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Air Conditioning Activity Effects in MOBILE6

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1 ABSTRACT

MOBILE6 includes revised estimates of exhaust emissions resulting from air conditioning operation. This will require air conditioning behavior and the resulting emission levels to be predicted over a wide range of ambient conditions. Emission test data used to develop these factors were gathered under conditions meant to represent a single extreme set of conditions. This report addresses EPA's proposed methodology for applying the "extreme" data over the broader range of ambient conditions in which air conditioner operation occurs in-use. Using air conditioning activity data collected in Phoenix, a methodology has been developed which relates temperature and humidity levels to air conditioner load using a combined measure known as the heat index. This methodology also incorporates some solar load impact and will allow adjustments for cloud cover if desired by the user. Estimates have also been developed for the fraction of vehicles equipped with air conditioning systems, and of those, the fraction of malfunctioning systems.

2 INTRODUCTION

The emission data to be used in the development of the MOBILE6 air conditioning factors were gathered using a test procedure intended to represent extreme ambient conditions. From these data emission factors will be developed which represent emission levels at full air conditioning load (referred to as "full-usage" emission factors). These emission factors cannot appropriately be applied to all ambient conditions, since less severe conditions will result in only partial A/C loading and hence lower emissions. The development of the full-usage emission factors will be the topic of a separate report.[1] This report presents EPA's proposed methodology for applying the full-usage emission factors across the broad range of ambient conditions for which estimates of air conditioning emissions are required. A second aspect of air conditioning activity is market penetration; namely, the fraction of vehicles equipped with air conditioning systems, and of those, the fraction of malfunctioning systems which have not undergone repair. Proposed estimates for these factors are also presented and discussed.

Subsequent to publication of the draft version of this report in January 1998, the document was put out for stakeholder review. Formal peer review comments were also solicited from two independent sources. No comments were received through the stakeholder review process, hence peer review comments represent the only external feedback received on this report. A summary of peer review comments and responses is contained in Appendix B.

3 OVERVIEW OF PROPOSED APPROACH

As detailed in M6.AC.002, the "with air conditioning" emission levels used as the basis for MOBILE6 were generated using a test procedure meant to induce the level of A/C system load on the vehicle which would occur in the real world under extreme ambient conditions. However,

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[1] "Air Conditioning Correction Factors in MOBILE6", M6.AC.002, July 2001

MOBILE6 will need to model air conditioning emissions at less severe conditions where the majority of vehicle operation will occur. A method for modeling air conditioning effects under intermediate ambient conditions is therefore required.

The method proposed for use in MOBILE6 is to link emissions directly with the operation of the vehicle's air conditioning compressor, which is propelled by the engine using a belt in a similar manner to the vehicle's alternator. The compressor is the focus rather than driver behavior because it is the direct cause of additional load on the engine and is therefore the best indicator of how A/C system operation impacts emissions. Compressor load varies and the compressor cycles on or off (i.e. is engaged or disengaged) depending on user demand and the vehicle's response to ambient conditions. As a result, it is generally not inducing full load on the engine 100% of the time the A/C is turned on under intermediate ambient conditions. With this approach driver behavior is accounted for implicitly; however, because the compressor will only engage when the A/C system is on, compressor engagement over the course of a vehicle trip is strongly driven by A/C demand from the user.

An ideal model of this sort would link ambient conditions and emissions by modeling changes in compressor load (torque) as a function of changes in ambient conditions. Unfortunately, activity data which would allow such a link does not appear to exist. Available activity data does not include a direct measure of compressor load, but only the total time the compressor was engaged over a single vehicle trip. Therefore, the methodology developed for MOBILE6 is based on the relationship between emission response and the percentage of time the compressor is engaged. Since the fraction of time the compressor is engaged over a trip (compressor-on fraction) has a direct impact on the additional load experienced by engine during a trip, it is assumed that the impact of compressor engagement on overall engine load is linearly proportional (1:1). The second assumption is that changes in emission response correlate 1:1 with changes in engine load, and hence with compressor-on fraction. With this methodology, the compressor-on fraction is equal to the factor by which the full-usage emission factor is scaled in MOBILE6 to derive the emission factor appropriate for the ambient condition. In other words, a compressor which is engaged 100% of the time would result in the full-usage emission factor. If the compressor is engaged only 50% of the time, 50% of the full-usage emission factor would be applied. This scaling factor is termed the "demand factor".

The key to this approach is the assumption that the relative emission impact due to A/C correlates 1:1 with compressor-on fraction for all pollutants. It should be noted that air conditioning system experts from the automotive industry have identified several limitations with this assumption. Specifically, compressor load fluctuates significantly when the compressor is engaged, depending on a number of factors including ambient conditions, vehicle speed, vehicle cabin temperature, and A/C system setting (e.g. fan setting, recirculation vs. outside air); A/C system response to changes in all of these factors is highly vehicle-specific.[2] Using only compressor-on fraction is a rough estimate of actual compressor load since it assumes that

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[2] EPA/AAMA/AIAM meeting on MOBILE6 air conditioning issues, November 6, 1997

fluctuations in relative compressor load average out over periods when the compressor is engaged. Further, the impact of compressor load on emissions is likely not linear. However, the complexity and data demands of a compressor-load based model are prohibitive within the timeframe and scope of MOBILE6. Future research activity will need to address this lack of information.

4 DEVELOPMENT OF DEMAND FACTORS

4.1 Phoenix Activity Survey

The activity data used in the development of the proposed demand factors are based on an instrumented vehicle survey conducted as part of the Supplemental Federal Test Procedure (SFTP) rulemaking process on 20 vehicles over almost 1000 trips in Phoenix, Arizona from August-October 1994[3]. Data gathered for each trip included time and date, total trip time, total time the air conditioner was on, and total time the compressor was engaged. The datalogger also recorded summarized trip information including trip distance, total idle time, and time spent in five mile-per-hour trip bins. Hourly weather information taken from Phoenix's Sky Harbor International Airport available through the National Climatic Data Center (NCDC) was used to estimate dry bulb temperature and relative humidity at the start of each trip.

4.2 Treatment of Data

The initial dataset used for this analysis contained 987 trips. It did not include the first and last trips for each vehicle if the trip was less than 0.25 miles; these cases were removed as part of an earlier analysis because they represented trips taken by the contractor during the datalogger installation and deinstallation process. For the MOBILE6 analysis, this trip file was further modified to improve the representativeness in the following manner:

a. Trips with a duration of 30 seconds or less were removed to eliminate stalls and other potential queuing-related cases.

b. Since the location of each trip was not known, it was necessary to assume that the linked weather information was appropriate in characterizing the conditions experienced by the vehicle on every trip. To reduce the chance that a trip was taken outside of the greater Phoenix area, all trips greater than 60 miles were deleted from the trip file. In addition, all trips for a given vehicle which followed a trip of more than 60 miles were also deleted, to reduce the chance that a vehicle made one long trip outside of the Phoenix area and remained outside the area for the remainder of the monitored trips. 60 miles was chosen as a cutpoint based on the estimated radius of the greater Phoenix area, the distance to higher altitude locations outside Phoenix along highway routes, and the distribution of

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[3] "Study of In-Use Air Conditioner Operation in Phoenix, Arizona", Automotive Testing Laboratories, Inc. report to EPA (EPA Docket No. A-92-64 Item IV-A-1)

trips below and above 60 miles in the dataset. For two of the vehicles for which trip distance data was not gathered, a trip duration cutpoint of 45 minutes was used.

c. Preliminary analysis of the trip data indicated that trips that were comprised solely of idle had radically different behavior than all other trips. As shown in Figure 1, the average compressor-on fraction for all-idle trips is much lower than trips consisting of even very high percentages of idle. MOBILE6 will predominantly need to predict A/C emissions over trips consisting of non-idle driving, and we were concerned that inclusion of all-idle trips would skew the non-idle results. All-idle trips were therefore dropped from the trip file for the purposes of developing the demand factor relationships. It is important to clarify that this does not mean the trip dataset does not contain idle events; as indicated in Figure 1, many of the remaining trips in fact have significant percentages of idle operation.

These modifications reduced the number of trips in the dataset to 672. All subsequent analyses were performed on this dataset.

4.3 Temperature, Humidity and Heat Index

Temperature and humidity are the most important drivers of A/C system demand. While temperature is a widely recognized influence, the load placed on the air conditioning system by humidity can account for over half of the total load under the ambient conditions of the SFTP air conditioning test procedure[2]. It is considered important, therefore, to develop a demand factor methodology which incorporates both temperature and humidity. This was supported by several comments received following the March 1997 MOBILE6 workshop that advocated the inclusion of humidity in the MOBILE6 air conditioning component.

To assess the effect of ambient variables (temperature, humidity, heat index) on air conditioning demand, the Phoenix dataset was analyzed by “binning” trips according to the variable being analyzed. For example, for temperature, all trips at a given temperature were combined, and the compressor-on fraction was calculated at each temperature as total time with the compressor engaged at that temperature divided by total trip time at that temperature. This aggregation step was taken to reduce the variability from individual vehicle and driver behavior, since the operation of air conditioning over the “composite” fleet and population is of more concern for MOBILE6. Total trip time (including trips when the air conditioner was not turned on) was used as the denominator in order to characterize air conditioning usage directly from ambient conditions. This is a more direct approach than trying to model both a) air conditioning usage as a function of ambient conditions, and then b) compressor operation when the air conditioning is on, which is less supportable from the Phoenix data.

Analyzed in this way, the Phoenix dataset indicates a strong correlation between temperature and compressor-on fraction, as shown in Figure 2 (compressor-on time is expressed as the fraction of time the compressor is engaged over the total trip time at each temperature point). The relationship between humidity and compressor-on fraction is weak, however (Figure 3), and ANOVA results indicate that when humidity is modeled with temperature it is not a significant variable. Because humidity does physically affect overall A/C system load, this is judged to be an artifact of the limited humidity range in Phoenix. Figure 4 shows relative humidity at the start of each trip as a function of temperature (the reference lines show SFTP temperature and humidity conditions); the average relative humidity for temperatures greater than 80° F was only 28%. By contrast, historical data in Houston indicate that during the summer months (when the average daily maximum temperature is over 90° F) average relative humidity at noontime is around 60%[4]. The development of demand factors which could be applied to humidity levels like those observed in Houston would require significant extrapolation of the Phoenix data. Given the weakness of the relationship between humidity and compressor-on fraction within the boundries of the Phoenix humidity levels, extrapolation of these data is not desirable.

In an attempt to more accurately assess the relative impacts of temperature and humidity on air conditioning load, a metric known as the heat index will be used in developing the demand factors. Heat index is used by the National Weather Service to quantify discomfort caused by the combined effects of temperature and relative humidity. The basis of the index is the human body's ability to maintain thermal equilibrium through perspiration, taking into account numerous factors including clothing thickness, atmospheric pressure and ambient conditions. Equations have been developed which allow heat index to be calculated using only temperature and relative humidity; these equations are proposed for use in MOBILE6 to compute heat index based on temperature and humidity values input by the user (Appendix 1) [5,6]. Heat index as a function of temperature and humidity is shown in Figure 5.

The approach for addressing intermediate conditions is to develop demand factors by modeling compressor-on fraction as a function of heat index based on user input of temperature and humidity. An attractive feature of this approach is that the air conditioning activity component of MOBILE6 would be based directly on driver discomfort, the most likely factor impelling a driver's A/C behavior and thus a strong determinant in the vehicle's emission response. As shown in Figure 6, the Phoenix data exhibits a strong correlation between compressor-on fraction and heat index, after "binning" trips by heat index as discussed. Using heat index instead of temperature does not necessarily improve predictions of compressor-on fraction for the Phoenix data, because the Phoenix results are driven almost completely by temperature. Heat index does not detract from the relationship between temperature and compressor usage, either; for low humidity conditions, the heat index is generally identical to the temperature, so using heat index

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[4] Gale Research Inc., *The Weather Almanac*, Sixth Edition (1992)

[5] Meisner and Graves, "Apparent Temperature", *Weatherwise*, August 1985

[6] The base humidity correction factor currently in MOBILE5 will be carried over to MOBILE6. The computation of this factor and the air conditioning demand factor will be based on the same humidity data. A default specific humidity value of 75 grains/pound (as in MOBILE5) is proposed. Users will be able to input alternate humidity levels in either specific humidity or relative humidity (see Section 6), with appropriate conversions made within MOBILE6.

or temperature would provide the same result for low humidity conditions. The intent of using the heat index is to introduce a more equitable balance in the effect of temperature and humidity on air conditioning load not provided by the Phoenix data. The underlying assumption of this methodology is that the temperature-driven effects seen at high temperatures in Phoenix would be replicated under lower temperature but higher humidity conditions seen elsewhere in the country. Given the stated importance of humidity on air conditioning load, this assumption is believed to be more reasonable than ignoring or understating the impact of humidity altogether.

4.4 Solar Load

The proposal for air conditioning effects in MOBILE6 presented at the October 1997 workshop did not include any accounting for solar load. Comments received subsequent to the workshop, however, expressed a strong desire for the inclusion of solar load, and automotive industry experts have indicated that it is a contributing factor. Subsequent analysis of the Phoenix data indicates that a solar load impact can be discerned, and consequently a method which accounts for solar load and cloud cover (addressed in Section 4.6) is being used in MOBILE6.

Since solar load or cloud cover data were not available in the NCDC dataset linked to the Phoenix survey, an empirical relationship between these factors and compressor activity could not be developed directly. As an alternative, the impacts of solar load were isolated by binning all of the trips based on time of day at the start of the trip. Four “period” bins were created: night (sunset-sunrise), morning (sunrise - 10 am), peak sun (10 am - 4 pm), and afternoon (4 pm - sunset). Sunrise and sunset times for each day in the survey as reported by the U.S. Naval Observatory[7] were used to determine appropriate trip bins. The bin definitions were determined by analyzing solar radiation data gathered as part of the National Oceanic and Atmospheric Administration’s (NOAA) Surface Radiation Budget Project (SURFRAD)[8]. A regression across all trips of compressor-on fraction by heat index was performed within each bin, with the results shown in Figure 7. Because this analysis considered all trips instead of combining them by heat index level, the regression was weighted by trip length to give more creedance to longer trips. Since cloud cover information was not available, it could not be considered as a variable in the analysis. Historical data from Phoenix indicates that at the time of year the survey was conducted direct radiation from the sun (i.e. little or no cloud cover) is present close to 90% of the time[9], so for the purposes of this analysis all daytime trips were assumed to be taken during periods of no cloud cover. The lines show a clear difference in compressor-on fraction between nighttime and daytime at the same heat index level, indicating the importance of solar load and meriting a separation of daytime and nighttime demand equations. In support of this conclusion, ANOVA performed on the trip file with compressor fraction as the dependent variable and heat

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[7] U.S. Naval Observatory Sunrise/Sunset Web Site (http://riemann.usno.navy.mil/aa/data/docs/rs_oneyear.html)

[8] NOAA SURFRAD Web Site (http://www.srrb.noaa.gov/surfrad/surfpage.htm)

[9] Gale Research Inc., *The Weather Almanac*, Sixth Edition (1992)

index and period as the independents indicated that period is significant to the 0.01 level.

A second question is whether a significant difference exists between the daytime periods. Figure 7 shows that as would be expected, the peak sun curve is higher than the morning and afternoon curves above 75°, while the morning and afternoon curves are similar for the mid-range heat index levels. To investigate this issue further, ANOVA analyses of compressor-on versus heat index and period were performed for all daytime trips and again for trips taken only in the morning and afternoon periods. The period of the day was again significant to the 0.01 level for all daytime trips, but was not significant when only the morning and afternoon trips were analyzed. From this it was concluded that the peak sun period is the cause of the difference between the daytime curves and merits separate treatment.

4.5 Proposed Demand Equations

Three demand factor equations were developed for MOBILE6: nighttime, morning/afternoon and peak sun. The "raw" equation for each period, as well as for all daytime trips and all trips, are shown in Table 1; these equations were developed by fitting a quadratic equation through all trips by period, weighting by trip length. The relatively low R^2 values compared to the composite result shown in Figure 5 are attributable to the regression being performed over the entire trip sample. A quadratic curve form is favored over more complex forms because it provides a balance between goodness of fit and more reasonable behavior at the high and low ends of the heat index range. Still, because a smaller sample of trips occurred at the high and low ends (only 5% of trips occurred when the heat index was less than 75°) the behavior of the fitted curves at these ends tend to defy engineering judgment. In particular the morning/afternoon curve is higher than the peak curve below 75°, and the night curve is higher than the daytime curves above 100°. To rectify this, separate demand equations will be applied only in the middle of the heat index range, while the higher and lower ends will be modeled with composite equations. The "daytime combined" will be used for all daytime periods at the lower end, and all individual curves will be modeled with the "all combined" equation at the high end. The heat index values at which the composite equations and period-specific equations diverge (at the low end) or converge (at the high end) are determined based on the respective points of intersection. This progression is outlined in Table 2, with the revised equation forms for each period shown in Figure 8.

Since MOBILE6 will calculate emission factors on an hourly basis, changes in solar load throughout the course of a full day will be modeled by applying the appropriate demand equations at each hour. The night equation will be applied from sunrise to sunset, the morning/afternoon equation will apply from sunrise - 10 am and 4 pm - sunset, and the peak equation will apply from 10 am - 4 pm. The peak sun cutpoints were determined based on analysis of the NOAA data on different days throughout the summer months, which indicated that direct solar radiation levels stay relatively high from 10 am to 4 pm but tend to drop off rapidly before 10 am and after 4 pm. However, the user will be allowed to input alternate time for which peak sun demand equations are applied if desired. Default sunrise/sunset times of 6 am and 9 pm will be used in MOBILE6 to approximate a typical summer day with daylight savings time. The user will also have the option of inputting alternative sunrise/sunset times in order to alter the hours for which the morning/afternoon and nighttime demand equations are applied.

4.6 Cloud Cover

As mentioned in Section 4.4, the daytime demand equations were developed from the Phoenix data under the assumption that all trips were taken during periods of no cloud cover (an assumption that likely serves to slightly understate solar load impact). Because of this MOBILE6 will assume as a default that a sunny day is being modeled. Comments received following the October 1997 MOBILE6 workshop advocated some accounting of cloud cover, particularly for modeling seasonal emissions. MOBILE6 will incorporate an optional input for percent cloud cover on a daily basis. The method for handling cloud cover input will be to scale back the default daytime demand equations. Analysis of NOAA solar radiation data indicates that direct solar radiation is reduced to zero when the sun is obstructed by clouds (Figure 9). Based on these data, the nighttime demand equation is proposed to represent 100% cloud cover. For intermediate cloud cover inputs, the model will interpolate between the appropriate daytime demand equation and the nighttime demand equation. Thus, 50% cloud cover at noontime would result in a demand factor halfway between the demand calculated with the peak and nighttime equations at the appropriate heat index.

4.7 Other Factors Considered

While ambient conditions are the primary factors in determining A/C system demand, trip-related characteristics are also likely to influence air conditioning behavior. Four such factors investigated for this analysis were soak time prior to the vehicle trip, trip duration, average vehicle speed, and percent of idle during a trip. A single Analysis of Variance was performed with compressor-on fraction as the dependent variable and these four variables and heat index as covariates, period as a factor, and vehicle as a random effect (as suggested in peer review comments), with the results shown in Table 3. A technical basis exists for considering each factor, and it is likely that the dataset implicitly contains the effects of each. However, none of these variables showed enough significance to merit individual treatment; to a large extent this is likely because the Phoenix dataset does not provide adequate resolution or sample size to discern individual effects. A discussion of each factor follows.

4.7.1 Soak Duration

The length of soak time prior to a daytime trip could influence A/C system demand because of the impact on cabin temperature. Vehicles parked in the sun for extended periods of time experience elevated cabin temperatures compared to short soaks. However, information on several factors which would greatly influence the impact of soak time were not available, including whether a vehicle was parked in a shady location (such as a parking garage) or whether the windows were left open during the soak. Without this sort of information a meaningful assessment of soak time is difficult; not surprisingly, the ANOVA results do not show significance for this factor. A more thorough investigation of soak time impacts would require a measure of cabin temperature and more detailed trip/soak information. It is likely however, that the solar load impacts discussed in Section 4.4 are driven in part by this effect, so the impact of differing soak times are subsumed in the solar load corrections if a representative soak distribution is assumed.

4.7.2 Trip Duration

Trip duration could also be expected to impact air conditioning behavior. Cabin temperature over the course of a longer trip will be reduced by the A/C system, thereby reducing the need for cooling and hence the amount of time the compressor is engaged relative to the start of the trip. Figure 10 shows a series of linear regressions for compressor-on versus trip duration over four heat index ranges. Two trends emerge from these regressions: the expected downward trend as trip duration increases, and a leveling of this slope as the heat index increases. The latter trend suggests that trip duration has a more significant impact for the intermediate heat indices where cooling needs can be met in the early stages of a trip, but for higher heat indices the cooling demand remains high throughout the trip. ANOVA results do not indicate significance, however. Since the Phoenix dataset contains a wide distribution of trip durations, these effects are assumed to be accounted for implicitly in the demand equations.

4.7.3 Average Speed

Average speed could have an impact on A/C system load because higher rates of air flow across the vehicle's A/C condenser will reduce the work required to cool the ambient air (although this could be offset to some degree by ambient air entering the cabin at a higher rate). Regression analysis indicates a downward trend in compressor-on as average speed increases (Figure 11). Again, this effect is more prevalent for the lower heat index levels, and drops off as the heat index increases. The ANOVA results again do not indicate significance, however. These effects are assumed to be accounted for implicitly in the demand equations since the equations are based on a distribution of average speeds.

4.7.4 Idle Fraction

The fraction of idle during a trip could impact overall compressor operation because A/C calibrations at idle appear to be unique, as discussed in Section 4.2. For many idle-only trips the compressor is either engaged 100% of the time or 0% of the time, with most idles in the Phoenix dataset exhibiting the latter. Not engaging the compressor at idle would presumably be used as a strategy for driveability, because the relative load place on engine by the A/C system at idle is high. As shown in Figure 1, the overall average compressor-on times for all trips with idle fractions less than 100% appear similar, indicating that the effect seen on idle-only trips doesn't carry over to idles during normal trips. The ANOVA results again do not indicate significance, but it is likely that idle fraction and average speed are higher correlated so an effect solely attributable to idle is difficult to separate out. Again, to the extent there are impacts they are assumed to be accounted for in the demand equations.

5 MARKET PENETRATION ESTIMATES

The second component of activity determining how many vehicles in the fleet are equipped with air conditioning systems (market penetration), and of those, how many are functional. Three steps go into the development of these estimates: determining base market penetration rates by model year, estimating A/C system malfunction rate by vehicle age, and estimating how many malfunctioning systems are not repaired. This section addresses each issue.

5.1 Base Rates

Base market penetration data by model year were gathered from Ward's Automotive Handbook for light-duty vehicles and light-duty trucks through the 1995 Model Year. This information was available from 1972 for cars and 1975 for trucks. Year-to-year rates are more variable in the first few years of available data, so estimates for earlier model years will be estimated by applying the 1972 and 1975 rates for cars and trucks, respectively. In the later years, the rate of increase becomes more steady. Projections beyond 1995 were developed by taking the average yearly rate of increase from the last five years of available data and applying them to each subsequent year until a predetermined cap was reached. A cap of 98% was placed on vehicles and 95% on trucks under the assumption that there will always be vehicles sold without air conditioning systems, more likely on trucks than cars. The resultant base rates are shown in Figure 12. The caps are in place by the 1999 model year, and will remain for subsequent years.

5.2 Malfunction Rates

Of all vehicles equipped with air conditioning, it is appropriate to assume that not all of the systems are functional, requiring an estimate of the fraction of non-functioning systems by vehicle age. Unfortunately, there appears to be little publicly available data upon which to base these estimates. One available source is the annual Consumers Reports Automobile Purchase Issue, which began reporting reader survey results on A/C system malfunctions starting in 1994. The reported results from the 1997 survey were used to develop malfunction estimates by vehicle age based on a yearly increase in absolute malfunction rate of 1.5 percent (Table 4). Starting at age nine the malfunction rate will be held constant at 12.5 percent. This is based on the assumption that the increased probability of malfunction as a vehicle ages will be offset by the increased probability a vehicle will have already undergone repair as it grows older.

The second component in developing malfunction estimates is rate of repair. In the absence of concrete data, estimates were generated based on three qualitative assumptions: a) all vehicles up to three years old (assumed to be the standard bumper-to-bumper warranty period) would receive repair; b) after three years the majority of owners would still receive repair, but this percentage would decrease as the vehicle grew older, and c) vehicles built prior to the 1993 model year (estimated as a cutpoint for which Freon was replaced with R-134a on most vehicles) would experience a lower rate of repair due to the prohibitive cost of system recharging. From these assumptions, it was estimated that 100% of R-134a systems would be repaired during the warranty period, 90% in years four through eight, 80% in years nine through 13, 70% in years 14 through 18 and 60% in years 19 and up. The non-warranty period repair rates will be reduced by a factor of 0.75 for Freon (pre-1993) systems, but only if the modeled calender year is 1995 or later; if not, the R-134a estimates will be applied (in other words, lower repair rates for Freon-equipped vehicles will not be invoked if recharging with Freon was viable during the modeled calender year). The resultant rate of unrepaired malfunctions combine the malfunction rates from Table 4 with the rate of nonrepair in a given year. These estimates are shown in Figure 13. For a given model year, the estimate of vehicles on the road with functional air conditioning systems (referred to as adjusted penetration rates) will combine the base market penetration estimates for that model year (from Figure 12) with the unrepaired malfunction rates in Figure 13 for the appropriate vehicle age.

6 HANDLING OF AMBIENT INPUT DATA

A significant change in MOBILE6 will be the ability to model on an hour-by-hour basis, whereas MOBILE5 is geared towards providing daily estimates. Hour-by-hour temperatures can be entered if the information is available to the user; otherwise, daily minimum and maximum temperatures can be entered as was done with MOBILE5. There are no temperature defaults in MOBILE6, so at a minimum these daily temperatures must be entered. Humidity is entered as a single daily number, and for this reason it will be entered as absolute humidity (grains per pound of air) and converted to hourly relative humidity inside the model based on hourly temperature. As a default, absolute is assumed constant at 75 grains/pound, no cloud cover would be assumed, and the sunrise/sunset/peak sun times discussed in Section 4.5 would be applied.

7 ACKNOWLEDGMENTS

Several individuals contributed time, effort, ideas and consultation to this report. Rob French of OTAQ developed and provided guidance on the Phoenix dataset and contributed to the heat index concept. John Gilmore of OTAQ researched the base market penetration estimates and malfunction survey information. John German of Honda provided general consultation and input. Christine Dibble of the Office of Atmospheric Programs provided information on R-134a phase-in. John Augustine of NOAA provided information on the SURFRAD data. Dennis Kahlbaum of AIR, Inc. provided information on the derivation of the heat index measure. Harold Haskew of Haskew Associates and Dr. Mohunder Bhutti of Delphi-Harrison provided consultation on the theoretical aspects of air conditioner operation.

Figure 2 - Compressor-On vs. Percent Idle

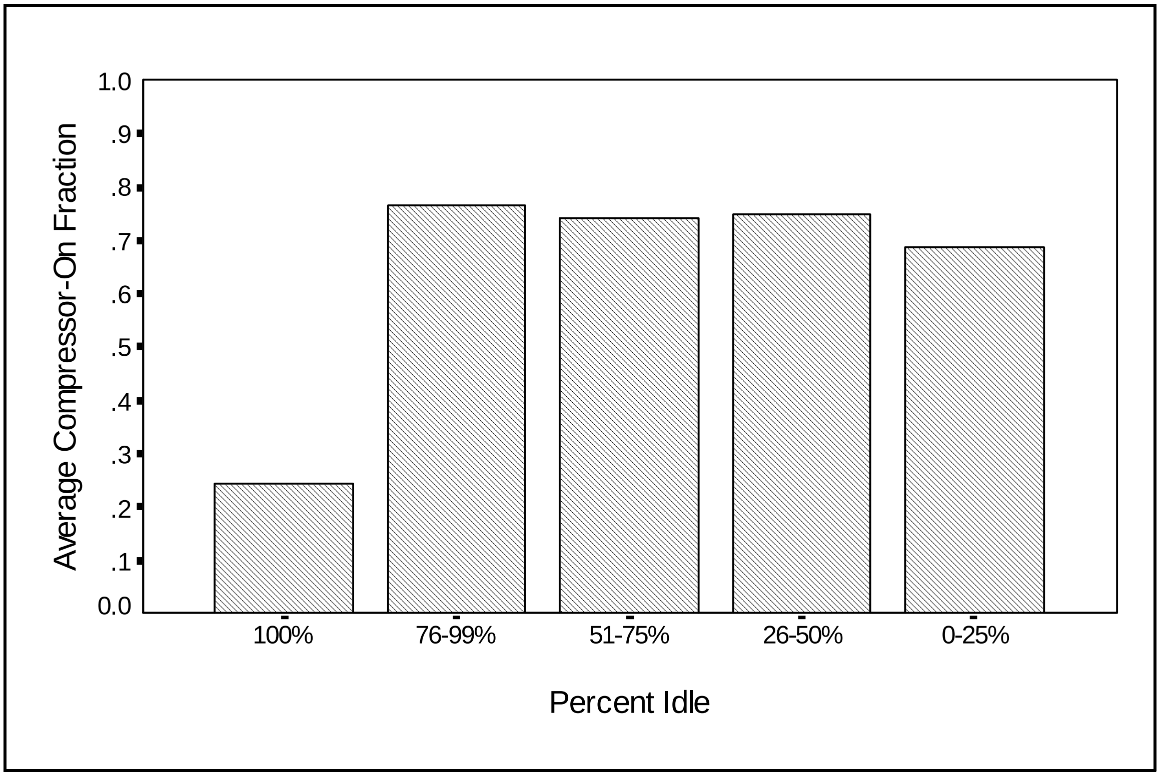


Figure 3 - Compressor-On vs. Temperature

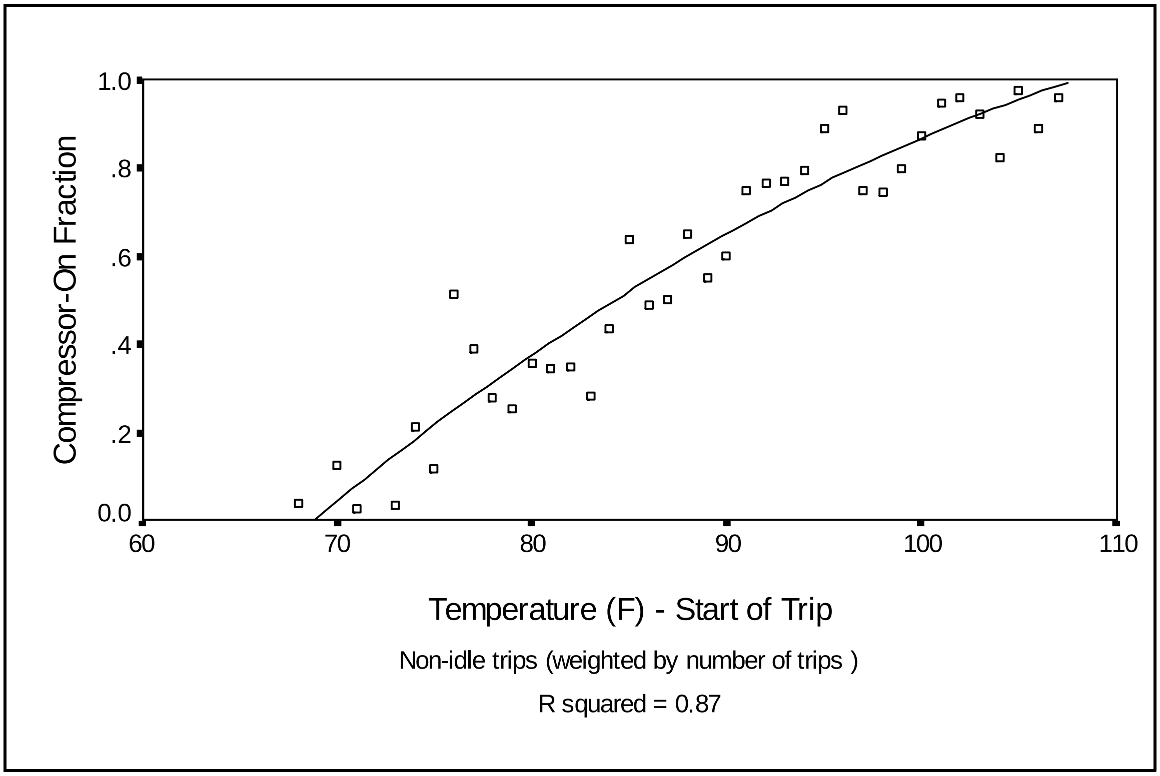


Figure 4 - Compressor-On vs. Specific Humidity

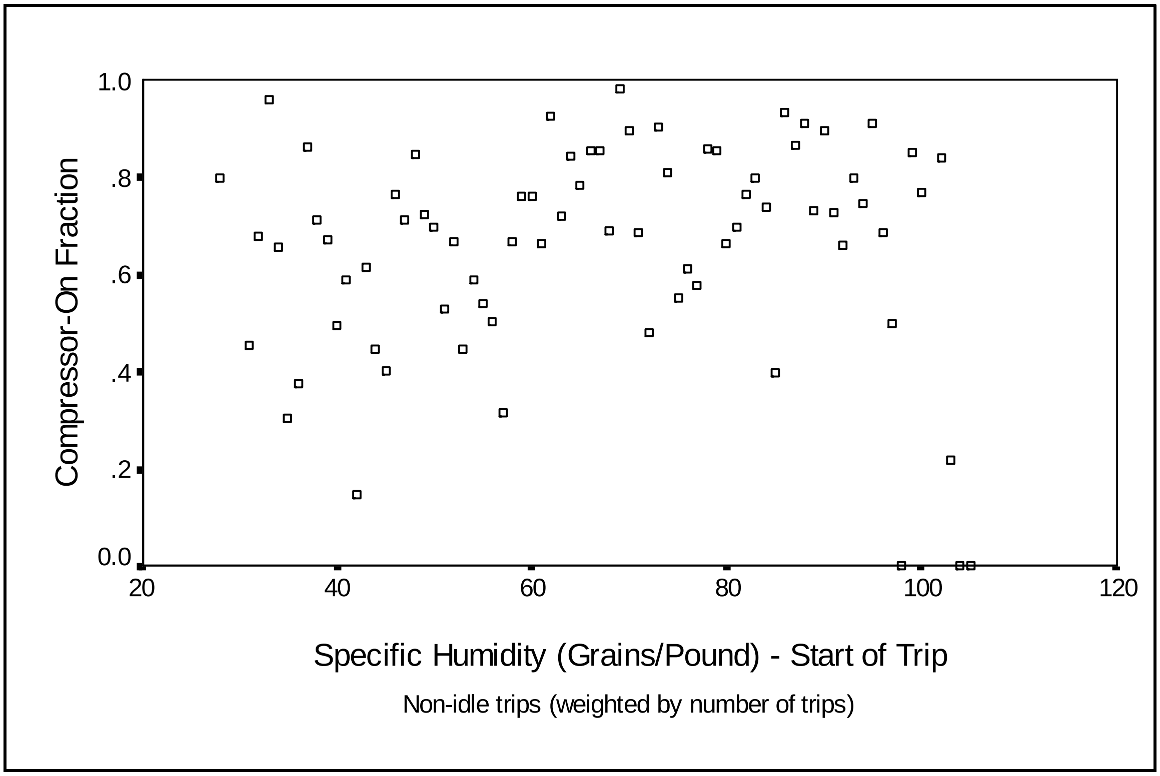


Figure 5 - Humidity vs. Temperature for Phoenix Dataset

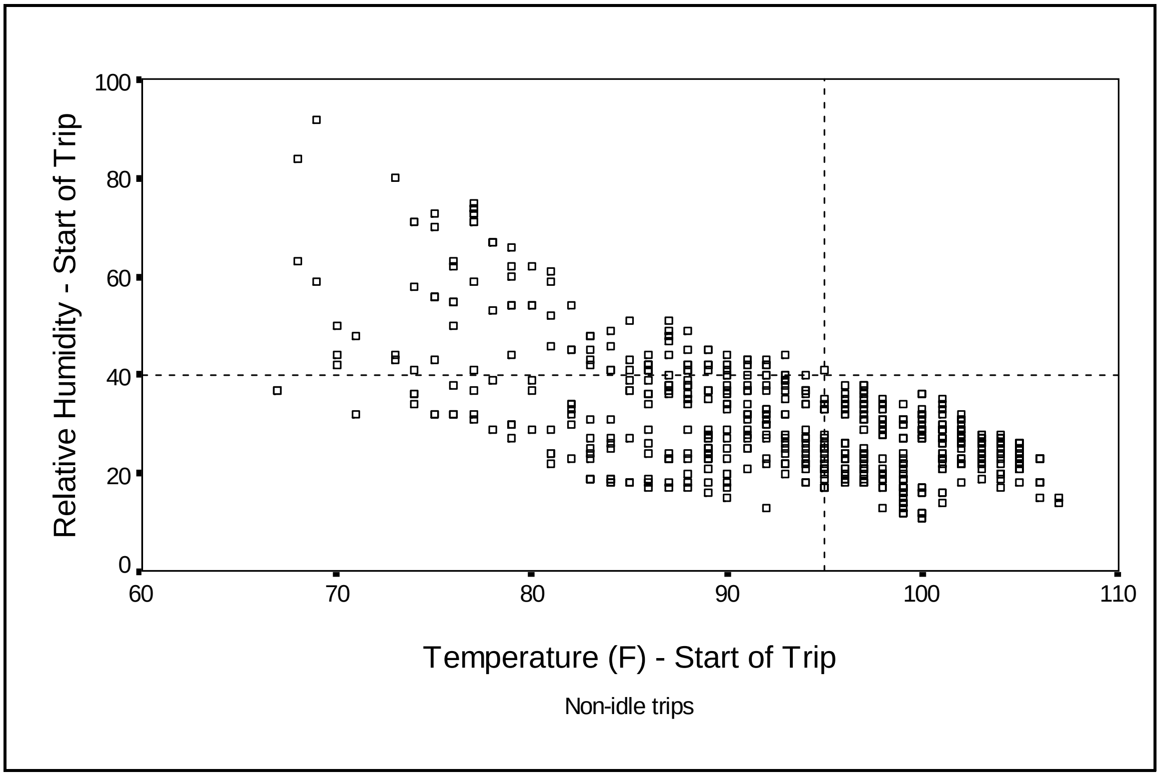
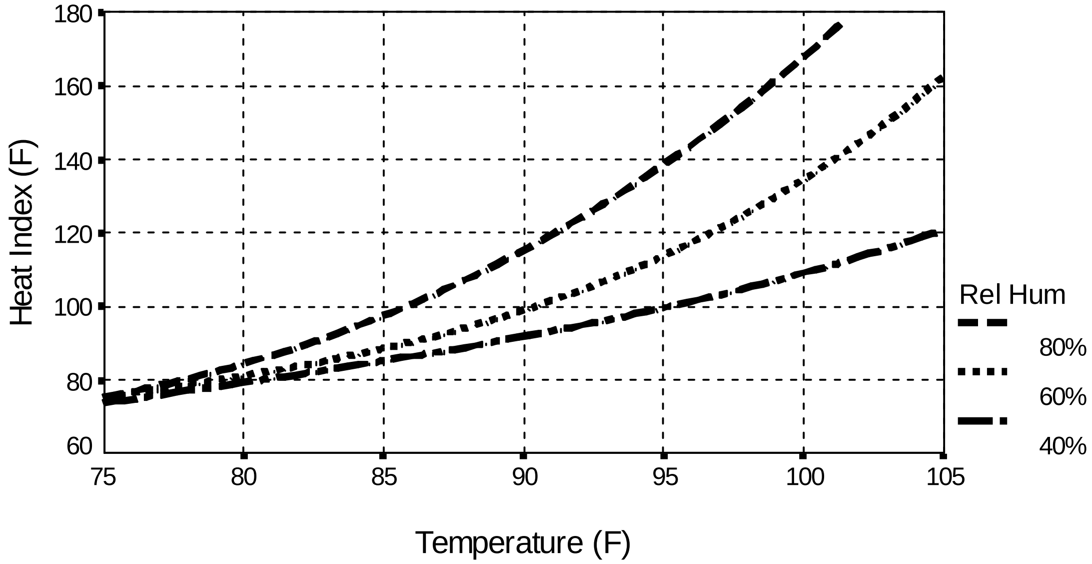


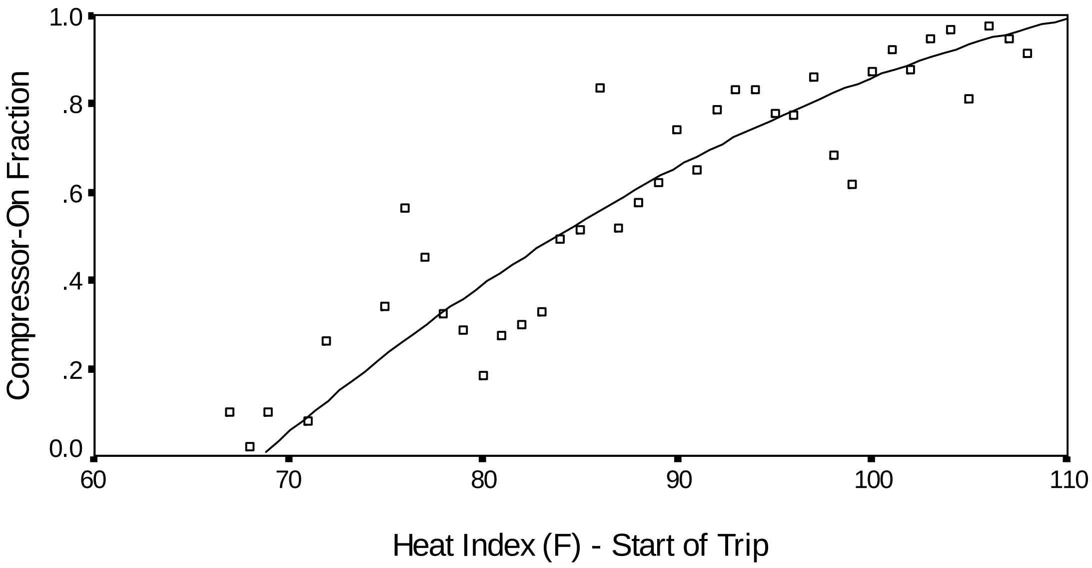
Figure 6 - Heat Index



Note: Heat Index values based on shady conditions

Lines represent curve fit of tabular data

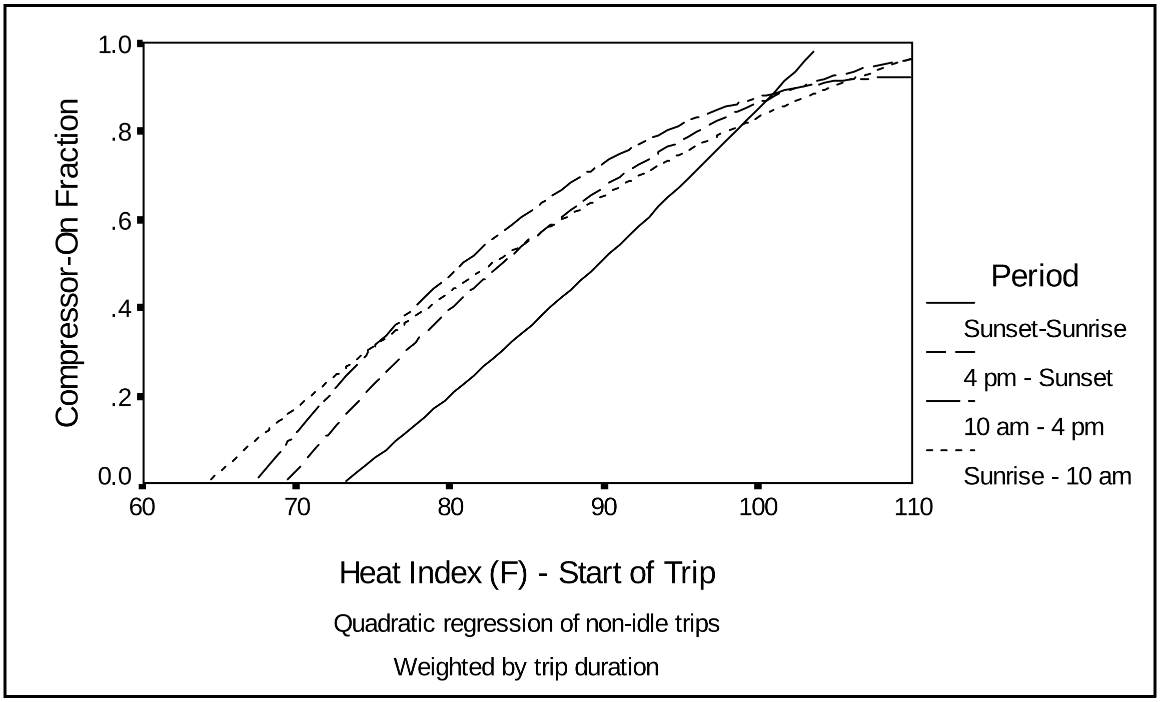
Figure 7 - Compressor-On vs. Heat Index



Non-idle trips (weighted by number of trips)

R squared = 0.84

Figure 8 - Compressor-On vs. Heat Index by Time of Day



Quadratic regression of non-idle trips

Weighted by trip duration

Table 1 - Proposed "Raw" Demand Factor Equations

(Demand Factor = Constant + a*(Heat Index) + b*(Heat Index)^2)

Period	***Constant***	***a***	***b***	R^2
Morning/Afternoon	-2.930273	0.059110	-0.000213	0.54
Peak Sun	-5.307355	0.113973	-0.000521	0.17
Daytime Combined	-4.101082	0.086382	-0.000367	0.43
Night	-1.257412	0.006753	0.000143	0.52
All Combined	-3.631541	0.072465	-0.000276	0.44

Table 2 - Proposed Demand Factor Equation Forms

Heat Index	***Morning/Afternoon***	***Peak Sun***	***Night***
65 & below	Constant = 0	Constant = 0	Constant = 0
66	Daytime	Daytime	"
74	Morning/Afternoon	"	Night
76	"	Peak Sun	"
96	All	"	"
101	"	"	All
104	"	All	"
110 & above	Constant = 1	Constant = 1	Constant = 1

Figure 9 - Proposed Demand Factor Functions

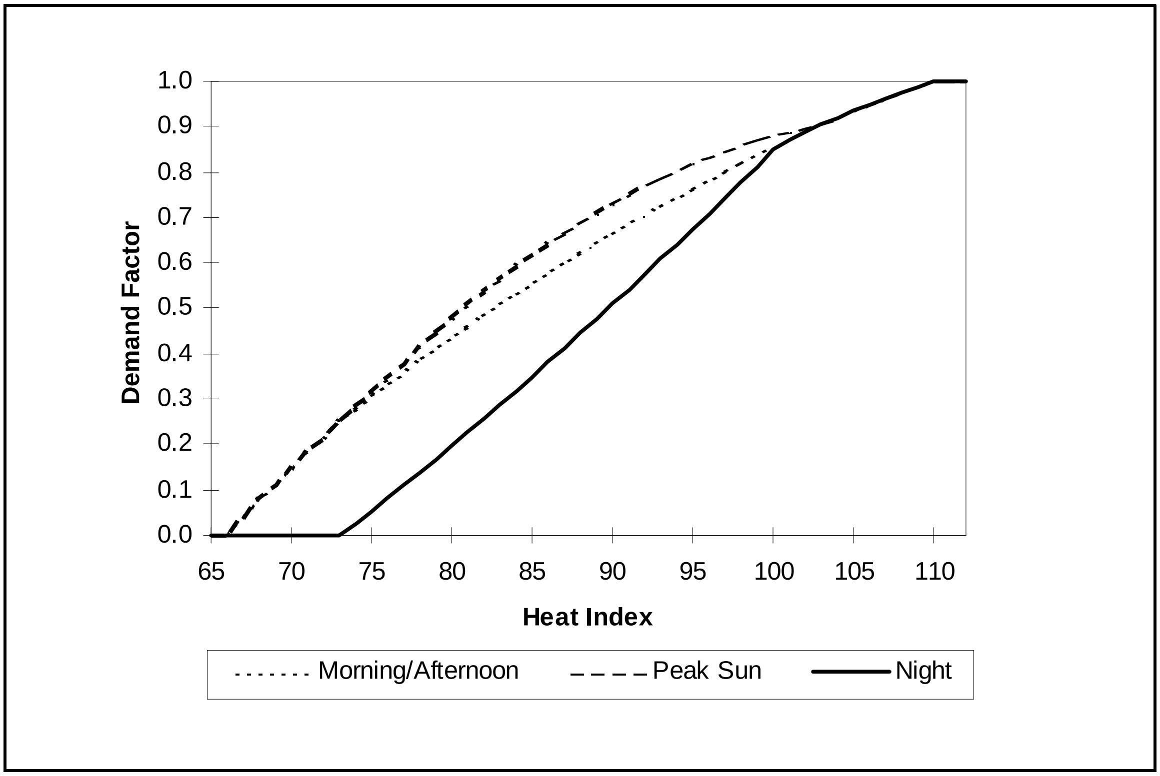


Figure 10 - Solar Radiation - Sunny and Cloudy Day (Fort Peck, MT)

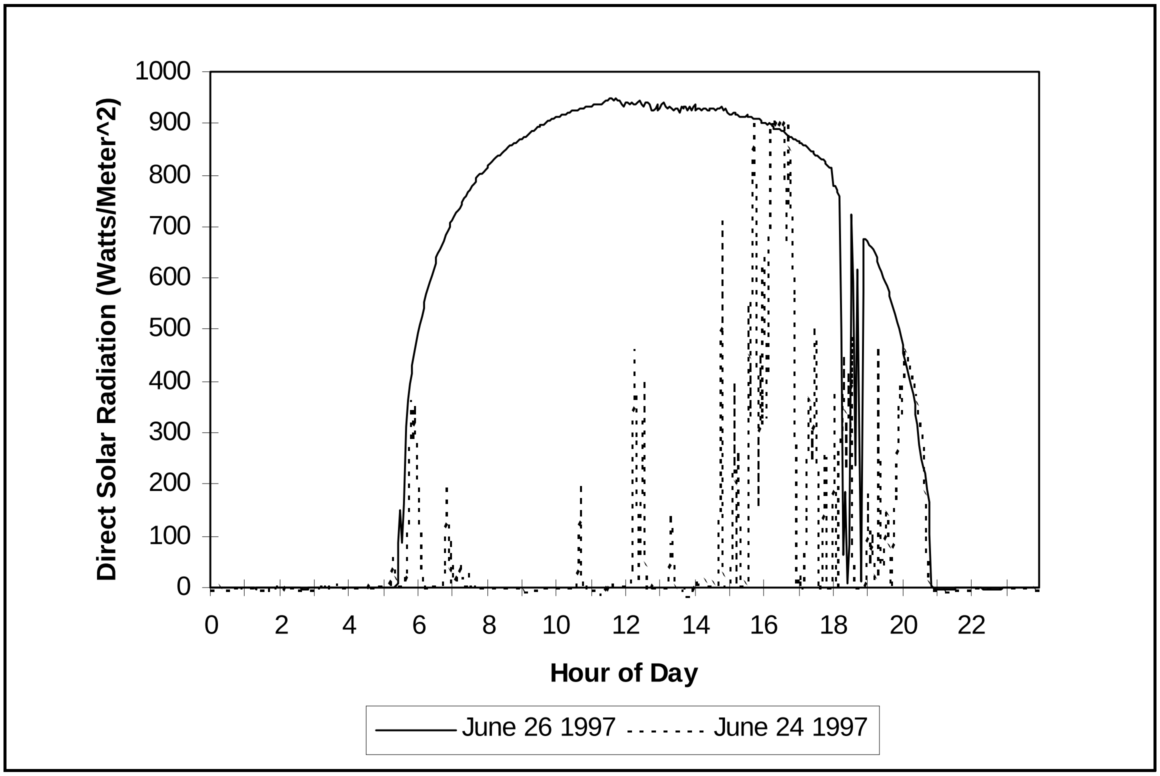


Table 3 - Analysis of Variance (ANOVA) on Non-Idle Trip Dataset
with Vehicle as Random Effect

Tests of Between-Subjects Effects
Dependent Variable: Compressor Fraction (fraction of time engaged / **all** driving)

Source		**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Intercept	Hypothesis	.712	1	.712	14.551	.000
	Error	25.255	516.244	4.892E-02		
Average Speed	Hypothesis	1.607E-02	1	1.607E-02	.337	.562
	Error	23.878	500	4.776E-02		
Trip Duration	Hypothesis	2.213E-02	1	2.213E-02	.463	.496
	Error	23.878	500	4.776E-02		
Soak Duration	Hypothesis	4.694E-04	1	4.694E-04	.010	.921
	Error	23.878	500	4.776E-02		
Idle Fraction	Hypothesis	4.418E-03	1	4.418E-03	.093	.761
	Error	23.878	500	4.776E-02		
Heat Index	Hypothesis	2.687	1	2.687	56.263	.000
	Error	23.878	500	4.776E-02		
Period of Day	Hypothesis	.787	3	.262	3.472	.020
	Error	5.336	70.612	7.556E-02		
Vehicle	Hypothesis	6.527	16	.408	5.063	.000
	Error	4.677	58.048	8.056E-02		
Period * Vehicle	Hypothesis	3.571	36	9.918E-02	2.077	.000
	Error	23.878	500	4.776E-02		

a 3.197E-03 MS(VEH) + 2.718E-04 MS(PERIOD * VEH) + .997 MS(Error)
b MS(Error)
c .541 MS(PERIOD * VEH) + .459 MS(Error)
d .638 MS(PERIOD * VEH) + .362 MS(Error)

Figure 11 - Compressor-On vs. Trip Duration

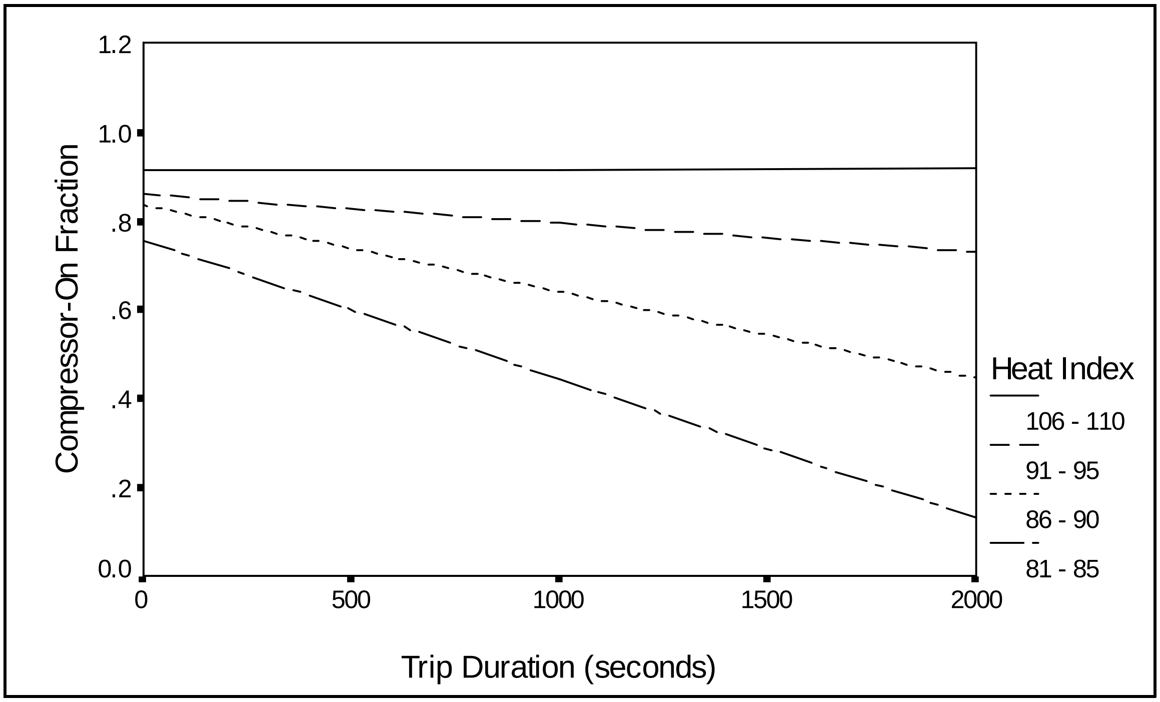


Figure 12 - Compressor-On vs. Average Speed

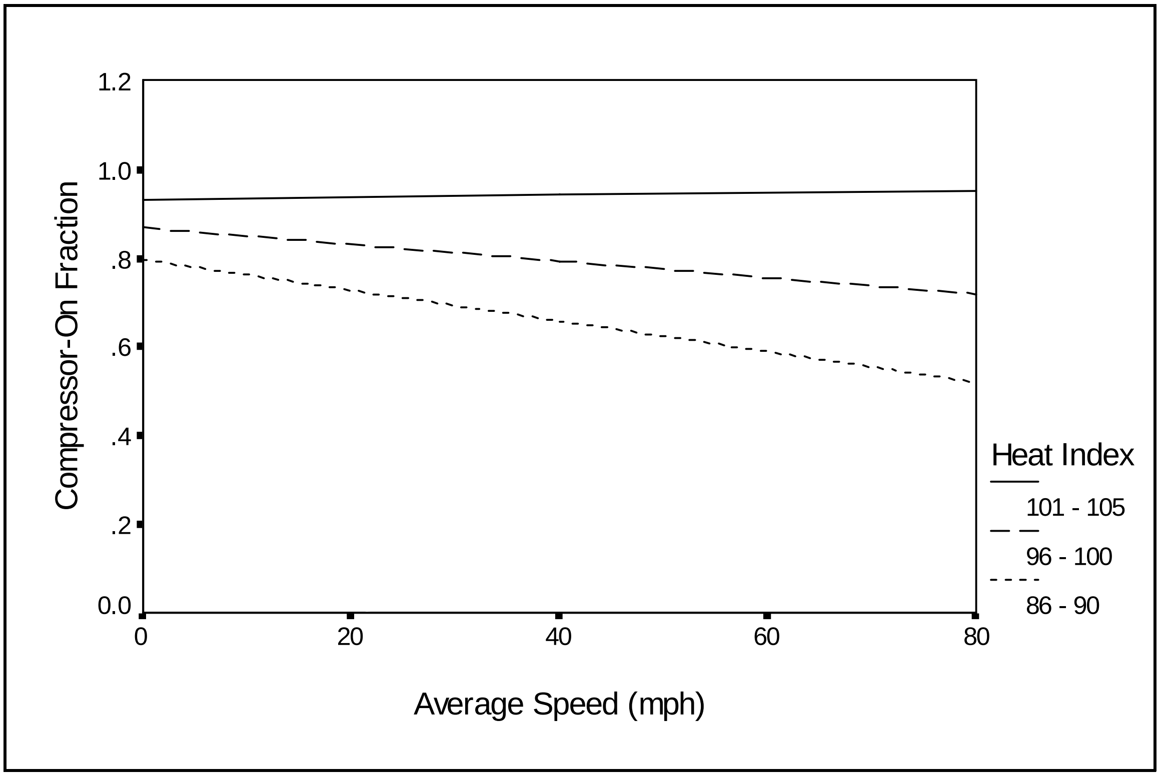


Figure 13 - Proposed Base Market Penetration Estimates

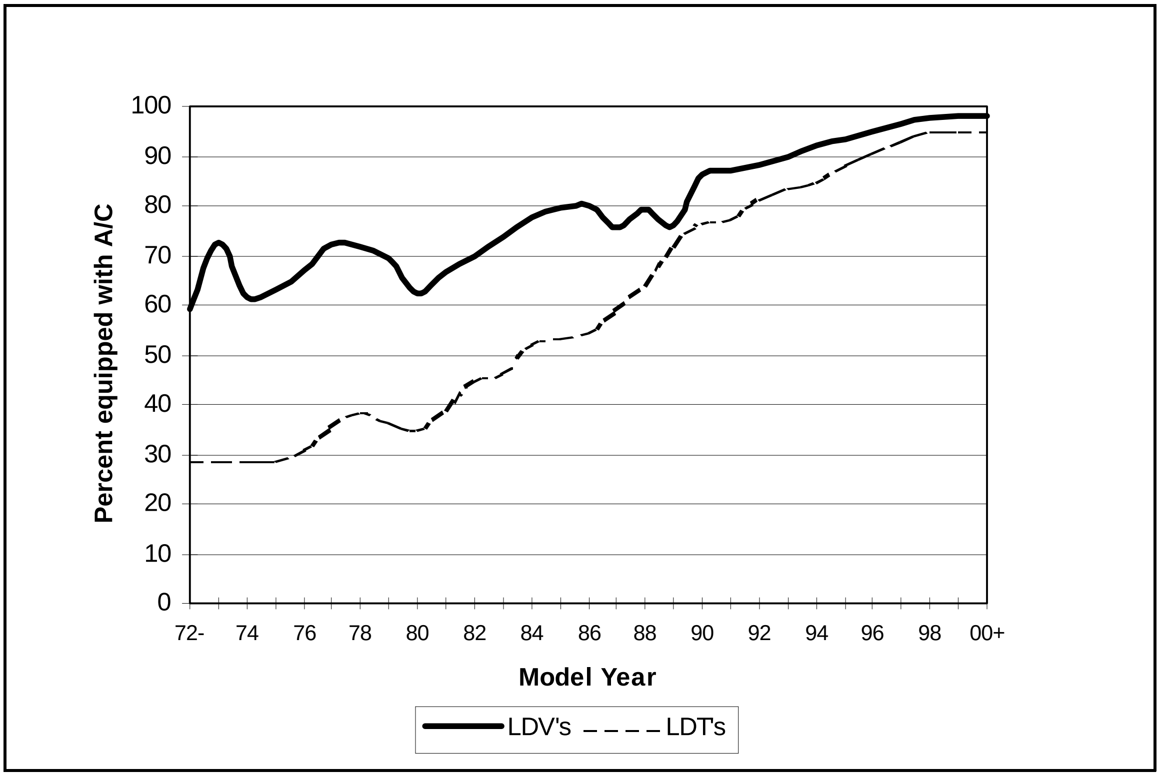


Figure 14 - Proposed Rate of Unrepaired Malfunctions

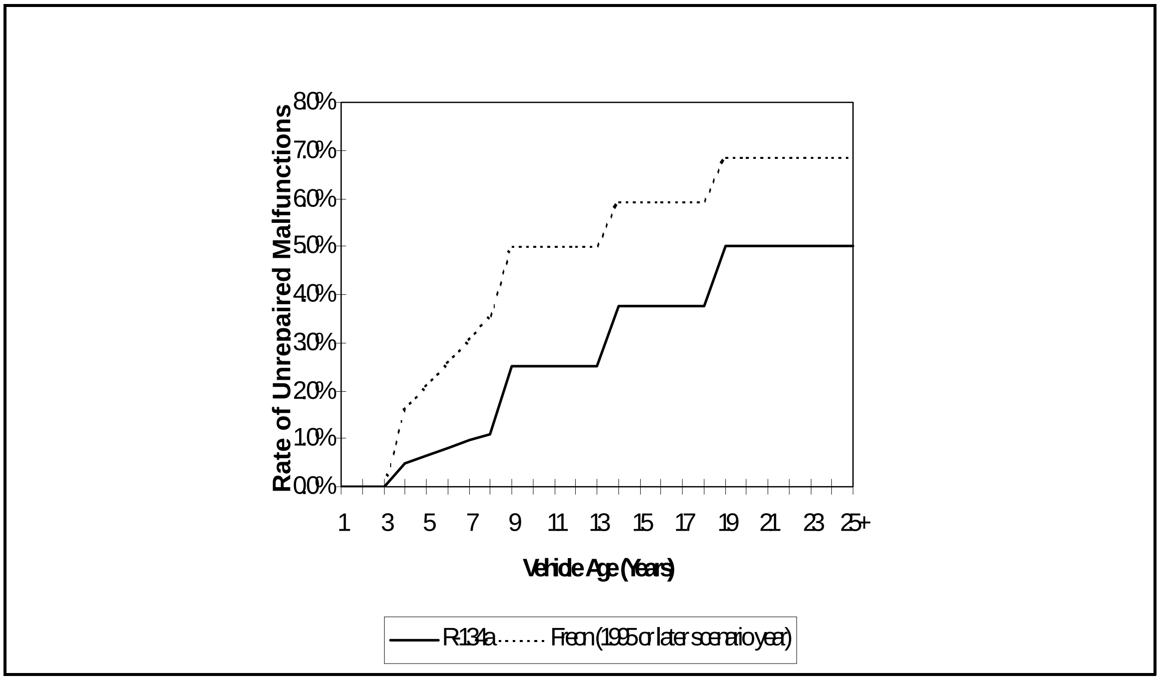


Table 4 - Proposed Rate of A/C Malfunction

Vehicle Age *(years)*	***Consumers Reports****	***Proposed Estimates***
1	< 2%	0.5 %
2	2 - 5 %	2.0 %
3	2 - 5 %	3.5 %
4	2 - 5 %	5.0 %
5	5 - 9.3 %	6.5 %
6	5 - 9.3 %	8.0 %
7	9.3 - 14.8 %	9.5 %
8	9.3 - 14.8 %	11.0 %
9-25	n/a	12.5 %

* 1997 Automobile Purchase Issue

Appendix A - Heat Index Equations

Source: Meisner and Graves, “Apparent Temperature”, *Weatherwise*, August 1985

This set of equations computes heat index under “mild” and “severe” sultriness. Mild sultriness indicates conditions under which thermal equilibrium can be achieved with reduced clothing thickness. Severe sultriness indicates conditions for which reductions in the skin’s resistance to heat and moisture flow are required to achieve thermal equilibrium. If the required clothing thickness is less than zero for the “mild” equations, the “severe” equations are used to calculate heat index. This set of equations is based on an adult wearing trousers and a short-sleeved shirt, walking in the shade at 3.1 mph, standard sea level air pressure, wind speed of 5.6 mph and a vapor pressure of 1.6 kPa.

Inputs: TF = Temperature (°F), RH = Relative Humidity (%)

Variable	Equation	Comment
TC	(TF - 32)*(5/9)	Temperature in Celsius
ES	6.11*10^ (7.567*TC)/(239.7+TC)	Saturation Vapor Pressure
E	0.01*RH*ES	Relative Vapor Pressure
“Mild Sultriness”:		
HER	4.18+0.36*TC	
ERA	1/(17.4+HER)	
QV	180*(143-0.00112*TC-0.0168*0.1*E)	
EZA	0.060606/EHC	
HR	3.35+0.049*TC	
ARA	1/(11.6+HR)	
AZA	0.060606/CHC	
Q2U	((TB-TC)+(PB-PINF)*ERA/(ZS-EZA))/(RS+ERA)	
QJ	(Q-QV-(1-0.84)*Q2U)/0.84	
K	(.0387+ARA)+(0.0521+AZA)/0.124-((37-TC)+(5.65-0.1*E)/0.124)/QJ	
L	((0.0387+ARA)*(0.0521+AZA)) - ((37-TC)*(0.0521+AZA)+(5.65-0.1*E)*ARA)/QJ)/R	
F	K*K-4*L	if < 0 use “Severe”
RF	0.5*(-K+ SQR(F))	

Variable	**Equation**	**Comment**
DF	60*RF	if < 0 use “Severe”
W1	0.2016	
W2	(1-0.84)/(0.387+ERA)	
W3	0.084/(0.0387+RF+ARA)	
W4	159.0984	
W5	37	
W6	4.05*ERA/(0.0521+EZA)	
W7	4.05*(RF+ARA)/(0.0521+0.124*RF+AZA)	
Heat Index	(-W4+W2*(W5+W6)+ W3*(W5+W7))/(W1+W2+W3)	
“Severe Sultriness”:		
HC	12.3	
HR	4.1+0.28*TC	
RA	1/(HC+HR)	
ZA	0.060606/HC	
QU	180-QV	
⇨ZS	((5.65-0.1*E)*RA)/(QU*(0.0387+RA)-(37-TC))-ZA	if < 0 set equal to 0
R3	(ZS/600000)^2	
C	ABS(0.0387-R3)	skips to N1 when C <= 0.0001
⇦RS	0.5*(.0387+R3)	iterates to ZS
N1	159.0984	
N2	37	
N3	4.05*RA/(0.0521+ZA)	
N4	RS+RA	
N5	0.2016	
Heat Index	-N1+(N2+N3)/N4)/(N5+1/N4)	

Appendix B - Peer Review Comments and Response

Subsequent to publication of the draft version of this report in January 1998, the document was put out for stakeholder review. Formal peer review comments were also solicited from two independent sources. No comments were received through the stakeholder review process, and thus the peer review comments represent the only external feedback received on this report. This section contains these peer review comments in full and our response to these comments. The author of the first set of peer review comments requested confidentiality, and hence is not identified here.

Commentor 1 (*EPA responses inserted as italicized text*)

The comment text is verbatim from the commentor, minus editorial corrections to maintain the confidentiality of the commentor.

General

The report documents a valuable initial step towards accurate estimation of exhaust emissions resulting from auto a/c operation. The approach is appropriate for a first step: focus scarce data collection resources on measuring emissions at extreme ambient conditions, and make a series of assumptions to estimate emissions at other conditions. It is a valuable contribution to the published literature because it presents and analyzes a unique set of data from instrumented vehicles.

Based on our review we offer a variety of suggestions, which fall into three major categories:

- evaluate changes in some analytical assumptions
- try to extract more information from Phoenix data
- plan to accomodate or acquire additional data

By making these suggestions, we do not wish to detract from the value of the report and its usefulness as an initial step. It is far better than nothing, yields results that provide a credible basis for policy, and provides valuable insights into operational aspects of mobile a/c systems that have never been published before.

Below we itemize suggestions by page and paragraph number in the draft report. But first we will provide a general statement of the three types of suggestions.

1. Evaluate alternative analytical assumptions

a) It is likely that the incremental emissions due to a/c operation vary with engine rpm. Presumably this effect is captured in the assumption that the effect of compressor engagement on overall engine load is linear, *at a given rpm and load*, thus accounting for the fact that engine efficiency is worse at idle. In other words, we assume that this compressor runtime data will be used in conjunction with measured data on emissions with compressor on and off, at each point in the driving (test) cycle.

Response: *An aggregate model such as MOBILE6 doesn't explicitly address*

RPM. These effects are assumed to be captured on an average basis through the use of representative driving cycles

b) Heat index was assumed to be a good indicator of humidity effects, but the Phoenix data are too anecdotal to confirm that hypothesis. On theoretical grounds, we would not expect it to be valid. It appears from this data that the statistical significance of runtime dependence on heat index is not significantly different from its dependence on outdoor temperature. As a measure of human comfort, it might predict a driverÕs decision to turn on the a/c unit. However it is unlikely to have a significant effect on compressor runtime fraction. Runtime will depend on the sum of the sensible and latent heat load. While the compressor is on, the temperature of the evaporator coil is approximately 35 F on most cars. The sensible load depends on the difference between the evaporator surface and indoor air temperatures. Latent load depends on the difference between the absolute (not relative) humidities of indoor air and that of 100% humid air at the evaporator surface temperature (about 35 ¡F). In the absence of indoor humidity data, the total latent load might be calculated directly from an estimate of the rate at which outdoor air infiltrates into the car. Assuming the infiltration rates are constant between Phoenix and other climates, the ratio could be used to extrapolate Phoenix results to Houston and other climates. The amount of air leaking into the car would have to be assumed.

Response: *The demand factor developed for MOBILE6 attempts to account for both driver behavior and vehicle behavior, and we think heat index is the most appropriate method for extrapolation into high humidity conditions. It is beyond the scope of MOBILE6, and available data, to separate these effects out, particularly given the complexity involved in accurately modeling the operation of the compressor, which will vary from vehicle to vehicle. Thus, we believe the deterministic approach relating ambient conditions to overall compressor runtime continues to be the most appropriate approach.*

c) Solar load is probably irrelevant to your methodology, because most cars that automatically control compartment air temperature do so using reheat. So do drivers who prefer more moderate temperature air blowing on them, or who use high evaporator fan speeds to ensure that air is distributed to throughout the vehicle. In virtually all cars the compressor runs whenever the evaporator is not frosted. Since many drivers control indoor air temperature by running the heater, they simply set the heater to a lower level on sunny days. Since emissions depend only on the total sensible plus latent loads, the composition of sensible loads (solar plus reheat) will not matter. The only case in which solar loads would increase emissions is when drivers control indoor temperature solely by decreasing evaporator fan speed. In the future, introduction of automatically-controlled variable-displacement compressors may change this, so now is the time to start understanding solar loads.

Response: *Solar load is very relevant in terms of initial cabin temperature, which will effect whether driver turns the A/C on at the start of a trip. As noted, it will be less of an issue once the vehicle is cooled down initially.*

d) The Phoenix data set contains no data on air leakage into the car, since it is under the control of the driver who sets it between zero and 100% fresh air intake to a/c system (about 250-350 cfm max, depending on vehicle). Actually infiltration is not zero even at idle, since even the "recirc" setting must prevent carbon dioxide levels from reaching reaching dangerous levels when the car is full of occupants. Air leakage is a strong determinant latent loads, but contributes only a fraction of sensible loads.

Response: *Air infiltration isn't something that can be realistically accounted within the scope of the MOBILE6 analysis*

e) Humidity affects compressor runtime only indirectly, so the reliance on relatively dry Phoenix data may not be as shaky as it may first appear. The effect of humidity is filtered twice. The first effect on compressor runtime is the latent load caused by the humid outdoor air infiltrating into the car; this increases load and therefore compressor runtime. However at the same time the a/c system efficiency increases because the water condensing on the evaporator surface raises the refrigerant evaporating temperature. That will partially cancel the effect of adding the latent loads. Therefore a rough estimate (based on a crude estimate of infiltration loads, which vary with vehicle and average speed and fresh air intake settings) should be good enough for now. It will probably be necessary to ask auto manufacturers for an estimate of leakage rates as a function of vehicle speed and ventilation settings, unless you can extract an average from the Phoenix data (see below).

Response: *Humidity is relied on for the heat-index calculation, primarily to account for changes in driver behavior rather than compressor behavior*

f) Fortunately your data were taken close to the fall equinox, so day length was approximately 12 hours. If you attempt further studies of solar loads, or calculations thereof, don't forget that day lengths in the US can exceed 15 hours near the summer solstice

2. Extract more information from Phoenix data

a) The effect of solar load should be most noticeable on short trips dominated by the "pulldown" period. On longer trips, solar is probably irrelevant due to use of the car heater to control air temperature. Solar load (by increasing heat stored in the passenger compartment's thermal mass) will determine the length of time needed to cool the air to comfortable levels. Elevated indoor temperatures translate directly into higher loads and to less-than-proportional increases in compressor torque, because of slightly higher a/c system efficiencies. This may explain the results shown in Figure 1: compressor runtime is high for trips having high % idle, because most of these are short trips with little cycling, in which pulldown of "soak" loads are a large fraction of the total. If true, the same behavior might be less noticeable in cloudier climates because the initial temperature of the vehicle's thermal mass should be lower.

Response: *To address this, we analyzed whether period of the day was a significant variable for trips longer than 10 minutes; it was. However, it dropped below 95 percent significance for trips above 15 minutes, which could be an indication of the small sample size for trips of this length across the four periods. In general, the average trip in MOBILE6 is estimated to be under 10 minutes. Thus, the "pulldown" effect would predominate the usage of A/C under average MOBILE6 conditions.*

b) Another hypothesis that might be tested concerns the slight decrease in compressor runtime on trips having low % idle: most of these trips were at high speed, so the a/c operated more efficiently due to the ram air effect cooling the condenser; the effect of greater infiltration at high speed was probably offset by the driver's use of reheat, since the cooling capacity of the a/c system at high rpm probably still exceeded the loads, as might be indicated by the cycling rate. Such an effect might have been hard to see in humid-climate data.

Response: *The decrease was relatively minor, but was not statistically significant due to small sample size. Because all trips were grouped together for the calculation of air conditioning demand factors, this effect would be represented in the results.*

c) Try to extract an estimate of the contribution of latent loads from the Phoenix data. Focusing on the longer trips, try to estimate the ratio of sensible to latent loads using the method described in 1(b) above. That is, assume that sensible loads are proportional to (Toutdoor - 75 F) and that latent loads are proportional to the difference between absolute humidities of indoor and outdoor air.

Response: *Data isn't available on indoor air humidity to perform this calculation.*

3. Accomodate and acquire additional data

a) Intensive testing of mobile a/c systems is underway at the Air Conditioning & Refrigeration Center, University of Illinios at Urbana-Champaign. That will provide compressor power and torque as a function of rpm and indoor temperature and humidity, and outdoor ambient temperature. It should be published within the coming year, so it would be wise to modify your models in anticipation of such data.

b) The next time cars are instrumented by EPA for testing, perhaps the estimate of latent loads could be improved by measuring indoor humidities and temperatures. Indoor humidities should be quite stable while a/c cycling rates are high; but indoor humidity could increase during long off-cycles. Also it might be useful to monitor fan and ventilation settings (fresh air vs recirculation), and the use of the heater (on/off at least). All these driver-controlled variables affect a/c compressor power, and measuring them for the purposes of making estimates is difficult. Now that a/c emissions are monitored by EPA, it is possible that future a/c systems will be controlled automatically to reduce emissions.

c) Ultimately it would be helpful to know how compressor rpm relates to vehicle speed, on an aggregate basis. That would facilitate linkage of the University of Illinois a/c test results to various driving cycles.

d) Nearly all today's cars cycle the compressor to keep the evaporator free of frost, and use the car's heater or the evaporator fan to modulate a/c capacity. Both are inefficient. Advanced systems using variable-displacement compressors can run the compressor continuously, operate the evaporator at (higher, above-freezing) temperatures that increase a/c system efficiency, with zero reheat. The overall reduction in sensible load due to elimination of reheat, plus the higher operating efficiency, may lead to substantial reductions in emissions. Automatic control of ventilation is another future technology that might significantly reduce both sensible and latent loads.

Response: *We will take these comments into account for future testing of air conditioning activity.*

4. Detailed comments

a) p 2 para 3: Data on compressor power as a function of rpm and evaporating and condensing temperature may be available from compressor manufacturers' calorimeter testing. It will tell you nothing about load (cycling rates etc) but would be better than nothing. Temperature differences between the refrigerant and air, indoors and outdoors, probably vary little with climate and do not vary much among cars.

Response: *Modeling an effect as a function of rpm would requires far more resolution than MOBILE6 provides; in addition, activity information of evaporating and condensing temperature isn't readily available, so it could not be easily implemented in an aggregate emission model.*

b) p 2 para 3: If in the future you want to improve predictions of compressor runtime as a function of climate and driving cycle, you will need data on cycling rate as well as compressor runtime. Transient losses and latent loads may depend strongly on the cycling rate (e.g. whether 50% runtime results from 10 cycles of 6 min duration or 100 cycles of 0.6 min duration).

Response: *The Phoenix data only provided the total time the compressor was on per trip, instead of real-time data. Future testing may be able to address this* *point, since real-time compressor function will be a target variable.*

c) p. 2 para 3: Your method appears to assume that compressor runtime is independent of rpm. It also acknowledges that this is probably untrue. We agree that it may be important to account for this because emissions vary so greatly with rpm.

d) p 4 para c: Mohinder Bhatti of Delphi Thermal Systems published an SAE paper in 1997 which assumed that idling accounted for 15% of compressor runtime. The Phoenix data appear to violate this assumption. You might want to ask him for the source of his data.

Response: *the Phoenix data indicates that trips with 100 percent idle have relatively low compressor-on time, but this doesn't necessarily contradict Dr. Bhatti's findings. The compressor fraction was significantly higher for trips with very high (but less than 100 percent) percentages of idle. The all-idle trips in Phoenix may not be representative of idle operation in general - for example, they may reflect very short key-on events. If all idle operation could be separated from the Phoenix dataset (including the idle events on non-idle trips), it is likely the overall compressor-on time would be high.*

e) p 4 para 5: We doubt that humidity will account for half of total loads, as it might on the test procedure. But it raises an interesting possibility for measuring indoor compartment humidity (and perhaps measuring condensate removed) on the test, and using it to calculate infiltration rates as a function of ventilation setting (fresh air vs recirculation). If reheat is not used on the EPA test, the total sensible load seen by the a/c is the sum of conduction and infiltration and solar. By controlling the solar load and varying wind tunnel speed, EPA would have a unique opportunity to gather data on load composition.

f) p. 5 para 1: Comparing noontime humidity to daily maximum temperature mixes apples and oranges. If it is 85 F and 40% humidity at noon, then the temperature peaks at 95 at 4pm, the relative humidity falls below 30% while the absolute humidity remains constant. It is the absolute humidity that determines latent load. Air at 40% relative humidity contains 40% more water at 95 than at 85 F.

Response: *this comparison was made simply to illustrate that humidity levels in other parts of the U.S. can be significantly higher than those observed in Phoenix.*

g) p 5 para 2 and 3: Fig 6 is not much different from Fig 2. Since humidity is so low in Phoenix, it is not clear that one can conclude from this data that the strong correlation between compressor runtime and heat index is better than a method based on the correlation with outdoor temperature, adjusted for absolute humidities.

Response: *The purpose of using heat index as the predictor variable instead of* *temperature is to develop a methodology to account for humidity as well as temperature, rather than to find the best fit for the Phoenix data. The heat index levels in Phoenix are driven almost exclusively by temperature, since very high humidity levels are required to affect the index beyond temperature.*

h) p 5 para 3: It may be true that using heat index is better than ignoring humidity, but we suggest that you try to track the physics better by using absolute humidities to estimate latent loads.

Response: *Absolute humidity was was found to not be a particularly good predictor of compressor fraction, as shown in Figure 3.*

i) p. 8, para 1: Assuming a sunny day is probably not a problem for most cases, since reheat will make up for loads blocked by clouds.

j) p 8 para 1: Radiative heat loading is very complex, and some of the suggested assumptions are problematic. For example even with 100% cloud cover, solar collectors work very well collecting the diffuse component of solar radiation. And nighttime radiative cooling reduces need for a/c, especially on clear nights when the surface of the car is radiating to the cold blackness of space.

Response: *this suggests that the treatment of 100 percent cloud cover as "nightime" may be overstating the effect of cloud cover (which is very small as it is). Because solar radiation data (or even reliable cloud cover data) was not available for Phoenix, we don't have the ability to separate "direct" and "diffuse" radiation.*

k) p 8 para 3: Soak duration is likely to have a large effect on short trips having little cycling, because of the effect on pulldown load. After indoor temperature stabilizes, effects of soak have vanished.

l) Fig 1: Clarify that the first bar is deleted from the data set.

m) Fig 2: It is clear that each data point represents the time-weighted average runtime of all data points in that temperature bin. But is the least squares fit weighted too? If so, explain how. Do the averages include trips taken with the a/c off for the whole time? Is there any systematic dependence of errors and scatter on long vs short trips or those having higher/lower cycling rates?

Response: *The demand factor curves were generated from data aggregated over every trip by heat index level. This approach accounts for the disparity in trip length implicitly, by calculating compressor fraction as the total time the compressor is engaged divided by total trip time at a given heat index. This approach also reduces the influence of random effects (such as vehicle), since the aggregate trips for a given heat index are comprised of several vehicles.*

n) Fig 6: Instead of using a parabola, why not select an exponential or other curve that naturally has a horizontal asymptote?

o) Fig 10: All curves should approach a horizontal asymptote. It would help if data points were shown along with the curve fits. Try re-fitting with exponential curve to capture asymptote?

> ***Response:*** *While the quadratic approach with truncation may not be the most elegant, the terms are significant, and another approach would be unlikely to yield results much different from the current approach.*

p) Fig 11: Lack of dependence on speed suggests that ram air flow into condenser improves a/c system efficiency. Load reductions due to wind cooling the solar-heated metal, and load increases due to increased infiltration are probably neutralized by reheat.

q) Table 1: Explain how this relates to Fig. 7. Also show formulae or explain better how the numbers were calculated.

5. Questions

a) p 2 para 1: is the 850 W/m2 solar load applied to a car in a wind tunnel or is the vehicle stationary? Stationary test will overestimate effect of solar, since car surface will be hotter than while driving.

> ***Response:*** *The vehicle is stationary, but a variable speed fan provides cooling and presumably produces conditions more representative of the road*

p 2 para 3: Compressor ontime fraction should be defined carefully to clarify whether the denominator is total trip time, or only that fraction of the trip during which the a/c system was switched on.

> ***Response:*** *Compressor time is the fraction of compressor time divided by total trip time, regardless of whether the A/C was on or not.*

Commentor 2:
John Warner, PhD
Center for Statistical Consultation and Research
University of Michigan

Verbatim comments not available electronically. Hard copies available upon request. Comment and responses are summarized below:

> **Comment:** Given that the analysis is focused on the population of the Phoenix dataset as a whole, rather than making inferences about idividual drivers/vehicles, vehicle should be included as a random effect. Ignoring random effects may lead to unrealistically small standard errors and unrealistically low p-values.
>
> ***Response:*** *The analysis for determining the significance of individual variables was redone, adding vehicle as a random variable. The fundamental conclusions (as predictor*

variables, only heat index and period are significant) are unchanged. The ANOVA results presented in Table 3 have been updated to reflect this change.

Comment: Main effects should be tested individually, or alternately it should be made clear what approach was taken to determine the significance of individual effects.

Response: *The methodology for performing the Analysis of Variance on main effects has been added to the report.*

Comment: There are likely approaches to modeling demand factor which are better than a quadratic fit, given the level of truncation required with the quadratic curves to maintain results between 0 and 1. Examples include a non-linear least-squares with random effects (which a quadratic form would adderss); and “ideal” component would be to give higher weights to trip lengths and for compressor fractions close to zero or one.

Response: *The demand factor curves were generated from data aggregated over every trip by heat index level. This approach accounts for the disparity in trip length implicitly, by calculating compressor fraction as the total time the compressor is engaged divided by total trip time at a given heat index. This approach also reduces the influence of random effects (such as vehicle), since the aggregate trips for a given heat index are comprised of several vehicles. While the quadratic approach with truncation may not be the most elegant, the terms are significant, and another approach would be unlikely to yield results much different from the current approach.*