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Intelligent energy management control of vehicle air conditioning via look-ahead system

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ABSTRACT

Air conditioning systems (A/C) significantly increase the energy consumption of a vehicle and negatively influence its performance. A/C can be considered the main auxiliary load on a vehicle engine when it is operating. Thus, there are significant savings to be made by operating an A/C system smartly, both in terms of running costs and the effect on the environment. This paper presents an intelligent energy management system that is able to reduce the energy consumption of a vehicle with an air conditioning system and improve its efficiency by using the look-ahead system uses information from various information systems to make intelligent decisions. The new energy management system features: a prediction of road power demand by using look-ahead control of vehicle systems, an intelligent control strategy to manage the operation of the A/C, the blower, and the gates, to provide the optimum comfort temperature with the consideration of the in cabin air quality while minimizing energy consumption. Two simulations are performed by using the developed fuzzy air conditioning enhanced look-ahead System and ordinary fuzzy air conditioning and then the results are compared together with the results from Coordinated Energy Management System (CEMS). The results of fuzzy air conditioning enhanced with look-ahead system demonstrate it is capable of saving 12% and 3% more energy comparing with CEMS and ordinary fuzzy air conditioning system respectively.

1. Introduction

Air conditioning systems (A/C) significantly increases the energy consumption of a vehicle and negatively influences its performance. A/C can be considered as the main auxiliary load on a vehicle engine when it is operating. According to a study by the National Renewable Energy Laboratory [1], the United States uses 26.4 billion litres of fuel per year to operate light-duty vehicle A/C systems. This is equivalent to 5.5% of the total light-duty vehicle fuel use in this country. Lambert et al. [2] reported that the mechanical compressor of an A/C system could increase the fuel consumption of the vehicle by 12–17% for subcompact to mid-size vehicles.

According to ASHRAE [3], general considerations for air conditioning design should include such factors as cabin indoor air quality and thermal comfort, ambient temperatures and humidity, the operational environment of components, vehicle and engine parameters, electrical power consumption, cooling capacity, number of occupants, insulation, solar effect, vehicle usage profile, and so on.

In recent years, extensive studies have been carried out on various aspects of vehicle air conditioning systems and of management of energy utilization. These efforts have resulted in further improvements in the efficiency of the air conditioning system.

Jabardo et al. [4] described a model for the refrigeration circuit with a variable capacity compressor that was run by an electric motor. According to experiments, the model indicated that the maximum deviation was within a 20% range, although most of the simulated results were within the 10% range. It also shown that the coefficient of performance (COP) is always affected negatively by increments in refrigerant charge.

Daanen and Vliert [5] studied the role of ambient temperatures in driving performance and on the impact of the air conditioning system. They concluded that a thermo-neutral temperature in the cabin enhances driving performance and may positively affect safety. Durovic and Kovacevic [6] considered the vehicle air conditioning

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system as a very complex multiple-input multiple-output system. They presented an algorithm on how to design a simulator to generate enough data necessary to train a neural network. This data is consistent with the data collected during some actual trips. The architecture and the training algorithm for the neural network that control the air conditioning actuators were also given.

Yeh et al. [7] reported that making the fan speed adjustable adds more flexibility to the design of the control system and can thus cause an improvement in the performance and energy efficiency. They presented two algorithms that reduce power consumption in steady state and transient time incorporating fan control.

Park et al. [8] conducted an experiment on indoor air quality (IAQ) of vehicle cabin by evaluating the CO_2 concentration level and fine-dust on the road. This experimental study confirmed that an increasing level of CO_2 can cause a passenger to become tired, sleepy, and develop headache or discomfort. Their study results show that CO_2 and fine-dust concentration is a result of the number of passengers, the driving condition and the HVAC user setting. The study also validated the necessity to enhance efficient use of the control devices to boost comfort inside the vehicle.

The control of ventilation and A/C is a difficult problem because even the simplest A/C models are multi-variable and nonlinear. Furthermore, these systems are acted upon by multiple uncertain disturbances.

Several methods have been developed to control A/C in vehicles. These methods include: PID and Fuzzy controller. Using classical PID controllers, it is very difficult to design nonlinear and complex systems. One recent PID control approach has been investigated by Khayyam et al. [9]. They presented a coordinated energy management system to reduce the energy consumption of the vehicle air conditioning system while maintaining the thermal comfort. The system coordinates and manages the operation of A/C, blower, and fresh air and recirculation gates to provide the desired comfort temperature and indoor air quality, under the various ambient and vehicle conditions, the energy consumption can then be optimized. The Coordinated Energy Management System (CEMS) was developed that includes one PID controller to control A/C, and three stepper controllers to adjust gates and set points. In the PID controller, a neural network tuner was employed to automatically adjust the parameters of the controller. Regarding the design of nonlinear and complex systems, fuzzy logic controllers have the capability to address the inherent nonlinearity of A/C components and to allow the control to be expressed in the same heuristic terms that an occupant would use in describing the level of comfort [10].

As reported in the literature [11–13], fuzzy logic has been a popular method for controlling the operation of A/C. Sousa et al. [14] present a method for designing a nonlinear controller based on a fuzzy logic for an air conditioning system consisting of a fan-coil unit installed in a test cell. They provide an optimization approach that alleviates the computational burden of iterative optimization techniques with an inverted fuzzy model of the process. The algorithm is applied to temperature control in the air conditioning system. Comparisons with a nonlinear control scheme based on iterative numerical optimization show that the developed method requires fewer computations and achieves better performance.

Frazaneh et al. [15] focus on thermal comfort temperature and energy. They use a Fanger's predicted mean value as controller feedback. Evaporator cooling capacity is selected as a criterion for energy consumption. Two fuzzy controllers are designed, one with a temperature feedback and the other with the predicted mean value index feedback. The results show that the predicted mean value controller better controls the thermal comfort temperature and energy consumption. They optimized the fuzzy controller using a genetic algorithm and reported an increase in the thermal comfort level and decrease in the energy consumption.

The development of vehicle air conditioning systems by using provided static and dynamic road geometry information can reduce fuel consumption. Khayyam et al. [16] demonstrated that the information about the geometrical specification and wind behaviour of the road ahead (look-ahead) of a vehicle can be used by an intelligent system to reduce fuel consumption of the vehicle. The whole direction and road geometry of the journey can be determined by GPS and GIS [17].

This paper presents an intelligent energy management system that is able controlling the operation of A/C, blower, and fresh air and recirculation gates to provide the desired comfort temperature and indoor air quality, under the various ambient and vehicle conditions, by using look-ahead system. The new method will be compared with recent approach by Khayyam et al. [9,18]. The new energy management system has the following features:

1) A look-ahead control of vehicle systems that uses information from systems such as Global Positioning Systems (GPS), Geographic Information System (GIS) and others are employed to predict road power demand.
2) The road power demand includes the following: rolling power, up and down hill power and aerodynamic drag from wind power.
3) The proposed system calculates the energy balance of the cabin based on ten different load parameters: direct solar radiation, diffuse solar radiation, radiation reflected by road, ambient, engine, exhaust, ventilation, cooling, metabolic and road power demand.
4) An intelligent control strategy that manage, the operation of the A/C, the blower, and the gates to provide the optimum comfort temperature and indoor air quality with the minimum energy consumption. This is done by controlling the mass flow rate of air through the operation speed of the blower, regulating the opening of fresh air as well as recirculation-air gates to optimise the indoor air quality by controlling the density of CO_2 concentration of the cabin, and controlling the operation of the A/C using an intelligent algorithm.
5) For various input heat loads such as ambient temperature, solar radiation, vehicle speed and humidity, the optimized energy consumptions are devised and presented.

The paper is organized as follows. Section 2 describes the energy balance equation associated with the vehicle cabin. Section 3 introduces the environment model and the look-ahead system. Section 4 depicts the intelligent control system used in the management of energy consumption. Section 5 describes the simulation methodology. The simulation results and associated discussions are presented in Section 6. Finally, The concluding remarks are provides in section 7.

2. Energy balance in the vehicle and cabin room

A vehicle engine can be treated as a controlled volume system for study purposes [19]. The inflows of energy to the controlled volume are air and fuel, while its outputs are mechanical power developed by engine, exhaust gas, warm air, and heat loss by convection and radiation to the surroundings (see Fig. 1(a)).

The energy balance equation of the controlled volume is given in Equation (1), where the left hand side term calculates the generated power and the right hand side terms give the consuming powers.

$$\begin{aligned}\dot{Q}_{\text{combustion}} &= \left(\dot{Q}_{\text{fuel}} + \dot{Q}_{\text{air}} - \dot{Q}_{\text{exhaust}}\right) \\ &= \dot{Q}_{\text{water/oil}} + \dot{Q}_{\text{heatloss}} + P_{\text{road power demand}} \qquad (1)\end{aligned}$$