Title: Enhanced EV and ICE vehicle energy efficiency through drive cycle synchronisation of deferred auxiliary loads

Abstract

This research investigates energy efficiency improvements by synchronising auxiliary air-conditioning (AC) with the vehicle drive train on a real road driving cycle pattern. The research findings are applicable to electric vehicles (EV), internal combustion engine (ICE) vehicles, and hybrids. An EV-converted Ford Focus was configured to operate the AC compressor solely from kinetic energy recovered from the drive train when coasting or slowing down. Test drives with the Ford Focus with standard AC operation increased the energy consumption by 11.6% compared to AC off, yet when the vehicle was synchronised with the drive train the energy consumption increased by only 5.8% compared to AC off, an energy saving of 8.1Wh km^{-1}. The configuration maintained comfortable cabin conditions (temperature and humidity) similar to driving with a standard AC system configuration. In vehicles with an interconnected automatic AC and engine management system data-bus, this efficiency improvement may require a software update only.

1 Introduction

Limited vehicle driving range, recharge infrastructure, and energy policy hinders electric vehicles (EVs) as a mainstream road transportation technology (Gass et al., 2011, Morrow et al., 2008, Dunstan et al., 2011, Mullan et al., 2011, Mullan et al., 2012, Wager et al., 2014, Lund and Kempton, 2008, McHenry, 2013, McHenry et al., 2011, Usher et al., 2011, Foley et al., 2013, Saarenpää et al., 2013). Energy from the EV main battery is not just required to drive the vehicle, but also to provide energy to the vehicle auxiliary loads (Tie and Tan, 2013, Opila et al., 2009, Walsh et al., 2010, Mi et al., 2008). Auxiliary loads can be significant for heating and cooling the vehicle passenger compartment (Bouvy et al., 2011, Bennion and Thornton, 2010). Driving with air-conditioning (AC) systems in operation can use up to 20% more energy and reduce drivable vehicle range (Hellgren and Groot, 2008). In addition, operating brake booster vacuum pumps, power steering pumps, electronic devices such as navigation systems, car computers and car stereos can add up to significant energy consumption, depending on driver preferences (Tie and Tan, 2013, Kelly et al., 2012, Francfort et al., 2009, Walsh et al., 2010, Zhang et al., 2009b). A considerable amount of energy is lost by operating friction brakes, and the majority of internal combustion engine (ICE) vehicles and EVs that do not have regenerative braking waste the kinetic energy available (Fuhs, 2009, Zhang et al., 2008, Katrašnik, 2013, Walsh and Bingham, 2009). Previous driving cycle experiments have shown that the amount of kinetic energy available for potential reuse is significant and depending on the vehicle mass and the drive cycle, can increase vehicle energy efficiency by up to ~20%. Conventional vehicles use mechanical friction brakes that convert the vehicle's kinetic energy directly into waste heat and recently developed kinetic energy recovery, using electric generators, flywheels, mechanical springs, compressed air absorbers, etc., have been utilised to increase vehicle energy efficiency (Walsh and Bingham, 2009, Green Car Congress, 2011, Wicks et al., 2002, Rayess and Kleinke, 2009). This research investigates the benefits of synchronising auxiliary loads with the vehicle's driving cycle to immediately use available kinetic energy rather than convert and store it in a battery with the associated conversion losses and micro charging issues. The aim of the experiment was to assess improvements in EV energy efficiency and to ascertain whether it is possible to maintain a comfortable temperature in the car by driving an AC compressor solely by the vehicle's kinetic energy during coasting or slow down. As compressors on cooling devices (fridges, AC, etc.) generally run on specified duty cycles, the experimental design enabled the option of synchronising the duty cycle to the drive cycle by operating the vehicles compressor every time the vehicle was slowing down or coasting.

2. Method

The test car (Figure 1) is a standard factory Ford Focus ICE vehicle that was converted by EV-Works in Landsdale, Western Australia (WA) into an all-electric EV and used in the WA Electric Vehicle Trial

(Mader and Bräunl, 2013). The EV is equipped with an electric main drive motor (80kW), controllers, a main battery (144V, 23kWh), and a manual factory gearbox. The Ford Focus' AC compressor is driven mechanically by a belt from the main motor drive shaft as commonly implemented in standard IC vehicles. The direct drive provided the option to drive the compressor mechanically, solely by recuperation through the vehicle's drive train whenever the vehicle was slowing down or coasting (Figure 2). Although the compressor is the largest energy consumer in an AC system, a considerable amount of energy is used for the AC condenser fan, vehicle compartment fan, and electrical compressor clutch - all powered from the main battery. While test driving on a chassis dynamometer provides a more uniform test environment (Nam, 2009, Delphi, 2010, United Nations, 2005), the absence of direct sunlight and heat makes AC testing on an indoor chassis dynamometer unfeasible. Therefore, road testing was used to ensure realistic driving conditions where solar radiation and high temperatures are naturally present.

A twenty seven km test route was selected to represent city driving (Figure 3). The intention of the selected route was to create a relatively uniform driving pattern similar to the US Federal FTP75 standardised vehicle drive cycles commonly used in the automotive industry. The route starts at the University of WA in Crawley and follows Stirling Highway to Fremantle, with the midpoint of the journey between the west and east bridges across the Swan River; the return journey completes the route, terminating back at the university campus. To standardise the influence of incident solar irradiance on the vehicle temperature in the passenger compartment, the experiment commenced in November when the sun at solar noon is relatively normal to the Earth's surface. To achieve uniform testing conditions, the test drives were conducted over six consecutive days, starting each day at 11.45AM and finishing at 2.15PM. To reduce the influence from clouds on outdoor AC testing conditions, the test drives were conducted on a series of days with a relatively stable weather pattern with clear skies (Figure 4).

The level of thermal comfort of a person is a subjective concept specific to individuals and is dependent on external and environmental conditions on the whole body and individual body parts, and is also related to metabolic heat production and resultant body temperature adjustments (Zhang et al., 2009a).For a passenger in a vehicle, the interaction of convective, radiative and conductive air exchange is very complex and a number of comfort indices are used, which rely on a variety of parameters to determine the degree of general comfort such as hypothalamus temperature, mean skin temperature, thermal insulation of clothing, air temperature, mean radiant temperature, air velocity, and humidity ratio (ASHRAE, 2013, International Organization for Standardization, 2005). A standard procedure is to use thermal manikins, surface sensors that simulate human bodies positioned in the vehicle seats, together with physiological and psychological comfort models, to assess passenger comfort in vehicles (Wyon et al., 1989, Rugh and Bharathan, 2005). In this preliminary study, for the purpose of simplicity only the ambient temperature and the EV passenger compartment temperature and relative humidity (RH) in the different test drive configurations were measured and compared. The preselected temperature for the EV AC system while in standard operation was selected at a comfortable level for the driver, and was used as a benchmark to compare temperature and humidity levels achieved during the driving in recuperation mode. Prior to testing, the EV battery was fully charged and the vehicle was parked in the shade to prevent preheating by direct sunlight. Table 1 shows the testing strategies with its three different driving modes. During each test day the first test drive was driving with the air-conditioning in recuperation mode where the AC compressor was driven solely by kinetic energy. The second test drive on each day had the AC system switched on (standard operated without modification) and the third test drive had the AC switched off. The sequence of the experiments was chosen so that driving the first two experiments with AC kept the car's interior at a steady temperature. It was assumed that the driving without AC first (with open windows), would have heated up the car's interior excessively and would have influenced the subsequent experiments.

[Insert Figures 1, 2, 3, and 4, and Table 1 approximately here]

Synchronising the AC duty cycle to the drive cycle by operating the compressor when the vehicle was slowing down or coasting required a modification of the electrical components of the AC system. The manufacturer's control strategy was bypassed by installing an AC clutch relay controlling the compressor so that the compressor only operated during the times when kinetic energy was available (Figure 5 and Figure 6). The system was designed such that when the inside temperature rises above a given temperature set point, the modified control system would be overridden and the compressor would operate as per the manufacturer's control system. The software was written by the primary author to log accelerator pedal position, vehicle speed, and passenger compartment temperatures. According to the vehicle status, the National Instrument (NI) interface switched the relay and the AC compressor on or off regardless of the manufacturer's control strategy. As modern cars with full electronically-controlled AC systems and engine management are interconnected by data-bus system (such as controller area networks or FlexRay), the modifications developed here can be easily implemented on modern EV and ICE vehicles, including other non-road modal transport.

Figure 7 shows the custom-made data acquisition system designed, built, programmed, and calibrated to log: date and time; passenger compartment temperature; outside temperature; outside relative humidity (RH); passenger compartment RH, and vehicle speed. The passenger compartment temperature and humidity sensors were mounted at chest height in the centre of the EV. The outside temperature and humidity sensors were mounted in a shaded area underneath the EV to prevent direct solar irradiance influencing the readings. The EV chassis temperature was manually recorded by a hand held laser thermometer before and after each test drive. Quantification of the energy consumption (Wh km^{-1}) from the EV main battery during test drives was achieved by multiplying the logged average battery voltage, using the EV motor controller, by the battery Ah readings from a TBS energy meter, and dividing by the distance driven. The energy consumption was calculated without considering EV recharging losses.

[Insert Figures 5, 6, 7 approximately here]

3 Results

3.1 Comparison of energy consumption

Figure 8 shows the average energy consumption for each of the six days, as well as the overall average energy consumption when driving under the three different AC operating conditions. Despite the changing traffic conditions on the roads over the six days, the energy consumption for each day was relatively uniform. As expected, on all test days driving in AC recuperation mode required less energy than driving with the AC switched on, and driving without the AC achieved the lowest energy consumption. Figure 8 shows that in terms of overall average energy consumption, the highest value was 156.1Wh km^{-1} with the AC switched on, followed by driving with AC and in recuperation mode (148Wh km^{-1}), and the lowest value was when the AC was off (139.9Wh km^{-1}). Figure 9 shows a time series selection of one test drive cycle EV speed and compressor status when driving in recuperation mode. The data overlay shows how the compressor was switched on and off by the modified controller, triggered by the falling edge of the EV speed profile. The majority of the time in recuperation mode the compressor was driven by the vehicle's kinetic energy. The modified control system was overridden for a couple of seconds only on the hottest days. The authors note that the speed profile is similar to standardised drive cycle profiles such as the FTP75 US Federal Drive Cycle.

[Insert Figures 8 and 9 approximately here]

3.2 EV and passenger compartment temperature and humidity

Figure 10 presents the EV chassis temperature before and after each individual experiment, as measured by the hand held laser thermometer. The vehicle temperature variation (increase or decrease) during the test drives were between 2^{0}C to 8^{0}C. Over the course of the six test days the vehicle experienced an approximate increasing temperature gradient of between 1^{0}C to 3^{0}C due to the increasing daily weather maximums (between 25^{0}C to 33^{0}C). The moderate chassis temperature fluctuations demonstrate a relatively uniform testing period for the daily consecutive test-drives. Figure 11 shows 16 minutes of the recorded temperature over the course of a test drive. For both AC modes, the falling passenger compartment temperatures indicate that the AC compressor is in operation whilst rising temperatures indicate that the AC compressor is switched off. In AC recuperation-mode the compressor was switched on by the modified control system whenever recuperation was possible. Therefore, as long as the inside temperature does not exceed the set point, the AC duty cycle and hence the temperature fluctuation was governed by the driving pattern. In contrast, the compressor duty cycle in the AC mode was controlled by the standard AC control mechanism. Both modes (AC ON; Recup. ON) and (AC ON; Recup. OFF) show a similar temperature fluctuation of +/-2^{0}C due to their respective AC compressor duty cycles. Figure 12 is a scatter plot of the passenger compartment and outside air mean temperature versus the RH over the 18 test drives and three different driving configurations. The measured mean outside road air temperatures and RH ranged 25^{0}C to 41^{0}C and 6% to 50%, respectively. The average difference in passenger compartment temperature and RH in recuperation and standard modes over the six days was 0.6^{0}C and 5%, respectively. Thus driving in AC recuperation mode results in slightly higher temperatures and humidity but in general, the temperature range for both modes were similar, with 24^{0}C to 26^{0}C in recuperation mode and 24^{0}C to 26^{0}C in standard mode. There was greater variation in the RH range for both modes with 37% to 55%, in recuperation mode and 28% to 55%, in standard mode. Since the car windows were open during driving tests without AC, the passenger compartment temperatures and RH followed the outside temperatures and RH.

[Insert Figures 10, 11, and 12 approximately here]

4 Discussion

4.1 Energy consumption

The overall energy consumption of each driving mode over all test drives was relatively stable. The lowest energy consumption was measured on day five (a Sunday) without AC, and was assumed to be due to less traffic congestion on that day. The results demonstrate that driving the vehicle with AC increased the energy consumption by 11.6% compared to driving without AC. By driving the EV in recuperation mode the energy consumption increased by only 5.8% compared to driving without AC. This represented a saving of 8.1Wh km^{-1}, or about half the energy recovered by previous research by the authors on a Lotus Elise EV conversion with a regenerative braking system (RBS) on a comparable drive cycle. In a vehicle with an RBS and without the synchronised auxiliary system the 8.1Wh km^{-1} would be reduced by the losses associated with the EV battery charging and discharging. Similarly, in a conventional ICE vehicle with a synchronised auxiliary system, this would enhance energy efficiency even without an RBS or battery storage system.

Energy efficiency values are in terms of the power consumption from the battery compared to the distance driven. If the recuperated kinetic energy could run all components of the AC system then one would expect the energy efficiency to be similar to the situation with the AC off. As mentioned in Section 2, not all the energy required for the AC system, however, can be recovered from the available kinetic energy. The main battery is required to power the AC condenser fan, vehicle compartment fan, and electrical compressor clutch, with the AC condenser fan alone drawing approximately 300W of power. Figure 11 shows that there are differences in the duty cycling of the AC compressor in the two different modes. In standard operation the duty cycling is temperature dependent. When the desired temperature is achieved, the control system switches off the compressor, and when the temperature increases above a preset level, the compressor is switched on again. Such an on/off scenario was observed during the test drive with AC switched on. In recuperation mode, the compressor was switched on by the modified control system whenever recuperation was possible and the AC duty cycle was vehicle speed dependent, as illustrated in Figure 9. The difference in these duty cycle operations is another reason that explains the relative energy efficiency values for the two modes in relation to the situation with the AC off. However, if the inside temperature exceeded the set point while driving with the AC in recuperation mode, the AC operation would revert to standard mode. This was a limiting factor in the energy efficiency gains of operating the AC in recuperation mode.

4.2 Temperature and RH

Figure 11 and 12 show that the available kinetic energy from the EV thermal mass enabled the maintenance of temperatures and RHs within a similar comfort region as driving with the AC switched on. Driving without AC required opening the windows of the EV. Although some airflow from the outside provided some relief during the milder days, the driver experienced significant discomfort during the warmer days. Figure 10 shows how the test drive inside temperatures without AC followed the ambient temperatures through to the hottest day when 41^{0}C was recorded. Furthermore, solar radiation, noise, and air pollution levels inside the passenger compartment by driving the vehicles without AC and with windows open reduced the driver's subjective comfort level. The results demonstrate it is possible to maintain comfortable temperature and humidity levels inside the EV by operating the AC compressor solely from recovered kinetic energy. The driving style is an important factor to consider for the recuperation system as significant amounts of kinetic energy would be lost as heat by abrupt braking. The authors emphasise that efficiently driving a car with recuperation systems requires drivers to be cognisant of immediate traffic conditions ahead, and the use of moderate braking. Additional limitations of this research include the recovery of kinetic energy to drive large loads such as an AC system, the success of which depends on how much energy can be saved, and if a comfortable level of car inside temperature can be maintained. The research did not include the efficiency investigation of the whole AC system. It was limited to investigate options to drive the compressor by kinetic energy. Further research may include investigating the efficiency of the AC system with its fans and insulation properties and the cooling performance in conjunction with a latent cold storage system, and a detailed study about thermal comfort in a vehicle using surface sensors that simulate human bodies in seats and additional physiological and psychological comfort models.

5 Conclusion

The findings show the potential for increasing the energy efficiency of EV, ICE, and hybrid vehicles by recuperating energy through synchronising a large auxiliary AC load. The results show that a considerable amount of kinetic energy is available to operate an AC system or other large auxiliary loads during urban driving. The drive cycle and auxiliary AC load synchronisation was effective at maintaining a comfortable range of passenger compartment temperature and humidity values when in recuperation mode, while a very uncomfortable cabin environment was experienced on days without AC operation during warmer (>40^{0}C) ambient temperatures. Modern vehicles with electronically-controlled AC and engine management systems interconnected by a data-bus system may be modified to synchronise with the AC system using a simple software update only. Implementing similar recuperation strategies into mainstream EVs, hybrids, and ICE vehicles will require further research, including; impacts on the AC compressor clutch or other AC components of an assumed increase in short-run duty cycles, and; the option of using a latent cold storage system with the AC to store the additional kinetic energy available and enable improved synchronisation. The authors also recommend researching the influence of 'everyday' driving behaviour on EV and ICE vehicle energy efficiency modifications.

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Table:

Table 1 Testing schedule and AC operation modes during driving.

Day	Experiment	Day	Experiment
1	1: AC ON; Recuperation ON	4	10: AC ON; Recuperation ON
	2: AC ON; Recuperation OFF		11: AC ON; Recuperation OFF
	3: AC OFF		12: AC OFF
2	4: AC ON; Recuperation ON	5	13: AC ON; Recuperation ON
	5: AC ON; Recuperation OFF		14: AC ON; Recuperation OFF
	6: AC OFF		15: AC OFF
3	7: AC ON; Recuperation ON	6	16: AC ON; Recuperation ON
	8: AC ON; Recuperation OFF		17: AC ON; Recuperation OFF
	9: AC OFF		18: AC OFF

Figure captions and Figures:

Figure 1 The research test vehicle: a Ford Focus converted to an EV

Figure 2 Power flows: schematic of the EV AC compressor driven by the main motor drive shaft in recuperation mode (top) and driven by the main battery in standard mode (bottom)

Figure 3 The test drive route from the University of WA in Crawley to Fremantle, and back again.

Figure 4 Weather patterns during the period of the outdoor EV testing [http://www.seabreeze.com.au/graphs/wa.asp].

Figure 5 Schematic of a standard AC control system (left), and the modified AC control system (right) developed for the experiment.

Figure 6 A flow chart of the control strategy for the modified AC control system.

Figure 7 The custom designed logging system.

Figure 8 The Ford Focus EV average energy consumption over the six testing days and the overall average (in Wh km^{-1}) with standard deviation error bars.

Figure 9 EV speed profile and compressor status operated primarily by recuperation.

Figure 10 Vehicle chassis temperatures during the course of the experiments.

Figure 11 EV passenger compartment temperature fluctuations over 16 minutes of a test drive.

Figure 12 Outside air and passenger compartment mean temperatures and humidity over the six test days under different driving configurations.

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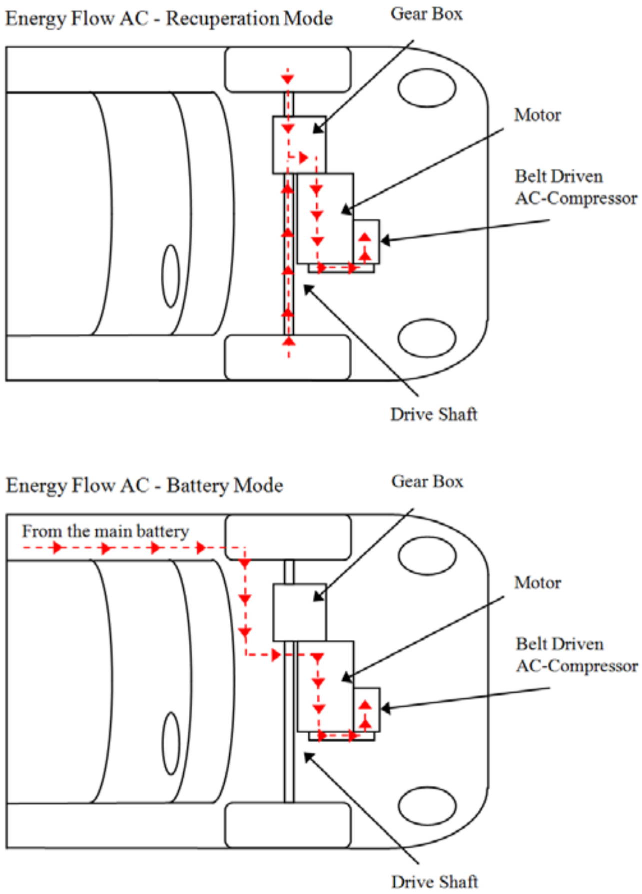

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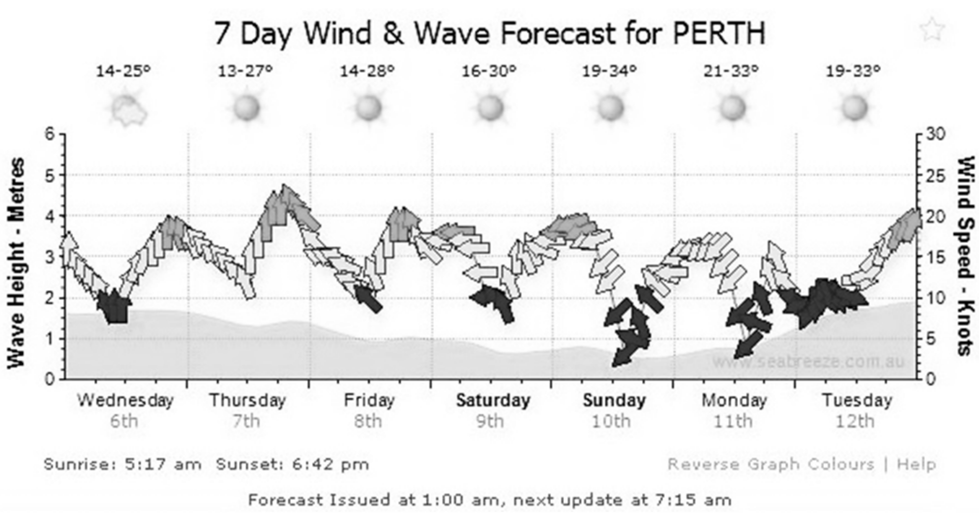

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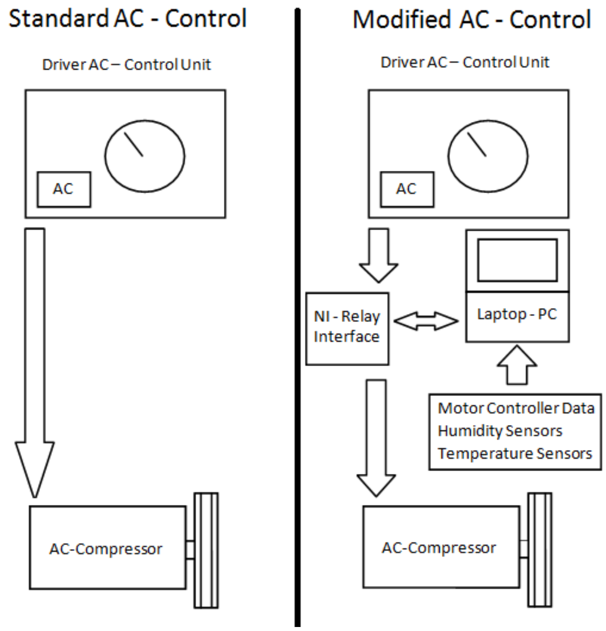
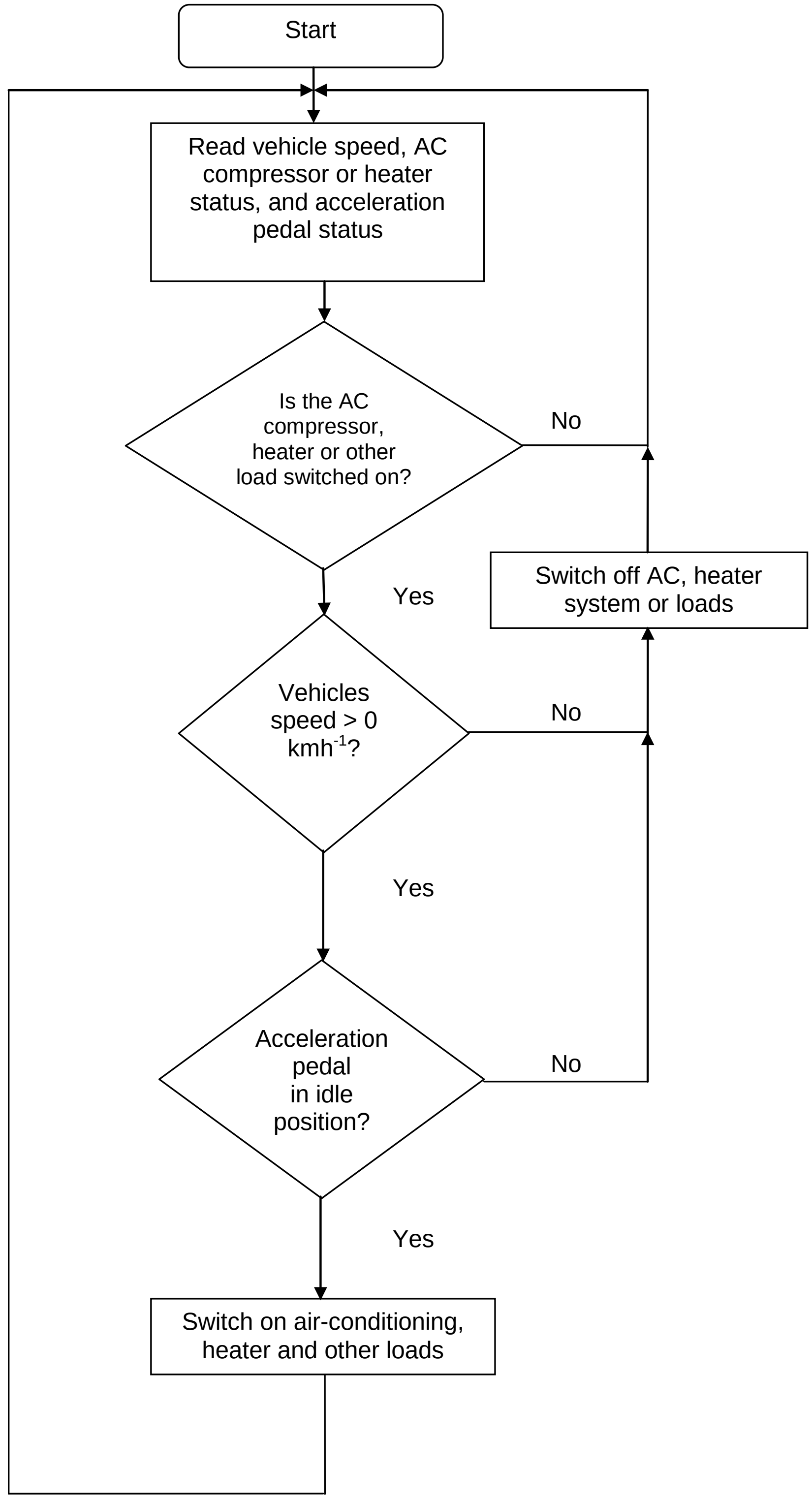


Figure 6 A flow chart of the control strategy for the modified AC control system.



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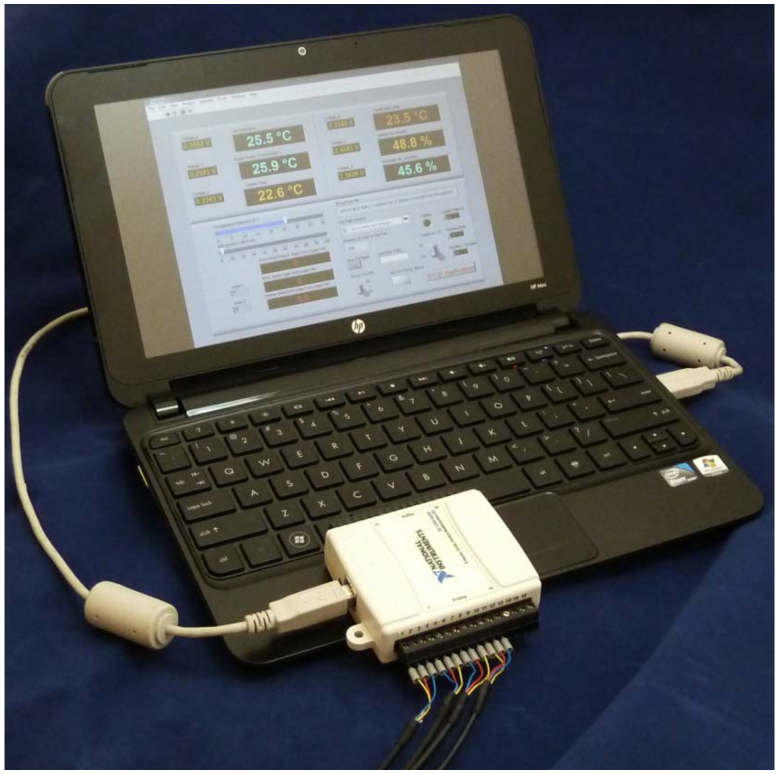

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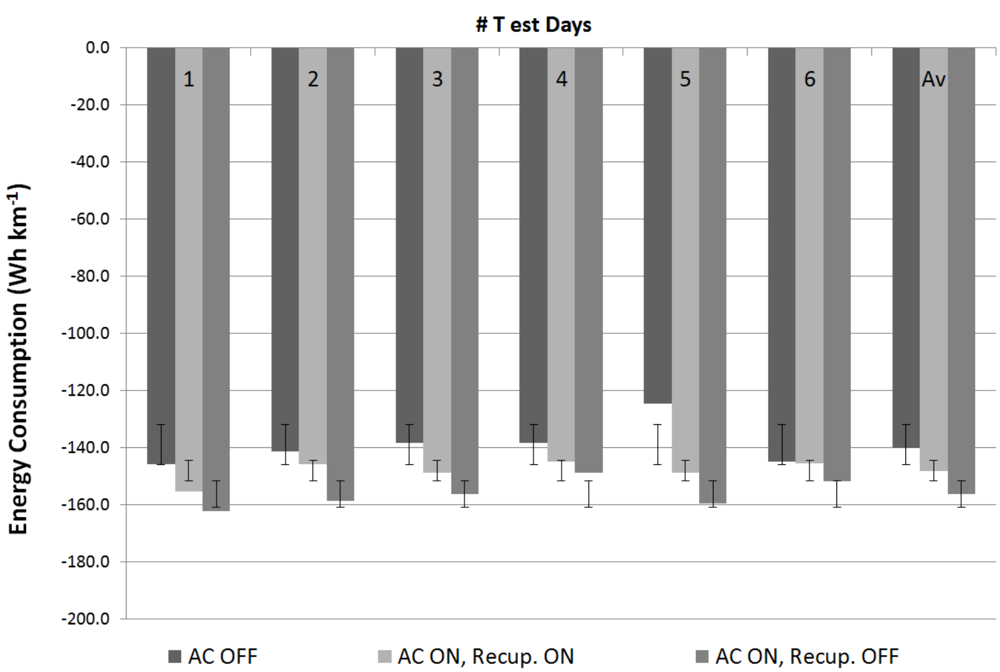


Figure 9 EV speed profile and compressor status operated primarily by recuperation.

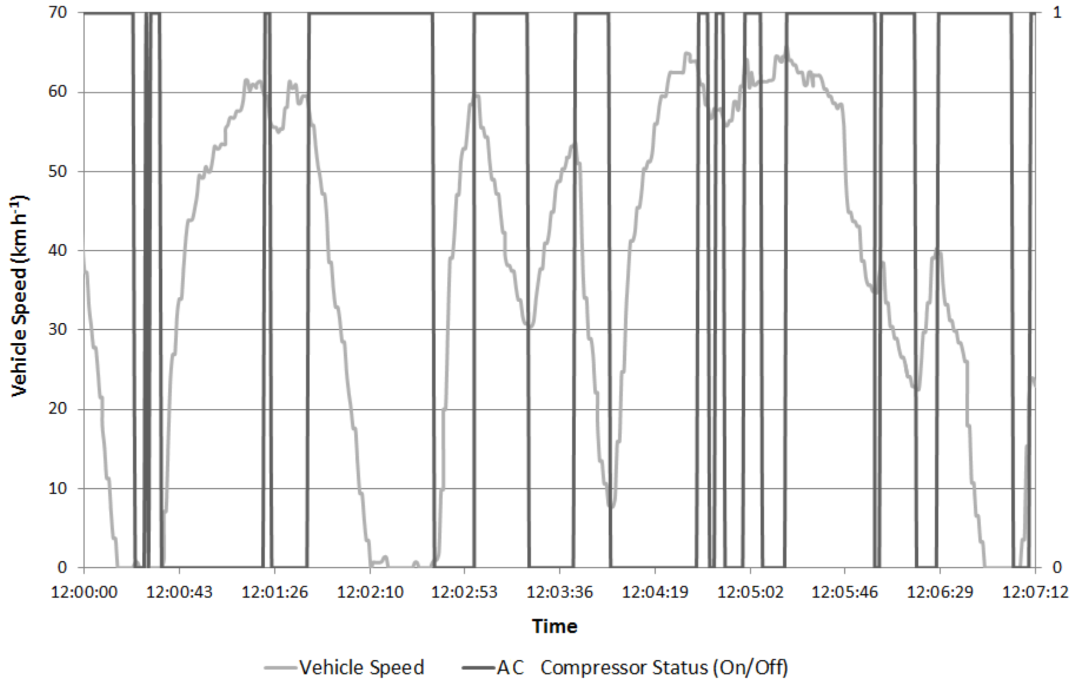


Figure 10 Vehicle chassis temperatures during the course of the experiments.

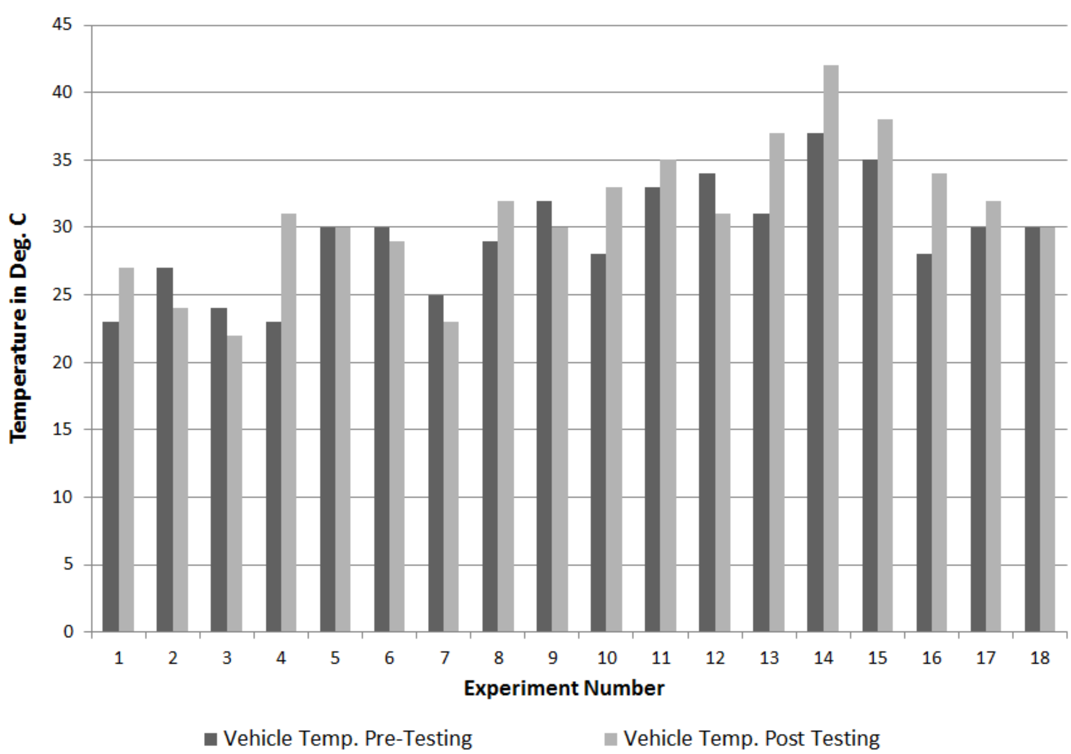


Figure 11 EV passenger compartment temperature fluctuations over 16 minutes of a test drive.

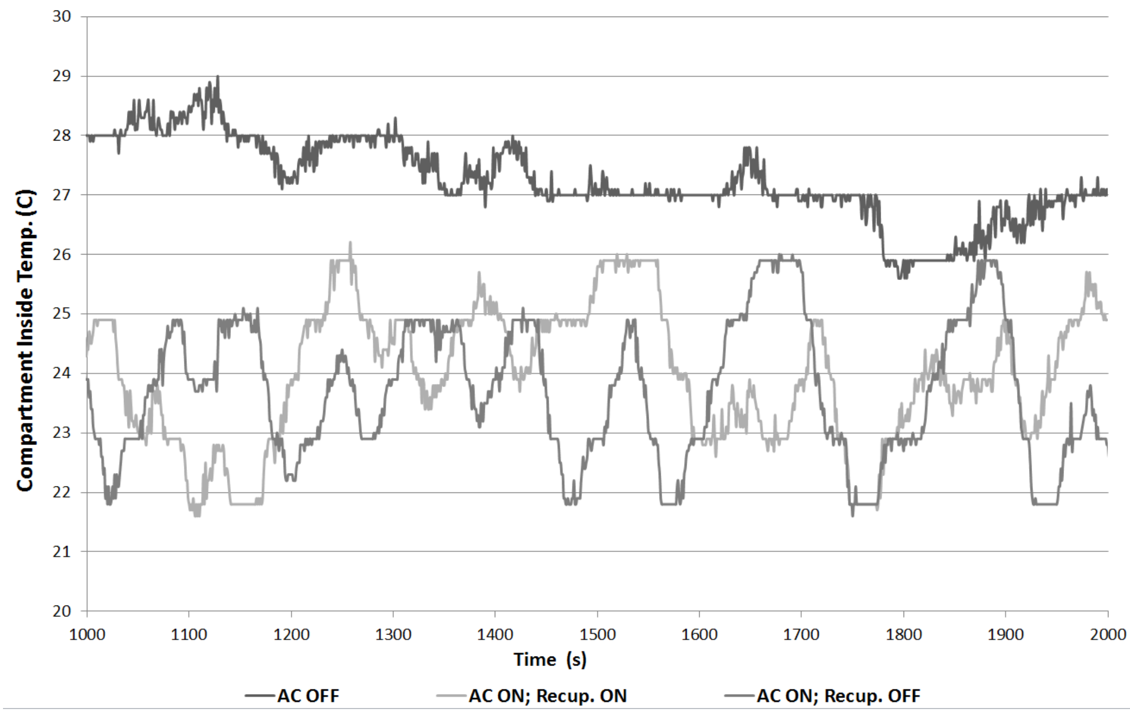
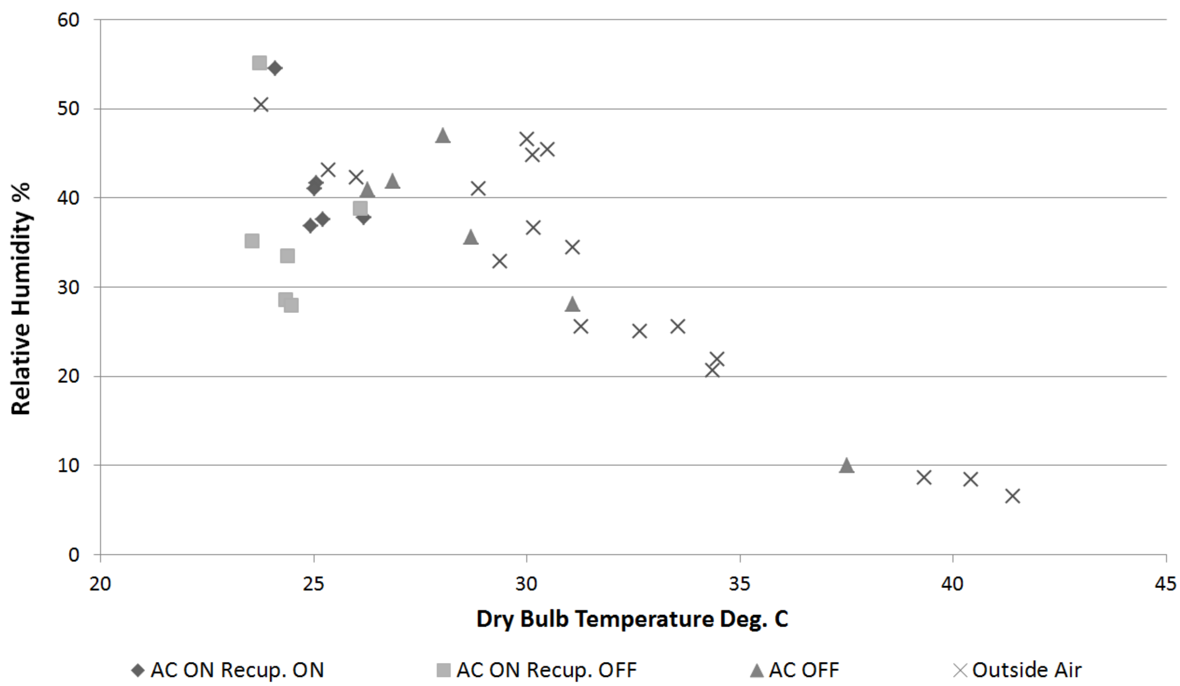


Figure 12 Outside air and passenger compartment mean temperatures and humidity over the six test days under different driving configurations.



Biographical notes

Guido Wäger

Guido Wäger is a PhD student at the University of Western Australia, Perth, where he investigates inefficiencies in operating electric vehicles (EV). In addition he carries out research into the economic and engineering feasibility of EV fast-recharging stations in remote highway areas of WA where no electricity grid is available. His background in energy science, extensive experience in the automotive industry, and more than 6 years of working in research and development in the automotive engineering industry underlay's projects in his research area of electric vehicles and infrastructure.

Professor Dr Thomas Bräunl

Thomas Bräunl is Professor at The University of Western Australia, Perth, where he directs the Renewable Energy Vehicle Project (REV), having converted several road-licenced cars to battery-electric drive. He is Technical Director of the West Australian Electric Vehicle Trial and the Principal Investigator of the ARC Electric Vehicle Fast-Recharging Project. He has worked on Driver-Assistance Systems with Daimler and on Electric Vehicle Charging Systems with BMW. Professor Bräunl holds a Diploma from Univ. Kaiserslautern, Germany, a M.S. from USC, Los Angeles, and a PhD and Habilitation from Univ. Stuttgart.

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Jonathan Whale is a Senior Lecturer in Energy Studies and Renewable Energy Engineering in the School of Engineering and Information Technology at Murdoch University, Perth, Western Australia. He has worked in the area of sustainable energy in the UK, USA, and Australia over the last 22 years, including periods working on projects with the International Energy Agency (IEA) and the US National Renewable Energy Laboratory (NREL). Jonathan was director of the National Small Wind Turbine Centre in Australia from 2009 - 2013 and was a Research Fellow at the Hanse-Wissenschaftskolleg Institute for Advanced Study in Germany in 2013.

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Mark researches within the School of Engineering and Information Technology at Murdoch University, Australia. Mark's diverse research interests include: clean energy technology; agricultural system productivity; international, regional, and rural development; technology performance; energy policy; carbon markets; water technology, and research collaboration. Mark has an extensive publication history in peer reviewed journal articles and edited books, and is involved in various international collaborative activities as a Fulbright scholar (USA), an Endeavour Research Fellow (Philippines), and with several projects in Australia, South Africa, Mozambique, Tanzania, Kenya, Nigeria, etc.