The ‘Energy Recycling Driving Trailer’ for Trains

by John Kinghorn

The general idea of regenerative braking for electric vehicles has been around for over a century now. In this concept, the electric motors driving the vehicles are used as generators as well, so that energy can flow in both directions. Electrical power in gives traction force and acceleration, or braking for deceleration results in electrical power out.

Some tramways in the early 1900s pioneered the idea, so trams slowing for a stop or restraining speed going down a hill returned power to the overhead cable. This would then assist other trams going up hills or accelerating away from a stop. Subsequently these ideas were scaled up to the railway environment, one example being the Woodhead electrification between the Manchester and Sheffield areas in the 1950s, a route with heavy freight traffic and steep gradients. Trains going down the hills helped others going up, with reductions in brake wear and maintenance costs as well as electricity consumption. More recently such principles have been applied to the DC passenger trains of southern England, and electronics technology now makes it possible to do the same thing on AC routes too.

Of course for almost all road vehicles there is no connection to a power distribution network, so electricity from regenerative braking has to be stored on the vehicle for later use. This energy storage is typically in batteries, but can also use flywheel or compressed air methods. Although the basic principles have been known for a long time, it is only relatively recently that these technologies have improved sufficiently to make electric and hybrid vehicles a feasible proposition to compete with established internal combustion engines. However things are steadily improving, and there is an enormous effort to develop these methods as the only practical way to solve the horrendous air pollution problems of most of the world’s cities.

Not all railways are electrified, and the situation then is similar to road vehicles on a bigger scale. Although air pollution contributed by a diesel-worked railway is usually small compared to car use for the same traffic density, all transport modes should play their part in contributing to environmental improvement. Railways can use the same technology developed for roads, just more of it. Over 50 years ago a battery electric train was tried successfully in the Aberdeen area, and recently experiments on the Harwich branch line with a train using newer battery and motor control technologies confirm that these ideas are scalable to the railway environment.

Pondering these issues a few years ago I wondered whether some new architectural approaches for trains would facilitate the adoption of regenerative braking more widely. The ideal solution would work for both diesel and electric trains, give environmental improvements, allow for sensible re-use of existing vehicles, allow for changes of train formation to meet differing capacity requirements, and (eventually, when the technology has advanced sufficiently) be cost effective; with operating savings justifying additional capital costs. Here’s what I came up with.

Currently passenger trains using electric motors for traction have a variety of different architectures.

First there is the ‘distributed power’ concept, where all the coaches (or many of them) have traction motors. This is potentially a good architecture for regenerative braking, as relatively high acceleration and braking rates are possible. The disadvantages include cost: in the electric version a lot of copper is needed for the cables to get substantial amounts of power to the motors throughout the train, and in the diesel version there are high maintenance costs as each coach has an engine. The arrangement tends to be inflexible too; the train is designed to operate as a complete unit and adding or subtracting coaches to match demand is difficult. At best two or more units of several coaches can be coupled together.

Secondly we have the ‘locomotive hauled’ train. This has just one vehicle with traction motors, and all the others are unpowered. Usually nowadays the ‘push-pull’ system is used to avoid having to move the locomotive to the front of the train every time it reverses: there is a locomotive at one end and an unpowered vehicle with a driving cab at the other end, known as a ‘driving trailer’. This is not such a good architecture for regenerative braking, as only a small part of the train’s weight is applied to the wheels driven by the traction motors and consequently electric braking rates are limited. On the other hand it is a cheaper solution if the train is longer than about 5 coaches, and it is easy to add or remove coaches to match demand. As there is only one vehicle with traction motors and drives or engines, maintenance costs are lower too.

A third configuration has unpowered coaches but a locomotive at each end, an arrangement used in the highly successful diesel InterCity 125 High Speed Train (HST). This is somewhat intermediate in attributes between the two previous solutions. Potentially it is quite a good compromise for regenerative braking, with moderate deceleration being possible, while still having flexibility and moderate maintenance and construction costs. It would be nice to make an electric version of this arrangement for the future: but there is a problem. At high speeds it is infeasible to have electric locomotives at each end of the train, as the leading pantograph whizzing along disturbs the overhead wiring and the resulting movement disrupts current collection at the second pantograph. Up to about 100 mph is OK, but anything faster apparently needs expensive redesign of the overhead catenary.

So I thought: why not have a driving trailer like a locomotive with regenerative braking and a battery but no power input at all? This avoids the ‘two pantographs’ problem in electric trains, as only the locomotive needs power for acceleration in the conventional way. For deceleration, however, both the locomotive and the driving trailer use regenerative braking, the locomotive returning power to the overhead line and the driving trailer charging up the battery. The driving trailer acts rather like an old fashioned ‘brake van’, but instead of wasting the energy heating up brake discs and wearing away brake pads much of it can be stored away instead. At lower speeds conventional friction brakes are brought into use as well, but by that time most of the recoverable energy has been safely captured.

The next question is what to do with the stored energy in the driving trailer. It could, of course, provide additional traction, but only for a limited time as the recovered energy is relatively small. Also losses are greater for high current drains over short periods than a lesser flow over a longer period. So I propose instead that usually this energy is converted to the standard form required to power the heating, lighting and air conditioning of the train, known variously as Electric Train Supply (ETS), Head End Power, or Hotel Power. Normally the locomotive supplies this power, but when the batteries in the driving trailer are charged up sufficiently it can take over and the locomotive power switched off for a while until the batteries run down again.

Overall the energy efficiency of the train is improved using this ‘energy recycling driving trailer’. The vehicle itself might look something like the model shown below.

To get a rough idea of how this might work out in practice, suppose we have a 500 tonne inter city type train travelling on a flat route at 120 mph which then decelerates to a station stop. Assume that regenerative braking only is used from 120 mph down to 40 mph, and friction brakes then take over from 40 mph to a stop. The kinetic energy of the train ($\frac{1}{2}Mv^2$) at 120 mph (53.6 m/s) is

$$\frac{1}{2} \times 500000 \times (53.6)^2 \text{ J} = 718 \text{ MJ}$$

and at 40 mph (17.9 m/s) the remaining kinetic energy will be

$$\frac{1}{2} \times 500000 \times (17.9)^2 \text{ J} = 80 \text{ MJ}$$

In theory the difference between the two (638 MJ) could be recovered by regenerative braking, but there are inefficiencies to account for. Firstly, some of the energy will be lost in overcoming air resistance anyway during the period of deceleration. As a rough guess assume 30% disappears this way, so you are left with the remaining 70% or 447 MJ.

To decide how this would split between he locomotive and driving trailer, assume the locomotive is 50% heavier and exerts a correspondingly greater braking force. So the driving trailer gets 40% of the energy (178 MJ), and the locomotive 60% (268 MJ).

In converting this stored energy in the driving trailer back into electrical power for ETS there are three further inefficiencies to be allowed for. Firstly there is the efficiency of conversion from braking force through the motors used as generators into electricity in a suitable form for the battery through the charging control system. Secondly there is the efficiency of the battery itself (you don’t get out quite as much energy as you put in). Thirdly there is the efficiency of the inverter reformatting the power from the battery into the desired ETS standard. For the sake of argument assume that each of these processes is 80% efficient, the net result being that the three combined have an overall efficiency of 0.8 x 0.8 x 0.8 = 0.51, about half (it might be rather better than this in future).

Anyway, the overall result is that one station stop has generated 0.51 x 178 = 91 MJ of reusable electrical energy, which is equivalent to 25kWh. Since such a train might have a typical air conditioning and lighting load of 250kW, that single stop could power the train's services for 0.1 hour or 6 minutes using energy which would otherwise have been wasted. If the train stops at a station every half hour on average, say, the power input required for train services has been cut by 20%. Of course in practice things are not this simple. Few trains have the luxury of unimpeded running at maximum speed and only braking for station stops; often there will be speed restrictions, signal checks and the need to restrain speed going down gradients. So every time the brakes are used a little energy can be squirreled away and put to good use later on.

Here's an electrical model I built to demonstrate how the concept works:

Exactly the same design of driving trailer works regardless of whether the locomotive has regenerative braking or not, or uses electric, diesel or any other form of motive power. The system also incorporates automatic redistribution of electrical power when train formations change: but that's too complicated a story to describe concisely here.

If the energy savings of the concept seem modest, it has other advantages too:

- Maintaining power to the train while locomotives are being changed (e.g. electric to diesel at the end of an electrified route)
- Allowing the shutting down of diesel engines in stations to cut noise and pollution
- Maintaining power to both sections of a train when it splits for different routes
- Reducing slipping of the train under poor rail conditions (extra traction available)
- Shunting vehicles at either end of the train (sufficient traction energy is stored)
- Allowing use of locomotives without ETS facilities (e.g. redundant 'freight' locos), as surplus traction energy can be converted into ETS power indefinitely

More information about this idea can be found on the WRTI website www.wrti.org.uk under Membership Information – Members' Inventions in Development, or in my book 'Beyond the HST' (Melrose Books, £16.99), or in my patent description GB2487224.