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A SIMPLE MODEL OF RAIL INFRASTRUCTURE CAPACITY AND COSTS

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ABSTRACT

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1.INTRODUCTION

The recent White Paper on "New Opportunities for the Railways" (Cm 2012, 1992) proposes that British Rail's responsibilities for operation and infrastructure will be separated. A new track authority, Railtrack, will be established and will operate without subsidy, except for capital grants in cases where a satisfactory cost-benefit return is achieved. It is acknowledged that these new arrangements will lead to some difficulties in allocating and charging for infrastructure, especially where rail infrastructure is congested, and consultants have been hired by Government to examine this issue. The principles that Government has specified should underly the access and charging regime are that it should:
(a)Promote efficient operation
(b)Promote competition and innovation
(c)Encourage efficient use of infrastructure and other resources
(d)Not discriminate unfairly between competing operators and services
(e)Provide the means for financing Railtrack's infrastructure.

The relevant theory is embodied in the literature concerning peak load pricing and optimal investment for public enterprises as expounded in standard text books (Turvey, 1971, Rees, 1984, Brown and Sibley, 1986.) and put into practice in most areas of the transport sector (eg Hansson and Nilsson, 1989, for rail, Small and Winston, 1988, for road, Bishop and Thompson, 1992, for air). The aim of this paper is not to make a contribution to this theory but to use it in conjunction with simple models of rail's infrastructure requirements and costs to highlight the key problems in infrastructure allocation and charging.

The structure of this paper is as follows. In section two we consider a hypothetical rail line and the likely costs of different service levels. In section three, we relax the assumption that all trains are operated at the same speed and re-examine the likely costs of different service levels. In section 4, we go on to examine the pricing implications of our findings. In a final section, the implications of this analysis for policy are assessed.

2.RAIL INFRASTRUCTURE REQUIREMENTS AND COSTS - SERVICES SAME SPEED

2.1INFRASTRUCTURE REQUIREMENTS

Suppose two towns, A and B, are 25 km apart and are linked by a single track railway. The average speed of trains on this track is 60 km/hr and it takes 5 minutes for the trains to turn round at each end of the line. The capacity of this line can be estimated by a simple formula:

$$K = 60/[2\ (D/S + T)] \qquad (1)$$

where K = Capacity (in trains per hour)
D = Distance (in km)
S = Speed (in km/min)
T = length of layover/Turn-round time (in minutes)

This is sometimes referred to as the one engine-in-steam problem

In the above example, it should be evident that K=1. The maximum capacity of the line is one train per hour. If additional capacity is to be provided then passing loops need to be installed. The capacity of the line is still estimated by formula (1) but D now becomes the distance between passing loops and T = the time spent in a loop. Suppose the minimum length for a loop is 200 metres and T remains 5 minutes, then:

with 1 loop the capacity is 1.72 trains per hour
with 3 loops the capacity is 2.70 trains per hour
with 7 loops the capacity is 3.77 trains per hour
with 15 loops the capacity is 4.71 trains per hour etc

It is assumed in this example that loops are added incrementally, once one loop is installed at the half-way point, the only additional way to increase capacity is to instal loops at the quartile points (so that there are three overall). This is likely to be more cost effective than removing the existing loop and installing two new loops.

A further point that needs to be taken into account is that each additional loop increases end to end journey time by 4.8 minutes. In practise this would rule out the installation of loops unless the value of T could be reduced. These assumptions lead to the installation of loops exhibiting a diseconomy of scale.

The alternative is to install double track. The appropriate formula for capacity becomes:

$$K = 60/ (H/S) \qquad (2)$$

Where H is the headway or block distance between trains. For example, if the headway was 2 km, then the capacity of the line could be as high as 30 trains an hour. However, this theoretical capacity is likely to be curtailed in practice for a number of reasons. In particular, in this example the trains need to be turned round at the terminals. This might be dealt with by adding the variable T to the denominator of (2) resulting in an estimated capacity of 8.57 trains per hour. Without switches, trebling the track would only increase capacity to 9.57 trains, whilst without switches quadrupling track would increase capacity to 17.14 trains per hour.

In the above we are dealing with a non integer number of trains per hour. If we assume the capacity is determined by passenger flows during the peak two hours capacity can be re-expressed as the number of peak train runs (see Table One). However for double and quadruple track railways this leads to non-integer headways, the number of train runs are therefore further adjusted. However, even the revised service intervals fails to result in a clock-face pattern. The clock-face service patterns possible are also shown in Table One.

2.2SERVICE COSTS

Assume that the service has uniformly distributed demand throughout a sixteen hour day and a 350 day year. The single track when utilised at full capacity has average costs of £15 per train km [Box (1991) reports British Rail as exhibiting unit costs of between £10 to £15 per train mile at 1991 prices]. Suppose further that one-third of costs are assumed to be fixed, relating principally to the provision of terminals and track [Box estimates these items accounted for around 34% of British

Rail's costs in 1991, although they should not necessarily be considered fixed]. It is assumed that passing loops can be provided at an additional cost of £80k pa per loop. Doubling track is assumed to result in a doubling of fixed costs as economies in, for example, land purchase are assumed to be cancelled out by increased costs due to signalling.

The resultant cost profiles based on these assumptions are given by Table Two and Three and illustrated by Figures One and Two. We assume that rail infrastructure exhibits indivisibilities and over the range of output considered only five levels of infrastructure provision are feasible. If infrastructure is at full capacity, we observe a pattern of declining average costs up to a minimum efficient scale (96 trains a day), after which costs are constant. It is this feature of rail technology that is the main source of economies of scale. However, in practice rail infrastructure is not always operated at full capacity and the Average Total Cost (ATC) curve exhibits the familiar "saw's tooth" pattern and is the main source of economies of density.

The Short Run Marginal Cost (SRMC) curves in Figures One and Two also exhibits a familiar pattern. For the most part, they are horizontal and co-incide with the average variable cost curve. In this example, we have assumed that operating costs exhibit constant returns although in reality we might expect some increasing returns due to better utilisation of staff and vehicles, use of longer vehicles and operation of more direct services (Keaton, 1991). Where additional infrastructure is required, the short run marginal cost curve becomes vertical. Given indivisibilities of this type, the concept of a Long Run Marginal Cost (LRMC) is not really meaningful, but an approximation may be provided by an Average Incremental Cost (AIC) measure which, given n levels of infrastructure provisions might be written as:

$AIC_{n,\,n-1} = [\ TC_n - TC_{n-1}\ ] / [\ Q_n - Q_{n-1}\ ]$ (3)

where TC = Total Cost

Q = Output (Trains per day)

The AIC curve in Figures One and Two is drawn at the mid-point of Q for each level, n. The AIC curve is always below the ATC curve, initially is downward sloping, but rapidly adjusts to exhibit an upward slope.

3.RAIL INFRASTRUCTURE REQUIREMENTS AND COSTS - DIFFERING SPEEDS

3.1INFRASTRUCTURE REQUIREMENTS

We now assume that two types of service are operated on the branch line, a fast service with a speed (S_F) of 2 km per minute and a slow service (S_S) with a speed of 1 km per minute (as before). The capacity for single track can be estimated by modifying equation (1) to give:

$K = 120 / [2\ [\ D/S_F + T] + 2\ [\ D/S_S + T\ ]]$ (4)

The capacity for double track can then be calculated as:

$K = 120 / [\ H/S_F + (D/S_S - (D - H)/S_F + T\ ]$ (5)

where D = Distance over which fast and slow trains follow each other

The implied capacities, expressed in terms of trains per day rounded down to the nearest even integer, are given by Table Four. Assuming non-clock face headways it can be seen that, compared to Table Two the capacity of the branch line has increased by up to a third as a result of the speeding up of every other service. By contrast, the capacity of the double track has been reduced by almost one-fifth, as has the capacity of the quadruple track. This is caused by the fast trains catching up to slow trains. Capacity can be increased by bunching fast or slow trains together, a scheduling process known as `flighting' (for an illustration see White, 1986, page 175). However, this violates our assumption of alternate fast and slow trains. Alternatively, the capacity of double track can be increased by the installation of switches or passing loops, thus reducing the distance, D, that fast trains follow slow trains. Some hypothetical examples are given by Table Four. The installation of one short section of treble track with switches increases capacity by over 40%, with three sections of treble track capacity increases by over 90%. However, although capacity utilisation is increased, so is end to end journey time, whilst the pattern of alternate fast and slow trains may break down.

3.2SERVICE COSTS

As before, we assume a sixteen hour day and a 350 day year. The variable cost of slow services remains at £10 per km but for fast services is assumed 20% higher at £12 per km. As the result of providing for fast services the infrastructure `fixed' costs are also higher, by 10% for single track (so that costs are £1540k per annum). Similarly, the costs for a passing loop are higher at £100k pa for each loop (up 25%). This illustrates the well known finding that some so-called fixed costs vary with service quality requirements (Joy, 1989).

The resultant cost profiles are given by Figure Three. The ATC curve again is downward sloping over most of the output range but does begin to slope upwards with the installation of quadruple track. However, this is largely due to the fact that, under our assumptions, quadruple track without switching is technically inefficient compared to alternative track configurations. The ATC curve again exhibits a `saw's tooth' pattern, although this is less marked than before, except for the more double/quadruple track. The predominantly horizontal SRMC, with vertical off-shoots when capacity is reached is as before, but our approximation of LRMC, the AIC curve exhibits a different shape to that exhibited in Figures One and Two. The W-shape of the AIC curve results from the (unrealistic) assumptions concerning the capacity constraints imposed on the double and quadruple track. Nonetheless, the AIC curves does intersect the smoothed ATC curve at its (approximate) minimum point.

4.PRICING IMPLICATIONS

4.1SERVICES SAME SPEED

Suppose the demand for a rail service linking A and B at 25 minutes journey time is given by the straight line curve D_o D_o in Figure Four. There are at least three pricing/output possibilities.

(i)Traditionally public utilities in Britain are required to price at LRMC. Assuming that the AIC curve is a reasonable approximation of the LRMC curve, this would be at point A, which theory tells us should be the welfare optimal point. However, because of the increasing returns to scale inherent in rail technology, pricing at A will fail to cover total costs by an amount equivalent to AB per train run. However the White Paper requires the Railtrack authority to operate without subsidy, thus precluding the financing of this deficit.

(ii)Alternatively, price may be set equal to SRMC, in this case at D. Quadruple track is not supplied, instead price is used to ration capacity to double track levels. In this case, the Railtrack authority earns a profit of DE per train run. Such super normal profits will be prohibited by the White Paper's proposed Rail Regulator.

(iii)Thus, the most likely outcome would be to price at ATC, in this case at point C. This will lead to welfare losses compared to the price/output combination at A, although these can be reduced if demand elastic and inelastic market segments can be identified and Ramsey pricing used to have higher mark-ups on LRMC in the latter than the former. However, the scope for Ramsey pricing is likely to be limited by the White Paper's requirement that infrastructure charges should not discriminate unfairly between competing operators and services. The more likely alternative would be the development of a two-part tariff, with an access charge to cover fixed costs (administered on a per vehicle basis) and as cost per vehicle kilometre to cover variable costs.

4.2SERVICES WITH DIFFERENT SPEEDS

The same three price/output combinations are relevant where services are not homogenous but, as Figure Five shows, the infrastructure implications are more diverse. This stems from the fact that demand for train services is related to the quality of the service provided. The demand curve D_oD_o in Figure Five is drawn parallel and outwards of the corresponding demand curve in Figure Four to reflect the higher average speeds in the former case. Similarly, in both diagrams demand curves D_1 D_1 and D_3 D_3 are drawn inwards but parallel to D_0 D_0 to reflect the effect of one and three passing loops respectively on increasing end to end journey time. However, in these diagrams no attempt is made to reflect the effect of increased output on demand, in terms of reducing wait times. The result of these assumptions is that the relevant demand curve is discontinuous, and may be represented by the bold line $D_1D_1D_3D_3D_0D_0$ in Figure Five. The resultant price/output combinations are as follows:

(i)Pricing at LRMC results in point A and losses per train run of BA. Only single track with three passing loops is provided.
(ii)Pricing at SRMC results in point D and profits of ED. Only single track with one passing loop is provided.
(iii)Pricing at ATC results in Point C. Double track with no passing loops is provided.

5.POLICY IMPLICATIONS

5.1ACCESS ISSUES

Our simple models highlight some of the problems that are likely to arise from a policy of open access. Suppose we take our first model (Table Two, Figure One) as an example and assume that capacity is restricted to 120 trains per day (ie double track). The existing operator operates 120 trains a day. A new operator wishes to operate an half-hourly service (32 trains per day). Four measures might be considered:

(i)Administrative measures, usually based on historical precedent (`grandfather rights'). In this case, the entrant would be refused access, but such a policy would be contrary to the White Paper and EC directive 91/440. If the principle of integer minute headways is abandoned partial access can be accommodated with the entrant being granted 16 train runs. If the incumbent operated a clock-face timetable (from Table 3, 96 trains an hour) entry could be physically accommodated. There is a likelihood that open access will put pressure on clock face timetables even though these are valued by passengers (see, for example, Ford and Haydock, 1991).

(ii)Auctioning. For our simple branch line service this would be relatively straightforward as the good being auctioned, the train path, is clearly defined. Operators would bid up to the price implied by the demand curve D_0 minus AVC associated with operations (as in Figure Four) allowing near perfect price discrimination. In the long run the super normal profits earned by Railtrack would be used to invest in new infrastructure. The main problem here is that our simple example is not realistic. In reality, rail services are a complicated mixture of interconnected train paths and platform allocations at stations. A further complication is how such an auctioning process would work with franchising. Two bodies, Railtrack and the Franchising Authority would be competing for income from rail operators. There is a danger of rent appropriation by the Railtrack authority, whilst it is not clear whether the Franchising Authority's decisions will take into account payments made to Railtrack.

(iii)Slot trading. In this scenarios, the incumbent would assess its 120 train runs and determine those 32 that it values least or the entrant values most (note this would not produce a half-hourly service, but could be a close approximation). The entrant would then be entitled to bid for these 32 paths. In effect, an auction takes place for slots 89 to 120 but in this case the rents are likely to be appropriated by the incumbent operator (the Rail Regulator permitting).

(iv)None of the above measures appears satisfactory. A particular problem is that they fail to specifically relate prices to costs. A suggested alternative is administrative procedures based around a published tariff. This will be examined further in the next section.

5.2PRICING POLICY

We maintain our assumption that capacity is fixed at double track and the incumbent operates 120 trains per day. An ATC pricing approach would suggest that an entry fee of £23,333 per train run should be charged, plus a charge per km based on the proportion of AVC related to variable cost of infrastructure. This assumes that the incumbent is producing at the output level where the demand curve intersects the ATC curve. The proposed entry gives a signal that this is not the case and that the demand curve D_0 is above the incumbent's estimate of it. In this case, it is up to the Railtrack to estimate where D_0 really is and price at SRMC. From Figure One this would suggest an entry fee of around £35,000 per train run. Administrative procedures, possibly based on franchising, would be used to allocate train runs to those operators prepared to pay the entry fee. In the long run, the supernormal profits would be used to expand capacity.

So far, we have assumed uniform demand throughout the day. This is relaxed in Table Five. We assume that existing capacity is provided by double track. This track is operated at capacity during the peak four hours (30 train runs in total). In this case, the MC of providing additional off-peak train runs is merely AVC. The entry fee should be zero. By contrast, the marginal cost of providing extra capacity in the peak is substantial. For cost-recovery, an entry fee of at least £93.33 per peak train run should be charged. In other words, the entry fee for a two-part infrastructure tariff should be based on peak train runs as they determine capacity requirements. A problem here is that of the shifting peak. Operators are likely to move services just outside of the peak periods in order to avoid the peak entry fees. An alternative might be to base the entry fee on fleet size (and composition) as this is likely to be closely correlated with peak requirements and will also take into account the fact that the nature of the service operated will effect infrastructure requirements eg gross train weight, train speed etc.

Lastly, we consider the effect of train speeds. Again our starting points is double track provision and the incumbent providing 120 train runs per day. Suppose, as a result of privatisation, the incumbent is split into two. One of the two operators decides to introduce a service at twice the existing speed. Table Four indicates that this will reduce capacity to 98 trains per day, if a timetabling policy of alternative fast and slow trains is implemented. How should infrastructure be allocated and priced in this situation? Firstly, an administrative decision needs to be made whether the decrease in train frequency is worth the increase in speed. Suppose the answer is yes. Secondly, the entry fee needs to be determined. Based on ATC, this should be at least £31,429 per train run. However, the reduced capacity is not the result of the slow train operator's actions. In this case, the slow train operator might still be charged an entry fee of at least £23,333 per annum per train run and the fast train operator a fee of at least £35,000 per annum per train run.

6.CONCLUSIONS

Despite a number of simplifying assumptions, our models' illustrate the complexities of determining access and pricing regimes for rail infrastructure. These problems stem from rail infrastructure's cost characteristics, its declining costs over a broad output range, its indivisibility and the high proportion of joint and common costs. This leads to expectations of economies of scale, density and scope.

Given Railtrack should not receive subsidy and should not discriminate unfairly between users it seems that some form of ATC pricing is likely. This might be based on a two-part tariff, with an entry fee per peak vehicle and a variable charge per vehicle km. This charges will need to be differentiated to take into account the effect of train speed and gross weight, in particular, on capacity requirements. Departures from ATC pricing might be expected in situations where infrastructure is congested. In such cases, the entry fee would be increased to reflect SRMC. The resultant profits could be re-invested in capacity expansion. A pricing regime of this form would appear to satisfy the Government's requirements for an access and charging regime provided a narrow definition of efficient operation is made. Theory tells us that pricing at ATC rather than LRMC is welfare sub-optimal. Simulation work is required to assess the extent of this welfare loss and the economic costs of a regulation regime that allows pricing at LRMC.

One issue we have not addressed is the operational impacts of congestion. Our capacity calculations have not included margins for late running or for track maintenance. As output reaches our `theoretical' capacity limit, reliability problems are likely to increase and this congestion effect needs to be considered. We have assumed that external costs are zero, in practice they are likely to be substantial. Analysis therefore needs to be extended from private to social costs. However, this would then lead to second best issues arising from a pricing regime that reflects social costs of rail infrastructure provision and use but does not reflect the social costs of road infrastructure provision and use.

A further problem relates to our implicit assumptions of perfect knowledge. It assumes that Railtrack has perfect knowledge of the demand for rail travel and, hence, infrastructure. In practice, there are likely to be symmetries in that this information will mainly be possessed by the rail operators. This problem is confounded by the fact that the level of infrastructure provision and, therefore, service quality, effects demand. A particular problem we have highlighted is the pressure that open access is likely to place on clock face timetables.

The last problem we would highlight is that of transaction costs. Suppose a route is franchised and the winning operator proposes to supply a service of 120 trains per day at regular 8 minute intervals. We have previously suggested that an entry fee of £23,333 per train per annum should be set. Alternatively, assuming the service could be provided by 8 train sets, a fee of £350,000 per train set per annum might be charged. However, suppose that one quarter of fixed infrastructure costs are related to terminals and that terminals A and B are owned by separate property development companies. Assume further that variable costs are £10 per km, of which 10% are variable infrastructure costs. In this case operator Z makes the following cost and revenue estimates (£k per annum).

Payment to Railtrack:	4200
Payment to A:	350
Payment to B:	350
Operating Costs:	18900
Operating Revenue:	21000
Subsidy from Franchising Authority:	2800

In this situation Z is covering variable costs, but requires a subsidy to cover fixed, infrastructure costs. This could be dealt with by one transaction but, in this case, involves four transactions, each of which needs to be overseen by the Rail Regulator. Extended over the entire network the increase in transaction costs is likely to be very substantial.

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Table One: Assumed Service Capacity with Different Infrastructure Provision -Peak Hour

Infrastructure provision:	Single Track	One Loop	Three Loops	Double Track	Quadruple Track
Train runs	1	1.5	2.5	8.50	17.00
Service interval (mins)	60	40.0	24.0	7.06	3.53
Revised trains runs	1	1.5	2.5	7.50	14.00
Revised service intervals	60	40.0	24.0	8.00	4.00
Clockface train runs	1	1.0	2.0	6.00	12.00
Clockface service interval	60	60.0	30.0	10.00	5.00

Table Two: Cost of Infrastructure and Service Operation - Sixteen Hour Day, 350 Day Year Non Clock Face Headway.

	Single Track	One Loop	Three Loops	Double Track	Quadruple Track
Train runs	16.00	24.00	40.00	120.00	240.00
Train kms pd	800.00	1200.00	2000.00	6000.00	12000.00
Variable Cost pa (£k)	2800.00	4200.00	7000.00	21000.00	42000.00
Fixed Cost pa (£k)	1400.00	1480.00	1640.00	2800.00	5600.00
Total Cost pa (£k)	4200.00	5680.00	8640.00	23800.00	47600.00
Av. Cost per Train (£k pa)	262.50	236.67	216.00	198.33	198.33
Av. Cost per km (£)	15.00	13.52	12.34	11.33	11.33

Table Three: Costs of Infrastructure and Service Operation - Clock Face Headway

	Single Track	Two Loops	Five Loops	Double Track	Quadruple Track
Train Runs	16.00	32.00	48.00	96.00	192.00
Train kms pd	800.00	1600.00	2400.00	4800.00	9600.00
Variable Cost pa (£k)	2800.00	5600.00	8400.00	16800.00	33600.00
Fixed Cost pa (£k)	1400.00	1560.00	1800.00	2800.00	5600.00
Total Cost pa (£)	4200.00	7160.00	10200.00	19600.00	39200.00
Av. Cost per Train (£)	262.50	223.75	212.50	204.17	204.17
Av. Cost per km (£)	15.00	12.79	12.14	11.67	11.67

Table Four: Costs of Infrastructure and Service Operation - Sixteen Hour Day, 350 Day Year. Services Different Speed Non Clock Headway.

	Single Track	One Loop	Three Loops	Double Track	One Loop	Three Loops	Quadruple Track
Train Runs	20.00	32.00	50.00	98.00	140.00	190.00	196
Variable Costs	3850.00	6160.00	9625.00	18865.00	26950.00	36575.00	37730
Fixed Costs	1540.00	1640.00	1840.00	3080.00	3180.00	3380.00	6160
Total Costs	5390.00	7800.00	11465.00	21945.00	30130.00	39955.00	43890
Average Costs per Train	269.50	243.75	229.30	223.93	215.21	210.29	223.93
Average Cost per km	15.40	13.93	13.10	12.80	12.30	12.02	12.80

Table Five: Peak - Off Peak Charges

	Total	Peak	Off-Peak
No of train runs	42.00	30.00	12.00
Variable Cost	7350.00	5250.00	2100.00
Fixed Cost	2800.00	2800.00	1400.00
Total Cost	10150.00	8050.00	3500.00
Average Cost per train run (k)	241.66	268.33	291.66
Average Cost per train km	13.81	15.33	16.66

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