Economics of Bus Drivelines

Contents

Executive summary

The economics of bus drive-lines is described in terms of the principal components which may be either mechanical or electrical in nature. The factors influencing the market for such components are discussed as well as possible improvements in efficiency. Generic drive-lines are identified which will meet the Government's target of 30% reduction in carbon consumption: one is all mechanical, the second all electric and the third is a hybrid diesel/electric.

The capital and operating costs are derived for these three systems based on information derived from the principal suppliers. Computer simulation is used to model the key parameters like mass, speed and passenger load as a function of fuel consumption and local pollutants.

It is concluded that electric drive-lines are much more efficient than diesel or diesel/electric drive-lines in terms of primary energy and much less polluting. Consequently the bus market could contribute a significant amount to the UK's 2020 carbon goal and using the same technology for urban delivery vehicles in a subsequent phase could double such savings.

The option is considered of modifying the subsidy formula to transform the economics and encourage the investment in energy efficient buses. Both a capital and operating allowance should be considered based on the overall efficiency and carbon content. In this way it would be possible to reduce operating costs, fares, subsidies, local and global (carbon) emissions. Any revised formula should also be available to operators willing to retrofit their existing stock.

The UK bus market is too small to influence the major component suppliers and so the UK should request the European Commission to set a European target for low carbon buses as part of the Commission's new directive on energy efficiency of vehicles scheduled for drafting by this autumn.

This report has been prepared by Rayner Mayer, Sciotech Projects and University of Reading, and Terry Davies, University of the West of England, Bristol.

1. Introduction

The Department for Transport is reviewing the bus subsidy formula [1] and has posed a number of options for revising the formula. Sciotech Projects, like some other organisations, has suggested a further option based on distance covered [2]. One advantage of this last option is that it could be applied to all types of drive-lines and not simply to internal combustion engines as at present.

At the request of the DfT, this study therefore examines the likely capital cost for drive-line components and its impact on pollutants during inner city operation. The inherent difficulty is to decide what technology, what time frame, how to price components when no market for these currently exist and what happens to these components when they are assembled into a drive-line.

The information within this study is based on the authors' personal knowledge over the past 25 years, in surveying component suppliers and discussions with knowledgeable persons within the industry.

There has been little improvement (if any) in energy efficiency over the past 25 years because any increase in drive-line efficiency has been counteracted by an increase in both bus mass (up to 50% in the case of double-deckers) and in traffic congestion, and also partly because the present subsidy provides limited incentive to save fuel. .

The bus industry by its very nature is very conservative because of the need for high reliability. We have therefore only selected technology whose technical promise has been demonstrated in buses i.e proof of concept. In addition we only consider technology which when combined with other components can deliver 30% or more improvements in efficiency. This coincides with the Government's target for low energy buses [3]..

We do not consider existing drive-lines which can be low carbon by substituting one or other form of biofuel as we adopt the SMMT viewpoint [4] that such fuels are best used as fuel extenders to supplement existing liquid hydrocarbons.

2. Background on Electric drive-lines

Electric drive-lines were used in the first vehicles to be manufactured. The introduction of the carburettor, fuel pump and starter motor allowed internal combustion engines to take over. As oil was cheap and easy to obtain, this became the dominant technology..

However electric drive-lines are by their nature continuously variable transmissions, a technology which mechanical drive-lines have yet to adopt. Such transmissions give smooth acceleration and deceleration and the inherent ability to save the inertial energy of the vehicle on braking. This latter attribute is a prerequisite for vehicles whose motion is dominated by the stop/start nature of city traffic.

The biggest current market for electric drive-lines is the ubiquitous milk float, which encapsulates all the requirements of inner city traffic. This has demonstrated that electric drive-lines are very durable, easy to maintain and cheap to operate, all attributes that bus operators would find desirable. In terms of fuel usage, the typical consumption of a diesel bus is 50 litres/100 km equivalent to 36p/km (full cost including duty and VAT). An electric bus uses 0.7 - 1.0 kWh/km or 6p/km. Electric buses are therefore very cheap to use.

As one litre of diesel fuel has the energy content of 10.8 kWh, 50 litres/100 km gives an energy content of 5.4 kWh/km. Thus electric drive-lines are typically five times as efficient as diesel drive-lines in terms of energy usage. A similar reduction in carbon emissions is attainable if electricity is produced from renewable energy sources.

In terms of local pollution, electric drive-lines have zero emissions and so can operate in clean air zones such as city centres. They are also much quieter in operation and induce less ground borne vibration.

If one day fuel cells become a commercially viable source of energy then the electric drive-line will be the enabling technology which will use the electricity to drive the vehicle and recover its inertial energy on braking.

3. Factors influencing the market for drive-line components

Diesel drive-trains

The market for buses is small compared with that of trucks - in the UK some 3000 city buses are sold annually compared with 100,000 or more trucks. So engine development emanates from trucks rather than buses, and EU legislation now requires Euro 3 emission levels which concern local rather than global emissions like $CO2$.

The most noticeable development of engines has been the down sizing of engines sizes typically from 9.6 to 7.3 litres in the case of Volvo. The same power output is achieved with the smaller and lighter engine with no reduction in emission quality.

Engines now-a-days are built into the bus, almost always at the rear in order to maximise the low floor area. Engine life is now typically 15 years and does not have to be removed from the vehicle for overhaul, due primarily to advances in lubrication. Some manufacturers only supply to their own assembly plants whilst others sell to a world wide market.

Gearboxes on the other hand are specifically designed for bus operation as smooth acceleration is required rather than simple automatic gear changes. Such gearboxes are generally epicyclic in nature and manufactured by specialist manufacturers.

Continuously variable transmissions (CVT) are a stepless type of gearbox whose development has been pursued intensively since the mid 1970s. The industry has recognised the potential of the technology but has not yet accepted it as necessary. Such types of transmission enable significant savings to be made in fuel consumption and reductions in pollution because the diesel engine is driven as much as possible within the most efficient torque/speed range.

CVT's such as the Perbury type transmission have two further advantages for bus drive-lines - their very smooth acceleration and their ability to recover the inertial energy of the bus on braking. They are currently being developed for the non bus market and so scale of volume could be realised unlike with conventional bus transmissions.

Electric drive-trains

Unlike diesel drive-trains which are a mature market, electric drive-trains are still an emerging technology. The simplest concept of an electric drive-train is a direct current (dc) link to which all the sources of and sinks for electricity are coupled electrically. This concept is common for suburban trains, light rail and trolley buses as the dc link voltage is maintained by the supply of energy from or to the net(grid).

However for electric buses there is no direct connection to the net and so the dc link voltage can vary. The prime method of supplying energy to the dc link is by using batteries, but the dc link voltage will fall as the batteries lose charge. Recharging at bus stops, on board storage like flywheel or a small diesel generator are the preferred means of maintaining the dc link voltage but are still at the demonstration stage.

The result is that there is at present no agreement on the level of the mean dc link voltage for electric buses nor the permissible fluctuations about the mean value. This makes coupling of components from different suppliers difficult and costing very difficult.

Current technology of electric drive-trains is based on that of traction drives which is dedicated technology requiring high power levels. There is no reason in principle for light weight city buses why industrial drive technology should not be used. These are sold in large numbers for driving pumps and motors for example so scale of volume is already being achieved. However this technology has yet to be fully demonstrated in buses.

Traction motors can be reduced in size and weight if cooled usually by water. This waste heat can then be used for space heating during the winter. For low speed, direct drive to wheels such as hub motors, permanent magnet motors offer the highest efficiency and the most compact size. Alternatively a high speed electrical machine operating through a fixed ratio, high efficiency gear box can provide a smaller and lighter alternative.

A further advantage of the hub motor is that the power flows are all by cable and so can eliminate the rear axle and traction motor. However the market demand for such motors has so far been very small and so they have only been produced in small batch quantities.

Batteries

For traction usage, special design of battery plates are used to permit high currents and deep discharges. The battery life is therefore limited and is the biggest single operating cost for electric buses. The current choice lies between lead acid, which is heavier but cheaper, and nickel metal hydride (NiMH), which is lighter but more expensive. The NiMH battery is able to take larger depth of discharge than the lead acid battery. It is also able to give and receive charge at a greater rate. It has generally been used for cars where the space constraint can offset the extra cost. Lead acid has generally been favoured for buses since space is not really a constraint but cost is a major factor.

High temperature sodium/sulphur batteries are now also becoming available which have higher power and energy densities than the other two types. This battery has been used in a number of bus demonstration trials including IVECO, MAN and Daimler Chrysler. A high system voltage is also available thus reducing the need for a static convertor to increase the battery voltage to that of the dc link.

Storage systems

Flywheel storage is the most advanced technology with both Magnet Motors and BP KESS systems being ready for scaling up to volume production. The BP system can be used with either mechanical or electrical drive-lines whilst the Magnet Motor system is only suitable in its present form for electric drive-lines.

Supercapacitors are being demonstrated in one city bus operated by MAN to prove the concept and so are not considered further.

Hydraulic pump storage was demonstrated in the early 1980's by storing compressed gas. This technology has been refined by Ifield Technology and consists of an integrated pump/motor/storage system. Proof of concept has been recently demonstrated by Ford on a utility vehicle.

Drive-by-wire

Drive-by-wire is now standard in all drive-lines as the driver's request to speed up or slow down the vehicle can now be undertaken in the most economical and least polluting way. For diesel drive-lines this results in the transmission and engine controllers talking to one another in order to ensure the optimum engine torque for a given gear ratio.

4. Possible improvements in efficiency

Drive line

There has been substantial advances in all the enabling technologies since the last oil crisis of 1978 - 1980. Moreover some of these advances have been applied together rather than individually. Where these have been used in non-transport applications, they are now able to be applied to drive-line components. These are summarised in table 4.1

Table 4.1: Advances in enabling technologies

Engine technologies	advances in engine combustion and reduction in local pollutants through micro-processor control (Euro series of engines)
Diesel generator	improvements in small diesel engines follows that of large engines
Batteries	better understanding of resistance losses and potential for fast charge regimes
Microprocessor control	improvements in basic speed and processing capability
Continuously variable transmissions	improvements in design know how (Torotrak)
Lubricants	development of synthetic lubricants and traction fluids (Shell)
Traction drives	increase in switching speeds and power ratings of semi-conductor devices
Traction motors	use of rare earth materials to reduce eddy current losses; development of high speed motors
Flywheel storage systems	advances in fibre reinforced plastic materials and moulding technology

The corresponding increase in drive-line efficiency when these technologies are applied can be ranked in terms of the contribution of the individual components. These are summarised in table 4.2 for diesel drive-lines and table 4.3 for electric and diesel/electric drive-lines.

Table 4.2: Possible efficiency improvements in diesel drive lines

Component	Possible Efficiency Improvement	Comment
Euro 3 engine	base line	
Euro 4 engine	?	by 1 October 2006
Continuously variable transmissions (CVT)	10 - 15%	like Perbury
CVT + regenerative braking system	25 -30%	requires on board storage like flywheel

From table 4.2, it can be seen that the key to improving the diesel drive-line efficiency is the introduction of a continuously variable transmission in place of the current automatic transmission. This also allows a regenerative storage unit like flywheel to be added.

For the diesel/electric hybrid, the simplest solution is to use a small diesel engine close to its optimum efficiency to drive an electric generator. The remainder of the drive line is electric enabling the optimum torque to be provided to the drive wheels. The electricity generated will also maintain the dc link voltage and the charge state of the battery thus enhancing the efficiency of the battery.

Table 4.3: Possible efficiency improvements in electric drive lines

Component	Possible Efficiency Improvement	Comment
Traction drives	base line	
Industrial drives	2 - 3 %	
Traction motors	base line	
High efficiency motors	1 - 2 %	
Battery lower depth of discharge	5 - 10%	dc link voltage kept within close limits
Small diesel generator	2 - 5%	helps maintain dc link voltage so increasing battery efficiency
Regenerative braking system	25 - 30 %	requires on board storage like flywheel

For the pure electric bus a regenerative drive-line will clearly extend the range by storing the braking energy, but even more importantly will help maintain the dc link voltage so getting the extra efficiency gain out of the battery pack.

Chassis and body

There is scope for further improvements in efficiency by reducing mass in both chassis and running gear and the aerodynamic drag of the body.

Waste heat

It is also possible to reduce the energy demand of auxiliary components primarily that of climate control. Waste heat from diesel engines is already used for space heating whilst the waste heat from electric drive-line components could also be collected and used for this purpose (table 4.4). This base heat supply could then form the input to a water to air heat pump system whose efficiency is typically three times that of normal resistance heating giving a further increase in efficiency.

Table 4.4: Waste heat from electrical drive-line components with 100 kW output

Component	Overall Efficiency	Waste Heat
Traction drive	96% ?	4 kW ?
Traction motor	90% ?	10 kW ?
Batteries	90% ?	10 kW ?

Conclusion

According to this analysis all three drive-lines i.e. diesel plus regen, diesel/electric and electric plus regen, are capable of achieving a 30% efficiency gain against the base line of a current diesel drive line comprising a Euro 3 engine and automatic transmission. The all electric drive-line has the highest potential as electricity can be generated more efficiently at power stations and has the largest scope for efficiency improvements even with current technology.

5. Optimum sizing of drive-lines

Diesel drive lines

Power limits are set by the supply of diesel engines to the commercial vehicle market. So engine powers vary from 100 to 250 kW. Gear boxes are then sized to handle the power flow from the engine.

Electric drive-lines

The power limit of 90 kW provides a step change in terms of costs of the IGBT devices that comprise the motor (traction) drives. So this suggests that the industry should standardise on components rated at 80 to 90 kW for small (midi) buses (defined as upto 10.2m) and 120 to 150 kW for large (city) buses (defined as over 10.2m and typically 12m to 15m in length). These powers are significantly lower than that for diesel drive-lines but this is acceptable because the electric drive-line has a much better speed/torque relationship especially at low vehicle speeds.

It is also very important to keep any additional mass as low as possible -

- a battery pack stores energy much more inefficiently than diesel fuel and one option is to use lighter weight batteries than lead acid
- industrial motors tend to be very heavy so lighter weight traction motors are essential

So the lower the power required the smaller size can be the battery pack and motors.

Regenerative drive-lines

Vehicles tend to decelerate faster than accelerate partly because of traffic conditions and partly because passengers are sitting down when the vehicle is slowing down. So regenerative drive lines which store the energy on braking need to be sized somewhat higher (say 30%) in order to recover a higher proportion of the braking energy.

Conclusion

Because of inherent losses at low loads or idling, power trains should be sized at their lowest limit compatible with vehicle acceleration. The acceleration limit will differ for city buses whose time is mainly spent in stop/start city traffic and those operating country routes and inter city.

6. Capital cost of drive-line components

Methodology

Firms were selected on the basis of their expertise and their demonstrated ability to supply components with the requisite efficiency (table 6.1) A survey form was sent to them and this was followed up by telephonic contact or personal discussions.

They needed to be convinced that these were serious enquiries because the UK is so far the only country in Europe, which has set a target for low carbon buses. Whilst the technology to increase efficiency has existed for some years, no one had ever asked them for budget prices.

Power optimisation has not been required up to now and so no one has seriously considered the lowest power required to perform a particular drive cycle. Providing more power is easy and relatively cheap for diesel drive-lines engines but very expensive for electric drive-lines. So the modelling we have undertaken as part of this work and the previous study for the Department of Trade and Industry has demonstrated much more clearly what is needed for the two size of buses - midi and city.

Table 6.1: Suppliers approached

Bus manufacturers	Transbus	Guildford
Diesel engines	Volvo	Warwick
	Cummins	Darlington
	MAN	Munich, Germany
Batteries	Enersys	Manchester
	Varta	Hannover, Germany
Mechanical transmissions	ZF	Nottingham
	Allison	
	Torotrak	Leyland
Traction drives/motors	Kiepe	Dusseldorf, Germany
	ABB	Manchester
	SRD	Harrogate
	Control Techniques	Newtown
Hub motors	Magnet Motor	Munich, Germany
Flywheel storage	Sciotech Projects	Reading
	Magnet Motor	Munich, Germany
Hydraulic pump/motor/ accumulator	Ifield Technology	Isle of Man

Costs and volume

Budget OEM prices have been obtained from suppliers. Energy sources are all in volume production with the exception of the nickel metal hydride battery and sodium sulphur battery. For the continuously variable transmission, Torotrak only regards itself as a Tier 2 supplier and so volume design and manufacture would have to be undertaken by one of the existing gearbox manufacturers.

For some components like industrial drives, large production may achieve small reductions in costs as higher volumes do not create any bigger savings as silicon pricing is the key issue which relates to volume, power level and packaging.

There is a jump in price above 90 kW level when the design moves from dual power semi-conductor modules with two devices in the same package to single device modules. For traction applications, overloads are somewhat different to those in industrial applications, which will require some additional components and hence higher price.

Actual prices will vary with bus size, etc but the proportion of costs for the various components will remain approximately the same. The typical breakdown of capital costs for components for the diesel and electric base line cases is shown in the pie charts in figure 6.1 and 6.2 respectively. Note how the electric drive-line is dominated by battery costs

Figure 6.1: Typical breakdown of capital costs of drive-line components for diesel bus base line

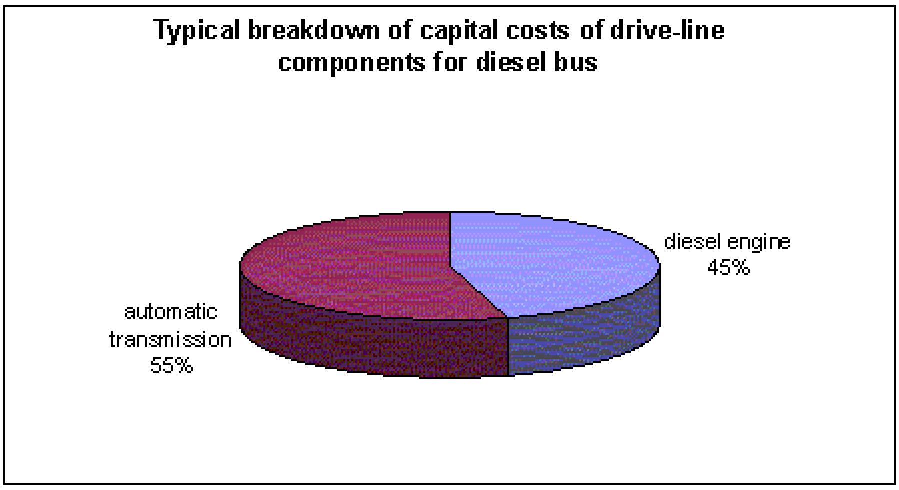
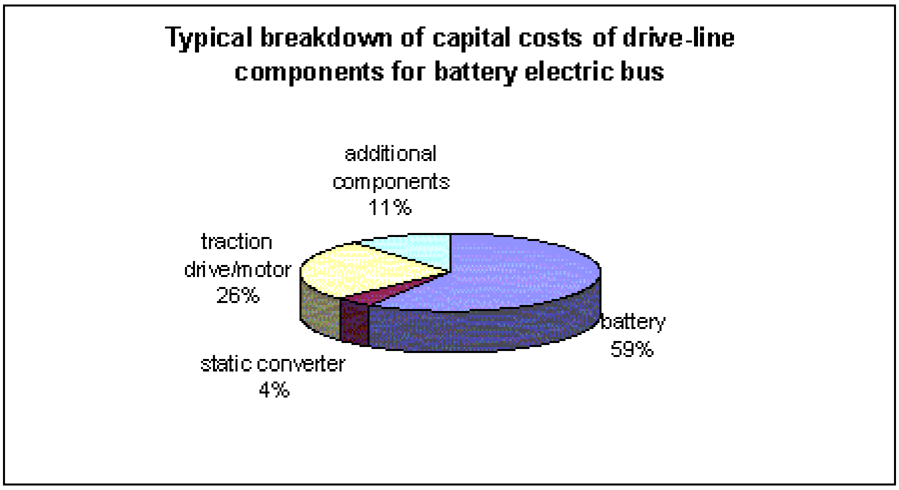


Figure 6.2: Typical breakdown of capital costs of drive-line components for battery electric bus base line

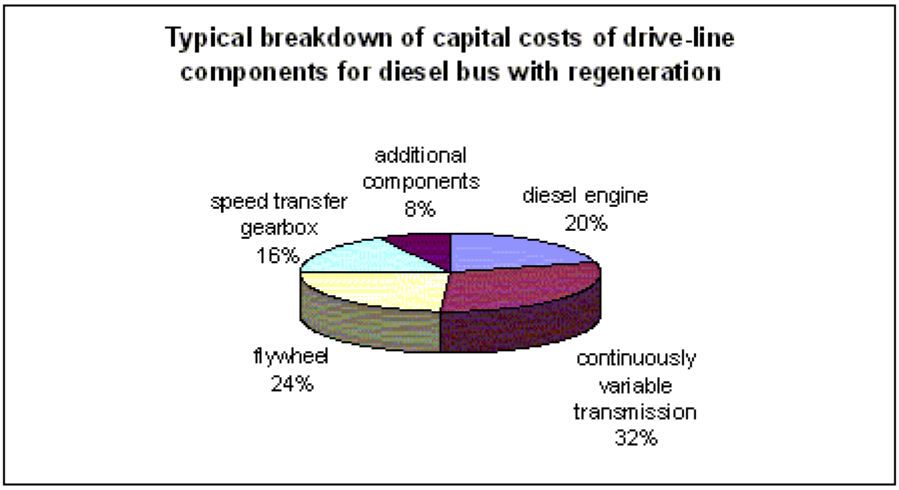


Diesel plus regen

The base line is that of a diesel engine (say Euro 3) with a 4 or 5 speed automatic transmission (figure 6.3). Replacing the automatic transmission by a continuously variable transmission (CVT) gives a 10 -15% improvement in efficiency whilst storing the energy either mechanically (flywheel store) or hydraulically will give a further 20% improvement (table 4.2).

Flywheel storage costs are based on the BP design and knowledge about materials and moulding costs derived from Eureka projects Eurospring and Eurobogie*. Apart from the initial tooling cost, component prices are likely to stabilise at volumes of a few hundred per year.

Figure 6.3 Typical breakdown of capital costs of drive-line components for diesel bus with regeneration

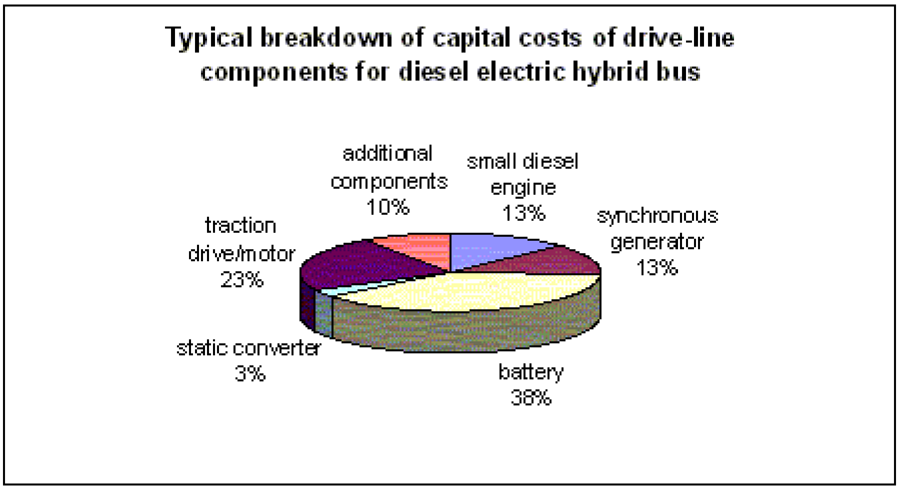


These projects are developing the generic technology of advanced road and rail suspensions based on fibre composite materials. A flexible design route enables primary load bearing components to be moulded direct to final shape without any need for machining.

Diesel/electric

The diesel/electric hybrid replaces the mechanical transmission with an electrical system. The diesel engine is downsized and drives a generator whose electricity is used to top up the battery, which is the prime power source (figure 6.4).

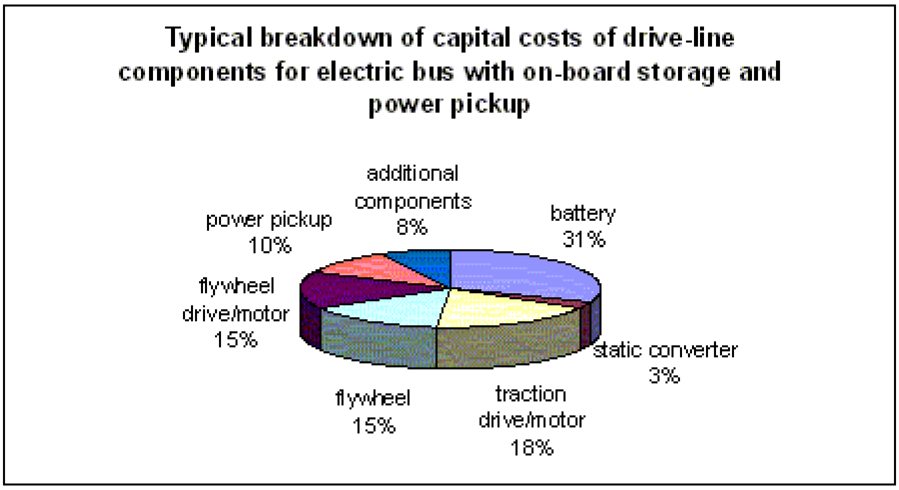
Figure 6.4: Typical breakdown of capital costs of drive-line components for diesel electric hybrid bus



Electric plus regen

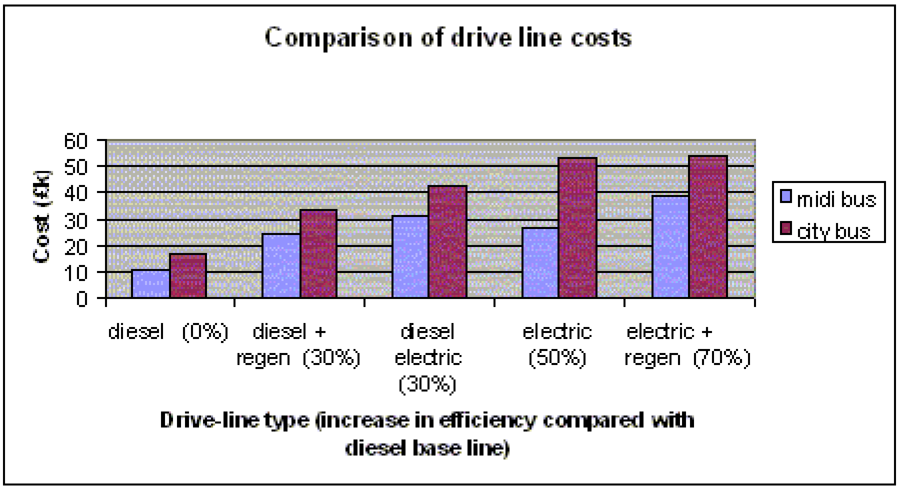
In the all electric drive-line (figure 6.5), the overall efficiency is increased by storing the braking energy for subsequent reuse when accelerating (table 4.3). In this system, rapid charging at a bus stop or terminal is also possible.

Figure 6.5: Typical breakdown of capital costs of drive-line components for electric bus with on-board storage and power pickup



6.9 A summary of drive-line costs are shown in bar graph form in figure 6.6 for midi buses and city buses.

Figure 6.6: Comparison of drive line costs for midi bus and city bus



From the bar chart, one can observe an increase in capital cost with drive-line efficiency. This is due to the additional components required to increase the efficiency by, for example, as storing the inertial energy on braking (figures 6.2 to 6.5). In addition, the city bus will always cost more than the midi bus because of the higher power rating of the drive-line.

The prime consumable for electric buses are the initial and replacement cost of the battery pack. This has been discussed elsewhere in more depth [6]. For the sake of this study, lead acid can be regarded as the only proven technology and is therefore used in the electric base-line case and that of electric + regen case.

For the diesel electric hybrid drive-line nickel metal hydride is likely to be the preferred choice because this drive-line relies in its basic form on a small diesel engine and battery pack. So the battery is the prime power source and so has to be fully reversible in terms of state of charge and depth of discharge. There is no firm price yet available and so we have taken a cost factor of two compared with lead acid based on current information. Because of manufacturers claims we have also allowed a three year rather than two year replacement time.

Sodium sulphur is not regarded as a suitable technology for buses because of the need to keep such battery packs at a constant temperature of 260°C. It is therefore not considered further in this study.

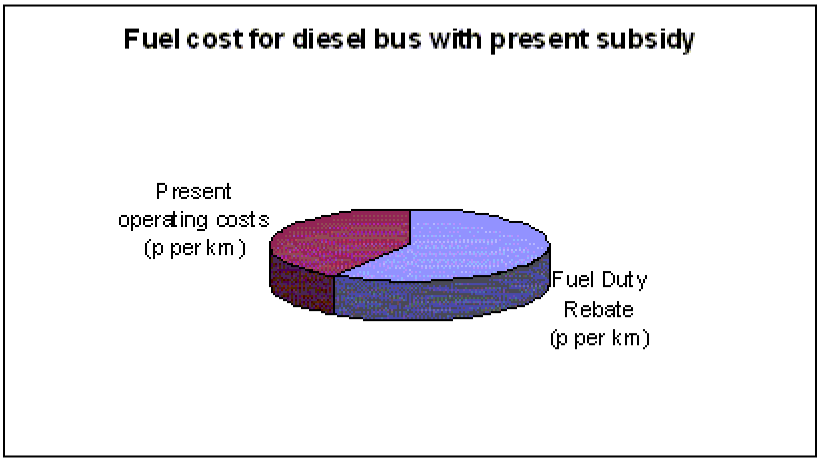
Whilst higher efficiency requires a capital costs, the additional efficiency reduces the energy (or running) cost as shown in the next section.

7. Running costs, carbon dioxide emissions and modelling energy consumption

Running costs and emissions

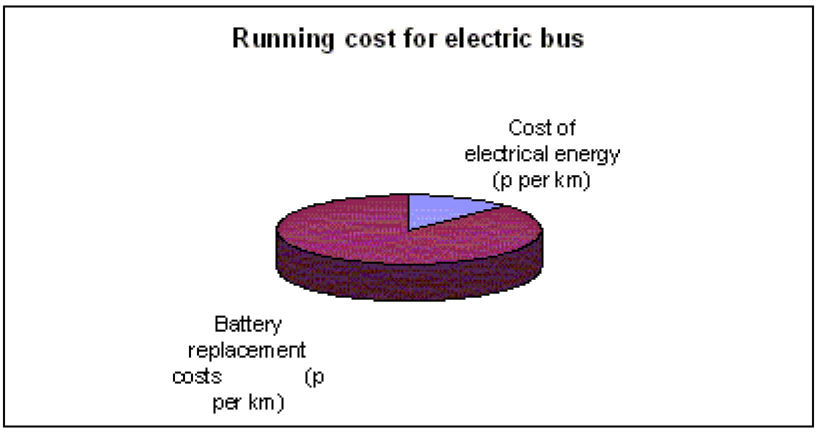
We assume that the average cost of diesel purchased by the operators is 72.9p/litre ie ex VAT 62p/litre, the fuel duty rebate is set at 80% equivalent to 36.6p/litre and the price of electricity 5p/kWh. All costs are given in p/km in order to make a fair comparison between diesel and electric. Figure 7.1 shows how the fuel duty rebate reduces the cost of diesel fuel for bus operators.

Figure 7.1: Typical breakdown of full cost of diesel fuel showing actual cost to operator and fuel duty rebate



In the case of the electric bus, running costs must also include the cost of replacing the battery perhaps every two years during the lifetime of the bus. Figure 7.2 shows a typical breakdown of running costs for an electric bus showing the proportion equivalent to the cost of electricity and that to cover the cost of battery replacement.

Figure 7.2: Typical breakdown of running costs for electric bus showing proportion of electrical energy cost to battery replacement cost



The charts in figures 7.3 and 7.4 show the running cost for each type of drive-line.

Maintenance costs are assumed to be similar when drive-lines are produced in similar volumes and are not considered further in this report. With the current level of subsidy, diesel is the cheapest whereas without the subsidy it is the most expensive. By storing the inertial energy on braking, the running cost is reduced because less fuel or electricity is used.

Diesel/electric and electric have higher running costs due to the need to replace the battery pack (figure 7.2). Electric + regen will have a longer battery life because less current is drawn from the battery pack.

The impact of CO2 emissions can be calculated from the average UK power station of 0.44 kg/kWh and an average diesel consumption of 50 litres/100 km and that burning one litre of fuel gives rise to 3.2 kg of CO2. As can be seen, there is a very significant decrease in CO2 emissions from typically 1600 g/km to 300 g/km with increasing drive-line efficiency.

When comparing the cost without any subsidy, it is clear that electric buses are cheaper to operate than diesel with the exception of the electric city bus whose costs are dominated by having to switch battery packs at regular intervals throughout the day. The effect of storing the braking energy on the running costs is clearly shown.

The reduction in average CO2 emissions per km of using more efficient drive-lines is also clear. Carbon dioxide emissions are taken to be 3.2kg/litre of diesel fuel, which is equivalent to 1.6kg/km for an energy consumption of 50 litres/100 km [9] and the average UK power station emits 0.44 kg of C02/kWh [10].

The operating costs with the current level of subsidy for diesel results in the diesel bus being cheaper to operate than electric buses in their present form (diesel and electric base-line). This effect is strikingly clear in figures 7.3 and 7.4. However the diesel is also appreciably more polluting than the electric bus. The CO2 emissions presented here for the electric bus relate to the pollution from power stations in the production of electricity for recharging the battery and are based on the current UK average for CO2 emissions from power stations.

Figure 7.3: Comparison of running costs for midi-bus with and without subsidy and CO2 emissions

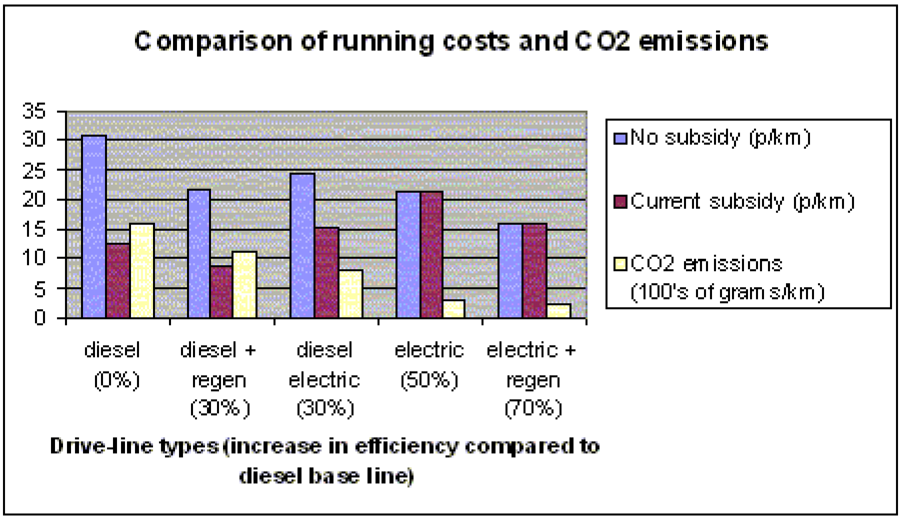
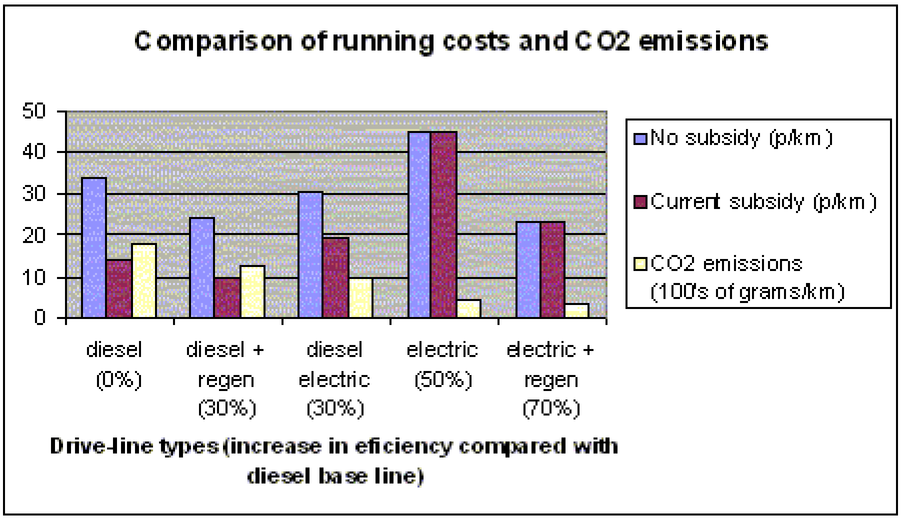


Figure 7.4: Comparison of running costs for city bus with and without subsidy and CO2 emissions



Computer simulation model

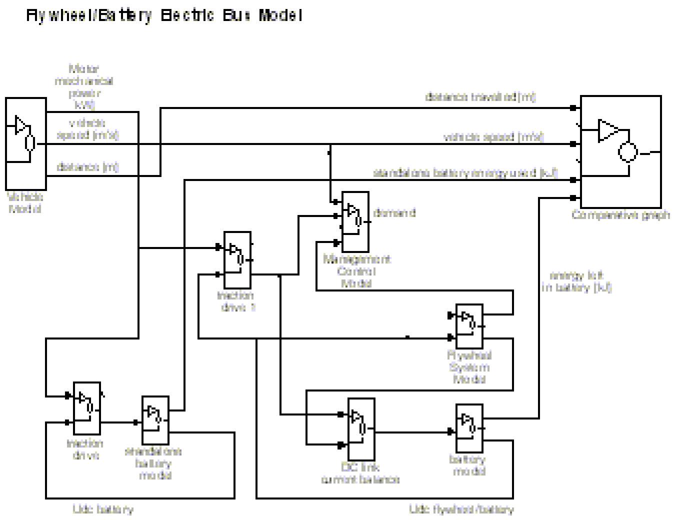
Computer simulation can be used to size the subsystems (battery, flywheel, wheel drive motors) of the electric/hybrid bus and compare the performance (in terms of engine size and exhaust pollution) with the equivalent diesel powered bus. The computer simulation has been developed using the Matlab/Simulink computer simulation package. It can also be used to compare alternative driveline control strategies for operating an electric hybrid bus through a specified driving cycle or, by interface to the traffic flow simulation package Vissim, over a particular route within a city.

The model assumes that the bus must respond to the driver's commands. The energy needed in order for the vehicle to meet the required performance is then calculated. Various strategies have then been investigated for supplying the required energy

- from the diesel engine or
- from the battery or
- from the battery including recovering braking energy through a flywheel storage system
- vehicle rolling and air resistance,
- vehicle drive motor peak power capability and efficiency,
- flywheel maximum energy and power capability, parasitic losses and efficiency
- battery internal resistance as a function of charge state

Figure 7.5 shows the block diagram for the model. Comparison can also be predicted with regard to exhaust emissions.

Figure 7.5: MATLAB model comparing performance of electric vehicle and flywheel/battery hybrid electric vehicle



Specifications

The specifications for the city bus and its alternative drive-lines are given in table 7.1 & its duty cycle in table 7.2.

Table 7.1: City bus specification

8, 10, 12 or 15 tonne city bus

vehicle rolling and air resistance with following drive line alternatives-

diesel drive-line

- 100 kW diesel engine with no regenerative braking capability

battery electric drive line

- 100 kW electric traction motor/drive with 25kW regeneration capability (efficiency 75% either direction)
- 64 kWh battery pack (lead acid) battery internal resistance as a function of charge state

battery/flywheel electric drive line

- 100 kW electric traction motor/drive with 100kW regeneration capability (efficiency 75% either direction)
- 64 kWh battery pack (lead acid) battery internal resistance as a function of charge state
- 0.4 kWh flywheel storage system
- flywheel losses 400W at full speed
- 100kW flywheel motor/drive with 100 kW regeneration capability (efficiency 85% either direction)

Table 7.2: Duty cycle specification

- Cycle time 50 secs

- dwell time stop 20 secs
- average distance between stops 200 m
- journey time 36 minutes
- maximum vehicle speed 15, 25 or 36 km/hour
- distance covered depends upon maximum speed

The bus mass has been varied from 7 to 12 tonnes tare mass with an allowance of 1 to 3 tonnes to simulate the passenger load depending upon bus capacity. The maximum vehicle speed has been varied from 15 to 36 km/hour, which gives an average speed range of 10.3 to 15.3 km/hour. Even this may be too high as for many inner-city routes the average speed is much lower. For example, the Millbrook London Transport Bus cycle (based on a data-logged route 159 bus) has an overall average speed of 8.8mph for distance of 8.967 km, which involves the Outer London phase (6.465 km) of 10.5 mph and the Inner London phase (2.502 km) of 6.2 mph. Route 53 in Paris, which runs from Opéra to Pont de Levallois through one of the main shopping areas, has an average speed of 7 km/hour.

Model predictions

The outputs from the 12 runs are summarised in the form of graphs in figure 7.6. These show the consumption of energy as a function of vehicle mass for the three maximum speeds.

In order to compare the diesel performance with the two electric vehicles directly, one can assume that the energy content of one litre of diesel fuel is 10.8 kWh.

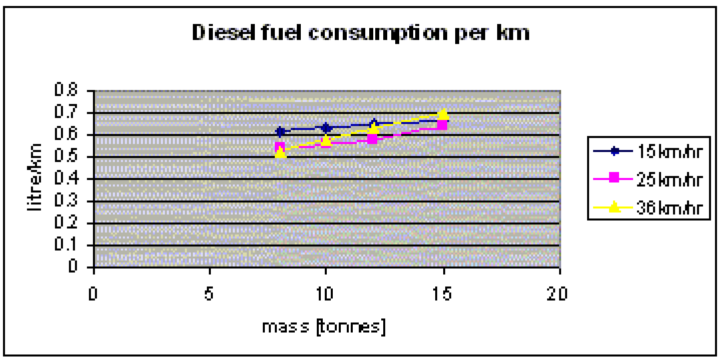
The diesel bus has a small dependence upon mass and speed. This results from consideration of the engine performance whose fuel consumption depends upon speed/torque requirements. Thus its economy is very dependent upon duty cycle.

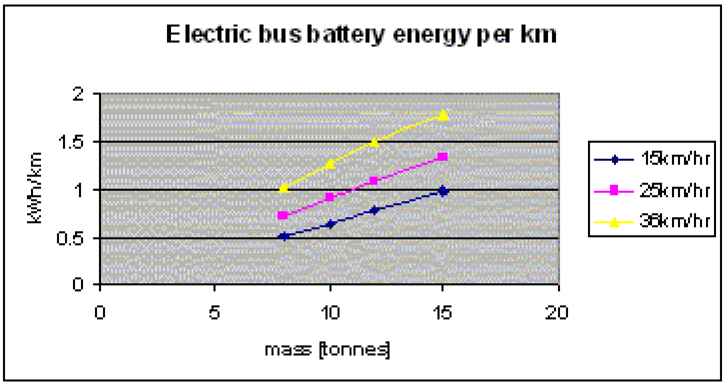
The electric bus has a much larger dependence upon speed and mass as its speed/torque relationship is much simpler and more linear. Capturing the braking energy can result in savings of up to 50% of the energy supplied.

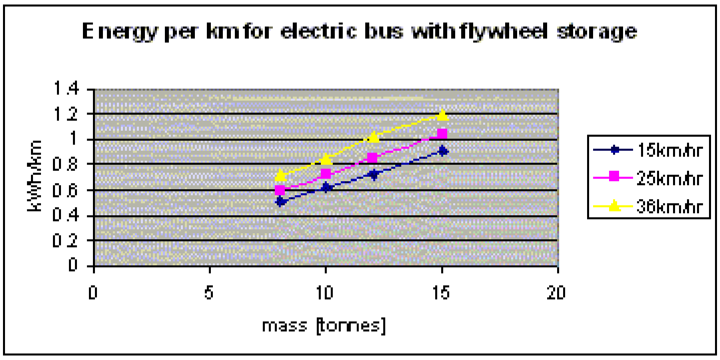
It should of course be recognised that these duty cycles will not often be achieved in real driving conditions since the driver will have to respond to the traffic conditions within which the bus is travelling. In inner-city situations traffic conditions will significantly influence the energy consumption.

The CO2 output can be calculated well to wheel by converting kWh/km using the equivalence for diesel of 0.3 kg/kWh (1litre of diesel provides 10.8kWh) and electric of 0.44 kg/kWh (see section 7.5).

Figure 7.6: Comparison of rate of fuel consumption for diesel bus [l/km],battery bus [kWh/km] and flywheel/battery electric bus [kWh/km] for different top speeds and vehicle masses







Effect of different drive cycles

The energy consumption for different drive-cycles has also been modelled very extensively in a much earlier study by Stefan Martini (MAN) for diesel buses [5] including that of recovering the braking energy. One set of his results is given in table 7.3.

Table 7.3: Effect of different drive-cycles including regenerative braking for diesel buses

Maximum speed (km/h)	**Number of stops (km)**	**Diesel only (l/100 km)**	**Diesel plus regenerative braking (l/100 km)**
30	3	39	27
40	3	42	29
50	2	41	28

As with our predictions, the impact of drive cycle has little effect due to the nature of the performance of the diesel engine. The potential for recovering the braking energy using a mechanical drive-line based is illustrated. This was subsequently demonstrated using flywheel storage by both MAN and Leyland/BP using ZF and Torotrak transmissions respectively.

Comparison

The overall average energy consumed by the diesel bus is about 6.0 kWh/km or 0.55 litre/km whilst for the city electric bus it is about 0.8 kWh/km (figure 7.7). These values are very close to those provided by Paris, London and Uppsala (diesel; 50 to 55 litres/100 km) and Uppsala (electric; 0.7 kWh/km for midi buses). The close comparison of measurements and predictions suggests the predicted data is appropriate for bus fleets operating in a city or urban environment. The model does not take into account the supply of auxiliary services such as climate control, door opening and compressors which affects electric drive lines much more than diesel.

The presence of passengers has been considered within the modelling by adding the additional mass of an average loading. For higher than average loadings, the mass will increase but average speed decreases as the increased number of passengers will take longer to get on or off the bus.

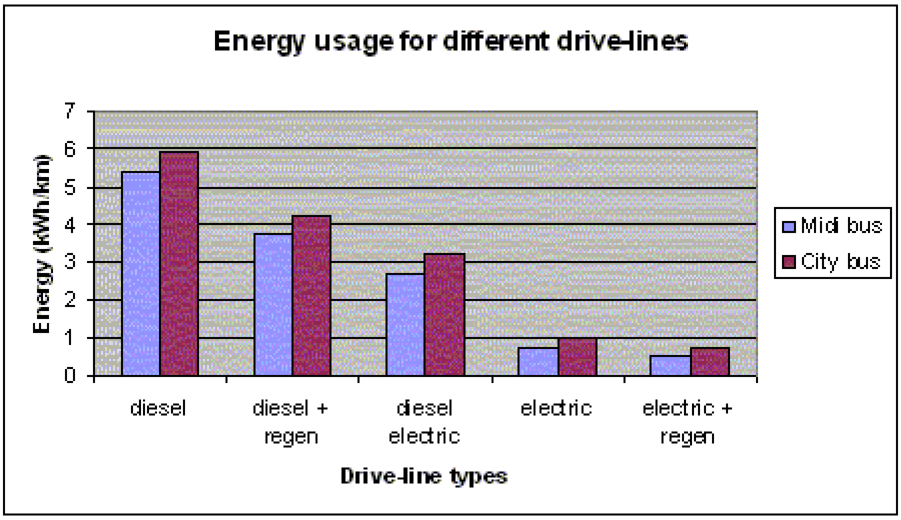
The potential for reducing energy consumption is very considerable as can be seen in figure 7.7. When fossil fuels are abundant and there is little concern about environmental pollution then fuel consumption is not of paramount concern.

However for drive-lines using batteries, this reduction in energy consumption is the key to extending the range and life of the battery pack

It is instructive to compare energy consumption with capital cost (figure 6.6)

The drive-lines with the highest capital costs have the lowest energy consumption and therefore the economics which are typical of any energy efficient product. The life time cost is considered in section 9.

Figure 7.7: Comparison of energy usage for different drive-lines



8. Air quality

There is increasing concern about local as well as global air quality. WHO guidelines can be exceeded during both summer and winter time in some British cities and vehicles are a primary source of much of this pollution.

Agreements between the motor industry and the EU have resulted in a series of Euro engine limits for various local pollutants of which Euro III is the current standard. However Euro III can be easily reached by a Euro II engine with a catalytic reactor and particle trap (CRT).

Clearly the more efficient the drive-line the less fuel will be consumed by the prime mover be this a diesel engine or a battery pack. The lower the fuel consumption the lower in general will be the pollution at both local and global level.

The diesel drive-line has been very extensively modelled by Stefan Martini with a Euro 0 engine. Results relevant to this study are shown in table 8.1, which illustrates clearly the benefits of adopting a regenerative drive-line with a continuously variable transmission and being able to store the inertial energy on braking. Even larger reductions in local pollutants can be obtained by switching off the engine at bus stops and not restarting until the store is almost exhausted.

Table 8.1: Increasing drive-line efficiency and effect on local pollution

Technology	fuel savings	soot	NOX	HC	CO
Smaller engine	12%	+30%	+40%	-10%	-12%
Stepless transmission	12%	-3%	+30%	-3%	-5%
Regenerative drive using flywheel	30%	-30%	-18%	-18%	-30%

We have modelled a Euro 2 engine and an automatic gearbox to illustrate the effect of mass and vehicle speed. These are illustrated in figs 8.1 and 8.2 and summarised in table 8.2 for a typical urban driving cycle (table 7.2).

The effect of mass (that is size of the bus) is to increase all pollutants particularly NOX and HC because the engine has to work much harder. Increasing speed has the greatest effect on HC and less effect on NOX because the engine is able to work more efficiently.

For the electric drive-line, we have used emission data averaged across UK power station mix in 2000. The overall conversion efficiency of energy to electricity is assumed to be 45%. From table 8.2 it can be seen that the higher the efficiency of the drive-line, the less NOX is produced. In addition electric drive-lines have a further benefit that this pollution is not produced locally.

Table 8.2: Modelling of pollutants for a typical urban driving cycle

	CO	HC	NOX	PM	CO2
Euro II (g/km)	7.0	3.5	4.5	0.8	1700
Mass doubled (%)	30	10	50	50	
Speed doubled (%)	15	30	30	70	
Electric bus (%)			-80		-80

All pollutant reduction technologies will result in a higher capital cost, some of which is already attracting a grant from the EST. If technologies also have a higher operating cost then this can only be considered if the vehicle fleet is in public ownership or some other form of subsidy can be accessed (such as the 100% fuel duty rebate for gas buses). The great advantage of energy efficient drive lines is that they will have a much lower operating cost once this technology is established.

In table 8.3, the available data from measurements and modelling is summarised for various drive-line options. The diesel drive-line with euro 2 engine and 4 speed gearbox forms the base line. Reducing the bus size reduces local pollution because the engine will not have to work so hard; however the bus fleet will need to be correctly sized to cope with rush hour traffic.

Table 8.3: Summary of various drive-line options on reducing air quality compared with euro II engine and automatic gearbox (base line) re - reducing; in -increasing

	Pollution		Operating Cost	Comments
	Local	Global		
smaller bus	re	-	-	need to size fleet correctly
lower speed	re	re	re	slightly longer duty cycle
diesel + CRT	re	-	-	can be retrofitted
gas + CRT	(re)	in	in	reduces some local pollutants poorer fuel consumption
diesel + regen	re	re	re	uses fuel more efficiently
electric	re	re	in	higher operating cost without any subsidy

Fitting a catalytic converter and particle trap will reduce the local emissions, but not necessarily global pollution or fuel consumption. Replacing a diesel by a gas engine reduces overall drive-line efficiency but can improve local pollution

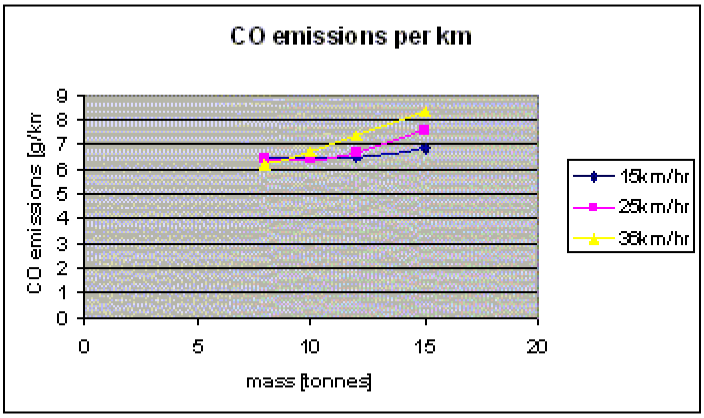
Several options meet the requirement of reducing both local and global pollution. These include

- lower maximum speed between stops which only marginally affects journey time
- using less fuel such as diesel + regen, electric and electric + regen.

Although the simulation studies previously show that operating the vehicle at a higher top speed marginally improves efficiency of the diesel engine, a bus operating in city traffic will never be able to achieve the idealised driving cycle simulated. It is widely recognised that under inner city driving conditions, lower maximum speed will achieve lower emissions.

Options do exist for improving air quality and consideration should be given to altering the current bus subsidy formula to encourage the uptake of such drive-lines.

Figure 8.1: Comparison of rates of emissions of CO and NOx for diesel bus in g/km for different top speeds and vehicle masses



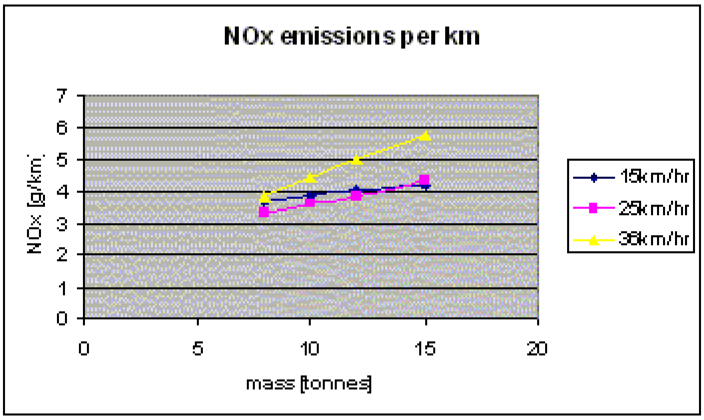
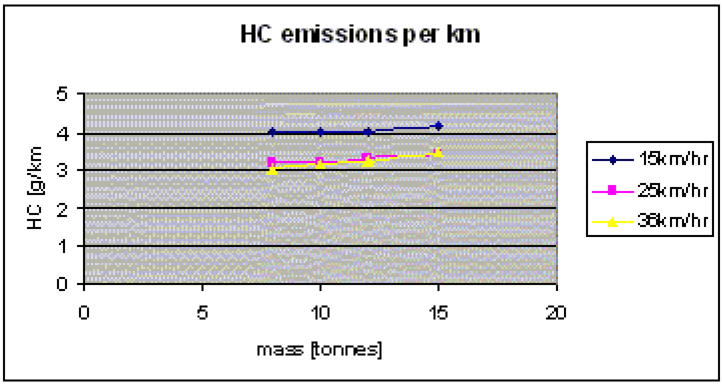
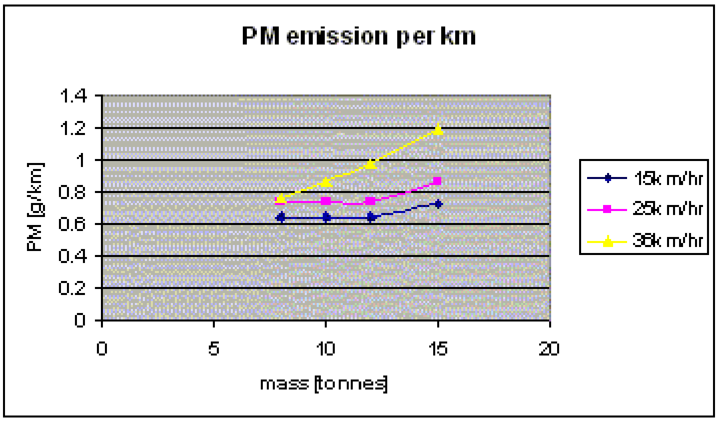


Figure 8.2: Comparison of rate of emissions of HC and particulates for diesel bus in [g/km] for different top speeds and vehicle masses


HC emissions per km
HC [g/km
mass [tonnes]
15km/hr
25km/hr
35km/hr
0
1
2
3
4
5
0
5
10
15
20


PM emission per km
PM [g/km]
mass [tonnes]
15k m/hr
25k m/hr
35k m/hr
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
5
10
15
20

9. Lifetime costs of energy efficient drive-lines and CO2 savings

Energy efficient drive lines, like all energy efficient products, are characterised by a higher initial cost and lower operating cost than less efficient buses. Different industries have different criteria for payback times on investment. In the bus industry this is likely to be no more than 5 years, the average leasing or franchise period for most bus fleets.

The initial costs are summarised in figure 6.6, which includes the cost of the battery pack for the electric drive-line. However the battery has also to be regarded as an operating cost because its current life-time is of the order of two years for lead acid.

The life-time cost and payback can then be calculated on the basis that the maintenance of energy efficient drive-lines will be comparable to that of current diesel drive-lines once the technology has matured. An asset life of 15 years and an annual distance of 45000 km per year has been chosen as typical of current urban usage.

The results are shown in figures 9.1 and 9.2 together with the lifetime CO2 output.

For smaller buses, with no subsidy, the diesel is the most expensive and the electric+ regeneration the cheapest to purchase and operate. For much larger buses, the standard electric bus becomes more expensive than the diesel bus because of the disproportionate increase in battery costs due to the extra mass of the vehicle and payload. The diesel bus is still significantly more expensive than the electric + regeneration. In fact the lifetime cost of the latter is about half that of the former for a midi bus whilst for a city size bus, the difference is 20%.

The effect of the bus subsidy is to reverse the economics with the diesel now being the cheapest and the electric drive-line the most expensive to operate. This is not surprising because the diesel is subsidised per litre (figure 7.1) whilst the electric drive-line is not.

The payback time for recovering the capital costs of energy efficient drive-lines is calculated from figures 6.6, 7.3 and 7.4 and is shown in figure 9.3. With no bus subsidy.

Three of the four technologies have pay back times but only the diesel plus regen falls within the 5 year time limit set above. The effect of the bus subsidy is to increase the payback times such that only the diesel plus regen has any payback within the asset life time.

In terms of CO2 figures 9.1 and 9.2 show clearly that the cheapest bus to operate with the subsidy has the highest CO2 output (that is diesel)

One therefore can conclude that the current bus subsidy formula is likely to reinforce the status quo and that the economics of energy efficient drive-lines are simply not attractive enough to overcome any difficulties with introducing new technology. So these new types of drive-line will remain a niche market and the Government's targets for low carbon buses by 2012 are unlikely to be met.

For the energy efficient drive-lines described as diesel + regeneration and electric + regeneration, the battery costs have been subsumed within fuels costs as discussed previously.

For the diesel/electric hybrid it is assumed that all the electricity is generated by the diesel. Again, battery costs have been considered on the basis of a pence per km replacement cost.

Figures 9.1 and 9.2 also show CO2 outputs over the lifetime of the bus for each bus type. It is clear that the diesel bus has the greatest pollution and, with the present subsidy, the lowest running costs. As the operator is only interested in low running costs the diesel bus has dominated the British public transport for a period now approaching 50 years displacing all other modes in the process.

Figure 9.1: Comparison of life time costs with no subsidy and present subsidy together with CO2 emissions for midi bus with each drive-line type

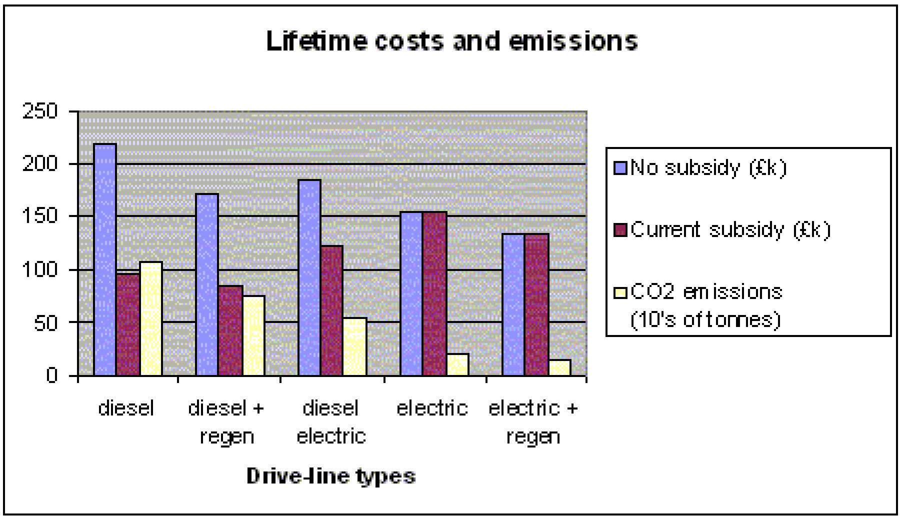


Figure 9.2: Comparison of life time costs with no subsidy and present subsidy together with CO2 emissions for city bus with each drive-line type

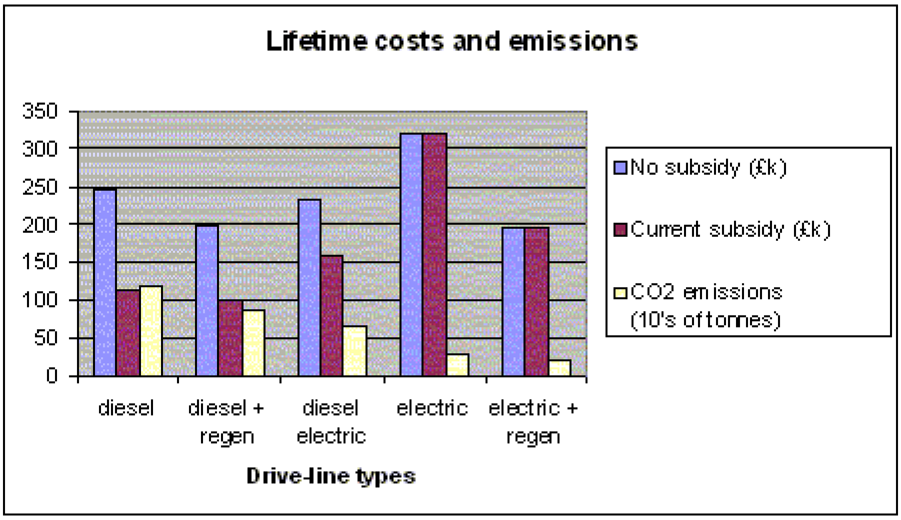
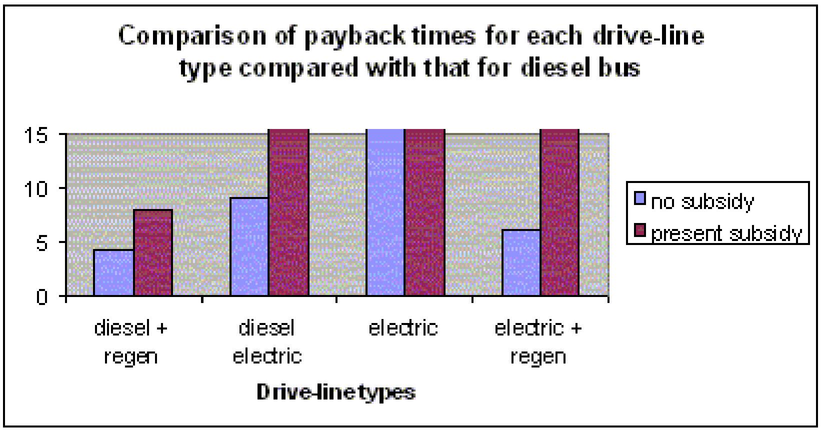


Figure 9.3: Comparison of typical payback times each drive-line type with no subsidy and present subsidy


Comparison of payback times for each drive-line type compared with that for diesel bus
15
10
5
0
diesel + regen
diesel electric
electric
electric + regen
Drive-line types
no subsidy
present subsidy

10. Options for making energy efficient drive-lines more economic

The rationale for making energy efficient drive-lines more economic than at present rests on four presumptions described previously. They can simultaneously reduce -

- fuel consumption thereby conserving scarce resources
- local pollution
- global pollution
- operating costs

The current bus subsidy distorts the economics in such a way that it tends to reinforce the current status quo.

We therefore consider various options for making such drive-lines more economic

No subsidy

The effect of not subsidising the operating costs directly is that the costs of operating diesel drive-lines increases so that other drive-lines become more economic (figure 9.3). If the Government wishes to promote social cohesion then it could subsidise the passenger fares instead and there would be no distortions in the cost base but operators are still likely to opt for vehicles with low capital costs i.e. diesel.

Extending the current subsidy to electric drive-lines

The current diesel fuel rebate equates to 18.3 p/km (section 7.1). If this rate were granted to all drive-lines then the operating costs of electric drive-lines would compare very favourably with that of diesel (cf fig 7.3 and fig 7.4). The outcome is that electric drive-lines are now substantially cheaper to operate than diesel particularly for the regenerative electric drive-line.

This has also the effect of reducing the payback time for energy efficient drive-lines as shown in paragraph 10.2 so that only the diesel/electric drive-line remains uneconomic. This concession will have no effect on the bus subsidy as it is simply replacing one bus by another. As in 10.2, however, operators might still tend to opt for vehicles with low capital costs and proven technology; there is no reward mechanism either for low polluting drive-lines (local or global).

Pollution shift allowance

To reward buses with high efficiency and low pollutants, the current subsidy could be split into two elements -

- an initial capital (or pollution shift) allowance
- a reduced operating subsidy

so that the effect would be revenue neutral. The pollution shift allowance could have various levels with the highest level reserved for the most efficient and least polluting (local and global) drive-line. The operating subsidy should be reduced in accordance with the drive-line efficiency taking the current diesel drive-line as base.

The result would be that all the drive-lines would have similar capital costs whilst the lower operating cost could induce operators to choose more efficient and less polluting drive-lines.

Leasing of batteries

As the battery is the highest proportion of an electric drive-line's operating costs (figure 7.2), some companies (like battery or utilities) might be willing to lease the battery and supply the necessary electricity an appropriate amount per km. This could vary from 15 to 45 p/km as can be seen from figs 7.3 and 7.4. This could make the purchase decision easier for the bus operator because it is analogous to buying diesel fuel. The risk of battery life is also moved from the operator back to the leasor.

A further advantage to the operator is a lower capital cost

Maintenance and servicing

We have presumed that all technologies will ultimately have similar maintenance and service costs. The available evidence is that motors and drives are used on a vast scale with high mean times between failure whilst tram and trolley bus technology has been in use for more than 100 years. So the technology is relatively mature and it should be possible to acquire the necessary expertise fairly quickly.

Demonstration leading to production

As discussed earlier, prices used in this study reflect large scale batch production equivalent to small scale volume production. The subject of transforming the market for energy efficient drive-lines has been discussed in a separate study for the DTI, which lists some 20 recommendations[6].

However within this context, we simply note that a fundamental requirement is to manufacture and demonstrate sufficient energy efficient drive-lines on a European wide scale so that the necessary expertise can be acquired to produce in volume and reduce maintenance costs to acceptable levels.

11. Recommendations & conclusions

There are three basic forms of energy efficient drive-line which will meet the 30% target set by the UK Government - these are

- diesel + regen
- diesel/electric hybrid
- electric plus regen plus power pick up.

A further option is the use of biofuels which we have not considered as the SMMT report [4] makes clear that the best use of such fuels would be as a fuel extender in existing drive-lines.

The components and technology have been identified which would comprise these drive-lines. We have restricted the survey to technology that exists and has been demonstrated in buses generally in demonstration form. There is no need for new technology to meet the target only a requirement to demonstrate that the various technologies and components can work together and achieve the efficiency improvements ascribed in this study. Also that they can achieve (ultimately) the reliability and maintainability of the existing technology.

There is no reason why such technology could not be retrofitted to some of the existing bus fleet particularly if the oil price continued to rise. Any revised formula for the bus subsidy should also encourage this substitution if the remaining asset life was 5 years or greater.

The potential carbon savings are significant - for 45000 kms/year up to 60 tons per year. Taking the UK fleet as 50,000 city buses this would equate to 3 million tonnes of CO_2 per annum. This would equate to a reduction in oil consumption of 150 tonnes/bus/year or 7 million tonnes of diesel over the bus fleet, a not inconsiderable amount of savings.

Much of the technology has found or could find application in markets other than buses. Stimulation of these technologies for the bus market could then be spun off into other markets of which urban delivery vehicles would be the next appropriate sector. As the number of such vehicles could be 5- 10 times higher than the bus fleet the carbon savings from transport could be at least doubled.

Revision of the bus subsidy formula provides a unique opportunity for creating a market for energy efficient drive-lines. It is essential that all types of drive-line will in future benefit from subsidy support and not simply those using internal combustion engines as at present.

One option to start the transformation to low carbon buses is to use a distance based formula which would depend upon the efficiency of the drive-line. Part of the subsidy could then be in the form of a capital ('carbon' shift) allowance in order to encourage operators to invest in more efficient buses as no market currently exists. This is possible because more efficient drive-lines would have a lower operating cost and so require a lower subsidy.

The market will not differentiate between the various technical options as long as the current oil price does not increase much above ∈30/barrel and no environmental charge is levied on pollution. As no one can predict at what rate the oil price will increase or carbon dioxide emissions will have to decrease, we propose that the Government should discuss with the industry how to ensure that any new buses could be retrofitted with more efficient drive-lines at any time during their life-time.

It is important to realise that there are many factors which influence operator choice and transforming the market is not simply a matter of altering the current bus subsidy formula. This topic has been the subject of a separate study for the DTI [6] on electric drive-lines and the reader is referred to this document for more details about the advantages of electric drive-trains.

The UK market is not sufficiently large to simulate the market for energy efficient drive-lines. This will require action at European level and there is reason to believe that the European Commission would seriously consider such a request as part of the targets for an Energy Sustainable Europe, whose program was formulated and agreed last year by Member States [7].

The stimulation of the market should take place in discrete steps. The first step will be to demonstrate the proof of concept and operating economics - the following demonstrations are under way or being planned -

- diesel/electric - Wright Bus and Transbus demonstrations under way
- diesel with regenerative braking - Martin Smith (together with Torotrak) has applied to EST for funding though no bus manufacturer has yet been identified
- electric with regenerative braking - this forms part of a European collaboration within Eureka project E! 2462 TRUS with Neoplan as the lead bus manufacturer [Sciotech Projects is the coordinator]

The second step would be to obtain sufficient operating experience that reliability and maintainability can be assessed under normal service conditions; TRUS is likely to involve trials of up to 50 buses in cities across Europe if its plans come to fruition. This number is sufficiently large that component suppliers should be able to start batch production.

The third step would be to release 'proven' designs into the market possibly with new bodies and chassis. The budget costs given in section 6 would seem to lie somewhere between step 2 and 3.

Whilst the bus subsidy has been designed for social purposes, it is important to accept that it should also reward operators of low emission drive-lines. These rewards can either be by access to restricted areas such as 'clear zones' or a higher subsidy or both.

12. References

1. Review of bus subsidies, consultation paper, DfT, August 2002
2. Review of bus subsidies, Sciotech's response to consultation paper by DfT, Scio 04/02 d 28.10.02
3. Powering future vehicles, the Government Strategy, DfT, July 2002
4. Future fuels report, SMMT, March 2002
5. Stufenlose wirkende hydrostatiches lastschaltgetriebe, S Martini, Ph.D thesis, Ruhr- Bochum, 1988
6. Transforming the market for electric vehicles for use in public transport - Sciotech report to DTI, Scio 03/10 October 2002
7. Public awareness initiatives for an energy sustainable Europe, Rapporteurs Report, by Rayner M Mayer, Scio CC #02/11 d 25 November 2002
8. The best reference to the global scale of the problem is by Campbell and Laherrere in Scientific American in March 1998 entitled 'The end of cheap oil'. Mayer and Bentley have presented more recent evidence to the Select Committee on the House of Lords on Energy Security, HL paper 82, dated 12.0.2.02
9. Adrian Wickens, paper to Low CVp, 4 February 2003
10. Scottish and Southern Energy annual environmental report, 2002
11. UK energy white paper, February 2003, sets a target of carbon savings in the range of 15 to 25 Mtons carbon by 2020.