Brake energy recovery in urban transport

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Abstract

Urban transport is estimated to account for up to 16% of global CO₂ emission, of which up to 40% is due to energy dissipated in friction brakes. Hybrid propulsion systems incorporating efficient energy storage not only allow the optimal operation of the engine at constant speed and load but also allow brake energy recovery. Moreover, electric vehicle ride quality and passenger comfort is offered without the need for overhead electrification.

This paper describes a flywheel energy storage system, with 93% energy storage efficiency, developed for passenger transit vehicles by which over 30% fuel savings can be achieved on urban driving cycles. The constant load on the engine allows a variety of prime movers to be considered, including the gas turbine and the fuel cell. A hybrid system comprising flywheel energy storage and a gas turbine as prime mover, developed in the ULEV-TAP project, is described, along with proposed tests and demonstrations on a light rail vehicle. The test vehicle is to be demonstrated in operation in Reichshoffen during the PROSPER congress in Karlsruhe, 19/20th September 2001 [10]. In addition, a bus application, using a 2 litre gas engine as prime mover, is described, which will also be demonstrated in PROSPER.

The ULEV-TAP system is expected to find application on light rail routes, and on bus routes where trolleybus standards are required but where electrification is unjustified, intrusive or impractical. Adoption of the technology throughout urban transport worldwide could result in a saving of up to 5% in global CO₂ emissions.
1 Introduction

The transport sector, which is causing increased congestion and pollution in our cities, will need to undergo radical transformation if these adverse trends are to be reversed. Development of collective transport can contribute to this in three ways -

- by making such transport an attractive alternative to private car use
- by improving the energy conversion efficiency of the engines
- by recovery of brake energy

Adoption of hybrid propulsion technology can contribute in all three cases by

- use of electric transmission to improve ride quality
- use of clean engines or fuel cells at optimum efficiency
- use of an efficient energy storage system

The technology is now available and currently being demonstrated on buses and will shortly be demonstrated on a light rail vehicle [10]. It could also be applied to a range of vehicles which are subject mainly to urban drive cycles where brake energy recovery is most effective. This includes waste trucks and delivery vehicles. The technology is also being applied in the automotive industry with the advent of hybrid vehicles such as the Toyota Prius and the Honda Insight. The high fuel efficiency of these cars is due to the small engine size and efficient engine operating conditions. It is estimated that if 30% energy savings could be achieved in urban transport, by use of hybrid propulsion, global CO₂ emissions could be reduced by up to 5% [1].

2 Design considerations

In hybrid vehicle design, the higher the energy storage capacity provided, the smaller the engine needs to be. At one extreme, the pure electric vehicle relies totally on electrical energy storage whilst at the other, the conventional vehicle relies on energy stored in the fuel tank. Hybrid vehicles lie in between these extremes and combine the benefits of each. Urban driving conditions favour the use of sufficient electrical energy storage for assured brake energy recovery, whereas motorway conditions require an engine which can maintain maximum speed continuously. On road vehicles, hill-climbing capability is also an important consideration. The fundamental point is that the energy storage has to be able to assist the engine during acceleration and to absorb brake energy, whilst the engine has to overcome average energy losses, including aerodynamic, wheel, transmission and auxiliary. In urban centres, these are lower on average than on fast motorway runs. These design considerations are discussed more fully by Jefferson and Barnard [2].
3 The CCM hybrid bus demonstration

At present, hybrid systems are perhaps most advanced in buses. Applications in cars have tended to be limited in their brake energy recovery capability because full capability would presently require an excessive weight of battery storage. This is because of the limited capacity of batteries to accept high levels of regenerated power and also because of their limited cycle life, particularly on deep discharge [3]. Because cars are also used for long distance high speed journeys, the scope for reducing engine size is limited.

The research and development company CCM in the Netherlands has been investigating the use of flywheel energy storage and has successfully demonstrated it in a hybrid bus, in urban operation, using a 2.6 litre Audi car engine as prime mover [4]. The engine runs on liquified petroleum gas or petrol.

The bus has been demonstrated in operation in Eindhoven and up to 30% fuel savings and, compared with standard diesel operation, 90% reductions in harmful emissions have been achieved, resulting in EURO V limits being effectively met by substantial margin.

The principle of operation is that, at the start of the journey, the flywheel is charged up by the engine (or by external power if in the depot). There is then sufficient energy in the flywheel to accelerate the vehicle to full speed and consequently sufficient capacity to recover brake energy. In fact, the capacity is sufficient to power the vehicle over a distance of 2km without the use of the engine, if required. The gas engine generates approximately 35kW of electrical
Figure 1 Simulated hybrid bus start-stop cycle over a 500m distance.
power, which is sufficient to cover all losses and auxiliary. It thus provides unrestricted range in urban areas. The engine power can be increased to 70kW to maintain continuous higher speeds, for instance, on motorways, if required. Figure 1 shows the results of a computer simulated start stop cycle over a distance of 500m with a maximum speed of 50 km/h during 20 s. The simulation model SIMTRIP is described in detail by Ackerman and Jefferson [3]. These results support the conclusions of the test results showing that a 35 kW prime mover is sufficient in this application. This makes the commercial application of future prime movers such as the fuel cell far more viable in the short term, since only a 35kW power source is required, rather than the 150kW required for a conventional bus. The model has since been developed to predict vehicle emissions [7] and the results support the claim that EURO V standards are met by a clear margin.

4 The ULEV-TAP project

This system has been developed under the EU BRITE EURAM project ULEV-TAP for a light rail vehicle. An ex-service Karlsruhe tram is being converted in order to test and evaluate a hybrid propulsion system comprising a compact direct-coupled gas turbine and high speed alternator and a high efficiency flywheel energy storage unit. The latter is a development of the flywheel system used on the CCM bus to give higher power and energy storage capacity.

The ULEV-TAP demonstration hybrid tram

The aim of the project is to deliver the same electrical demand power as would be drawn from the overhead supply, and also to recover brake energy. The tram
will thus be able to operate in autonomous mode, i.e. without using the overhead supply, without any reduction in performance. It is estimated that, though the peak power demand of the traction motors exceeds 230 kW and the energy storage system is designed to deliver or absorb 300 kW, the demand on the prime mover (engine), in city centre operation, is estimated to be under 40 kW, because of the very low energy losses. This is predicted by computer simulation using SIMTRIP [3] and is to be verified shortly during the test programme. The tram is to be demonstrated during the PROSPER congress [10].

5 The ULEV-TAP drive system

Figure 2 presents the basic structure of the power and the data connections of the subsystems. All components of the power system are built up around a common DC-bus. The prime mover unit (PMU) consists of a gas turbine with direct-coupled high speed generator and a rectifier [8]. The PMU is able to provide the average power the vehicle needs for its duty cycle and to overcome all energy losses. A DC/DC chopper unit (DCU) adapts the rectifier output voltage to the DC-bus. The starter unit (SU) consists of an inverter, which accelerates the gas turbine by the generator (acting as a starter motor). A vehicle auxiliary supply (VAS) covers the required auxiliary power and two voltage levels are provided.

Because of the existing motor technology of the demonstration vehicle, a drive brake chopper unit (DBU) has been incorporated into the traction system. During regenerative braking, the recovered kinetic energy is stored in the energy storage unit (ESU) as on the CCM bus. The ESU consists of a flywheel (a larger version of the CCM flywheel) with power inverter [5]. The ESU assists the PMU during vehicle acceleration.

The central control element of the hybrid vehicle is the supervisory control unit (SCU) which is the master of system and mainly responsible for safe vehicle operation. It is responsible for power management between the units. For data communication between the units, a communication line conforming to the Control Area Network standard (CAN) is used. The vehicle can be supplied by overhead line or autonomously, as described here, and can thus operate in dual mode.

Because of its relatively high dynamic, the control of the DC-bus voltage is one of the most important aspects of this project. The control of the DC-bus voltage is achieved in the same way as for the CCM hybrid bus [6]. To control the DC-bus voltage at a constant value (650 VDC), the following condition must be continuously satisfied.

\[ I_{PMU} + I_{ESU} + I_{VAS} + I_{DBU} = 0 \]  

(The sum of all currents amounts to zero)
In order to achieve the lowest emissions of the PMU, the SCU manages the power of the PMU ($I_{\text{PMU}}$) to be nearly constant and equal to the average vehicle losses. This requires the link voltage between the subsystems likewise to be held nearly constant.
In order to be highly responsive to the driver traction demand \( (I_{DBU}) \), the SCU controls the ESU current \( I_{ESU} \) very dynamically. To increase the dynamic of the voltage feedback controller, a load current feed-forward element is used. The controlling element ESU works like a fast current source. It receives its set point from SCU using a special fast-CAN communication line. Guarding this unidirectional fast-CAN line is achieved using standard CAN-communication.

### 6 Applications

The ULEV-TAP system can be applied wherever the load imposed by the vehicle follows the typical urban drive cycle. It therefore applies mainly to urban passenger transit vehicles, delivery vehicles and waste trucks, for example, where the driving conditions involve a particularly high frequency of start-stop cycles. This applies in urban traffic fairly generally and it can also apply in other applications such as cranes and local or emergency power supplies, which are subject to rapid power demand fluctuations, for which the system is designed to cope. The flywheel effectively acts as a load leveller, as well as a sink for regenerated power.

In urban fleet transport, an advantage of the system is the wide choice of prime movers (including fuel cells) and clean fuels which can be used. In the demonstration described above, a gas-turbine engine generator set is being evaluated, particularly for its smooth operation and low maintenance cost. A further advantage of the ULEV-TAP system is the electric transmission system giving the ride quality and performance equal to fully electrified trolleybus or light rail systems, so could be equally effective in attracting passengers from private car use.

Adoption of hybrid propulsion technology can thus be considered as a viable and less costly alternative to electrification, particularly on less intensive routes, but with the increased environmental benefits of lower energy consumption and visual intrusion. Indeed, many cities are considering the introduction of light rail systems for environmental reasons but are dissuaded by the investment cost or the impact of overhead wires in city centres [9]. Hybrid powered light rail transit (LRT) vehicles are foreseen, for example, for the new LRT system in the region of Braunschweig. Most of the regional railway tracks are not electrified and electrification would be very expensive. In this case it was recommended to use dual mode vehicles (750V and diesel or other available prime mover units). The hybrid option would be particularly suitable here, and also in the regions of Schwerin or Tübingen, which are considering similar light rail systems. In Tübingen, the integration of overhead wires in the city centre is a particular problem. Here, the hybrid flywheel system could provide an effective solution.
7 Conclusion

Hybrid propulsion technology, using a clean prime mover and efficient energy storage can offer

- the benefits of the performance and quality of electrified systems without the need for electrification,
- up to 90% reduction in emissions relative to the diesel engine,
- up to 30% fuel savings.

Adoption of hybrid propulsion technology in transport generally could result in 5% reduction in global CO₂ emissions.

Though other technologies, such as weight reduction, could also yield benefits, given the increasing necessity for the introduction of energy saving measures to combat global warming, brake energy recovery could make an important and cost effective contribution. Moreover, the hybrid system described here could considerably increase the viability of urban passenger transit schemes by avoiding the need for electrification. The environmental quality of many urban centres could thus be considerably improved without major infrastructure costs.

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The partnership was lead by Alstom DDF, Reichshoffen, France, who were also responsible for preparation of the test vehicle and management of the test programme. The prime mover unit comprises a compact high speed gas turbine with a direct-coupled alternator, the result of development by the company Turbomeca, Bordes, France who supplied the gas-turbine, and Imperial College, London, UK, who developed the high speed alternator and who were also responsible for the technical management of the project. Further design work on gas turbine optimisation was undertaken by the National Technical University of Athens.

The energy storage unit was developed by the company CCM. The drive brake unit (DBU) and the supervisory control unit (SCU) were developed by the company Kiepe Elektrik, who were also responsible for electrical integration. The Porto passenger transport undertaking STCP evaluated the system for an articulated bus. The Karlsruhe passenger transit company VBK and the rail transport consultancy TTK provided the test vehicle and are evaluating the project for potential light rail applications. The University of the West of
England, Bristol was responsible for vehicle performance modelling and for analysis of the system in a range of end use applications.

References


