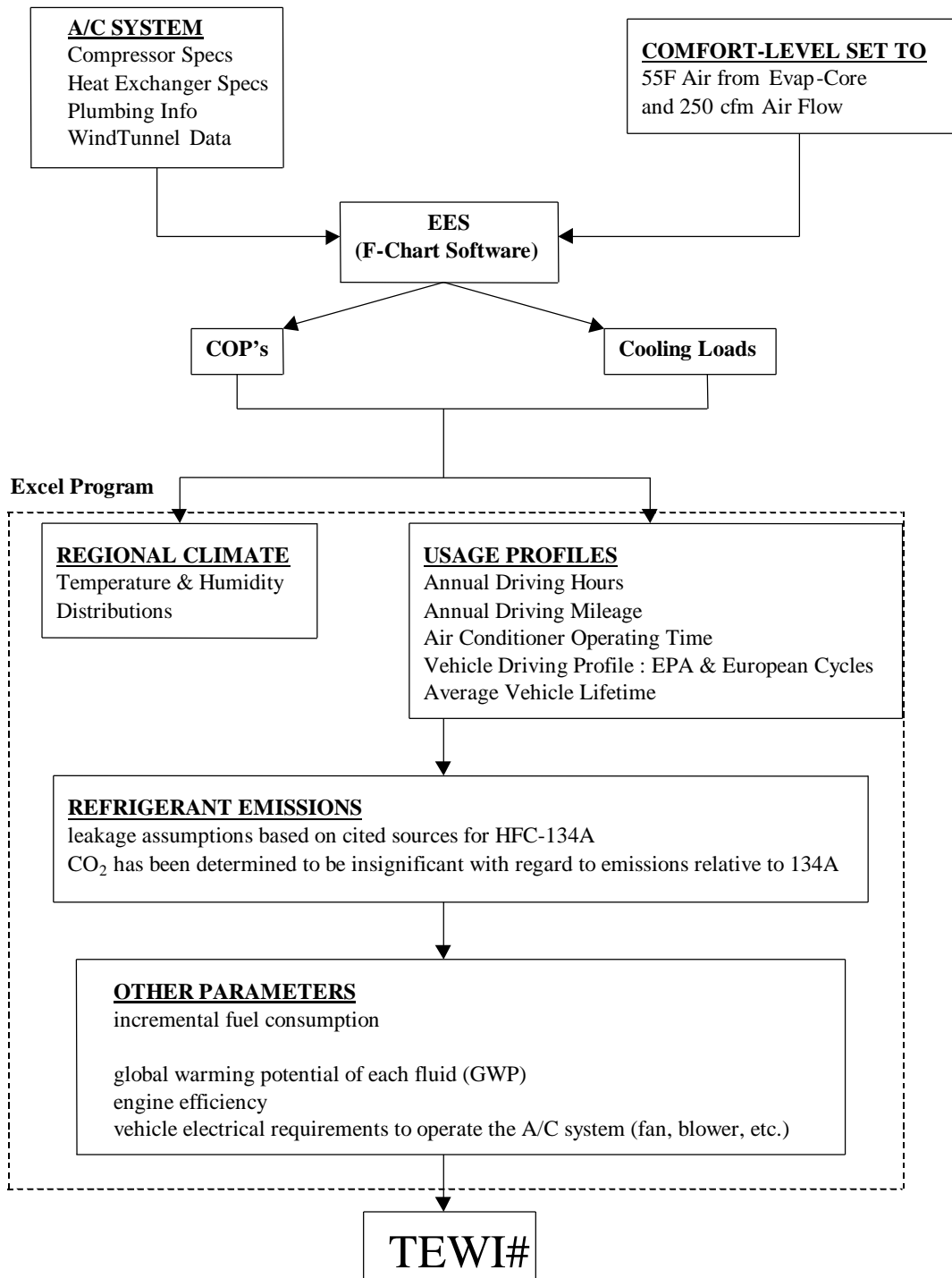


Figure 8. TEWI calculation program flow chart.

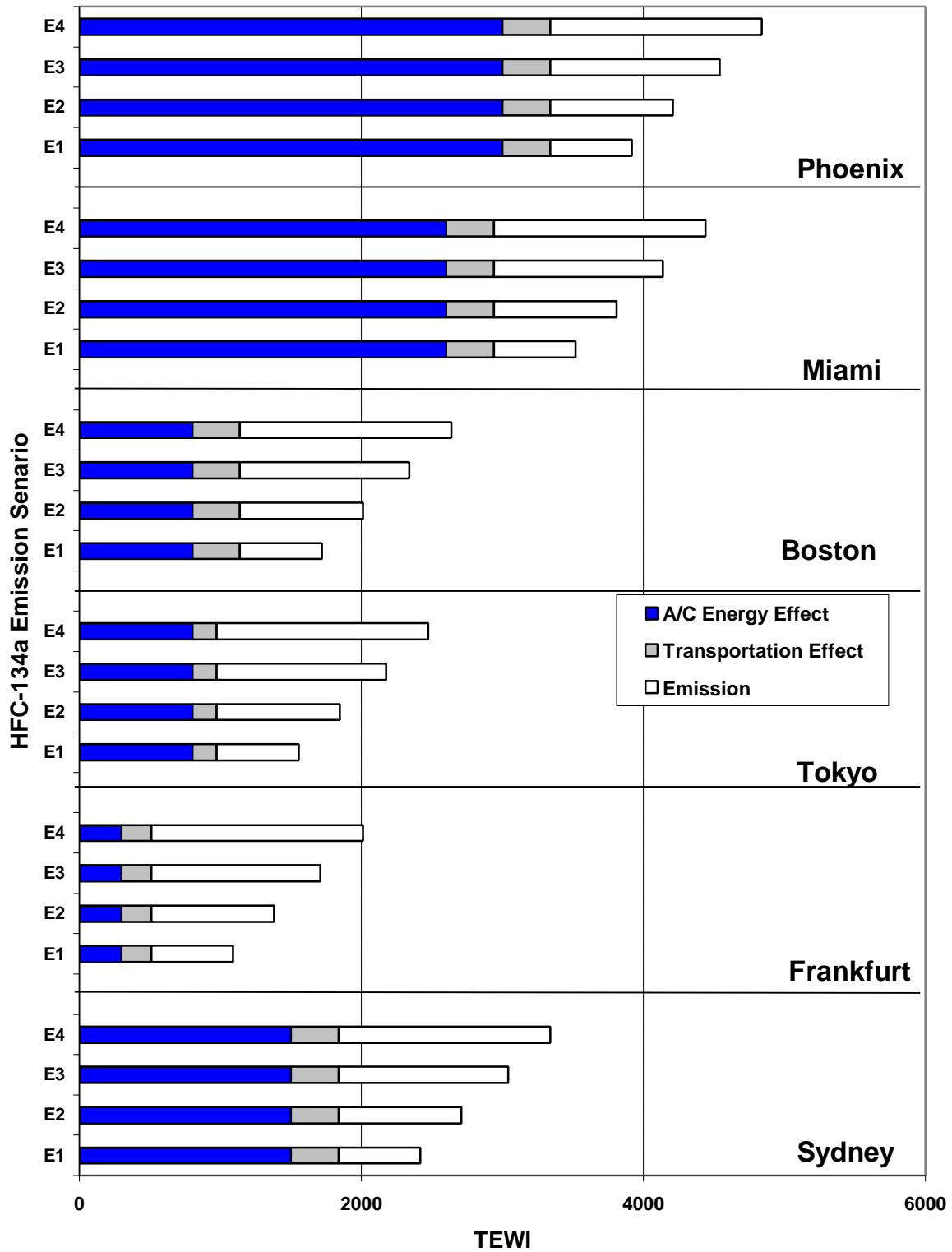


Figure 9. Effects of HFC-134a emission rates on TEWI for the Mid-size car in different climates.

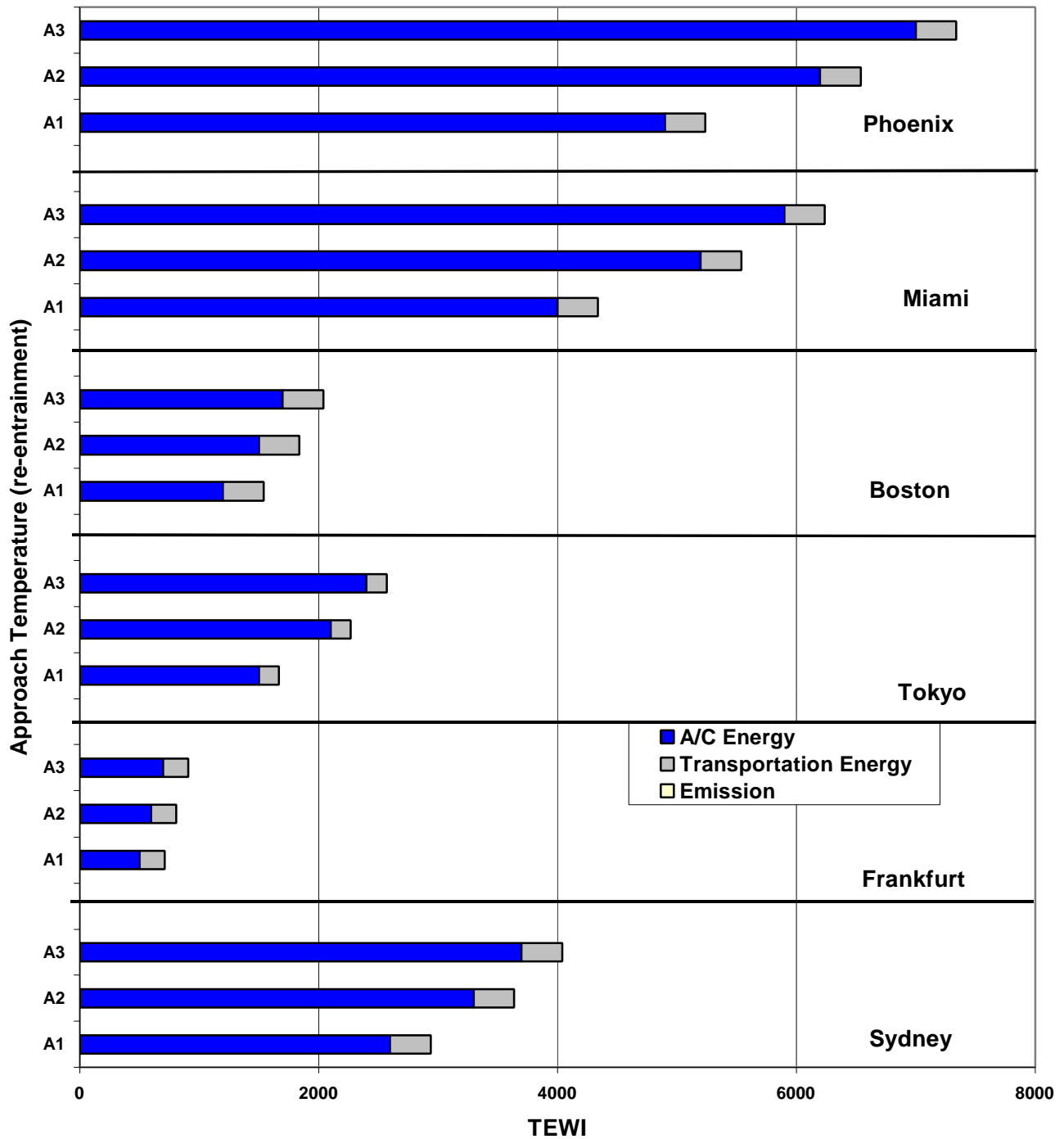


Figure 10. Effects of approach temperature (hot air re-entrainment) on TEWI for CO2 system for the Mid-size car in different climates.

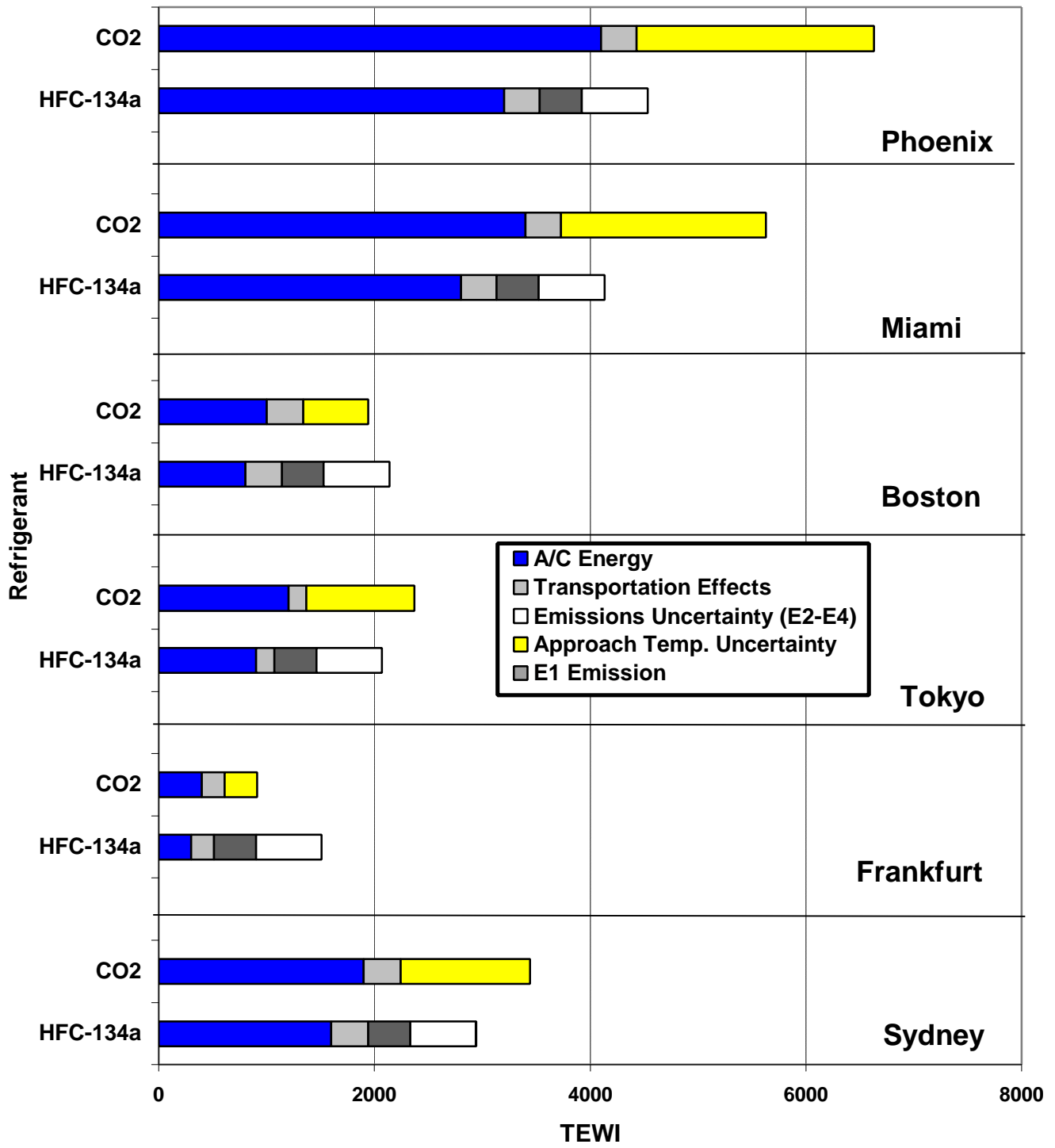


Figure 11. TEWI variations for the HFC-134a and CO2 systems for the small car.

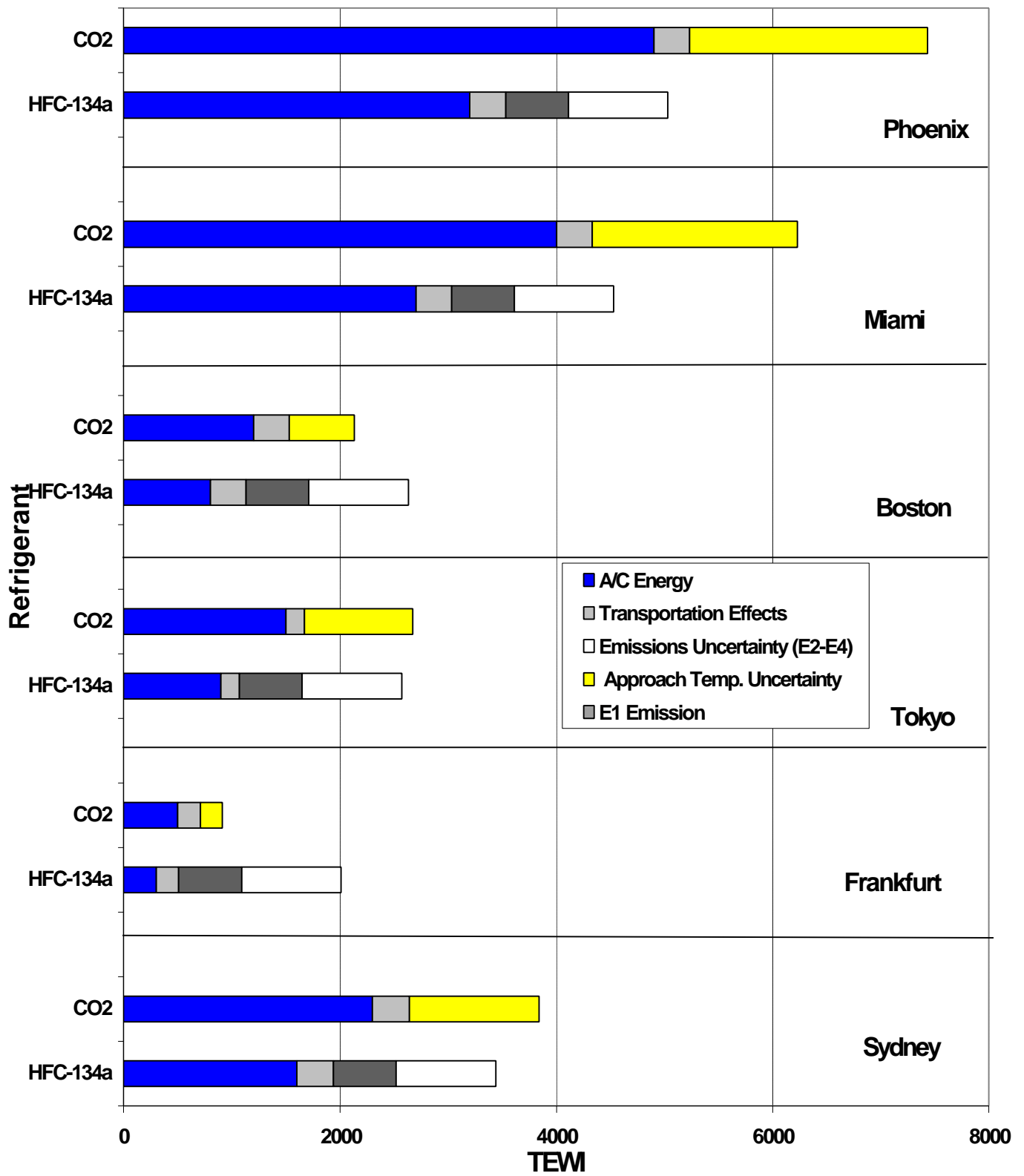
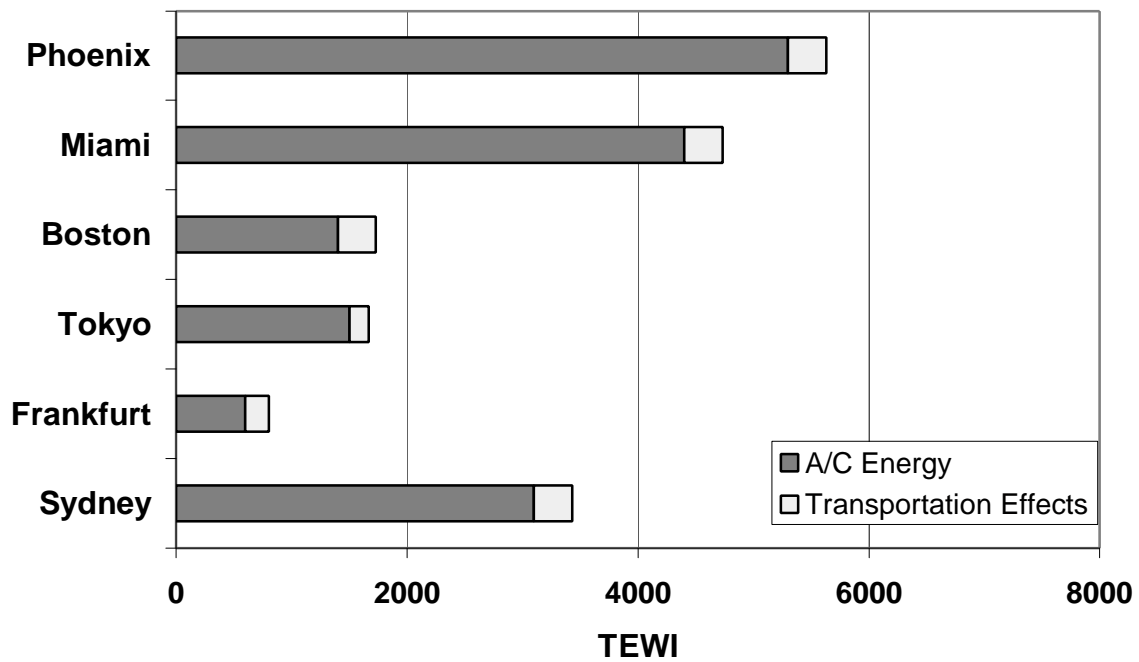
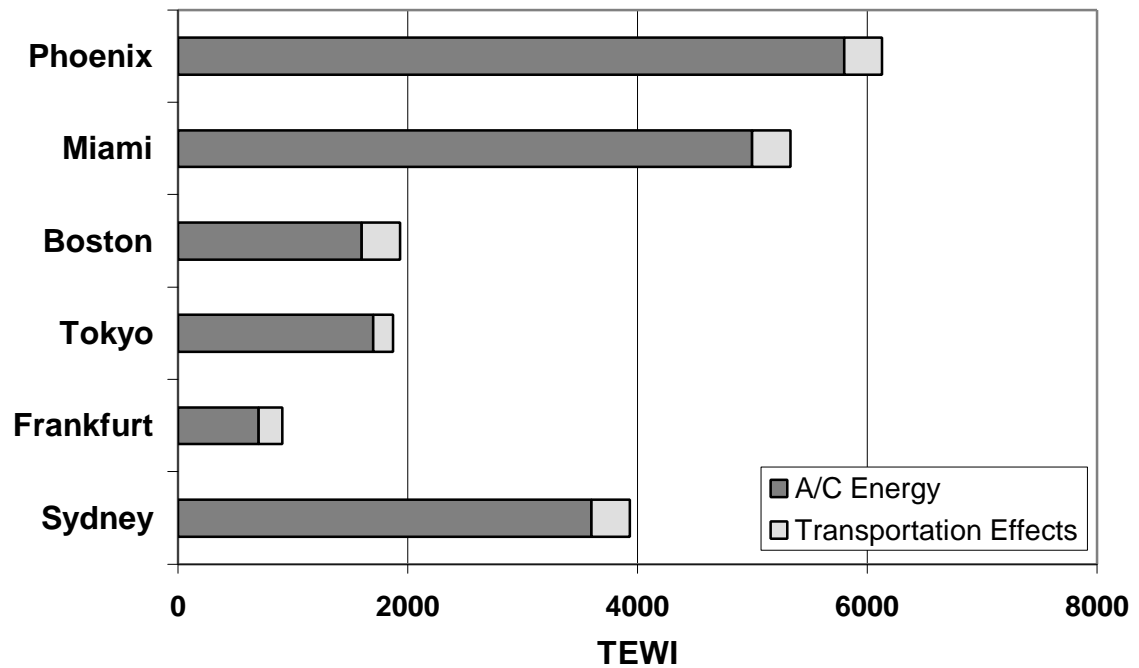


Figure 12. TEWI variations for the HFC-134a and CO2 systems for the Mid-size car.



Propane



(a) Iso-butane

Figure 13. TEWI results for two hydrocarbons in different climates for the mid-size car.