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Inno-VACS

Executive summary

One of the largest obstacles to mass adoption of electrical vehicles (EVs) is their relatively low driving range, compared to traditional combustion engine cars. A possible way to solve this issue can be reduce the power consumption of the vehicle's auxiliary systems. In particular, the most consuming auxiliary system is the Heating, Ventilation and Air Conditioning (HVAC) system, which can lead to a range reduction up to 50%, depending on outside weather conditions and driving cycle.

Inno-VACS project aims at applying a novel model-based design process to the car cabin of Pop.Up, an innovative concept developed by Italdesign, in order to minimize HVAC power consumption. The first step of the novel procedure consisted in devising a detailed thermal model of the cabin, implementing conventional technologies and materials used at present in the automotive industry. Secondly, a sensitivity analysis was performed, which consisted in registering through simulations how the Air Conditioning load changed by adjusting some design parameters of the car cabin (e.g. transmissivity of glazing, thermal transmittance of insulation). The outcomes of the sensitivity analysis were then used as guidelines for the selection of innovative technologies for the cabin. Specifically, advanced high reflectivity coatings for external opaque surfaces, controllable opacity electrochromic glasses and aerogel insulation material were identified as the set of solutions able to minimize AC load and maximize passenger thermal comfort. The adoption of these technologies leads to a range extension from 12% to 28% for the Pop.Up, depending on the considered scenario. On top of this, the insulation weight of the vehicle can be reduced by 22%. Thermal efficiency of the cabin is expected to increase by 66%, while the theoretical size of the HVAC system is expected to be reduced by 73%. Finally, using unprecedented control strategies, the temperature fluctuations inside the cabin air volume can be suppressed and the energy consumption can be decreased up to 15%.

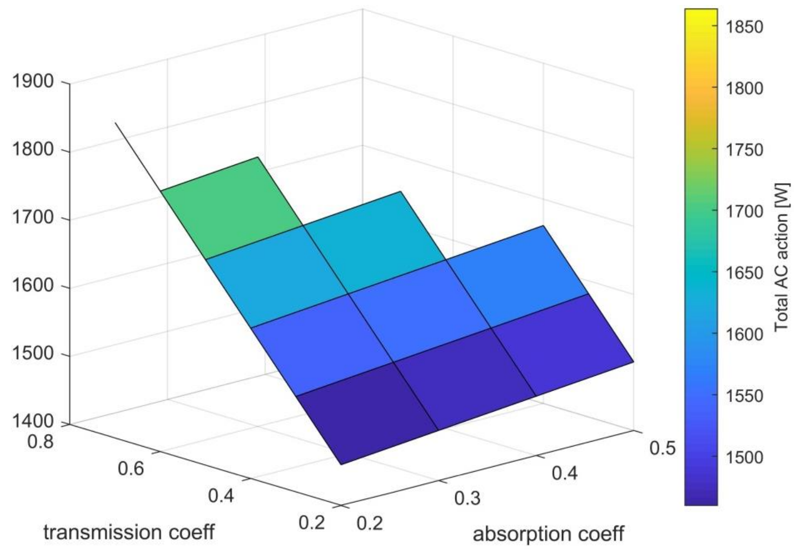
Key Words

Air Conditioning - Smart materials - Thermal comfort

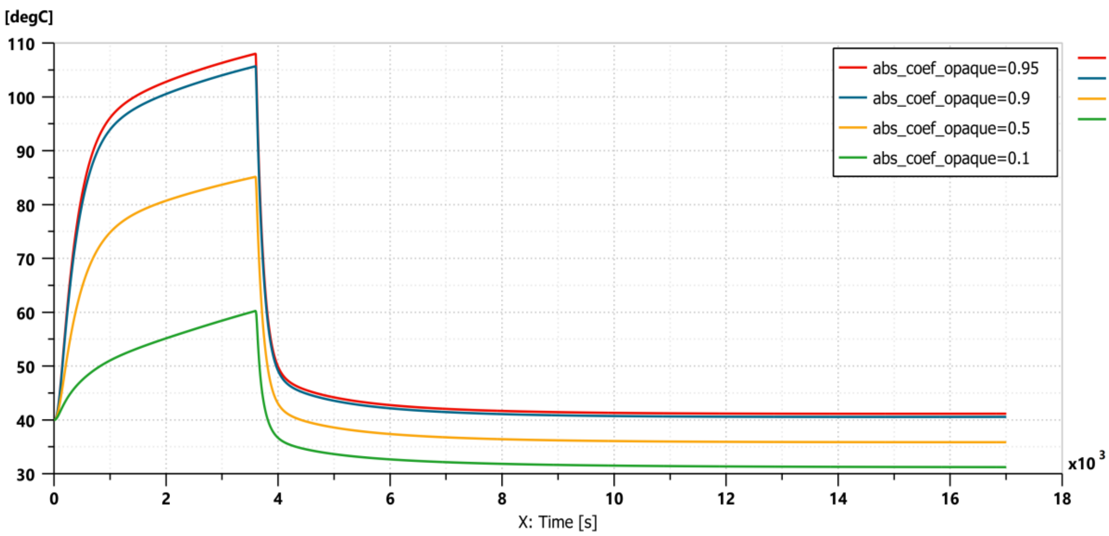
Sustainable mobility - Range extension

Pop.Up prototype: air and ground modules

Inno-VACS team at Italdesign Virtual Reality Lab



Example of outcome of the sensitivity analysis: influence of glazing properties on the AC load



Transient evolution of cabin roof temperature during pull-down test with different roof reflectivity

Project description written by the Principal Academic Tutor

Mobility is undergoing a profound revolution, driven by concern on energy sustainability, environmental impact and safety. The technological revolution of the transportation sector involves a number of disruptive technologies, namely IoT and electrical propulsion: autonomous driving, fully electric vehicles are set to become a key player in future smart cities. However, some critical technological challenges still have to be solved in order to make such vehicles the key players in the market, particularly the range extension that is now capped by the limited capacity of available batteries. Therefore, the reduction of auxiliary systems energy consumption - among which the Air Conditioning System (AC) is by far the main contributor - becomes one of the key goals to achieve.

The ASP Inno-VACS project has tackled this complex problem, combining the academic expertise of students and faculty of several cultural areas (Mechanical, Aerospace and Energy Engineering, and Industrial Design) with the industrial expertise of one of the key players of the automotive sector, Italdesign. Italdesign proposed the case study on which the ASP Team has worked: the Pop.Up, jointly developed by Italdesign and Airbus. Pop.Up is a modular, fully electric, zero emission vehicle system, designed to relieve traffic congestion in crowded megacities. Pop.Up envisages a modular system for multi-modal transportation that makes full use of both ground and airspace.

The students' team has developed a novel model-based design approach to achieve AC sizing and improve the cabin thermal efficiency. A detailed, dynamic numerical model of the cabin and AC system was developed using the multidomain simulation software Amesim, which served as the main tool for the optimization process. A sensitivity analysis was then developed to investigate the effect of the thermal parameters of the car cabin: surface reflectivity, glass solar transmissivity and thermal insulation. A thorough literature research was conducted to identify the most promising technological solution for passive thermal control of the car cabin. A parallel literature search was carried out on the active AC technologies, identifying alternative solution for the production of heating and cooling. Finally, novel control strategies have been investigated to achieve further efficiency improvements.

Team description by skill

Being the project a multidisciplinary work, the skills required in order to find the best solutions have been several and different. The team is composed by three mechanical engineers, an energy engineer and an aerospace engineer.

A crucial contribution was given by the Energy Engineer Enrica Raheli. Exploiting her knowledge about thermodynamics, the team was able to realize an accurate thermal model of the cabin and face with great confidence the issues concerning passenger thermal comfort.

Great contribution to the whole cabin modelling has been given by the Mechanical Engineer Daniele Ramirez. Thanks to his knowledge in controls' theory, the team has been also able to develop innovative and unprecedented model based controllers able to sensibly reduce the energy consumption of the AC unit.

The core of the project has been the research and study of new materials and technologies able to reduce the thermal loads entering the cabin. This ambitious goal has been reached thanks to the efforts of the Mechanical Engineer Francesco Pilosio, who carried on a deep analysis of coating technologies for opaque surfaces, and of the Mechanical Engineer Federico Ribatti who instead studied solutions concerning innovative glass technologies and insulation materials.

The expertise of Aerospace Engineer Saverio Tavernese has been very important in order to focus the attention of the team on the physical requirements needed for a flying car cabin. His contribution has been relevant also in the phase of individuation of the main stakeholders of the project.

Goal

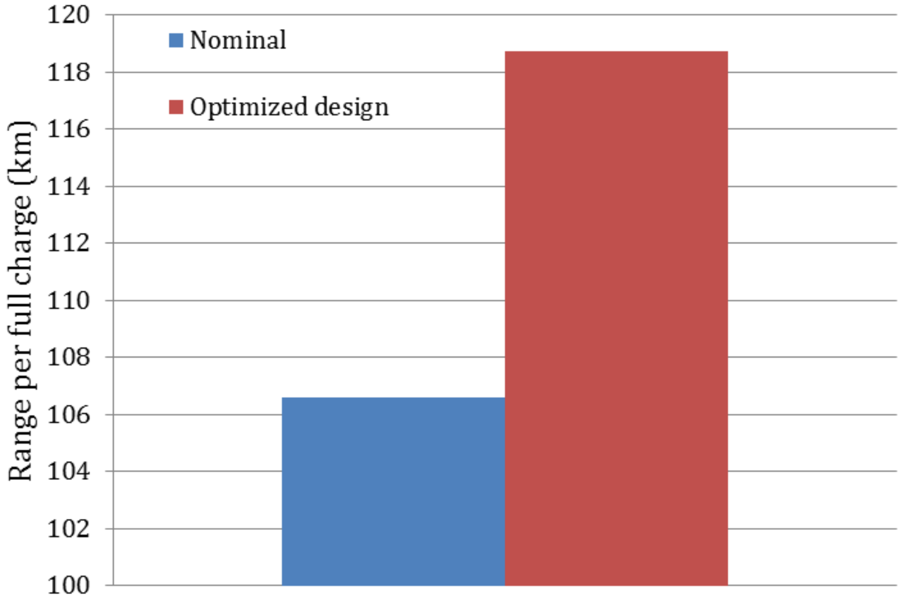
Inno-VACS is a team project born to design the Air Conditioning system of the innovative vehicle concept Pop.Up. Pop.Up is a revolutionary modular, electric, zero-emission vehicle, capable to provide multi-modal transportation, both on ground and up in the sky. It is one of the most ambitious projects, both from a technological and service point of view, in the scenario of future mobility.

Air conditioning innovation could seem to play a little role in this foreseen future. However, the AC system is the second largest power drawn from the electric battery. Lowering the required AC power in electric cars has the effect of increasing the vehicle driving range, and this phenomenon is crucial for this future mobility scenario. The team has been assigned the ambitious goal to produce a general design of the Air Conditioning system of the cabin, taking into consideration the specific requirements of the vehicle, along with economic and market factors influencing the development of the product and its commercialization. The strong inter and multidisciplinarity of the team members and of the academic tutors, jointly with the fruitful contribution of the industrial client Italdesign, has led to the remarkable results of this investigation.

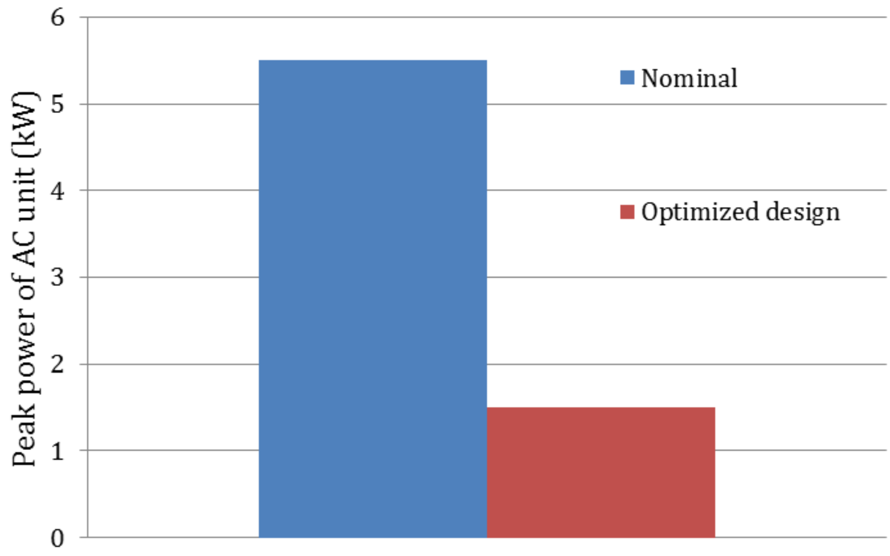
Understanding the problem

One of the biggest issues related to electrical vehicles is their driving range, which is low and incomparable with traditional combustion engine's driving range, due to the much lower energy density of current Li-Ion batteries with respect to conventional liquid fuels. Achieving operational driving ranges above 300 km is often impossible due to the limited capacity-weight ratio of current batteries. While research is slowly and steadily increasing this index, an alternative path to overcome the problem can be identified in reducing the power consumption of the vehicle's auxiliary systems. The HVAC system of an electric car is the second largest power drawn from the battery after the electric motor itself. In particular, the HVAC system can lower the range of an EV from 5% to 50%, depending on the outside weather conditions, driving cycle and vehicle size. Recovering this electric energy, through thermal efficiency of the car cabin, is a viable and immediate solution to decrease the instantaneous energy consumption in EVs, thus increasing the range. The term "thermal efficiency" indicates whether cooling or heating the cabin is effortless or demanding: a better thermally efficient car cabin requires less cooling/heating power in order to maintain the desired inner temperature, thus resulting also in a more economic, light and compact HVAC system.

State of the art methods for sizing HVAC systems and thermally design a car cabin are not able to provide the above stated objectives. Indeed, the common practice in the automotive industry relies on a well-established linear workflow, where the cabin thermal design and HVAC system sizing are based on the designer's expertise, heuristic non-model-based calculations or outdated experimental results. With our work, we propose a novel model-based design process to achieve Air Conditioning (AC) sizing and improving the cabin's thermal efficiency.



Driving range comparison: traditional materials vs optimized design



Peak AC load comparison: traditional materials vs optimized design

Exploring the opportunities

Differently from the current methods, the novel model-based design relies on precise thermal models, developed for our specific cabin prototype. Using this approach, it is possible to identify the main thermal contributions to the AC load and the most suitable technologies to lower them.

In order to devise the model, the Siemens' software Simcenter Amesim has been used. Simcenter Amesim is a commercial integrated simulation platform for numerical modelling of multi-domain systems. The tool provides complex nonlinear time-dependent models for representing the system's hydraulic, pneumatic, thermal, electric or mechanical behavior. The use of this software allowed us to build a quite complex model, taking into account the intrinsic non-stationary nature of the problem and its complex geometry. Thanks to this software, it was possible to simulate standard test conditions (pull-down test for air conditioning and warm-up test for heating) and evaluate performances of different HVAC solutions and materials.

Generating a solution

Based on the results of the sensitivity analysis, the team has analyzed, classified and benchmarked the most promising technologies to achieve the maximum AC load reduction. This topic constitutes a totally novel scientific research and gives valuable insights to designers who are approaching the thermal management problem of car cabins. The most promising technologies for glazing surfaces, opaque surfaces and insulation materials have been identified to be respectively:

• Electrochromic glasses, which allow to control the solar radiation entering the cabin (high flexibility)

• Radiative cooling reflective coatings, which allow to reflect most of solar radiation and emit infrared heat back to the environment

• Aerogel insulation, which ensures excellent insulation properties, low specific weight and high recyclability

The application of those technologies drove to an increase of thermal efficiency by 66% and a reduction by 73% of HVAC size. Thanks to the adoption of these innovative technologies, the driving range was significantly improved. Moreover, it was possible to increase the passenger thermal comfort, avoiding that inner surfaces reach high temperatures (e.g. roof and seats).

The problem of AC load minimiazation has also been tackled from a control point of view. The team has investigated the possible implementation of novel model-based controllers for AC control and glass transparency control. In the research, several new Model Predictive Control (MPC) architectures have been developed, as well as new hybrid controllers, whose performances have been proven to be significantly better compared to conventional PID controllers. In particular, hybrid controllers for AC and glass transparency control were found to be 15% more efficient and able to eliminate temperature fluctuations in the cabin.

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