

# A Thermal Bus for Vehicle Cooling Applications - Design and Analysis

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## ABSTRACT

Designing an efficient cooling system with low power consumption is of high interest in the automotive engineering community. Heat generated due to the propulsion system and the on-board electronics in ground vehicles must be dissipated to avoid exceeding component temperature limits. In addition, proper thermal management will offer improved system durability and efficiency while providing a flexible, modular, and reduced weight structure. Traditional cooling systems are effective but they typically require high energy consumption which provides motivation for a paradigm shift. This study will examine the integration of passive heat rejection pathways in ground vehicle cooling systems using a "thermal bus". Potential solutions include heat pipes and composite fibers with high thermal properties and light weight properties to move heat from the source to ambient surroundings. An initial case study focuses on the integration of heat pipes in a thermal bus to transfer heat from the thermal load (e.g., internal combustion engine, electric motor, battery pack, power electronic, etc.) to the heat exchanger. A mathematical U-shaped pulsating heat pipe model is used to numerically describe the thermal behavior of a heat pipe based thermal bus. This is combined with models for a "cradle" to move energy from the load to the bus and a model for a heat exchanger to ambient. Simulation results indicate that the heat dissipation rate is significantly influenced by heat pipe length, diameter and the temperature difference between the heat load and the bus. The integration of this heat pipe based thermal bus within an active / passive cooling system will be demonstrated in future work.

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## 1. INTRODUCTION

Hybrid powertrains generate heat through the operation of the combustion engine, electric motors, generator, battery pack, and on-board electronics for propulsion. An important consideration is the cooling of these components to maintain the temperature within prescribed ranges. The emphasis on fuel consumption targets has necessitated a focus on power minimization including the cooling system in military vehicles [1, 2, 3, 4]. A variety of thermal management strategies exist as shown in Fig. 1. The most common cooling system design features an ethylene glycol liquid cycle radiator with fan, thermostat valve, pump, hoses, and engine block water jackets. Air cooled engines and components may be optional for lower heat loads. A novel design integrates both passive and active features that can be selected based on the operating conditions.

The monitoring and control of vehicle propulsion system temperatures can help ensure mission viability. Friction losses of engine parts vary as a function of lubricant and coolant temperatures with 90°C to 100°C the suggested oil temperature range [5]. The battery pack performance will decrease if its temperature is not properly

maintained. Likewise, electrical components must be operated within their rated temperature range. In previous studies, cooling system architectures and their energy consumptions have been investigated for different operation conditions. Park and Jung [6] examined the thermal behaviors of three different cooling system designs to identify power consumption factors. Bayraktar [7] integrated computational fluid dynamics to study cooling system thermal behaviors. Tao and Wagner [3,8,9] adopted nonlinear control theory to regulate the electro-mechanical actuators operation schedules in engines. Wang *et al.* [1,10] established mathematical models to optimize convection-based heat transfer by regulating actuator (e.g., fans, pump, and smart valve) operation. The radiator fan(s) consumes the greatest power within the engine cooling system [2].

The integration of energy-efficient passive heat rejection pathways in parallel with an active cooling for ground vehicles has not been fully investigated. An opportunity exists to innovate on the conventional cooling system to realize a flexible design that can accommodate increasing thermal loads and offer a "silent sentry" operational mode. The inclusion of high conductive materials/devices (e.g., heat pipes,

composite fibers, alloys, etc.) may offer a potential solution for passive heat rejection within a smart architecture to move heat from the heat load(s) to ambient surroundings. In this study, the term “passive heat rejection pathways” refers to heat transfer modes which do not require vehicle supplied power. A starting point for a hybrid passive-active cooling system design will be the introduction of heat pipes. Loop heat pipes have been recognized as two-phase passive devices with high effective thermal conductivity which are capable of transferring heat at any orientation with respect to gravity [11]. Heat pipes are utilized in various thermal management applications to increase thermal conductivity and temperature distribution uniformity. For ground vehicles, heat pipes have been used to control component and compartment temperatures. Rao *et al.* [12] implemented an electric vehicle heat pipe based thermal management system to regulate the Li-ion battery temperature. El-Sharkawy [13] used heat pipes to control the catalytic converter temperature. Hendricks [14] introduced heat pipes to cool passenger cabins and reduce the A/C system operation schedule time. Lastly, Burban *et al.* [15] investigated the performance of pulsating heat pipes for vehicle cooling system applications in terms of number of turns and working fluids for various driving conditions.

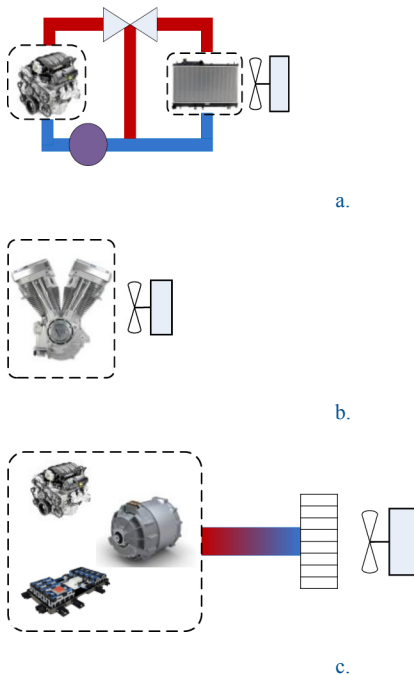


Figure 1. Overview of cooling strategies - (a) Traditional liquid system, (b) Forced convection system, and (c) Active/passive thermal bus.

The heat generated over the combustion process, propulsion and mechanical friction in ground vehicles must be managed effectively to ensure the system's durability and performance. An advanced automotive thermal management system is required to avoid exceeding the component's working temperature limits with minimum energy consumption in ground vehicles and enhance the engine performance. In this paper, the integration of passive heat rejection pathways in ground vehicle cooling systems is examined using a heat pipe based thermal bus with an attached cradle and heat exchanger with electric fan. The remainder of the paper is organized as follows. [Section 2](#) introduces the thermal bus concept with cradle

and heat exchanger. The corresponding mathematical model is presented in [Section 3](#) to describe the dynamic behavior.

Representative numerical results are discussed in [Section 4](#) for a convoy escort driving cycle. The conclusion and Nomenclature List are contained in [Section 5](#) and the Appendix, respectively.

## 2. HYBRID COOLING SYSTEM STRATEGY

Hybrid ground vehicles are typically composed of an internal combustion engine with electrical motor, electro-mechanical components, and accompanying battery packs in either a parallel or series configuration. The powertrain components generate a significant amount of heat that must be dissipated through the cooling system. In some instances, the heat rejection may be modest which reflects either a sentry type operating mode or low speed high efficiency electrical motor propulsion. For this case, a passive thermal management system may be designed to handle the cooling needs. The proposed advanced cooling system structure features a passive cooling heat rejection pathway associated with a smart active cooling system structure which operates based on the heat rejection needs. The recognition that a passive cooling approach for large prolonged thermal loads, especially internal combustion engines, will be insufficient leads to a hybrid design that also features a conventional radiator-pump configuration.

The individual heat loads may be interfaced to a thermal bus through an optimized surface area called a “cradle”. The cradle must be designed based on each individual heat load heat generation rate, operation conditions, and shape. Components with low convective heat transfer to surroundings may benefit by large cradle coverage. A cradle with high thermal conductivity and small thermal expansion provides the needed thermal connection between the heat sources and thermal bus. The external surface of the cradle will be encased in a low conductivity insulating material to route energy in the desired direction.

The thermal bus transports heat from the cradle to the radiator with attached fan(s). The thermal bus is defined as any devices, including passive or active heat transfer pathways, used to transfer heat from a given entity. For instance, devices using liquid based cooling to passive advanced materials with high thermal conductivity. The proposed thermal bus concept features a computer-controlled liquid cooling system which give the system capabilities to handle high heat removal needs if the temperatures of the heat load components become excessive. [Figure 2](#) shows a concept of a hybrid cooling system which benefits from passive cooling system in parallel with active cooling strategy. High conductive materials such as composite fibers, alloys, phase change materials as well as high thermal conductive passive devices like heat pipes will be implemented into the passive cooling strategy. Heat will be transferred between two points with temperature gradient. Studying high thermal conductive materials provides the foundation of understanding their thermal performance. Similarly, heat pipe structures are highly efficient systems which can be integrated in a wide variety of cooling applications which essentially extends their functional possibilities in practical applications.

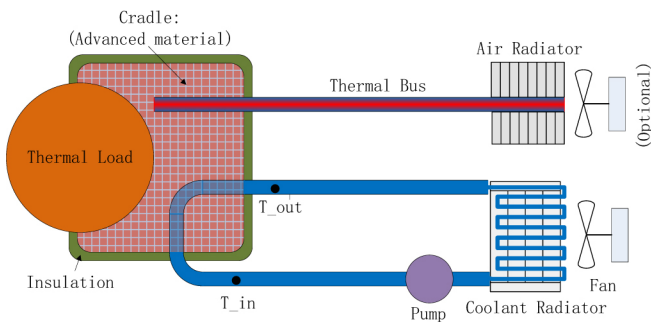


Figure 2. Advance hybrid cooling system design.

The integration of a high efficiency heat exchanger with an optional electrical fan(s) will increase the efficiency of the cooling system. A control strategy will be needed to operate the heat exchanger fan(s) through the monitoring of system temperatures and minimize power consumption while meeting the thermal demands for each component per various operating scenarios. Overall, the proposed cooling system may benefit from a lower weight system structure, enhanced flexibility and reliability, silent mode operation, high effective thermal conductivity, and smaller external power consumption.

### 3. MATHEMATICAL MODEL

Several mathematical models have been developed for the thermal bus system from the heat load, to the cradle to the heat exchanger. These include several models for pulsating U-shaped heat pipes (PHP) to study the impacts of various design parameters such as initial conditions, diameter, charge ratio, temperature difference and working fluid on the oscillatory behavior and performance of heat pipes [16, 17]. Heat pipes can be included as both parts of the cradle and/or the thermal bus. Results have shown the heat pipe diameter and temperature difference are effective factors on heat pipe heat transfer rates. It's been proven that heat is mainly transferred due to the exchange of sensible heat compared with latent heat [16]. Ma *et al.* [18] studied the effect of nano-fluid on oscillating heat pipe heat transfer rate. They proved that using nano-fluid as working fluid results in a significant temperature difference reduction between the evaporator and condenser sections in oscillating heat pipes. Yang *et al.* [19] have examined heat pipes in terms of light weight and performance and highlighted some limitations to the application of light weight material in heat pipes.

A reduced order passive cooling system containing a heat load, cradle, thermal bus, and a finned heat exchanger is numerically formulated and analyzed to describe the thermal behavior over the operation cycle. Figure 3a shows the flow of thermal energy and Fig. 3b displays the corresponding nodal network. The heat generation rate of the heat load will be set based on each heat load individually. The e-motor generates a significant amount of heat in comparison with the other heat loads in the ground vehicle. Therefore, a passive cooling system with the associated e-motor with respect to an actual driving cycle is investigated in this study.

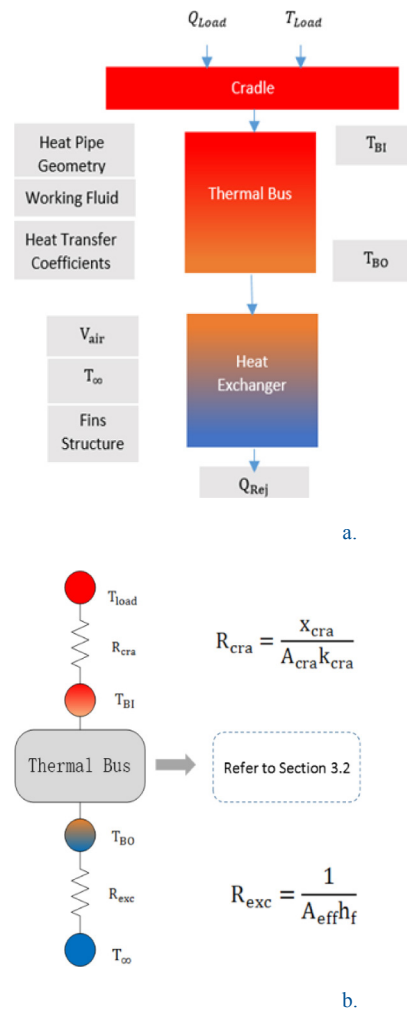


Figure 3. Integration of cradle, thermal bus, and heat exchanger in the (potentially hybrid) cooling system - (a) System architecture and (b) Temperature nodal network.

#### 3.1. Cradle Structure

The heat load cradle is used to efficiently transfer heat from the thermal load to the thermal bus (in this case the evaporation section of the pulsating heat pipe). Metals with high thermal conductivities are widely used as the media to transfer heat from the thermal load to the evaporation section of the heat pipe. Heat pipe embedded copper bases are widely used to transfer heat from microelectronics. A heat pipe based cradle can operate to dissipate heat from the heat load to the thermal bus. The configuration of the cradle is dependent on the structure of the thermal load. The cradle is assumed to be ideal in the current simulation so that the cradle can be considered as a simple thermal resistance so that:

$$R_{cra} = \frac{x_{cra}}{A_{cra} k_{cra}} \quad (1)$$

where  $R_{cra}$  is the thermal resistance of the cradle,  $x_{cra}$  is the thickness of the cradle,  $A_{cra}$  is the surface area vertical to the heat flow direction, and  $k_{cra}$  is the thermal conductivity of the cradle. The entire system temperature of the cradle is selected as the output such that: