Temperature Variations in a Parked Car

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Abstract

On a hot summer day temperature levels in the cabin of a car parked in the sun can be more than 20\degree C above that outside the car; a serious threat for children or pets left in the car. We develop a simple greenhouse model for predicting daily cabin temperature variations using readily available meteorological data. This statistical model is calibrated using meteorological data and car temperature data collected on parked cars over several summer seasons. The model uses environmental temperature and radiation data as input, and is shown to predict cabin temperatures to within about 1\degree C. Both the data collected and the model developed show that the temperature inside the cabin of a black car is typically 5\degree C higher than that inside a white car on a hot summer day. Also lowering the driver’s window of the car by 2.5 cms typically reduces cabin temperatures by about 3\degree C; this is not sufficient to reduce significantly the safety concerns for children or pets left in parked vehicles.

The primary motivation for this work was forensic; the determination of the time of death of suicide and homicide victims.

Key words: Suicide and homicide victims, Child safety, Greenhouse problems

1. Introduction

For forensic purposes estimates of the time of death (postmortem interval or PMI) of individuals that have either committed suicide by carbon monoxide poisoning in an enclosed vehicle, or of homicide victims deposited in vehicles, are required by the judicial system. In the case of homicide victims, approximately 4 hours following death in an open vehicle, and approximately 23 hours after death in a sealed vehicle, flies begin ovipositing on the body, maggots hatch, and the body undergoes a series of successional changes as decomposition proceeds, greatly enhanced by the growing fly population. A major factor in estimating the fly population growth rate is the cabin or boot temperature over the time period in question. During summer within approximately 20 days in an unsealed vehicle and approximately 6 weeks in a sealed vehicle only skeletal material remains, but again the time span is strongly temperature dependent.

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One of the investigators has carried out extensive experiments using dead pigs in cars (match-
ning the body weight of victims) going back to 2000, and in this way has obtained useful forensic
information concerning the time of death of victims, see Dadour and Morris[1]. Whilst such
experiments are useful in the specific forensic contexts for which they were carried out, he felt
that such time consuming and unpleasant experiments might be avoided if an accurate predictive
model could be developed to determine the temperature variations in the parked car over periods
of weeks of interest and if an accurate biological (entomological and physiological) decompos-
tion model could be developed. The simpler of these two tasks; the development of a reliable
physics-based mathematical/statistical model for determining temperature variations in a parked
car, has been undertaken and the results are described here. Preliminary work on the latter task
has also been undertaken by Sasha et al [2]. Further work is underway to combine the two models
in a useful way.

Of more interest to the general public is the child and pet safety issue. Because temperature
levels are typically 20°C hotter inside a parked car than outside on a hot summer day, children
or pets left in such a parked car for periods of the order of 30 minutes suffer heat stress and a
number of deaths are reported in Australia each year as a result. There has been much public
concern with this issue and in this context some experimental results concerning the temperature
rise in parked cars have been presented by McLaren et al [3] and Grunstein [4] et al. Whilst these
studies highlight the extreme cabin temperatures that can occur there is no attempt to model
the solar radiation input into a parked car, so that the results are not broadly useful. There has
of course been much work on such greenhouse effect modelling in agricultural, architectural
and solar collector contexts, see for example Ballinger [5] and Rabl [6]. However the relevant
length and time scales, and thus the heat transfer parameters, are very different in the parked car
context. In order to inform the public, health organizations would like to be able to predict the
temperature rise in parked cars and the time span required for this rise under prescribed weather
conditions. They would also like to know if car colour significantly effects the temperature rise,
and if opening the window a few cms or using an air conditioner before parking can effectively
reduce risk.

The time scales of interest are different in the two situations described above but the objective
is the same: to predict the cabin temperature variations in a parked car using readily available
weather bureau data (radiation levels, environment temperature, wind speed, moisture levels
etc.), and available information about car type, colour, and window status, as well as car location
and orientation. Also boot temperatures are of interest in the homicide cases, but will not be
modelled in this article.

A typical temperature record is shown in Figure 1 collected over a period of 10 days during
the summer in 2002 on a white Ford. Here temperature measurements were taken inside the car
(cabin (with closed windows), inside the boot of the car, and outside the car. Significantly the
temperature within the cabin is 20 – 30°C degrees higher than the temperature outside the car (at
40 – 45°C) in the middle of the day (a staggering maximum of 70°C is reached). The temperature
within the boot was still well above the outside temperature but significantly below that in the
cabin during daylight hours, primarily because of the radiative input through the windows of the
cabin, see later. Also noticeable is that the boot temperature profile is smoother than the outside
temperature or cabin temperature profile as one might expect due to conductive smoothing in
the boot case. During the evening both the cabin and boot temperatures settled down to the
outside temperature. Evidently this means that the records from day to day are essentially
independent; there is no memory beyond a day in the system. In fact there is no obvious time
delay between the three temperature responses, which suggests that the effective thermal mass is
It should be emphasized that our objective here is not to produce the most accurate model but to produce the most useful model in the present context. The most accurate model would necessarily be complex to take into account the large number of environmental and car variables that determine the temperature evolution, but in forensic or car safety contexts these variables are just not available. The most one can hope for is standard weather station data collected somewhere nearby the parked car and radiation data collected usually at a relatively remote spot or inferred from sun position or solar charts. Even if such variables were measurable/available it is highly unlikely that our understanding of the complex physics is at present good enough to support such a detailed model, and furthermore the associated mathematical processing required to use and interpret the results would also be suspect. What is needed here is the simplest model that reliably produces results of acceptable accuracy within acceptable error bounds. We claim that the model developed here is such a model. Whilst being based on simple physical principles the model developed was primarily and necessarily statistical with parameters determined using experimental data collected on cars parked at the University of Western Australia Agricultural Research station at Floreat Park, Western Australia over periods of weeks during the summers of 2005, 2007 and 2008.

In Section 2 we briefly describe and partially quantify the heat exchange processes that determine the cabin temperature development and underly the adopted statistical model. We then go on to describe the experimental data in Section 3 and present the statistical models with results in Section 4. In the Conclusion Section 5 we describe the application of the results obtained to the safety and forensic problems.
2. The Physics

In simple terms this is a greenhouse problem in which the solar radiation entering through the windows of the car is partially trapped inside the cabin of the car. What actually happens is much more complex. Incident or indirect radiation from the Sun is partly reflected and partially transmitted from all external surfaces of the car. Radiation (of all wavelengths) hitting the external metal surfaces is either reflected or absorbed (being opaque to all wavelengths). Glass is however ‘transparent’ to light (short wavelength) radiation, but ‘opaque’ to thermal (long wavelength) radiation, so that the primary heat input into the cabin during daytime is associated with light radiation (sunlight) transmitted directly through the windows (there is little absorption in the glass). This light radiation is subsequently absorbed (and thus converted into heat) by the dashboard, the seats and the floor of the car. Furthermore, since almost all of the (short wavelength) light radiation entering the car is absorbed and the windows as well as the car interior are opaque to the (long wavelength) heat radiation thus generated, we have radiation trapping; the heat loss from the cabin occurs through other mechanisms. Convection currents generated within the car by differential surface heating redistribute the heat to the air within the cabin. It is of course this air cabin temperature that is our primary focus. Heat losses from the car occur by conduction (primarily through the roof and windows of the car) combined with convective exchanges with the environment from all external surfaces. Also, and importantly, heat exchanges can occur because of the leakage of hot air from the car cabin into the environment especially through any open windows. All the above heat exchanges are strongly effected by prevailing climatic and local weather conditions.

Under steady state conditions (with fixed radiative input and fixed environmental conditions) the radiative heat input per unit time into the cabin of the car will balance the heat loss, a result that we model in the form

\[ S = C(T_c - T_0) \]  

where \( S \) is the total radiative power through all windows of the car, and \( T_c, T_0 \) are the cabin (air) temperature and the (air) temperature outside the car respectively. This model assumes that the cabin air temperature provides a measure for (or at least correlates with) the temperature of the cabin contents. Also the model assumes the heat loss per unit time from the cabin is linearly related to the temperature difference between the cabin and its environment. The complex heat loss mechanisms described above are all hidden behind (and collapsed into) a single heat loss transfer coefficient \( C \) which we hope will be characteristic of a particular car (colour and type) and ventilation state. Implied in this simple description is that variables not explicitly displayed play a relatively minor role for the environmental conditions of present interest and can be classified under the heading of ‘statistical variation’. For example prevailing winds conditions are not modelled. The thermal exchange parameter \( C \) is determined using the experimental data and the usefulness of this model may be judged in terms of the calculated error bounds.

In practice the radiative and environmental conditions vary with time of day and the cabin air temperature does not instantaneously adjust to the changed heat input and loss, so that one would expect time delays. Experiments have been performed on the thermal response time of a car to a changed radiative environment, see McLaren [3]. In this set of experiments a car was moved from a garage out into the strong sunlight and the cabin (air) temperature response was observed. The response time was about 1 hour with the cabin temperature approaching a steady state value exponentially. For our circumstances the conditions are changing much less abruptly, however our observations are consistent with these results. We will see later that the steady state model (2.3) does produce good results for cabin temperatures (because the effective thermal mass of
the cabin is small), but more accurate results can be obtained by modelling the delay and (in the
safety context especially) time delays are of interest in their own right. There are two obvious
ways for modelling in such effects. One can attempt to model the physics by introducing an
additional thermal mass parameter $M_t$ and describe the heat exchange using the model

$$M_t \frac{dT_c(t)}{dt} = S(t) - C (T_c(t) - T_0(t)). \quad (2.2)$$

There is no obvious choice for the thermal mass of the cabin contents $M_t$ so that $M_t$ would need to
be fitted to the data. Alternatively one can simply focus directly on the delay time $\Delta$ by writing

$$S(t) = C[T_c(t) - T_0(t - \Delta)]; \quad (2.3)$$

again $\Delta$ needs to be determined by fitting data. The rational behind this particular choice of
delay model is that, whereas the cabin responds ‘instantaneously’ to a change in radiative input,
exchanges of heat from inside to outside the cabin (i.e. losses) are relatively slow. Models of both
type were explored, however the more complex thermal mass model was eventually rejected
because the results obtained were not significantly better than those obtained using the simpler
time delay model. Here we will only describe the delay models. An account of the thermal mass
model can be found in Almanjahie [7].

2.1. Solar radiation input through the windows into the car

As indicated above it is the short wave length radiation input through the windows of the
parked car that is of interest. Primarily during summer daylight hours this is direct radiation
from the sun, but there will be some indirect ‘sky’ radiation due to scattering which can be sig-
nificant especially in the early morning (before the sun is up) or in the late afternoon when the
sun is setting. Various empirical formulae are used to try to account for scattering; the Hottel
formula is the best known, see Duffie and Beckman [8] and Reda and Andreas [9]. Of course the
amount of scattering is also dependent on weather conditions (for example winds can greatly in-
crease the density of particles in the sky), and additionally cloud cover and humidity also greatly
effect the amount of radiation reaching the Earth; Coulson[10], and Siegel and Howell[11] are
the classical reference in the area. The physics is complicated and even the design of radiation
instruments is something of a dark art, there being many different instruments designed to mea-
sure different radiation components. Using Hottel’s formula Almanjahie[7] has obtained results
for the radiation input into the cabin of cars under ideal conditions at any time of the year but
such corrections will not used here. The approach adopted here is ‘simple minded’ and based
on the observation that (except during the early morning and late afternoon) it is primarily direct
radiation from the sun through the windows that drives the heating.

If $(\alpha, \theta)$ are the elevation and azimuth of the sun as seen from a location P on the surface of
the Earth, then the direct radiative power received at P (outside the atmosphere) is given by

$$R_s = R_0 (\cos \alpha \cos \theta i + \cos \alpha \sin \theta j + \sin \alpha k), \quad (2.4)$$

where $R_0$ is the solar constant, and where $(i, j, k)$ are unit vectors in the SN (South, North), EW
and vertical directions measured from the car’s location P , see Figure 2. The formulae for the
elevation and azimuth angles as a function of latitude, longitude and time is given in Almanjahie
The sun’s location is specified by the azimuth and altitude angles \( \alpha \) and \( \theta \). The solar distance is \( r \). We processed our data using a Matlab implementation of the Carruthers [13] formulae.

A significant proportion (more than half) of this radiation is reflected off clouds and thus will not reach the Earth’s surface at \( P \), and also scattering will further reduce the direct radiation component. If \( R(t) = R(t)s \) is the radiative power actually reaching the Earth directly from the sun at \( P \) then a horizontal collector will intercept \( R \cdot k \) of this. It is the short wavelength component of this radiation that passes through the windows of the car; we will assume a fixed proportion of the total radiation received by the collector is in the short wavelength range and that this correlates with the direct solar component. Knowing \( (k, s) \) and using the radiation data collected at \( P \) (in our case at the Floreat Park State Agricultural weather station in Perth Western Australia) we thus determined the effective radiative power of the sun \( R(t) \) at \( P \) and used this to determine the total radiative input into all four windows of the car given its orientation; explicitly

\[
S(t) = \sum_{i=1}^{4} R(t)(A_i \cdot s(t)),
\]

where \( A_i = An \) specifies the area \( A_i \) and orientation \( n_i \) of the car windows. (We treat the two windows on one side of the car as a single window.) To facilitate this calculation we set up a local car based co-ordinate system \( (i', j') \) on the horizontal plane at \( P \) with \( i' \) directed along the length of the car (back to front), see Figure 3. In this co-ordinate system the \( A_i \)'s remain fixed. If \( \beta \) is the angular displacement measured from \( WE \) (i.e. \( i \)), then \( i' = \cos \beta i + \sin \beta j \) and one simply changes \( \beta \) to determine the changed radiation input into the car due to reorientation. It is interesting to

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\(^{1}\)Such a parameter would necessarily take into account the thermal status of the dashboard, the interior surfaces the seating etc.
Figure 3: Car orientation: \((\mathbf{i}', \mathbf{j}', \mathbf{k}')\) is a coordinate system centered on the car with \(\mathbf{i}'\) along the axis of the car.

note that the idealized (clear sky) calculations based on the above formulae with \(R = R_0\), the solar constant, show that the total radiative input into a car (in this case a Camry) over a day doesn’t change much with the car’s orientation, see Figure 4 (the dotted curves). The explanation is that windows into many modern cars (in this case a Camry) essentially form a transparent strip right around the car so that although the input through a specified window may vary significantly depending on orientation the summed input through all windows remains relatively unchanged as can be seen in the figure.

3. The Experiments

There have been experiments going back to 2000, however the analysis here is based on three sets of experimental records on parked cars collected during the summers of 2005, 2007 and 2008. The cars were parked on an open field, relatively sheltered from winds. In each of these experiments temperatures were measured in 15 minute intervals on the roof, in the cabin (at head level), on the back seat, on the boot roof, and inside the boot of cars parked at the UWA Agricultural Research Station in Floreat Park Western Australia. The State Agricultural Field Station located nearby in Floreat Park provided radiation data (in hourly intervals) and environmental temperature measurements in 15 minute intervals. In this work we concentrate on cabin temperature predictions, so that boot temperature and roof temperature data will only be presented as required for explanation purposes. To some extent the experimental setup was outside our control. Evidently we could not regulate the weather and the available hot summer days was limited by local climate and the vagaries of weather, but also the cars used were determined by availability. New cars were provided by a number of organizations (see Acknowledgments), generally one at a time. However for some of the experiments two cars were simultaneously available, enabling us to investigate more carefully the effect of the most important parameters. Specifically the records collected were:
3.1. Typical Results

Figure 4: The effect of car orientation on the radiative input through car windows: Computed (idealized) radiation input into all four windows of a car (front (thick curve), back (thin curve), left and right windows (medium curves) and total input (dotted) during a day (21 March in Perth) in different orientations.

2005: From 5 March to 17 data was collected on a white Commodore with NS orientation (ie. front facing North, rear facing South). The cars windows were closed. The primary motivation here was to check out the usefulness of the basic ‘steady state’ model.

2007O: From January 16 to February 19 2007 measurements were taken on a white Camry with windows closed but with different car orientations (EW, WE, NS, SN). The primary aim here was to check out the effect of orientation on cabin temperatures. In particular we wanted to check out the formulae used to determine solar radiation into the car.

2007C: From Feb 22 till March 1 from Feb 22 till March 1 2007 data was collected on a black Camry. The cars windows were closed and its orientation was always NS (front facing North, rear facing South). Evidently the effect of car colour was of primary interest here.

2008BW: From February 17 2008 till Feb. 29 2008 (with the useful data from February 18 2008 till Feb. 28 2008) data was collected on two Ford Focus cars, one white and the other black. The windows were closed and both were orientated EW. Again the effect of car colour was the focus of this study.

2008OC: From March 8 till March 31 2008 data was collected on two identical white Falcon cars both facing EW. For this set of experiments one car had all windows closed. The other car had the driver’s side window open 2.5cms and then later 5cms. Ventilation effects were the focus in this study.

Selected (but typical) portions of these records will be presented to highlight features of interest. For a more complete picture see Almanjahie (2008).
• As anticipated temperature differences between the cabin and the environment are brought about by radiative input into the cabin, so that such changes are initiated at sunrise and disappear at sunset.

• The cabin car temperatures (and also roof and boot temperatures) seem to change instantaneously in response to radiative changes, with spikes in the radiation record being duplicated in the car temperature records.

• Again as expected the temperatures outside the car are not so closely correlated to the radiation records. It is well known that it takes about two hours for air temperatures on the Earth to respond to radiative changes; thus for example maximum temperature levels are reached about two hours after the sun is directly overhead.

The experimental record using two Ford Focus cars identical apart from colour and exposed to the same environmental conditions (they were parallel parked) are interesting, see Figure 6, Left and Right. Note that the records indicate a significantly higher temperature inside the cabin of a black car compared with a white car during daylight hours (Left). The reason for the increased temperature can be seen in the roof temperature records for the two cars (Right). More of the radiation from the sun is absorbed in the metal skin of the black car than the white car because of the relatively higher absorbivity of the black surface. The effect of this is that the roof temperature of the black car is significantly higher than that of the white car during daylight hours and thus the flux of heat from inside the cabin to the outside is significantly reduced, and equilibrium is reached at a higher cabin temperature.

The effect of opening the driver’s side window by 2.5cms and 5cms on a hot summer day is seen in Figure 7, where results under identical or almost identical weather conditions are displayed. The effect of opening the driver’s side window by 2.5cms is to reduce the maximum
temperature reached on the summer day by 3°C. If the gap is increased to 5cms a 6 − 7°C reduction is observed.

4. The Statistical Model

As indicated in Section 2 three statistical models were examined; a steady state model described by (2.1), a thermal mass model (which was rejected), and time delay models described by (2.3). It should be noted that all these models only use $T_0(t)$ and $S(t)$ as input variables, the aim being to fit/determine the cabin temperature $T_c$ as output. There is no attempt to model in the possible effect of other weather variables (such as wind speed, humidity); the assumption being that such variables play a secondary role at least for the conditions under test. The cars were deliberately parked in a relatively sheltered location out in the sun to avoid complications. Note that the radiation input is modeled effectively; cloud cover effects etc. are accounted for in the input radiation data and as indicated earlier car orientation effects were accounted for. A check on the appropriateness of the linear response model was made by simply plotting radiation data against recorded temperature differences; the linear fit (ignoring nighttime results corresponding to $S = 0$) can be seen in Figure 8.

It should be noted that the cluster of points at the left hand end of the figure correspond to data collected during night time, with relative radiative input $S = 0$ and temperature differences changing as the car cools down. Ignoring these data points a linear regression fit to the data is displayed. Whilst the variability is relatively large there is no obvious trend missed by the simple linear model. A more detailed examination of the real data together with the predictions based on the linear fit with $C$ determined as above, see Figure 9, shows that, whilst the cabin temperature predictions $T_c(t)$ were good in terms of the predicted amplitudes, there is lag time between the temperature prediction and the actual recorded values; this prompted the investigation of the time delay models (2.3). Rather than fitting both $C$ and $\Delta$ using the data (and thus increasing
Figure 7: Ventilation effects

Figure 8: Testing the linear model (2.1): Falcon 2008 data. Here we plot the temperature difference $T_c - T_0$ between the cabin and the environment as a function of the total radiative input using collected data. The least squares linear fit is also displayed.
the complexity of the model, we decided to experiment with different fixed values of \( \Delta \) (explicitly \( \Delta = 1, 2, 3 \) hours; values that seemed sensible in terms of the physics) and simply fit \( C \) for these \( \Delta \) values. By examining the computed square residuals we found \( \Delta = 2 \) hrs best fitted all the available data (different cars of different colours with windows up or slightly open). Results obtained using this model are displayed in Figure 10; in this case for the Ford Falcon 2008 data set with the drivers window open 2.5cms. It can be seen that the time delay is now effectively modelled. The fact that \( \Delta = 2 \)hrs best fits all the data records is significant in that it suggests that the time delay is independent of vehicle type and ventilation status. The implications in terms of data collection and evaluation are significant. Furthermore this suggests that the linear delayed fit model, using a \( \Delta = 2 \)hrs delay, represents a reliable robust model for evaluating the thermal behaviour of different type of parked cars of different colors and different ventilation states. It should be remarked that although \( \Delta \) does not change with model/ventilation state the value of \( C \) does change significantly reflecting the observations presented earlier. The error estimates suggest that the models predict cabin temperatures to within 1\(^\circ\)C, which is certainly good enough to differentiate between car types and colours (where 3 to 5 degree differences are typical). Also the model appears to reliable for predicting cabin temperature levels over a broad range of environmental conditions; for more details see Almanjahie (2008). Although experiments were only performed at the Floreat Weather station in Perth WA, there is no reason to believe that the model results can be used elsewhere on the Earth, with the solar input appropriately applied as described. Probably the main source of error lies in the ignoring of wind data; one would anticipate significant exchanges in heat between the car and its environment if winds are significant and windows open.

5. Applications and Concluding Remarks

The reader will recall that there were two primary application areas that motivated the present work:

- safety issues associated with the leaving of children and pets in parked cars;
Figure 10: Delayed model fit. Falcon with window open 2.5cm.

Figure 11: The time delayed linear fit model with error bars. Falcon data
the forensic determinations of the time of death of suicide and homicide victims;

As far as the safety issue is concerned the models developed enable one to determine temperature levels inside parked cars under prescribed conditions. The data and models indicate that temperature levels quickly reach levels determined primarily by the instantaneous radiation input and temperature of the environment. The effect of partial shading of the car (trees) can also be determined using the model developed. Using these results heat stress levels can be estimated and safety limits estimated using available physiological models.

As for the forensic application the models developed here determine the elevated temperature levels within the parked car which promote decomposition. Adult flies are attracted by the odor and oviposit on the corpse and the fly larvae consume the bacteria decomposing the flesh of the corpse. The numbers entering the car is dependent on the population size and species of adult fly present in the general area, the season, and the access available to them to the interior of the cabin; some cars are better sealed than others, and of course a partially open window (often the case for suicide victims) will greatly improve access. The growth rate of the larval population is dependent on the body mass and car temperature, there being a temperature range within which the larval population will grow. It is an immensely complicated biological situation, see Sasha (2005). It seems likely, and preliminary estimates suggest, that cabin temperatures are unlikely to be significantly affected by the presence of the decaying body, so that the models developed in this work can be used to predict cabin temperatures under such circumstances and can be used as input into a suitable decomposition model.

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References
