QUANTIFYING THE HEAT-RELATED HAZARD FOR CHILDREN IN MOTOR VEHICLES

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A table of maximum rates of temperature change inside motor vehicles should be useful in educating the public about the dangers of vehicle-related hyperthermia.

The danger of leaving young children unattended in vehicles has been well documented. There are no unique codes for identifying vehicle-related hyperthermia deaths in the International Classification of Diseases (ICD) or in any U.S. federal or state data source (Guard and Gallagher 2005). However, vehicle-related hyperthermia deaths in children in the United States have been constructed from news accounts. Guard and Gallagher (2005) observed an average of 29 deaths per year during the years 1995–2002, while a more extensive dataset by Null (2009) observed an average of 37 deaths per year during the years 1998–2009. Most cases (54%) involve caregivers simply forgetting their children; however, more than a quarter of vehicle-related hyperthermia deaths (27%) involve children that were intentionally left in the car (Guard and Gallagher 2005). In some cases, parents did not want to disturb a sleeping child but were unaware of how quickly the car could heat up. Such behavior indicates a clear lack of understanding by parents and caregivers about the dangers of leaving children unattended in vehicles.

The interior of a car, along with the particular case of a child strapped into a child safety seat, represents a unique environment that may create particularly dangerous conditions. Multiple studies have investigated how ventilation, shading, and different meteorological conditions may affect maximum cabin temperatures and rates of temperature change (Table 1). With the car in direct sunlight and no ventilation, maximum temperatures may reach values exceeding 70°C (Table 1). These stunningly high temperatures are caused by a greenhouse effect, where the windows are transparent to solar radiation but opaque to longwave radiation. As a result, a positive net radiation balance occurs that leads to heating. In addition, the lack of ventilation from closed windows reduces the transport of energy via convection and further con-

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Table 1. Summary of rates of temperature change within passenger vehicles from different studies. Values were estimated from figures and tables presented in the various studies and selected to represent cases when the car had minimum ventilation and was in direct sunlight. Max is the maximum temperature reached while the car was parked. All values are rounded to the nearest degree Celsius. The asterisk means that day temperatures reached 89°C, and the car was parked for 12 h.

Study	5 min	10 min	30 min	60 min	Max	Instrument type and location	Parked (h)	Location and dates
Gibbs et al. (1995)	7	16	24	27	60	Electronic; placed on front seat	1.5	New Orleans, LA; 27 Jul 1995; 1430–1600 LT
Grundstein et al. (2009)					76	Electronic; 15 cm below roof center	6	Athens, GA; 1 Apr–31 Aug 2007
King et al. (1981)	19	21	25	25	66	Electronic; 15 cm below roof center	2	Brisbane, Queensland, Australia; summer 1978 and 1979; 1100–1300 LT
Marty et al. (2001)					89	Electronic	12*	Zurich and Chur, Switzerland; Jan 1995–Mar 2000
McLaren et al. (2005)	4–10	7–13	17–18	22–23	47	Electronic; 38 cm above rear seat	1	Freemont, CA; 16 days; 15 May–8 Aug 2002
Roberts and Roberts (1976)			15		45	Liquid in glass; 15 cm above front seat cushion	0.75	Baltimore, MD; Sep 1975; afternoon
Surpure (1982)					78	Liquid in glass; suspended from driver's seat	8	Oklahoma City, OK; first week, Jul 1980; 0800–1600 LT
Zumwalt and Petty (1976)					58	Liquid in glass; back seat	5	Dallas, TX; Jun–Oct 1975; 1200–1700 LT

tributes to heating. Zumwalt and Petty (1976) note that exposure to high environmental temperatures only leads to a large rise in body temperature when the temperature-regulating mechanisms are not operating efficiently. In a hot vehicle without ventilation, physiological mechanisms typically used for cooling, including longwave radiation and convection, would be ineffective. Furthermore, the efficiency of evaporative cooling would be reduced as evaporated perspiration accumulated in the vehicle.

The meteorological community, along with local health officials and the media, has been active in disseminating information about heat-related hazards. The National Weather Service (NWS), for instance, will issue "excessive heat warnings" or "heat advisories" depending on the severity of the conditions (NWS 1994). Many communities worldwide have adopted synoptic-based heat watch–warning systems where "heat alerts" and "heat warnings" are issued (Sheridan and Kalkstein 2004). Layered on top of these general heat alerts are more specific warnings by public and private entities about the dangers of leaving children unattended in motor vehicles. While most of these warnings include some statements about how hot a car might get, vehicle temperature data from many early studies were often obtained with small datasets and questionable methodologies, such as placing the temperature sensor directly on the car seat.

This research will focus on providing information that may aid public officials, child safety advocates, and the media in better educating the public about the dangers of leaving children unattended in vehicles. Results from this study may also be used as part of a public health response to a heat health warning to emphasize the extreme danger of vehicle-related hyperthermia in children during those unusually hot periods. The first portion of the study determines maximum temperature change at different time intervals using carefully positioned high-temporal-resolution temperature sensors. An extension from previous work involves placing the results in an easy-to-use table of vehicle temperature changes that shows conditions that may occur under the most severe circumstances. In addition, previous studies have discussed but have not quantified how the environmental conditions in a car would affect the energy budget of a child (e.g., Zumwalt and Petty 1976; King et al. 1981). Thus, a human heat balance model will be used to investigate the energy budget of a child in a hot car and the influence of variations in humidity and sun exposure on levels of heat stress.

DATA AND METHODS. Air temperatures within a vehicle were measured on 58 days—from April through 31 August 2007—in Athens, Georgia (33.95°N, 83.32°W). Measurements were taken within a metallic gray 2005 Honda Civic with gray cloth seats. Approximately 67% of vehicle-related hyperthermia deaths in children occur in cars as opposed to larger vehicles, such as minivans or SUVs; therefore, a car provides a representative vehicle for the study (Guard and Gallagher 2005). In addition, temperatures increase more rapidly in smaller vehicles (Surpure 1982), thus providing better estimates for "worst case" scenarios. The car was parked in an open asphalt-covered lot with direct exposure to sunlight. Additionally, the windows were closed during data collection to limit ventilation and maximize heating within the vehicle.

The vehicle temperature data were collected by an Onset Computer Corporation HOBO temperature sensor (H008-003-002; resolution = 0.4°C, accuracy = ±0.7°C) that recorded temperatures every 5 min. The sensor was attached to a string and suspended approximately 15 cm from the ceiling to avoid direct exposure to sunlight and to be sufficiently far from surfaces to accurately measure air temperature. Ambient outdoor air temperature, dewpoint temperature, and solar radiation data at a 5-min resolution were obtained from an adjacent weather station operated by the Department of Geography Climatology Research Laboratory (CRL), located on the roof of the building approximately 12 m higher in elevation than the car and 125 m from the parking lot. Solar radiation was measured with a Davis 6450 silicon photodiode sensor, and temperature and humidity were measured with a shielded and aspirated Davis 6382 temperature and humidity sensor. Cloud cover data at hourly resolution were obtained from a NWS Automated Surface Observing Station (ASOS) located approximately 5 km away at Athens–Ben Epps Airport.

For each day with vehicle temperature data, the maximum 5-, 10-, 30-, and 60-min temperature changes were computed. The focus of the study is on the most severe possible conditions with the greatest temperature changes. Thus, maximum temperature changes were examined only for clear days. In total, 14 days—ranging from 12 April to 24 July—were examined (Table 2). This period encompasses dates near the spring equinox and the summer solstice, providing for a variety of solar angles and solar radiation values. Maximum rates of temperature change were assessed from 1100 to 1300 EDT to capture the period in the vicinity of solar noon (around 1300 EDT) when solar heating would be most intense. Graphs of car temperatures (Figs. 1 and 2) show that the rates of temperature change are reduced approaching 1300 EDT, as the hot car emitted greater amounts of longwave radiation relative to incoming solar radiation, thereby reducing net radiation.

The second portion of the study examines the energy budget of a child in a hot car using a human thermal exchange model called the man–environment heat exchange model (MENEX). It has been employed in several experimental studies of the human thermal budget (e.g., Katavoutas et al. 2009; Tuller 1997) and is capable of computing the various energy budget components, including absorbed solar radiation,

TABLE 2. Interior vehicle air temperature change by time interval and average solar radiation (1100–1300 EDT) for study days in 2007. Temperature is in degrees Celsius, and the solar radiation is in watts per square meter.

Month	Day	5 min	10 min	30 min	60 min	Solar
4	13	1.7	3.3	9.6	17.4	794
4	16	2.0	3.3	9.3	16.8	821
4	17	2.5	4.7	12.3	21.0	850
4	25	3.4	6.4	12.9	20.4	810
4	30	3.0	5.5	14.7	24.0	840
5	01	3.6	6.8	14.1	21.0	829
5	21	3.0	5.6	15.6	25.8	860
5	22	2.1	3.8	10.8	18.6	794
5	30	2.6	5.1	13.5	24.0	790
6	18	1.8	3.2	8.7	15.0	776
6	21	3.5	5.8	13.8	25.8	884
6	22	2.8	5.0	13.5	24.0	878
7	12	2.5	4.5	12.6	22.2	850
7	24	3.0	5.9	15.6	24.6	813

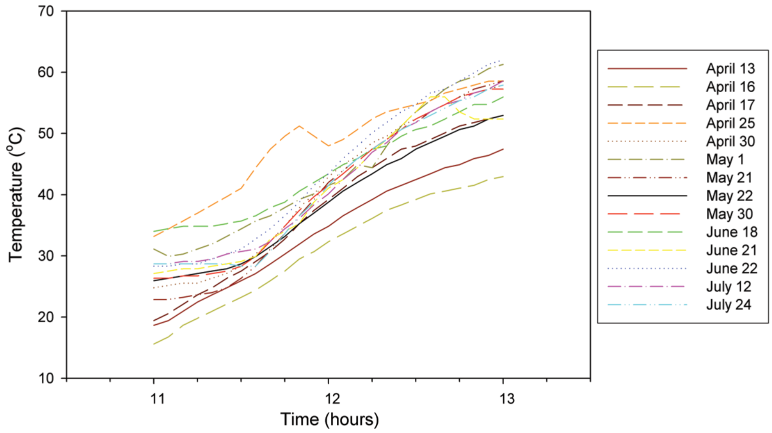

Fig. 1. Interior vehicle air temperatures between 1100 and 1300 EDT on 14 different clear days.

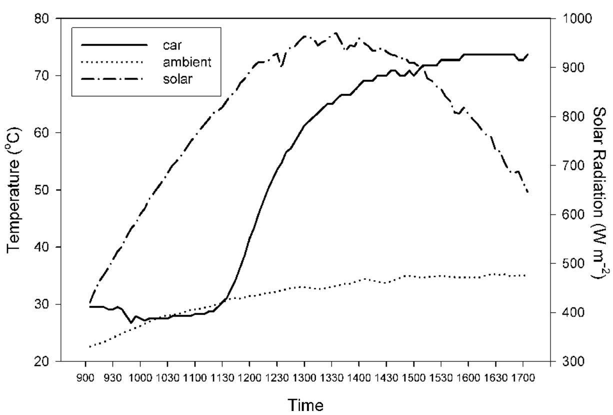

Fig. 2. Time series of interior vehicle air temperatures, ambient outdoor air temperatures, and solar radiation from 0900 to 1700 on 22 Jun 2007.

net longwave radiation, turbulent fluxes of sensible and latent heat, as well as metabolic heat production and heat loss through respiration (Błażejczyk 1994). Further, MENEX accounts for physiological factors such as skin temperature, skin wetness, and clothing albedo and insulation. The human heat balance equation is defined as

$$S = M + Q + H + \mathrm{LE} + C + \mathrm{Res}, \tag{1}$$

where S is the net heat storage or change in body heat content; M is metabolic heat production; Q is the radiation balance of the person; H and LE are convective transfers of energy via sensible and latent heat, respectively; C is conduction; and Res is the heat loss by respiration. Positive (negative) fluxes indicate a gain (loss) in net heat storage. Changes in the body heat content will be used to quantify the heat stress on the child. The degree to which changes in body heat content relate to particular health outcomes such as heat stroke or death, however, is not well established and may vary with the age and health of the child.

Model simulations were performed of a child seated inside the car as well as one outside the car to serve as a reference. The human thermal exchange model was modified slightly for the simulations of a child within the car. First, longwave radiation emitted by the interior of the vehicle was determined using the average interior surface temperature and the Stefan–Boltzmann equation with an emissivity of 0.97. Second, a conduction term was computed to account for the fact that a child would be strapped in a child safety seat as follows:

$$C = K(T_{\mathrm{car}} - T_{\mathrm{skin}})A, \tag{2}$$

where K is the heat transfer coefficient through clothing as computed by MENEX, $T_{\mathrm{car}} - T_{\mathrm{skin}}$ is the temperature gradient between the child's skin T_{skin} and safety seat T_{car}, and A is a constant that accounts for the portion of the child's body that is in contact with the seat. Here, the simulation is performed for a 2-yr-old toddler sitting in a forward-facing child safety seat. A contact value of 0.24 is used, which represents a child's torso, legs, and head in contact with the seat (Raja and Nicol 1997). The degree of contact, however, may vary somewhat with the particular child safety seat used. For instance, the degree of contact may be higher in an infant safety seat that is designed to cradle the child. Nevertheless, the results should approximately represent conditions for children 3 yr old or younger who are placed in child safety seats.

Several input values were adjusted to account for the physiology of the child and the climate conditions within the car (Table 4). The physiological characteristics of an average 2-yr-old toddler were used in modeling. The metabolic rate of the child was estimated at 61 W m^{-2}, which is consistent with the caloric needs of 700 kcal day^{-1} (Durnin 1981). Ambient air temperatures during the study period were generally high; therefore, it is assumed that the child is dressed in summer attire with clothing insulation of 0.6 clo[1] (Błażejczyk 1994). Also, the child is assumed to be

[1] ANSI/ASHRAE (1992) defines a "clo" as a unit to express the thermal insulation provided by garments and clothing ensembles, where 1 clo = 0.155 m^{2}*C/W.

unacclimatized to hot conditions with skin that is initially 33°C and dry (Fanger 1972; Hoppe 1998). Physiological changes are simulated by increasing the skin temperature and wetness. Modeled skin temperatures were not used, as Katavoutas et al. (2009) found the empirical equation used in MENEX may not be appropriate to use for unacclimatized people. Rather, skin temperatures were varied from 33°C to a maximum of 37°C in 20 min based on observations from Fiala et al. (2001), where unacclimatized subjects were exposed to high temperatures. All model simulations used the same skin temperatures, so that the influence of different environmental conditions could be isolated. Wetness is computed as a function of skin temperature, reaching complete wetness at temperatures >36.5°C (Błażejczyk 1994). Wind speed in the car without ventilation (i.e., windows rolled up) is minimal. A nominal value of 0.1 m s^{-1} is used, which is similar to values used in studies of indoor climates (Hoppe 1998).

Model simulations were performed for 22 June 2007 from 1300 to 1400 EDT using data collected from the study vehicle and the nearby CRL weather station. This was a clear day, falling near the summer solstice and providing suitable conditions for a case study of a worst-case scenario. Input solar radiation and humidity data were obtained from the CRL weather station. Initial humidity levels in the vehicle were assumed to be similar to outside values, as air was entrained in the vehicle while placing the child in the car. Over time, evaporated perspiration from the child would increase humidity within the vehicle. All perspiration was assumed to evaporate, and dewpoint temperatures were iteratively increased each time step. The windows of the vehicle attenuate some of the incoming solar radiation. Measurements of solar radiation taken inside and outside the car indicate that values within the vehicle were reduced by approximately 50%. Thus, only half of the measured solar radiation was input into the model. The interior surface temperatures of the car were obtained using an Omega OS530HR handheld infrared thermometer. Measurements were taken of the seats, floor, ceiling, and windows and averaged to provide a representative interior surface temperature. The average interior surface temperature was used in computing longwave radiation emissions from the car, and the seat temperature was used in calculating the conduction term.

RESULTS. *Maximum rates of temperature change.* The 14 days utilized in this study provide a representative sample for assessing ideal conditions for maximum heating (Table 2). The sample data are distributed over the entire study period, with days in each month from April through July. Overall, there were 36 days with clear skies and 30 of those days with solar radiation data. The average solar radiation during peak heating periods (e.g., 1100–1300 EDT) for those 30 days was 824 W m^{-2}, with a range from 758 to 884 W m^{-2}. The data used for this study had average solar radiation that was slightly greater at 828 W m^{-2} and a range from 776 to 884 W m^{-2}. The sample dataset includes the two days with the greatest average solar radiation and three other days among the top 10 in solar radiation.

There were different initial ambient air temperatures and rates of temperature change for the 14 peak heating periods studied (Fig. 1). Initial ambient air temperatures at 1100 EDT ranged from 15° to 34°C, with temperatures reaching 43°–62°C by 1300 EDT. Temperature changes were computed for 5-, 10-, 30-, and 60-min periods (Table 2). The average (maximum) temperature change over each time interval is 2.7°C (3.6°C) for 5 min, 4.9°C (6.8°C) for 10 min, 12.6°C (15.6°C) for 30 min, and 21.5°C (25.8°C) for 60 min. The comparatively lower rates of temperature change for cloudy days is indicated by looking at values on two days (4 May and 2 July) with complete cloud cover. Average temperature changes are 1.7°C for 5 min, 3.0°C for 10 min, 7.6°C for 30 min, and 8.9°C for 60 min.

At longer time intervals, these results are consistent with other studies that observed hourly temperature increases ranging from 22° to 27°C (McLaren et al. 2005; Gibbs et al. 1995; King et al. 1981). There are some differences with other studies at shorter intervals that are likely related to the positioning of the sensors. Large rates of temperature change may have been related to the exposure of the sensor to direct sunlight (King et al. 1981) or the location of the sensor on the car seat (Gibbs et al. 1995), which would be influenced by the seat temperature and not be representative of vehicle air temperatures. In all cases, the maximum temperature changes occurred around noon. This timing is tied to the radiation balance of the vehicle and can be illustrated using measurements of incoming solar radiation and vehicle air temperatures for 22 June 2007 (Fig. 2). The cabin and ambient air temperatures are relatively similar early in the day but diverge rapidly between 1130 and 1300 EDT. Between 1100 and 1300 EDT, the solar angles are high (61°–79°C, respectively), leading to intense solar heating of the car seats, which in turn warms the overlying air. Any increase in temperature of the car, however, will lead to increases in longwave emissions to the fourth power, as indicated by the Stefan–Boltzmann law. Thus, the enormous rise in car temperature during this time increases longwave emissions relative to incoming solar radiation and slows the subsequent rate of heating.

A table of maximum vehicle temperature changes. A table of maximum passenger compartment temperature changes was developed to aid in advising the public about the dangers of leaving children unattended in cars (Table 3). The table considers initial ambient air temperature when the car is parked, and the temperature changes for 5-, 10-, 30-, and 60-min intervals. The table is designed to show the maximum possible changes in temperature over each interval by using the greatest observed temperature changes from Table 2. Of course, factors such as whether the car is in direct sunlight, the time of day (i.e., different solar angles and solar radiation), the amount of cloudiness, and ventilation (i.e., windows rolled down) will influence the actual amount of temperature change.

Table 3 shows that the thermal hazard is a function of both the initial ambient air temperature and the time interval over which the heating occurs. One way to characterize the meaning of these temperatures in terms of a health hazard is to place them in the context of heat health warnings provided by the National Weather Service (NWS 1994). For example, a heat advisory is issued by the NWS when the heat index is 41°–46°C for less than 3 h. An excessive heat warning is issued when the heat index is ≥41°C for more than 3 h or exceeds 46°C for any period of time. Thus, one could say that if the outside air temperature is 34°C, then the vehicle could reach the level of a heat advisory within 10 min and an excessive heat warning within 30 min. Of course, the temperatures listed in the table only provide an indicator of the level of danger. One must consider the age and health of the child when assessing danger as well as the fact that children in general are particularly susceptible to heat-related illnesses (Hoffman 2001). Children's small size gives them a high surface-area-to-mass ratio that allows them to absorb more energy from the environment than an adult, and their ability to cool through perspiration is less efficient (Hoffman 2001). In addition, young children are not able to adjust their behavior in response to the heat, such as removing clothing or exiting the car (McLaren et al. 2005; Hoffman 2001)

Modeling the energy budget of a child in a hot car. A human heat balance model was used to examine the influence of humidity and full sun exposure on the heat stress of a child in a hot vehicle. The modeling study was performed using data collected from a 2005 Honda Civic that was parked for approximately 4 h. During the study period from 1300 to 1400 EDT, the sky was clear; outdoor air and dewpoint temperatures averaged 33° and 11°C, respectively; and solar radiation was 954 W m^{-2}. Outside wind speeds, adjusted from the roof to 1.5 m using a logarithmic wind profile, were low at approximately 1 m s^{-1}. The air temperature within the vehicle averaged 65°C, and the average temperature of interior surfaces including the ceiling, floor, seats, and windows was 69°C. Model simulations were conducted in 5-min time steps during the course of the hour.

Four simulations were performed for a child within the car, including a default simulation and simulations representing conditions with high humidity, low

Table 3. Maximum interior vehicle air temperature reached for different time intervals. The values are rounded to the nearest degree, so that the car heats by 4°C in 5 min, 7°C in 10 min, 16°C in 15 min, and 26°C in 60 min.

Initial ambient air temperature (°C)	5 min	10 min	30 min	60 min
50	54	57	66	76
48	52	55	64	74
46	50	53	62	72
44	48	51	60	70
42	46	49	58	68
40	44	47	56	66
38	42	45	54	64
36	40	43	52	62
34	38	41	50	60
32	36	39	48	58
30	34	37	46	56
28	32	35	44	54
26	30	33	42	52
24	28	31	40	50
22	26	29	38	48
20	24	27	36	46

Time interval

humidity, and shade. Dewpoint temperatures where varied by ±10°C about the mean observed dewpoint temperature of 11°C to simulate high (21°C) and low (1°C) humidity conditions. In the shade scenario, the child is not exposed to direct beam radiation but does receive some diffuse solar radiation, assumed to be 30% of global solar radiation (Rosenberg et al. 1983). For comparison, a model simulation was also performed for the same day and times of a child standing outside the car. Output from the model included absorbed solar, net longwave, latent heat, sensible heat, conduction, metabolic heat production, respiratory heat losses, and net heat storage.

The average change in body heat content of the child in the hot vehicle during the 1-h period was 250 W m^{-2} (Table 4). This is more than 3 times the net storage gain for a child standing outside of the car. The energy transfer mechanisms directed toward the child were very different inside and outside the vehicle. Within the vehicle, net longwave accounted for 44%, conduction for 28%, sensible heat for 16%, and solar for 12% of the exogenous energy transfers to the child. Thus, the dominant energy transfers were via conduction and longwave radiation. Outside of the car, most of the energy transfers to the child were from solar radiation, with approximately 89% from solar radiation, 10% from net longwave radiation, and 1% from sensible heat.

The great difference in both the magnitude and distribution of energy fluxes may be explained by the unique environment of the interior of the hot vehicle. The extremely high surface temperatures in the vehicle direct the vast majority of radiant energy in the form of longwave radiation toward the child as well as transferring large amounts of energy via conduction through the child safety seat. The relatively small contribution from absorbed solar radiation occurs because the windows attenuate some of the insolation, and the projected area that strikes the body is small during periods with high solar angles. The strong temperature gradient between the air and child's skin results in transfers of sensible heat toward the child; however, the flux is only 43 W m^{-2} because of the lack of turbulence. Evaporative cooling from latent heat transfers away from the child averages −80 W m^{-2}. The small value is related to the low turbulence and the negative feedback of increased humidity levels in the vehicle from evaporated perspiration. Indeed, moisture from the child increased the relative humidity (RH) from 6% to 19% during the hour. The results support the observations of Zumwalt and Petty (1976) that mechanisms that are generally available for cooling are either reduced (evaporation of perspiration) or actually lead to heat gains for the child (longwave radiation and sensible heat).

Table 4. Average input and output values for human heat balance model simulations of a child in a hot car for 22 Jun 2007 from 1300 to 1400 EDT. All values except for clothing insulation and wind speed are rounded to the nearest whole number.

	Variable	Outside	Initial car	High-humidity car	Low-humidity car	Shaded car
Biophysical inputs	Skin temperature (°C)	33	36	36	36	36
	Clothing insulation (clo)	0.6	0.6	0.6	0.6	0.6
Meteorological conditions	Air temperature (°C)	33	65	65	65	65
	Average cabin surface temperature (°C)		69	69	69	69
	Initial dewpoint (°C)	11	11	21	−1	11
	Initial/final RH (%)	26/24	6/19	11/20	3/19	6/19
	Wind speed (m s^{-1})	1.0	0.1	0.1	0.1	0.1
Energy fluxes	Absorbed solar (W m^{-2})	62	32	32	32	10
	Net longwave (W m^{-2})	7	119	119	119	119
	Sensible heat (W m^{-2})	1	43	43	43	43
	Latent heat (W m^{-2})	−53	−80	−60	−90	−80
	Conduction (W m^{-2})	0	77	77	77	77
	Metabolism (W m^{-2})	61	61	61	61	61
	Respiration (W m^{-2})	−5	−2	−2	−3	−2
	Net heat storage (W m^{-2})	78	250	270	239	228

Simulations were performed to examine how shading and variations in humidity would affect the change in the body heat content of the child. The first set of simulations varied the initial dewpoint from –1° to 21°C. As one would expect, the drier (more humid) conditions are associated with greater (less) evaporation. The high-humidity scenario resulted in 8% greater net heat storage as a result of reduced evaporative cooling. In contrast, the greater latent heat fluxes away from the child in the low-humidity simulation reduced net heat storage by about 4% compared with the default simulation. The relative differences among the different scenarios were small because of a negative feedback of evaporated perspiration; that is, increased perspiration will lead to greater humidity within the car, which will reduce humidity gradients and subsequent evaporation rates. This feedback explains how relative humidity for both the high- and low-humidity scenarios began at different values but converged near 20%. The second set of simulations involved the child being shaded from direct sunlight. This reduces absorbed energy by 22 W m^{-2} and the total heat storage by approximately 9%.

That case study represents a particularly harsh scenario. Some children are "forgotten" and left in the vehicle all day, while others are placed in hot cars in the middle of the day, in some cases with a broken air conditioner blowing hot air, and have died within 15 min (*Associated Press,* 24 August 2005 and 9 August 2006). Thus, the energy balance of the child and the rate at which the child would suffer a heat-related illness will vary depending on the particular conditions. Air and surface temperatures of the car, for example, will differ depending on how long the car has been parked, whether it is in direct sunlight, and the degree of ventilation. Also, absorbed solar radiation may actually increase earlier or later in the day as lower sun angles lead to larger surface areas on the body that are exposed to sunlight.

CONCLUSIONS. More than 2,500 children die each year from unintentional injuries in the United States (Borse et al. 2008). While the number of children who die from vehicle-related hyperthermia is only a small percentage of this total, it is a hazard that is so easily preventable. Children should never be left unattended in vehicles, regardless of ambient air temperatures, because of risks such as abduction or injury to the child from incidents such as being asphyxiated from entrapment by vehicle windows (NHTSA 2009). However, there is a clear pattern—both seasonally and by temperature threshold—to vehicle-related hyperthermia deaths that suggests targeted "reminders" may be helpful as a warning strategy. Approximately 75% of deaths occur during the summer months (Guard and Gallagher 2005) and data from 231 vehicle-related hyperthermia deaths during the 2003–08 period show that more than 70% occurred on days with maximum outdoor temperatures ≥31°C (Null 2009). In direct sunlight and during the course of an hour, temperatures within a car could exceed 57°C on such days. Modeling results show that the dominant transfers of energy toward the child (longwave radiation and conduction) are driven by temperature; therefore, passenger compartment air temperatures serve as a good indicator of the heat-related hazard. High humidity and exposure to direct solar radiation will also increase the net heat storage of a child; however, the influence of humidity variations is limited because of a negative feedback.

Unfortunately, many people are unaware of the dangers of leaving a child unattended in a car. Thus, education may be an important component in reducing vehicle-related hyperthermia deaths. Sheridan (2007) documented that heat health warnings are helpful in raising awareness of the dangers of heat-related illness. An easy-to-use table of vehicle temperatures changes, as presented here, may help public officials and the media communicate with the public about the hazard of vehicle-related hyperthermia in children. Temperature thresholds used by the National Weather Service for their heat health warnings may be used to place the temperatures in the context of health hazards. Importantly, these thresholds should only be used to emphasize how quickly temperatures in a car can reach hazardous levels and therefore as a warning to never leave a child unattended in a vehicle. We hope this characterization linking temperatures with an explicit warning about health dangers to children will modify the behavior of caregivers and result in fewer tragedies. Preventing injuries to children from vehicle-related hyperthermia will ultimately require a multifaceted approach including education, regulation, engineering, and legislation (Guard and Gallagher 2005).

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