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Carnot's Cycle Does Have a Long Road Ahead- But what about Fuel Cells?

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Slide 1. A thought starter.

Slide 2. Two, as yet, unanswered questions relating to automotive fuel cells.

Slide 3. 1824 sets the time scale for the publication of the most significant analysis of heat engines and their efficiency. This analysis still applies today to all engine systems using combustion processes, including power generation, aircraft, marine, automotive, heavy truck and earth moving.

Slide 4. A painting of Sadi Carnot, aged 17 in 1813, in the military uniform of a pupil at the Ecole Polytechnique in Paris. His paper of 1824 is his only known technical publication; this set the basis of thermodynamics but was ignored for many years. The paper would today be called a 'thought experiment', well before this description was used of Albert Einstein's papers of 1905. If the Noble prize existed in 1824, Carnot would have been a deserving recipient of the award.
He died in 1832 at the age of 36 following complications of scarlet fever and cholera.

Slide 5. The two fundamental axioms of the thermodynamics of heat engines.

Slide 6. Apart from early steam engines for pumping mines, the first regular steam powered ships were coming into use in the early 1800's, before Carnot's paper was published. Much uncertainty existed on such matters as how big a ship should be to carry enough coal to cross the Atlantic. The *Clermont,* first called *Steam Boat,* was an unexpected success, running from New York to Albany on a regular schedule and able to carry up to 140 passengers. She was in service for 7 years, powered by an engine from Boulton and Watt in the UK.

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Slide 7. The basic electro-chemistry of the fuel cell, pollutant free.

Slide 8. An overview of the massive world-wide interest in automotive fuel cells.

Slide 9. Compared to the well ordered and understood key characteristics of the modern internal combustion engines , in high volume production, designed to fully meet consumer expectations, several key open issues remain for ongoing fuel cell development to solve.

Slide 10. The basic reason why the fuel cell has such a strong attraction as a non-polluting high efficiency automotive power plant, provided low carbon renewable sources of hydrogen are developed to economic reality.

Slide 11. A further look back in history, now to the 1960's. The prospect of severe emission controls raised very serious doubts on the long term survival of the conventional reciprocating internal combustion engine, Otto or Diesel. Many hundreds of millions of dollars were spent by the 'Big Three' on designing and developing prototypes of combustion engines with potentially lower exhaust emissions.

Slide 12. A prototype produced in the UK of a gas turbine car.

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Slide 13. Shows a full size 'one-off' tractor trailer unit built in the late 60's, known as 'Big Red', powered by a Ford gas turbine, delivering 600 HP. This did not get beyond the prototype stage and efforts to make a marine version were no more successful, despite up to 100 prototypes being scheduled for build. Two important developments did emerge from these efforts. The regenerator in the Ford gas turbine was a large slowly rotating disc of ceramic honeycomb, made by Corning under licence from the Imperial Chemical Industries in the UK. This material later became the widely adopted substrate for exhaust gas catalysts, saving the ICE. There have been comments that the small automotive gas turbine technology and the larger Ford unit evolved into power systems in military applications.

Slide 14. Despite the large effort on the above alternatives, the reciprocating ICE is still the dominant automotive power plant.

Slide 15. This poses the most critical question facing the possible application of the fuel cell in high volume automotive use. The continuing development of the ICE systems has not slowed but is accelerating. Applicable technologies that will help to challenge the fuel cell include several in the 'pipe-line' and some not yet exploited.

Slide 16. The fuel cell is dependent on the availability of hydrogen from non-fossil and renewable sources. Much work has been done to establish how an ICE can burn hydrogen successfully. This slide picks out some key papers presented in September 2006 at Graz in Austria that showed the practical embodiment of hydrogen as fuel for conventional reciprocating engines

Slide 17. As shown by Carnot in 1824, the installed thermal efficiency is a key factor This slides refers to some background information showing that the installed thermal efficiency (actually, conversion of chemical energy to electrical output) of a fuel cell, whilst exceeding that of an ICE, may not have a big enough margin to be the outright winner.

Slide 18. Greenhouse gas emissions are an important discriminator for any proposed power system. It has been known for quite some time that the hybrid diesel presents a serious challenge to the fuel cell, especially when sustainable bio-fuels are available.

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Slide 19. A schematic of how the Torotrak plc Infinitely Variable Transmission operates to provide a continuous, step-free, link between engine output and the drive train. In combination with a simple epicyclic gear set, the IVT provides a very flexible link between engine and drive train such that the best use can be made of the fuel efficiency 'sweet-spot' characteristic of an ICE over much of the vehicle operating envelope.

Slide 20. The results achieved when replacing the 5-speed AT by a Torotrak IVT in a city passenger bus.

Slide 21. A comparison between the theoretical engine operating points for the IVT's optimal control line and those of the 5-speed AT, for the same duty.

Slide 22. Measured results for operating points on the city bus route for the IVT and the 5-speed AT.

Slide 23. The flexibility of an IVT lends itself to the layout of a simple but effective hybrid with potential for further gains in fuel consumption and greenhouse gas reduction

Slide 24. The IVT is playing a key role in the advent of Mechanical Hybrid Kinetic Energy Recovery Systems advocated by Torotrak. These use a flywheel to store energy recovered during the deceleration of a vehicle, later released to accelerate the vehicle. This type of KERS is imminent in the 'Flybrid' system proposed for Formula 1. Similar systems have been demonstrated in the past for a passenger bus and new proposals are coming forward to extend this possibility to other vehicles. This slide gives a schematic for a Mechanical Hybrid using the KERS with an IVT. As up to 30% plus of the energy provided by the engine driving through a typical city cycle is wasted in braking, significant greenhouse gas reductions follow by the recovery process. The more aggressive the driving style, the more braking energy is available for recovery by a flywheel

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Slide 25. There is a clear possibility that a KERS system with an IVT would be capable of running engine auxiliaries using flywheel energy alone WHEN THE ENGINE IS STOPPED. The widespread adoption of the previously explored ‘stop-start’ engine systems could follow when auxiliaries are sustained in an extended ‘stop’ period. The IVT as developed currently by Torotrak plc in the United Kingdom has sufficient flexibility to ensure the flywheel is re-energised using the ‘sweet-spot’ operating point of the engine when deceleration energy is not available.

Slide 26. This shows a possible metal flywheel capable of storing deceleration energy, say 0.5 kWh, and using this to accelerate a passenger bus from rest. The Kestrel activity is still in development today. In 1985 a flywheel based on a ‘fail safe’ composite material design was demonstrated in a passenger bus.

Slide 27. Some broad brush comments on the eventual outcome of the efforts to develop the fuel cell into the ideal power source for automotive application.

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