Ultra light rail developments

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Abstract: Ultra light rail systems are small-scale tramways that utilize energy storage rather than continuous electrification. They have excited considerable interest because potentially they are a very cost-effective way of providing attractive urban public transport.

This paper describes latest technical advances and service experience of the two principal developers. These are the Parry–Clayton range of vehicles, which are concentrating on mechanical and mechanical/hydrostatic transmission systems, and the EROS vehicle, which will have electric transmission. The paper also considers longer-term traction options and developments in related fields that should allow some transfer of technology to accelerate the process of achieving market-ready products.

Keywords: ultra light rail, tramway, Parry, EROS, flywheel, energy storage

1 INTRODUCTION

1.1 Context

It is significant that many cities are currently solving their transport problems by reviving a century-old technology. Trams were not taken seriously in the 1960s but now they are an important element of transport strategy. This revival started in the United States, where everything tends to be built on a larger scale than in Europe, so when new light rail systems first appeared in the United Kingdom, their scale and expense proved to be suitable only for the busiest corridors. Gradually promoters are realizing the value of smaller-scale systems, closer to the traditional tram but taking advantage of technological advances. Not many realize that the highly successful and efficient Zurich tramway network is a metre gauge system with cars only 2.2 m wide.

In the United Kingdom there are now light rail systems in five major cities and plans for several more. Despite this, during the last few years many have believed that somehow all transport objectives could be met much more effectively using buses. Fortunately, last year the government appears to have had a change of heart. In April 2000, Deputy Prime Minister John Prescott stated that 'accessible, integrated and environmentally sound light rail systems are twenty-first century public transport'[**1**].

There is wide gulf between the basic bus and a modern light rail system. The reaction of industry and promoter authorities has been to consider 'intermediate modes'. London Transport has carried out some excellent work considering how these ideas might be applied to provide high-quality transport links in Outer London [**2**]. Intermediate technology has already been applied: kerb guided buses in Ipswich and Leeds and electronic guided buses at the Millennium Dome. However, authorities have gradually realized that bus-based systems can be as expensive as rail-based ones, where they have to cover their own track costs.

Thus the fundamental question is what options are available if high-quality, attractive, congestion-free public transport is required on a relatively large scale?

1.2 The basic options

In simple terms there are three basic options for short-distance urban public transport: bus-based systems, rail-based systems and novel systems. Bus-based systems are potentially easy to introduce and 'flexible', but to avoid congestion they must have their own rights of way, which can be more expensive than new rail infrastructure. Such infrastructure is needed only where congestion is acute but, without guidance, buses have extreme difficulty providing level access for all. Kerb guidance works but has major limitations; it is totally unsuitable for pedestrian areas, for example, and cannot cope with tight curves. Electronic guidance is promising but at an early stage of development and is still relatively expensive. Flexibility, once promoted as a positive feature of bus operation, has recently been shown to be a negative aspect in that it deters rather than attracts patronage [**3**].

Rail-based systems, including ones that operate in streets as tramways, can provide an exclusive right of way to bypass congestion, and can use appropriate forms of traction to meet environmental objectives. In Britain, experience shows that people prefer to travel by rail vehicles than by bus, and trams fit particularly well into the modern city image with pedestrianized traffic-free areas,

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classic architecture and street furniture, street cafes and quality shopping environments. Continuous guidance provide high-quality access for all, while having rails flush with the road surface provides an efficient form of guidance and support that does not significantly impede other road users.

Novel systems that use entirely new infrastructure may seem attractive but these involve maximum risk. New infrastructure usually involves grade separation that is out of tune with modern requirements for ease of access and minimum impact. Many new technologies involve unmanned, automated vehicles that are not only grossly expensive but also increasingly inappropriate in a world where personal security has become a major issue. It is significant that, despite considerable effort to develop new forms of transport systems over the past few decades, nothing has emerged that has made any permanent impact on the types of system that cities choose.

Each of these options has its role, and rail-based systems are in a key position. The strategy should be to make each system more effective, developing subsystems rather than providing totally new ones. This was the recommendation of a high-level study undertaken for the Department for the Environment, Transport and the Regions (DETR) four years ago [**4**]. Light rail systems can be much cheaper without losing their advantages, given an appropriate business specification [**5**]. Ultra light rail is one of a number of ways of doing this; it is simply a smaller-scale light rail system appropriate for the low and medium traffic flows that are typical of most smaller cities, towns and urbanized districts. It is not a novel system; most of the technology it uses is well tried and tested.

2 PRINCIPLES

The key features that define an ultra light rail system are

(a) smaller-capacity vehicles,
(b) simpler light rail/tramway technology and
(c) use of energy storage.

Smaller-capacity vehicles arise from the market need. For a traffic flow that is, say, only a third that of a light rail system, the following options are possibilities:

(a) operate a conventional light rail vehicle two-thirds empty, which is uneconomic;
(b) operate with a service interval three times as long, which would make the service unattractive;
(c) use a smaller vehicle, which is the basic principle of ultra light rail.

If the vehicle is smaller then it can be lighter and the infrastructure can be simpler and less expensive. Curves can be tighter, allowing more route flexibility and scope for saving further costs.

Modern light rail track in streets has a substantial concrete base because of the vehicle weight and all underground services (sewers, water, power, etc.) are usually diverted before it is laid. This is extremely expensive. With ultra light rail there is a choice:

1. Route flexibility means that the proportion of street track can often be reduced to avoid the problem.
2. Lighter track bases mean that it is possible to access the underground services, so they do not have to be diverted.
3. If part of the route is closed for work on underground services, a detour on temporary light track is possible.

Lighter vehicles also make the third feature of ultra light rail a possibility, i.e. energy storage. The energy requirements are relatively low and with frequent stops the scope for regenerating braking energy is important. If energy is stored, there is no need for continuous electrification. Electrification is expensive, can be environmentally intrusive and introduces hazards and problems with current leakage and interference. Ultra light rail has the advantages of electric traction without these very significant disadvantages.

The use of light rail and tramway track is not revolutionary. It gives all the benefits of guided systems and makes ultra light rail especially suitable for city and town centre environments. It is not as expensive as might be imagined. Numerous studies have indicated that total system costs for ultra light rail systems should be £1–2 million per route kilometre, including vehicles. This is no higher than the costs of a properly engineered bus priority scheme [**6**].

3 EARLY DEVELOPMENTS

Despite what has been said so far, ultra light rail did not develop in direct response to these specific market needs. It arose out of an idea developed by John Parry, MBE to solve the urban problems of developing countries but was rapidly adopted by others who realized that it could be of considerable value much closer to home.

The early development of the Parry People Mover (PPM) was described at an Institution of Mechanical Engineers conference in 1996 [**7**]. John Parry decided to use a flywheel as his energy storage system. He considered batteries but their range is limited, whereas a flywheel can be rapidly recharged at stops. A series of prototype vehicles were constructed; these increased in size and complexity as his Cradley Heath workshops developed their ideas further. Some ran on a short pleasure line at Himley Park in the West Midlands and he also achieved working demonstrations in a number of towns around the country using temporary track. These attracted considerable attention and the list of towns and cities that have shown serious interest is very impressive. John Parry had proved that the idea worked and that people liked it.

The culmination of this early period was the construction of vehicle No. 10 by Parry People Movers in 1997 (Fig. 1). Early vehicles had been built to 600 or 760 mm gauges but No. 10 was built with the facility to alter its gauge up to standard (1435 mm), with railway wheel profiles. This enabled it to exploit opportunities for operation on railway lines, with specific Bristol- and Weymouth-based projects in mind.

No. 10 had a 500 kg flywheel that was 1 m in diameter and made of a series of flat steel plates. This form of construction is simpler and arguably less prone to catastrophic failure. The flywheel was designed to rotate at a maximum operating speed of 3600 r/min and to store 1 kW h of energy. The transmission system was mechanical and employed belts to link the flywheel to a shaft with the electric motor, primary clutch and four-speed forward and reverse gearbox and then to a continuously variable transmission unit ('variator') that gave a wide speed range. A further belt linked this unit to one of the two axles. The other 'axle' was in fact two independent wheel units attached to the underframe; one contained a disc service brake, the other a tread parking brake.

The flywheel is normally never operated above 1850 r/min. This provides 0.33 kW h of energy storage, which proved adequate for the slow-speed Bristol operation. At higher speeds of revolution it was found that vibration became a problem; the cause has been identified and later designs of flywheel should take account of this.

The flywheel was 'charged' by the electric motor, which took its power via a conductor shoe from a third rail at stops, at a 'touch safe' voltage of 70 V. Batteries were also provided to supply auxiliaries; these also had sufficient energy storage to allow the vehicle to crawl back to the depot in the event of total flywheel energy failure.

The vehicle body was double-ended with bus-type electrically controlled folding entrance doors on both sides. It had 16 seats with standing space, giving a total practical capacity of about 30 persons. It was a separate unit, mounted on resilient blocks on the underframe. The cladding was formed from glass-reinforced polymer attached to a stainless steel frame. Other key parameters are listed below:

Maximum speed:	40 km/h (operation at Bristol was restricted to 16 km/h within pedestrian areas)
Length:	7.3 m
Width:	2.4 m
Height:	2.5 m
Floor height:	399 mm
Weight:	6 t tare

Parry People Movers saw this as paving the way towards development of a series of single-ended vehicles that could be coupled in pairs to provide a capacity of 70, which was seen as appropriate to the market. Parry also developed a concept for an articulated vehicle with a central two-axle unit containing the traction system and two identical single-ended units with one small-wheel bogie on either end, to achieve the same capacity.

4 SERVICE EXPERIENCE

Trials of the PPM No.10 began in November 1997 on the Bristol Harbour Railway. A company, Bristol Electric Railbus (BER), was formed by James Skinner to operate the service on a regular basis. Skinner had acquired the vehicle from Parry People Movers Limited. Bristol City Council owns the railway and the service has received financial support from South Western Electricity, in

Fig. 1 Parry People Mover vehicle No. 10

recognition of its value in promoting environmentally friendly electric transport. Experimental passenger service commenced in May 1998, and operated virtually continuously until February 2000. During this period No. 10 travelled 14 600 km, and carried over 48 000 passengers. The service was then halted for track alterations and vehicle repairs but continued until October 2000.

The section of track used in Bristol was an unimproved harbourside tramway, which is standard (1435 mm) gauge and about 700 m long. There were four stops: Prince's Wharf, Bristol Industrial Museum, The Buttery and the SS Great Britain. All except The Buttery, which was a special request stop, had specially built low platforms allowing wheelchair access. There were charge points located at the Industrial Museum and SS Great Britain stops; each consisted of a single 70 V d.c. conductor rail. Although Her Majesty's Rail Inspectorate (HMRI) allowed use of this relatively safe voltage, they asked for a system to be installed so that the rail is actually only live when the vehicle is being charged. The vehicle was housed in a specially extended shed where space was rented from the Industrial Museum.

The track is relatively old with extensive pointwork and crossings. Road traffic crossed the route at several points and there is considerable pedestrian flow of visitors to the SS Great Britain and people enjoying the harbourfront environment. Speed was limited to 16 km/h. On certain summer weekends and bank holidays, steam trains operated by the Bristol Harbour Railway replaced the BER service.

Various tests have been undertaken and service reliability has been closely monitored by BER. In summary the experience has been as follows.

1. Flywheel no-load losses were significant at high rotational speed. High rotational speed therefore needs to be avoided to reduce such losses and also vibration, as mentioned previously.
2. Half of the energy supplied was being lost during the charge process. This emphasized the need for a more efficient drive system.
3. Significant losses were identified if the clutch was used to accelerate the vehicle in slipping mode (the correct method is to use the variator for this purpose).
4. Although regeneration was occurring, the effects were negligible.
5. Variator efficiency was low.
6. The low energy consumption of the vehicle (1.36 kW h/km measured by SWEB) was due to low operating losses, i.e. minimal drag and wheel losses at low speed.
7. Accelerations of $3.5g$ were experienced on the flywheel. Maximum peaks of $30g$ positive and $40g$ negative were experienced on the wheel bearings at track joints. These accelerations were reduced by the suspension to $10g$, both positive and negative.
8. There were a number of transmission failures in the beginning. These were eliminated gradually by replacing components and by a programme of 'preventative maintenance' that improved reliability to an acceptable level.
9. Various aspects of the design, such as transmission components, flywheel bearings, toothed belts and driving controls were identified for improvement.
10. Rail joints were uneven and loose at a number of locations, and the small wheels also dropped into the long gaps associated with the complex pointwork. The suspension characteristics of No. 10 noted above meant that the flywheel bearings were not being protected from the dynamic forces transmitted from the track. Although resiliently mounted, the flywheel was not intended to be used on track sections of such poor quality, and the mountings were not capable of providing protection. Bearing condition gradually worsened and resulted in noise, vibration and reduced run-down time. A new flywheel was fitted in August 1998 and at the same time the flywheel containment was modified. After instances of bearing failure, some minor track improvements were made and flywheel rotational speeds were reduced.
11. Drivers needed to exercise considerable care in the operation of the spin-up motor, as use of full power at low flywheel speed tended to result in slippage and rapid wear of the drive belts. The belts used were very long, and proved to be prone to regular failure. This design will not be repeated; the problem has been reduced on No. 10 by programmed replacement and the fitting by BER of an extra belt tensioner.
12. The drive axle broke in February 2000. BER re-engineered the running gear design to install thicker axles.
13. There was scope for simplification and improvement of the controls.

5 SUBSEQUENT PPM DEVELOPMENTS

Parry People Movers continued development of their vehicle concept based on mechanical transmission, and more recently a combined mechanical and hydrostatic transmission. The following have contributed to this:

(a) the DETR from the 'LINK' programme;
(b) the Engineering and Physical Science Research Council, who funded a project at the University of the West of England to develop, test and analyse suitable flywheels;
(c) syndicates of shareholders and associated firms.

The LINK project was led by Parry People Movers Limited and managed by Parry Associates. It took place between June 1997 and March 2000 and concentrated on the development of subsystems so as to improve the overall range, power and size of this form of ultra light rail vehicle [**8**]. Other partners were Brush Traction, Brecknell Willis, AEA Technology Rail and the University of the West of England (UWE). Clayton Equipment latterly provided assistance, although that firm did not become a full project partner (see also Section 7). The partners considered that an increase in energy capacity from 1 to 2 kW h would considerably improve commercial attractiveness. The most cost effective way of doing this was found to be to increase the nominal diameter of the flywheel from 1 to 1.2 or 1.4 m.

The laminated form of flywheel construction was confirmed as being appropriate. Critical stresses in the larger flywheel can be eliminated cost effectively by designing out the central shaft. The alternative design was developed and analysed using finite element analysis. This showed that it is possible to use a double-capacity, larger-diameter, cost effective flywheel that does not exceed stress levels at the planned optimum operating rotational speeds.

Modelling showed that maximum power throughputs of at least 100 kW are required with continuous throughputs of 50 kW to cope with gradients and long-distance running. To achieve this, PPM decided to concentrate on a hybrid concept using a small onboard petrol, diesel or LPG engine that would provide power as needed and to develop the transmission to suit. Work with prototypes showed that a very small 25 bhp engine proved sufficient to meet performance requirements for continuous operation using this principle. Various changes were also made to the transmission system to improve reliability; these included a shorter multiple V-belt drive and an air-operated clutch with a fluid coupling.

A further vehicle, No. 11, was built for use in public service. This is a narrow (600 mm) gauge vehicle for use on the Welsh Highland Railway. It utilized the hybrid principle and demonstrated the energy efficiency of this approach. The larger flywheel and improved transmission features were installed on a prototype test vehicle chassis designated as 'D'. Overall energy use was improved from approximately 1700 m/kW h on Car 10 to 1730 m/kW h on Car 11 and 2630 m/kW h on the 'D' prototype.

The hybrid principle was a change of direction but overcame the criticism that ultra light rail was only applicable for routes where there are frequent stops. For a typical 'tramway' this may be true in the central areas of towns and cities, but not in the suburbs. The option now exists of applying the concept to longer routes. The small engine should produce less pollution than one that would be sufficient to produce the same acceleration without a flywheel and it can be switched off completely in sensitive areas.

6 EROS

James Skinner, who had set up BER (see Section 4), also set up another company, Electric Railbus Operating Services (EROS), to develop and market ultra light rail vehicles using flywheel energy storage but with electric transmissions. The prototype EROS vehicle (Fig. 2) is being built by Severn Lamb at Alcester; the power equipment has been developed and tested at the University of East London. It is similar in size and capacity to PPM 10 but has been designed to meet Disability Discrimination Act (DDA) requirements. When completed it was intended to be operated by BER on an extended route to the Create

Fig. 2 Prototype EROS vehicle

Centre (1.8 km from Prince's Wharf). A new connecting line has been built to facilitate this. BER has plans to extend the route at both ends, as a tramway over the swing bridge along Narrow Quay to the city centre and at the other end to the Ashton Gate area. This will complement plans for full-scale LRT in Bristol and is a good example of how ultra light rail might work as a feeder system.

The power train contains motors and a generator that can operate either in a motor or a generator role according to the operating cycle. This principle is intended to provide flexible and optimal control of the flow of energy, improved system efficiency and power–weight ratio, and a more compact arrangement. In normal drive conditions, the vehicle is driven by two permanent-magnet brushless d.c. motors supplied from the flywheel generator, which converts the mechanical energy stored in the flywheel into electricity. There are two flywheels and four motor/generators in total. During braking, the vehicle kinetic energy is converted into electricity by means of the motors acting as generators. The generator then acts as a motor to spin the flywheel. It also acts as a motor at stops to provide swift re-charging. These operations are controlled by an electronic control unit via three power electronics converters, one for each drive motor and one for the generator. The control unit automatically changes the mode of operation and also provides vehicle dashboard displays. The use of brushless d.c. drive technology in vehicle applications is well known and has been proved in aerospace and military applications.

The vehicle uses two separate 500 mm diameter flywheel units, which operate in a vacuum. The use of two flywheels offers a number of advantages and is easier to implement with electric transmission.

The key specification details of EROS are as follows:

Capacity:	35 passengers including 2 wheelchair spaces
Maximum speed:	50 km/h
Length:	8 m
Width:	2.4 m
Height:	2.9 m
Floor height:	435 mm
Weight:	5.5 t tare target

A maximum speed of 50 km/h is essential for mixed operation in traffic and for competitive journey times. It proved difficult to achieve the commercial requirement for a charging time at stops no greater than 30 s with a 70 V d.c. system. EROS will eventually use 415 V a.c. to achieve this; it will also increase efficiency and remove the need for transformers either at stops or on the vehicles. A safety system is being developed to overcome the hazards associated with use of the higher voltage. At Bristol the vehicle will use the existing 70 V supply system, if PPM 10 continues to operate, at least in the short term. The charge point transformers will be modified. On this route a top speed of 40 km/h is adequate.

7 THE PARRY–CLAYTON INITIATIVE

In 1999 Parry People Movers joined forces with Clayton Equipment to manufacture and market electric and hybrid ultra light rail vehicles. Clayton Equipment is a member of the Rolls–Royce Group and is a world market leader in the supply of light locomotives and equipment for mining and construction railways. Clayton had decided to diversify into public transport applications and saw ultra light rail as an area of significant potential.

The principal manifestation of this partnership has been the development of a new vehicle, the PPM50. The first vehicle, No. 12, is under construction; the body has been completed (Fig. 3) and it is intended that this will operate initially on the Stourbridge Town branch line.

No. 12 will incorporate the developments resulting from the LINK-sponsored scientific and development work. It

Fig. 3 Parry–Clayton vehicle PPM50

will be a hybrid with a mechanical transmission and will be a standard double-ended (1435 mm) gauge vehicle, designed to accommodate 50 people, and will therefore be larger than any previous ultra light rail vehicle. It will have a high floor to provide level boarding at 915 mm high railway station platforms but has been designed so that it could be built with a 400 mm floor height without changing underfloor equipment or its arrangement.

Power will be provided by a 1500 cm^3 Ford LPG engine, a 1.2 m diameter flywheel and a 30 kW 70 V d.c. electric motor. The transmission arrangement is shown in Fig. 4.

Other planned key parameters are listed below:

Maximum speed:	70 km/h (operation at Stourbridge is limited to 32 km/h)
Length:	8.28 m
Width:	2.4 m
Height:	3.4 m
Weight:	12 t tare

No. 12 is to be fitted with conductor rail pick-up so that it can continue to be used to demonstrate electric operation.

The market for a vehicle of this type would be for operation on railway networks where there is no possibility of colliding with a conventional train. Certain local railways can be isolated in this way, including a handful of lines that now form part of Railtrack (the 750 m long Stourbridge Town branch is a good example) and 'off season' heritage railways. Overseas there will be many suitable locations. In broad terms the total operating cost, including vehicle leasing, is about half that of using the smallest single-vehicle conventional 'train'.

The Parry–Clayton partnerships planned to develop other types of vehicle aimed at the much more significant overall market for ultra light rail as described earlier. This included twin 'semi-metro' units with low floor and 100-passenger capacity.

The impetus for developing the PPM50 was initially the interest of Centro, the West Midlands Passenger Transport Executive, in planning for ultra light rail links and supporting trials on the Stourbridge branch line, for which it is responsible. A company has been formed, pre-Metro Operations Limited, to take this initiative forward. Centro offered financial support and the scheme has been assisted by Railtrack and Central Trains. The intention has been to introduce a Sunday service to supplement the weekday service provided by a class 153 diesel multiple unit. AEA Technology Rail has been assisting the various parties involved in engineering the equipment and procedures necessary for the 'switchover' between two radically different types of operation.

8 WHERE NEXT?

At present, the two principal promoters of ultra light rail are taking forward different forms of ultra light rail vehicle. EROS vehicles will have electric transmission and operate at 'domestic' power supply voltage. Parry–Clayton vehicles will have mechanical transmission and the option of either low voltage or a small LPG engine as the power source. Both will use flywheel energy storage.

Minitram Systems Limited have built a battery-powered ultra light rail vehicle, 'Minitram'. Current plans envisage a demonstration route in Stratford upon Avon. The company is interested in using electronic guidance from a buried wire at an early stage, in addition to shallow laid track.

Recent flywheel development in public transport has not been confined to ultra light rail. The ULEV-TAP project considered operating a full-size tram in Karlsruhe that operates for 2 km in the city centre using energy stored in a 4 kW h flywheel unit that it has collected from the electrical overhead supply in the suburbs. A fleet of buses

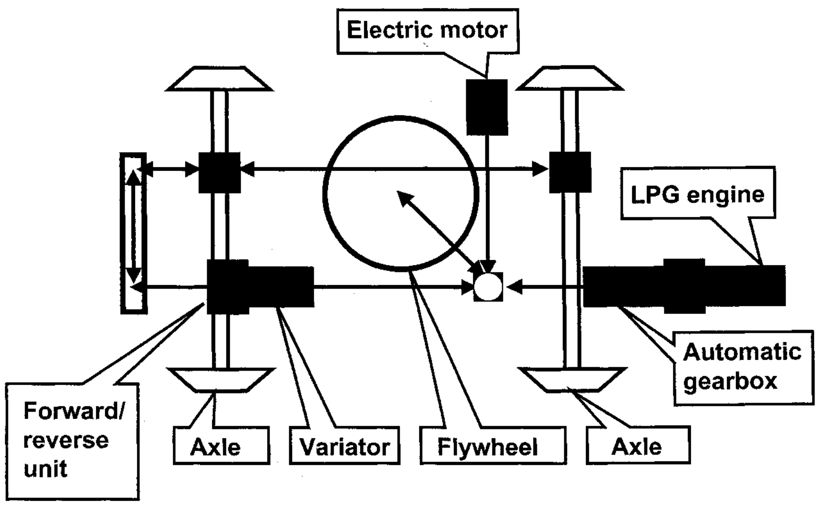

Fig. 4 PPM50 transmission arrangement

that use flywheel energy storage is operating in Eindhoven in The Netherlands.

Fuel cells would seem to be an ideal replacement for the power source, eliminating the need for either an internal combustion engine or conductor rail pick-up at stops. A fuel that provided hydrogen, such as natural gas, methanol or petrol, would need to be carried, but the only emissions would be harmless water vapour. The cost of fuel cells is currently proportional to their power input, so continued use of the flywheel to provide the peak power requirements would still probably make economic sense. An important reason for ultra light rail eventually adopting this path is that fuel cells could become the power source for a wide range of transport systems including cars, buses and trams and therefore it would not carry the development costs alone.

In a fuel-cell-powered transport world, ultra light rail would still maintain its competitive position as an extremely efficient form of guided, easily accessible and congestion-free system.

9 POTENTIAL

Ultra light rail is now much closer to being generally accepted as a serious transport option. The amount of interest shown by local authorities in the United Kingdom has been overwhelming, but all are waiting for someone else to take the first step. The experience of the pioneer route in Bristol is therefore very important. The hurdle represented by the Transport and Works Act is disproportionally great for a small-scale initial application. Other countries do not have such hurdles but most still expect to see a UK application before they will take risks with ‘untried technology’.

The principle of new small town- or city-centre tramways fulfilling an important transport role has been established in the United States where a large number of lines have been built. Other new tramways of this type have appeared in Stockholm, Christchurch in New Zealand and elsewhere. They all use ‘heritage trams’, either built new or taken out of museums. They could use ultra light rail vehicles instead.

The technology is also ideal in a ‘pre-LRT’ role, as a feeder, as a distribution system in shopping centres and for transport within traffic-free resorts and tourist attractions. It may also have a role in retaining services on the large tramway networks that have survived in Eastern Europe and the CIS. Ultra light rail is a simple but very effective concept that has great potential and recent development has brought this close to fruition.

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