ABSTRACT

Pediatric Heat Stress Injuries and Death in Vehicle Trunk Entrapments: Internal Trunk Temperatures Can Rapidly Reach Lethal Levels

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Over the last 15 years, more than 500 children have died in the United States after being trapped in the hazardous conditions within motor vehicles. Most of these deaths involved children left unattended in the cabin of enclosed vehicles on warm-to-hot days. Previous studies indicate that internal cabin temperatures can quickly rise well above 100°F (37.8°C), even if the outside environment is relatively mild. In a 100°F (37.8°C) setting with moderate relative humidity (>50%), children can rapidly overheat and develop heat stroke. Dangers associated with the deaths of children in motor vehicle entrapment have been well-studied and well-reported, increasing both the involvement of policy-makers and public awareness. While less publicized and certainly less studied, unintentional trunk entrapments account for nearly 10% of these reported deaths. Some of these deaths resulted from hyperthermia while others were classified as a combination of hyperthermia and asphyxiation. To date, no study has analyzed conditions within a trunk. The objective of this study is to investigate the magnitude and rate of temperature rise within a discontinuous trunk over a range of mild and hot environmental temperatures. For comparison, we simultaneously measured cabin temperatures. We also

applied thermal tolerance information to the data in order to estimate the minimum time required for the trunk and cabin to reach dangerous temperatures.

Trunk temperatures increased 15.5-22.2°F (8.6-12.3°C), meaning that the trunk quickly heated to lethal levels on warm-to-hot days. However, the trunk failed to reach lethal temperatures on cooler days. Applying this new information concerning trunk temperatures helps explain why asphyxiation is occasionally a factor in trunk entrapment fatalities. Because trunk temperatures were at least 15.2°F cooler than the cabin, the effects of hyperthermia are delayed enough in some cases to allow a trapped child to consume the oxygen within the trunk. Despite the preventative efforts of law-makers and vehicle manufacturers, incidents of entrapped children continue to occur. Increasing public and guardian awareness of the dangers of leaving a child unattended in or around motor vehicles may help reduce deaths due to cabin or trunk entrapment. Establishing an official record system of deaths resulting from trunk or cabin entrapment would help identify common underlying causes and would better equip law-makers, educators, and manufacturers in preventing vehicle entrapment.

PEDIATRIC HEAT STRESS INJURIES AND DEATH IN VEHICLE TRUNK ENTRAPMENTS: INTERNAL TRUNK TEMPERATURES CAN RAPIDLY REACH LETHAL LEVELS

A Thesis Submitted to the Faculty of

Baylor University

In Partial Fulfillment of the Requirements for the

Honors Program

By

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Waco, Texas

May 2012

TABLE OF CONTENTS

CHAPTER ONE

Introduction

Over the past 15 years, more than 500 children have died from hyperthermia due to motor vehicle entrapment (Null 2011; Guard and Gallagher 2005; Booth et al. 2010). Because the majority of these deaths occurred within the passenger area, previous studies examining the conditions within parked motor vehicles have almost exclusively focused on the cabin compartment. They found that cabin temperatures can quickly rise above 130°F in warm sunny conditions (McLaren et al. 2005; Grundstein et al. 2009). The potential effects of other variables such as vehicle color and window ventilation have also been analyzed (Roberts and Roberts 1976; King et al. 1981; McLaren et al. 2005).

Nearly 10% of the reported entrapment fatalities were children ages 2-6 unintentionally trapped within the trunk, typically a result of hiding while playing (Null 2011; NHTSA 2004) (Figure 1). Unlike heat-related deaths occurring within the passenger area, some of these deaths were classified as a combination of hyperthermia and asphyxiation (CDC 1998; Inman et al. 2003). One possible explanation is that cooler temperatures within the trunk may allow time to use up the supply of oxygen. However, little is known concerning trunk temperatures since previous studies have focused only on conditions within the cabin.

In this study, we document temperature increase in a discontinuous trunk over a range of starting temperatures. We assess the final temperature and the rate of temperature increase within the trunk. We also estimate the time required for the trunk to reach “dangerous” temperatures. For comparison of these variables, we measure temperatures within the cabin. In all cases we show temperatures within the trunk to be cooler than the passenger area. However, we demonstrate that both areas can quickly reach temperature levels capable of inducing hyperthermia. Further investigation, though, is needed into the role of humidity in vehicle entrapments as well as into understanding young child heat tolerance in passive heating settings. The information this study provides can help vehicle designers in developing solutions that reduce the threat of motor vehicle entrapment. In addition to the preventative efforts of manufacturers, health educators and the media should continue to raise public awareness so that these tragic deaths may finally be stopped.

Figure 1: Unintentional Trunk Entrapment Incidents and Deaths of Children Since 1987

Incidents	Deaths	Years	Source
9	19	1987-1998	CDC (1998)
11	22	1987-1998	NHTSA (2000)
‡	22	1995-2002	Guard and Gallagher (2005)
13*	21	1998-2003	NHTSA (2004)
14	21	2003-2011	Null (2011)

‡Number of incidents was not discussed
*One incident involved the death of a 25 year old.

CHAPTER TWO

Materials and Methods

Methodology

We simultaneously measured the temperature within both the cabin and trunk of a blue 1997 Honda Civic. The vehicle had gray interior, non-tinted windows, and a discontinuous trunk. Temperatures were taken in the early afternoon of sunny days between May 5 and October 14, 2011, in Waco, Texas. Outside temperatures ranged from 81°F to 110°F. For all experiments, the vehicle was parked in the same position in a large parking lot and received full sun. Prior to each run, internal vehicle temperatures were equilibrated with the outside environment. At equilibrium, the doors were closed and temperature measurements were taken every minute for one hour.

Data Collection

Outside temperature data were collected with an Oregon Scientific RMR803A Helios Solar Climate Monitor. Two Oregon Scientific Wireless THN132N Sensors were used to measure interior vehicle temperatures. One sensor was placed in the rear passenger area within the test vehicle approximately 6 inches above the seat. The other sensor was placed within the trunk of the car approximately 6 inches from the trunk floor. Neither sensor had direct contact with any part of the vehicle or was exposed to direct sunlight. The monitor and sensors had a resolution of 0.2°F (0.1°C) and accuracy of ± 1°F (0.6°C).

Scenarios

In addition to temperature, thermoregulation is also greatly influenced by humidity (Epstein and Moran 2006; Council on Sports Medicine 2011). To integrate humidity with our temperature measurements, we created three scenarios with discrete relative humidities. In scenario 1, the relative humidity was 50%, a value consistent with a moderately humid climate. In scenario 2, the relative humidity was 70%, a value consistent with a very humid climate. In scenario 3, the relative humidity was 90%. This last scenario may accurately describe the conditions within the poorly ventilated vehicle when a sweating response has been triggered in trapped individuals (CDC 1998).

Danger Zones

Apparent temperature is an estimate of how the body perceives the air temperature while taking into account humidity (NWS Office of Climate W and WS 2012). Prolonged exposure to apparent temperatures above 130°F can cause heat-related illness and puts individuals at high risk for heat stroke. For this reason, the National Weather Service's Heat Index considers apparent temperatures above 130°F "dangerous." In each of the presented scenarios, we use the Heat Index to estimate heat tolerance. Apparent temperatures of 130°F or greater within the scenarios are considered "dangerous." The Heat Index model, however, assumes ventilation and shade, and, as a result, will likely underestimate apparent temperature within motor vehicles. Consequentially, temperatures within a motor vehicle may feel even hotter than the Heat Index suggests.

CHAPTER THREE

Results

The trunk quickly reached hot temperatures, heating by a magnitude of 15.5-22.2°F (8.6-12.3°C) after one hour. The majority of the increase in temperature occurred within the beginning of the hour, with 48.6-59.1% of the temperature change occurring before 20 minutes. However the trunk had a slower rate of temperature increase than the cabin. Being consistent with previous studies, cabin temperatures increased by 31.4-42.8°F (17.4-23.8°C) within an hour. As seen within the trunk, over 50% of the temperature increase in the cabin occurred before 20 minutes. The difference in final temperatures between the two areas ranged from 15.2°F (8.4°C) to 22.2°F (12.3°C). Despite this difference, the final temperature within both the trunk and the cabin was largely determined by outdoor temperature. Outside temperature explained over 95% of the variance in internal temperature in both the cabin (r^2 = 0.9503) and trunk (r^2 = 0.9569). A strong correlation was also seen between the final temperatures of the passenger area and trunk (r^2 = 0.9786), suggesting that shared variables like external temperature contribute in a similar manner to the increasing temperatures of both compartments (see APPENDIX).

50% Humidity

On hot days with a temperature at or above 100ºF (37.8°C), the trunk required almost 10 minutes to reach the "dangerous" threshold (Figure 2). On cooler days with a temperature near 90ºF (32.2°C), the trunk required 30 minutes. Strikingly, trunk temperatures failed to reach the threshold after 60 minutes on mild days with a temperature around 80ºF (26.7°C).

Unlike the trunk, cabin temperatures reached “dangerous” levels on all days. Because of its faster heating rate, the cabin required less time than the trunk to reach the danger threshold. On hot days (100 ºF), cabin temperatures quickly rose to “dangerous” levels within 5 minutes. On mild days (80 ºF) when the trunk failed to heat to “dangerous” levels, cabin temperatures reached the threshold within 20 minutes.

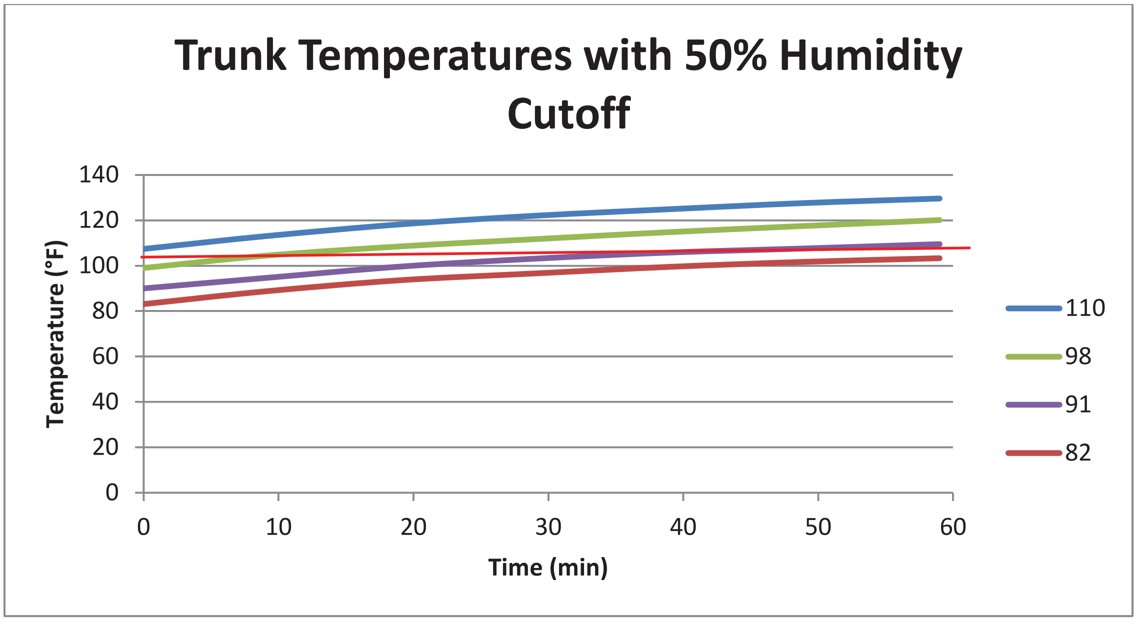
70% Humidity

At 70% humidity, days with temperatures at or above 97ºF began within the “danger” zone (Figure 3). Unlike scenario 1, all trunk measurements reached “dangerous” temperatures by the end of one hour. On days with a temperature near 90ºF, the trunk required over 15 minutes to reach the threshold. On mild days (80ºF), trunk temperatures reached “dangerous” levels after 40 minutes.

Like scenario 1, cabin temperatures required less than half the time needed for the trunk to reach the “danger” zone. On warm days (90°F), the cabin reached “dangerous” temperatures after 5 minutes. On mild days (80°F), cabin temperatures reached “dangerous” levels after 15 minutes.

90% Humidity

All days with temperatures >92ºF began within the “dangerous” zone (Figure 4). On mild days (80ºF), a “dangerous” Heat Index was attained within 10 minutes inside the cabin and within 15 minutes inside the trunk. Both areas quickly heated up to levels where heat stroke is possible.



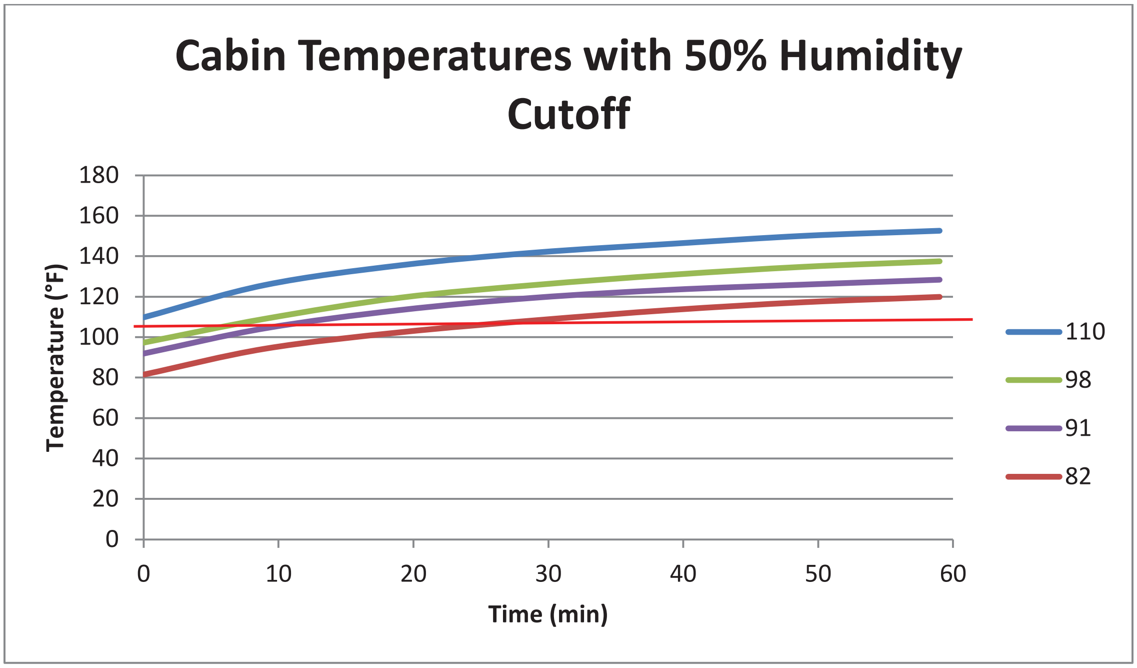


Figure 2: Cabin and Trunk Temperatures with 50% Humidity Cutoff
The temperatures measured of the trunk and cabin are shown with the Heat Index danger threshold at 50% relative humidity. At this humidity level, temperatures of 104ºF (40°C) or higher put individuals at high risk for heat stroke.

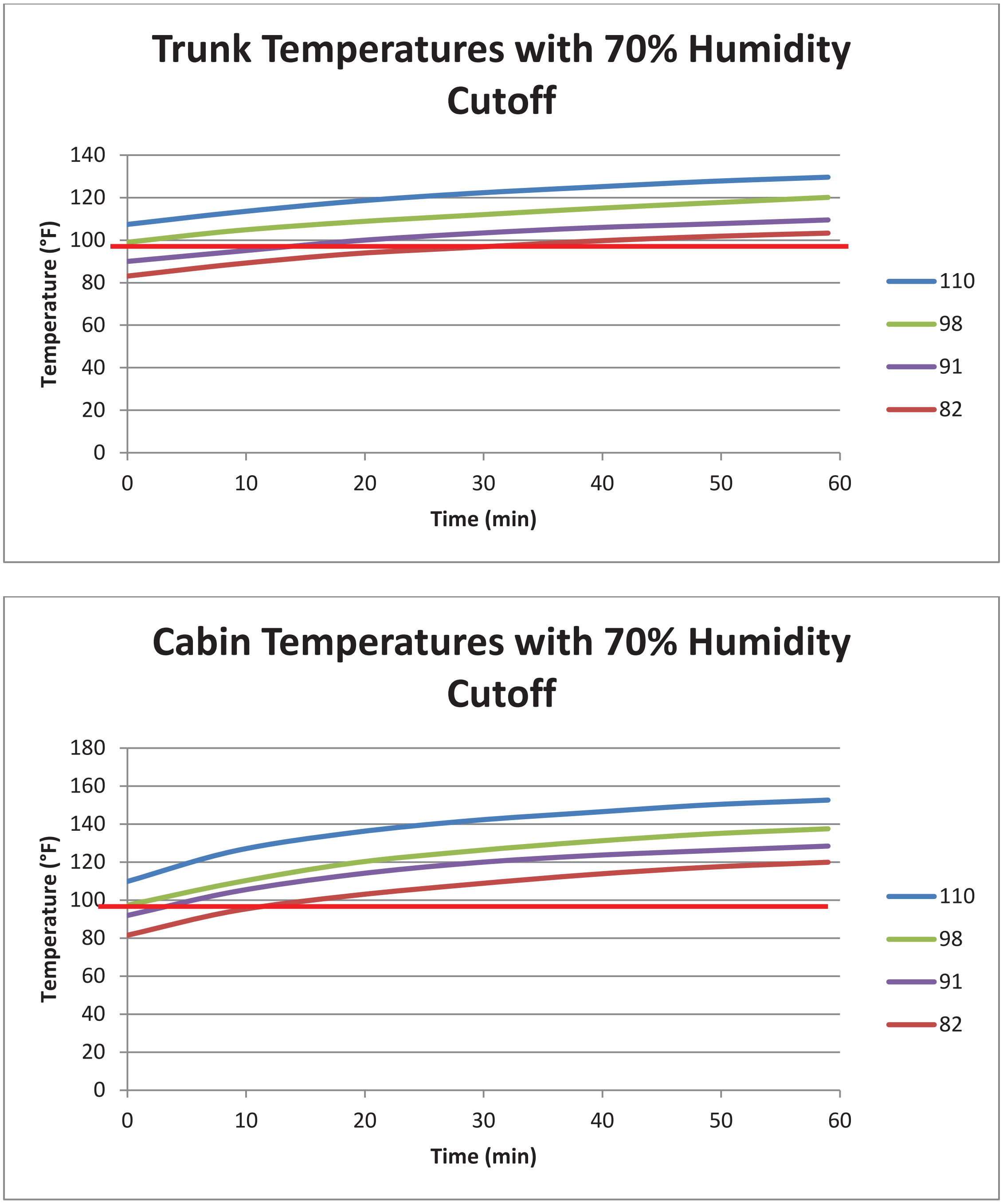
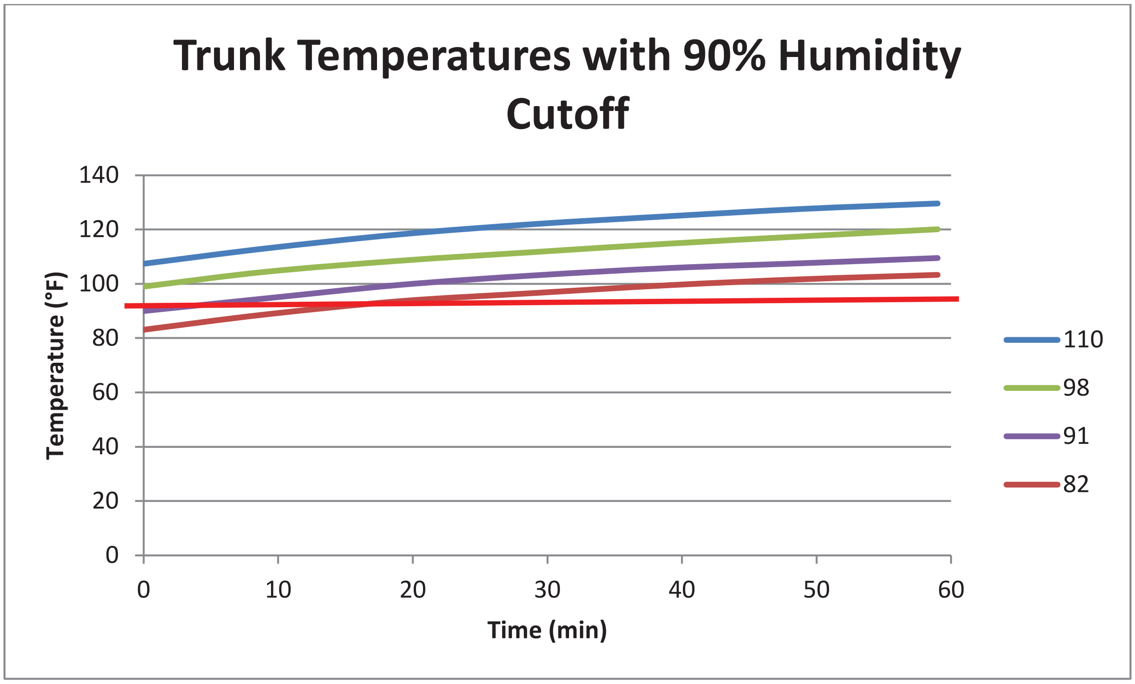


Figure 3: Cabin and Trunk Temperatures with 70% Humidity Cutoff

Trunk and cabin temperatures are shown overlaid with the Heat Index danger threshold for 70% relative humidity. In environments with this level of humidity, temperatures above 97ºF (36.1°C) put individuals at high risk for heat stroke.



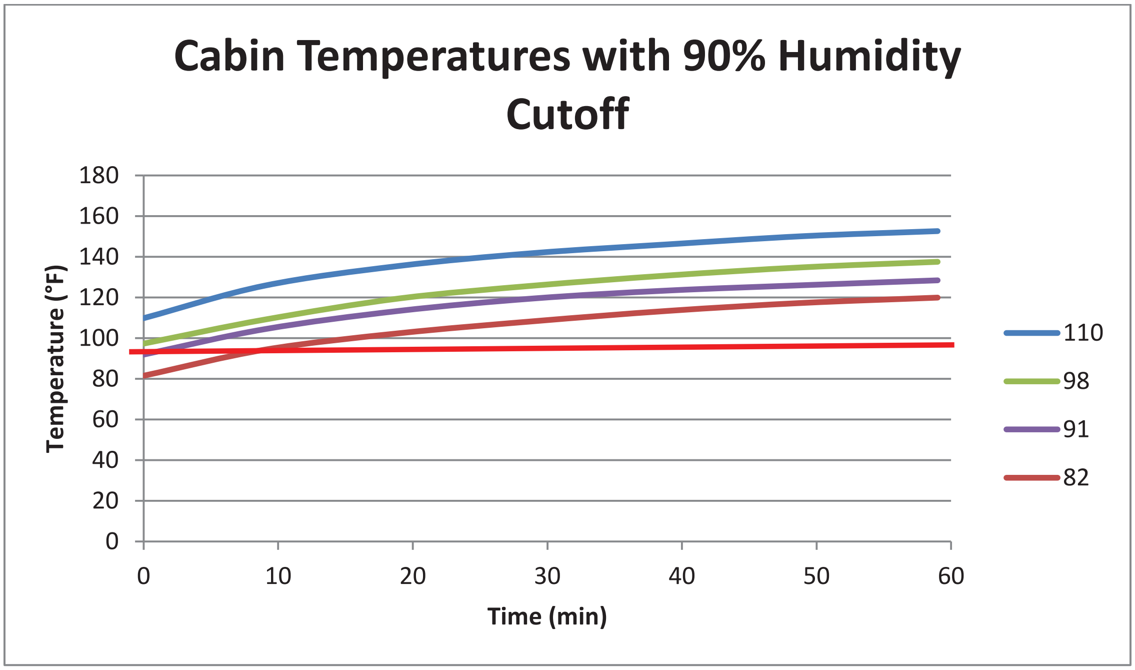


Figure 4: Cabin and Trunk Temperatures with 90% Humidity Cutoff

Measured trunk and cabin temperatures are shown with the Heat Index danger threshold for 90% humidity. At this humidity level, temperatures at or above 92ºF (33.3°C) put exposed individuals at high risk for heat stroke.

CHAPTER FOUR

Discussion and Conclusion

Discussion

Unlike previous studies analyzing only cabin temperatures, this study investigated temperature patterns within an enclosed trunk. Trunk temperatures quickly heated above 100°F (37.8°C) on all days of measurement. However, we found temperatures within the trunk to rise slower than temperatures within the passenger area of the vehicle. Because of this slower rate of heating, trunk temperatures were cooler than cabin temperatures during all measurements. After one hour, the trunk was at least 15.2°F (8.4°C) cooler than the cabin.

Because of its cooler temperatures, the trunk required more time than the cabin to reach "dangerous" temperatures in all three presented scenarios. When beginning below the "dangerous" threshold, the trunk needed at least twice as much time as the passenger area to reach the danger zone. This fact helps elucidate why asphyxiation is occasionally a factor in trunk entrapment fatalities (CDC 1998; Inman et al. 2003). Because of the trunk's cooler temperatures, the effects of hyperthermia may be delayed enough in some cases to permit a trapped child to consume the oxygen within the trunk compartment. However, the threat of heat stroke within both the trunk and cabin may be underestimated by the Heat Index because it assumes shade and ventilation (NWS Office of Climate W and WS 2012). Direct exposure to solar radiation and lack of ventilation can increase apparent temperatures by up to 15°F, thereby reducing the time required for both the cabin and trunk to reach lethal temperatures.

Although there is no clearly defined limit for human tolerance of heat, heat illness has been clinically divided into three stages: heat stress, heat exhaustion, and heat stroke (Bouchama 2002; Simon 1993; Council On Sports Medicine 2011). Heat stress is characterized by physical discomfort resulting from exertional and passive heat build-up (Simon 1993). During this phase, sympathetic cutaneous vasodilation resulting in enhanced blood flow to the skin increases the dry exchange of heat with the surrounding environment through convection (Gonzales 2012; Bouchama 2002; Rowland 2008). The other major thermoregulatory mechanism is evaporative cooling through sweating, which is crucial in environments hotter than body temperature (Bouchama 2002). Because the internal environment of motor vehicles rapidly heats to temperatures greater than 37°C and lacks adequate ventilation, both thermoregulatory responses in entrapped individuals are quickly defeated (CDC 1998). The cooling responses cannot continue indefinitely and will lead to heat exhaustion if a cooler environment is not found. Heat exhaustion is seen in people with a core body temperature below 40ºC and with symptoms related to dehydration, including thirst, headache, dizziness, and fainting (Bouchama 2002; Epstein 2011). The final stage in heat imbalance, heat stroke, is the cause of death in the majority of motor vehicle entrapment fatalities. Heat stroke occurs when the core body temperature exceeds 40ºC and is usually accompanied with central nervous system dysfunction and hot, dry skin (Bouchama 2002; Fajardo 1984; Council 2011). Thermoregulatory failure to this extent causes a systemic acute inflammatory response characterized by multiorgan dysfunction and encephalopathy (Bouchama 2002; Fajardo

1984; Council 2011; Epstein 2011). When it is not fatal, heat stroke often leaves permanent damage with symptoms like delirium and coma.

Previous research showed that young children were at greater risk for heat-related illness (Bouchama 2002; Falk 1998; AAP 2000). However recent studies suggest that children might not be as vulnerable to heat as once thought (Falk and Dotan 2008; Rowland 2008; Council On Sports Medicine 2011). Initial studies on child thermoregulation found that children heat up faster than adults in extreme heat environments (Tsuzuki et al. 1995; Falk and Dotan 1998; Falk 2008). Because children can have at least 20%-64% more surface area to body mass, children were thought to be capable of dissipating heat faster in neutral temperatures and absorbing heat faster in environments hotter than skin temperature (Falk 1998; Tsuzuki et al. 1995; Rowland 2008; AAP 2000). Other factors thought to contribute to this apparent difference in thermoregulation between adults and children include reduced cardiovascular response, decreased sweat rate, and maturation differences (Tsuzuki et al. 1995). However recent studies have shown heat tolerance to be roughly equivalent in children and adults, raising doubts about previously accepted ideas of child thermoregulation (Falk 2008; Rowland 2008; Council On Sports Medicine 2011; Inbar et al. 2004). To better understand the risk of hyperthermia in children during vehicle entrapment, heat tolerance comparisons in passive heating settings are needed because the recent studies analyzed thermoregulation only during exercise. Since most of the recent studies did not include children < 8 years of age, additional research is also needed for this younger group most at risk for motor vehicle entrapment.

Because of the temperature differences between the cabin and trunk, the dangers attributed to each are somewhat unique. Consistently, passenger compartment temperatures have been measured to quickly reach lethal levels in various ambient conditions (McLaren et al. 2005; Grundstein et al. 2009). Although cooler than the cabin, the trunk has distinctive threats to child safety. Because evaporation is the major mechanism for heat loss in environments hotter than body temperature, trapped individuals cause the humidity to increase within the unventilated trunk (CDC 1998). In turn, the rising humidity minimizes the evaporative cooling from sweating, making hyperthermia more likely. In addition to hot temperatures and rising humidity, asphyxiation endangers individuals trapped within the unventilated trunk, something not seen in cabin entrapments (CDC 1998; Inman et al. 2003; NHTSA 2004). Another common factor seen in several trunk entrapment incidents is the concurrent entrapment of multiple children (Figure 1). In entrapment cases involving more than one child, conditions within the trunk become even more hazardous due to quicker oxygen consumption and a magnified rate of increasing humidity.

The trunk and cabin may also differ in length of entrapment times. Because there is no visibility within the trunk and few parents think to check the trunk for their missing child, the trunk may have longer entrapment times than the cabin. A longer entrapment would allow more time for the cooler trunk to heat up to dangerous levels. However, not all entrapment times are known (Grundstein et al. 2011; CDC 1998). From reported deaths, cabin entrapment times have varied between 15 minutes to several days, with nearly half the cases reporting less than 3 hours (Grundstein et al. 2011). Also greatly varying, reported trunk entrapment times ranged between 2 and over 8 hours (CDC 1998;

Inman et al. 2003). The average entrapment time of all vehicle-related child hyperthermia deaths in 1998-2008 was approximately 4 hours, suggesting temperatures within both the cabin and trunk can easily kill entrapped children (Grundstein 2011).

Several government-based studies have investigated the prevalence of motor vehicle entrapment fatalities. However, unintentional trunk entrapment may be more prevalent than reported. Since media reports are the primary source of data, many incidents might have gone unnoticed or were not considered due to selection bias (Booth et al. 2010; Null 2011; Grundstein et al. 2011). The LEXIS-NEXIS database used to find news reports does not included all newspapers within its database, suggesting that some incidents may have been undiscovered by researchers (CDC 1998; Booth et al. 2010). Additionally, non-fatal incidents are missing in the statistics because they are rarely reported. These factors suggest that the documented numbers underestimate the magnitude of the issue. Establishing an official record system of deaths resulting from motor vehicle entrapment would demarcate the true extent of the problem and would better equip the public and parents in preventing the common underlying causes for these deaths.

Much effort has already been put into stopping unintentional motor vehicle entrapment, but the role of educators within prevention efforts continues to be crucial. About 30% of child deaths from vehicle entrapment between1998-2008 were caused by children gaining access to the vehicle, including those who perished within the trunk (Grundstein et al. 2011). This suggests the need to increase the education and awareness of guardians about the dangers motor vehicles pose to exploring children. General mass media can increase awareness within the general public during days with dangerous temperatures. Health-care providers and workers at day-cares and pre-schools can direct education efforts towards caretakers of young children which are most at risk for motor vehicle entrapment. Educators should stress the importance of supervision, locking the car when not in use, and keeping car keys out of reach of young children.

To help prevent trunk entrapment, the FMVSS No: 401 law was passed which requires all passenger vehicles made after September 2001 to have an internal trunk release hatch (Inman et al. 2003; NHTSA 2000; NHTSA 2004). In response, manufacturers included latches with florescent handles differing in shape (Inman et al. 2003; NHTSA 2004). However, a study analyzing the effectiveness of trunk latches suggests young children may be unable to operate internal latches (Inman et al. 2003). The 50% failure rate found among children ages 3-4 for all handle models was attributed to distress and to the tendency of the children to become passive when entrapped. To counter the passive response seen in entrapped children, manufactures are currently developing a sensor system that can open the trunk when a human is detected, such as General Motors' "TrapAlert." Further investigation into potential solutions is needed because manual trunk releases alone may not be effective for young children. Additionally, circulation of potential solutions like trunk latches should be improved so that their effectiveness can be maximized.

Conclusion

This is the first study to analyze temperatures within the trunk. Even though we show the trunk is cooler than the passenger area, both compartments are capable of heating to dangerous temperatures. The Heat Index provides an informative estimate of how quickly the trunk and cabin can attain hazardous temperatures. Unlike cabin entrapments, asphyxiation is often seen as a contributing factor in trunk entrapment deaths. On cooler days, increasing temperatures within the trunk can be delayed enough to allow entrapped individuals to asphyxiate. In order to better understand the dangers of trunk entrapment, further research is needed in understanding young child heat tolerance and the role of humidity in entrapment. A database including incidents of and deaths due to motor vehicle entrapment is needed for educators, researchers, and lawmakers to know the true magnitude of the issue. Manufacturers should build upon ideas like the trunk release hatch in order to minimize the threat of motor vehicle entrapments. For now, raising public awareness and targeting education efforts at caregivers of young children can help prevent these tragic deaths.

APPENDIX

APPENDIX

Supplementary Data

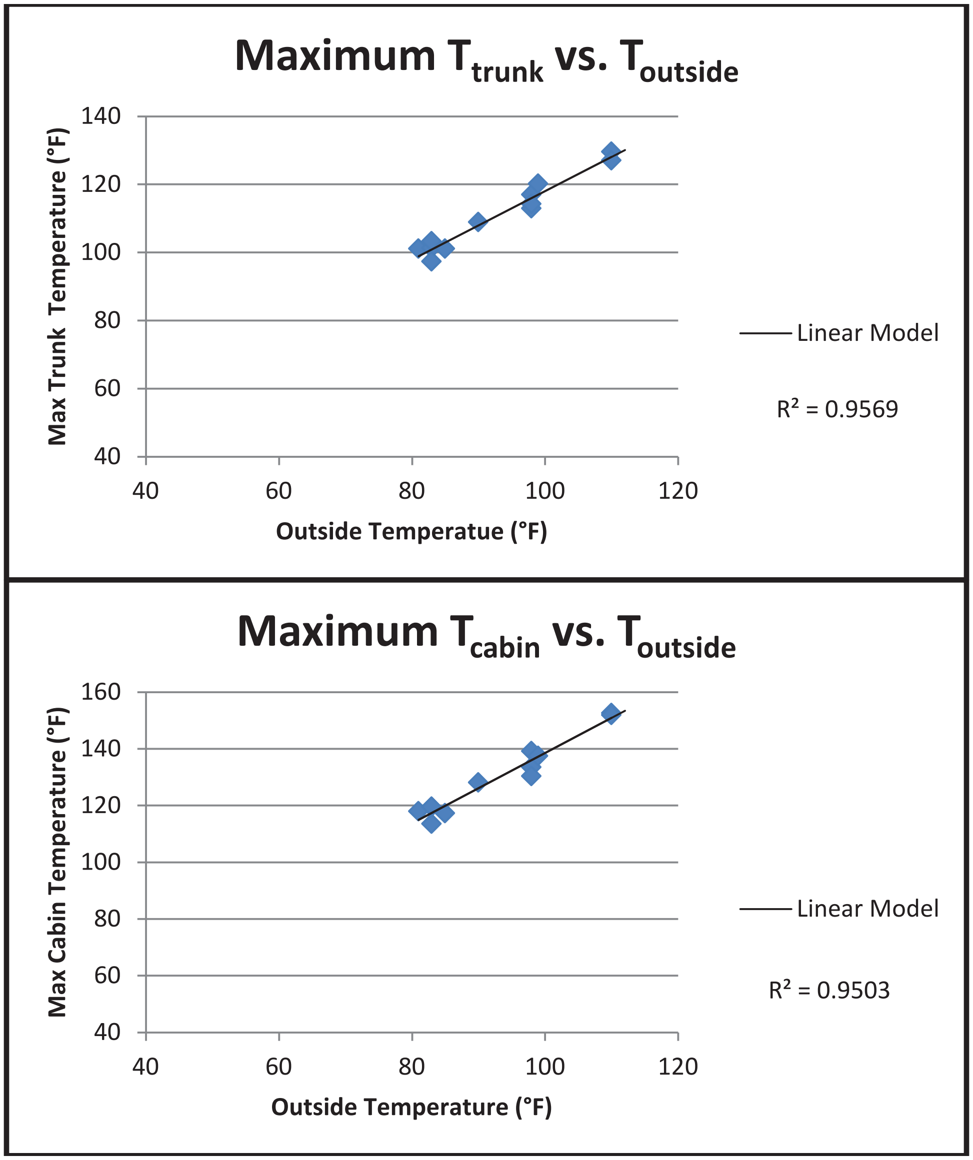


Figure 5: Correlation between Internal Vehicle Temperatures and Outside Temperatures A high correlation coefficient with outside temperature was seen in both the trunk (r^2 = 0.9569) and the cabin (r^2 = 0.9503).

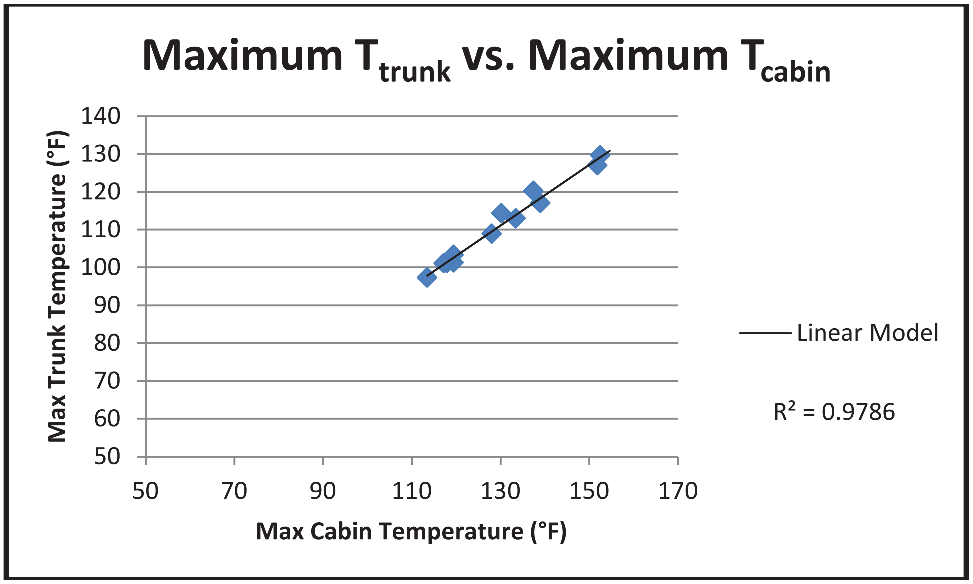


Figure 6: Correlation between Maximum Temperatures within the Trunk and Cabin
A high correlation coefficient ($r^2 = 0.9786$) was seen between the final temperatures attained within the trunk and cabin. This suggests a similar heating mechanism.

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