

Choice of Frequency and Vehicle Size in Rail Transport. Implications for Marginal External Costs

Piet Rietveld, Jasper Dekkers and Stefan van Woudenberg
Department of Spatial Economics
Vrije Universiteit
Amsterdam
The Netherlands
E-mail: prietveld@feweb.vu.nl

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Frequency of services and vehicle size are important policy instruments of railway companies. Extending Mohring's basic 'square root model' for frequencies, we arrive at more general formulations for frequency, vehicle size and price under alternative regimes of welfare and profit optimisation. It appears that in the more refined models the frequency response of railway companies with respect to changes in passenger volumes is not far removed from the standard square root result. Analysis of empirical data for the Netherlands shows that the responsiveness of the Dutch railway company in terms of frequency and train size to an increase in demand is low. It is estimated that an increase in the number of passengers of 1% leads to an increase in the supply of capacity of about 0.5 % (a frequency increase of about 0.35 to 0.40% and an increase of vehicle size of about 0.10%). This has important implications for the environmental costs of the railway company. An additional passenger does not lead to a proportional increase in capacity so that the marginal costs are lower than the average costs. It is further demonstrated that policies of keeping frequency and train size constant during the peak and off-peak have adverse effects on the environmental performance of railways.

1. Introduction

Producers of public transport services face decision problems with a considerable number of dimensions, including network structures, pricing, spacing of lines and stops, frequency of service, and vehicle size. In the present paper the focus will be on the latter two aspects: choice of frequency of service and of vehicle size.

Public transport services are usually characterised by economies of vehicle size¹: costs per seat tend to decrease with increasing size (Mohring, 1976). Thus, cost oriented public transport firms would be expected to employ large vehicles. However, from the perspective of the passengers, such a policy would be unattractive since it would lead to low frequencies and hence to high schedule delay costs and waiting times, and also to low speeds given the time losses for boarding and alighting. This leads to the question how public transport companies will weigh the various interests concerned. In this paper we will discuss extensions of Mohring's well known square root principle which says that frequency increases with the square root of demand.

The choice of vehicle size and frequency has important implications for the economic performance of transport companies and for consumer welfare. In the present paper another consequence is addressed that has not received much attention in the literature, i.e., the impacts on the environment. The issue of the environmental burden of public transport is important for at least two reasons. In the first place, the environment is important in its own right. Commitments of governments to reduce CO₂ emissions will not only have implications for private but also for public transport. Therefore, one needs to know more precisely what is the environmental burden of public transport and how it can be reduced. Secondly, subsidies to public transport are sometimes defended as a second best pricing instrument to correct for the fact that pricing of road transport is imperfect. This relates both to congestion pricing and pricing of road transport externalities. However, for an appropriate assessment one needs information on the marginal environmental costs of car users compared with public transport users. These two considerations play an important role in policy documents such as the EC paper on fair and efficient pricing (EC, 1995).

Since economies of vehicle size in transport do not only hold for monetary costs, but also for environmental costs, choice of size and frequency has implications for the environmental burden of public transport. Frequent services would imply a higher environmental burden of public transport. The square root principle would imply that when the number of passengers increases with 1% the frequency would only increase with 0.5%. An obvious implication for the environmental burden of public transport is that an increase in the number of passengers has a less than proportional effect on the environment. This is a partial result, however, since also vehicle size has to be taken into account. The aim of the paper is to clarify these issues and contribute to the discussion with figures based on empirical analysis.

This paper starts with a short literature review on frequency choice in collective transport (section 2). In section 3 we formulate our own theoretical model and investigate the implications of increases in travel demand for the adjustments in size and frequency of trains. In section 4 estimates are presented based on empirical data from the Netherlands Railways. Implications are discussed in section 5.

¹ The empirical part of this paper will be on railways so that vehicle size means train size. We will use the more general term vehicle size since the analysis holds for almost all modes of collective transport including bus, tram and aviation.

2. Choice of service frequency and size of vehicles in public transport. A short survey

The base model of frequency choice by public transport operators has been formulated by Mohring (1972). It can be outlined as follows. Consider the demand for trips per time period on a certain line (denoted as Q) as given ($Q=Q_0$). Further, let F denote frequency of service per time period and let costs of service equal

$$C_{\text{operator}} = u.Q + v.F \quad (1)$$

where u is the marginal cost per passenger and v is the cost of an extra vehicle used to serve passengers². In addition to the costs experienced by the operator there are also costs for the passengers related to waiting time and schedule delay. When the vehicles are equally spaced, the interarrival time between vehicles equals $1/F$. This implies that the average waiting time for a traveller going to a public transport stop without consulting the time table equals $0.5/F$. Since waiting time at platforms is valued more negatively than in vehicle time, the value associated to the waiting time is relatively high (say a factor a_1 , where $a_1 \geq 1$). Then, when the value of travel time is denoted as a_2 , the factor $a = a_1.a_2/2$ translates the inter-arrival time into monetary terms:

$$C_{\text{traveller}} = a.Q/F \quad (2)$$

Minimising the sum of total costs of company and travellers

$$C = C_{\text{operator}} + C_{\text{traveller}} = u.Q + v.F + a.Q/F \quad (3)$$

leads to the optimum frequency:

$$F^* = [a.Q/v]^{0.5} \quad (4)$$

This result is known as the '*square root principle*'. It means that an increase of demand Q with 10% leads to an increase of frequency of services of 5%. In a similar way optimal frequency will respond positively to changes in the cost of waiting time per passenger (factor a) and negatively to changes in costs of supply of an additional vehicle (factor v).

One of the limitations of this result is that vehicle size is not considered explicitly: it is assumed to be given. This has implications for the occupancy rate OR defined as:

$$OR = Q/[F.S] \quad (5)$$

where $F.S$ is the total capacity. Since the occupancy rate can be rewritten as:

$$OR = [Q.v/a]^{0.5}/S \quad (6)$$

it appears that it will increase with increasing demand, the pertaining elasticity being 0.5. Hence the square root principle means that with high demand the occupancy rate will rise above 1³.

When one is interested in occupancy rates, this is a somewhat implausible result, since one would expect that at higher volumes of travellers the operators would respond by increasing the size of the vehicles. This obviously calls for a joint analysis of choice of frequency and

² Note that we do not take into account delays related to boarding and alighting in this formulation

³ Whether it will be below 1 for low values of Q depends on the cost parameters.

vehicle size by operators. Another point that deserves attention is the possible response of travellers to higher frequencies. In the base line approach demand is inelastic ($Q=Q_0$), but in a more general setting one would expect that travellers respond to higher frequencies and that operators take this into account in their decision whether or not to increase frequency.

Jansson (1980) introduced the issue of vehicle size by formulating a model where operators jointly optimise size and frequency, and where peak and off-peak periods are distinguished. Based on the assumption of inelastic demand he derives optimal levels of frequency and size of buses. The assumption is that during the peak the occupancy rate is 100%, whereas it may be lower at other times. He concludes that at the time of research the structure of bus operations in Sweden was clearly sub-optimal since frequencies were too low and bus size was too large. The explanation of this gap between the actual and the optimum outcome is the neglect of user costs by public transport operators. Walters (1982) arrived at a similar conclusion for bus size in the situation of competition.

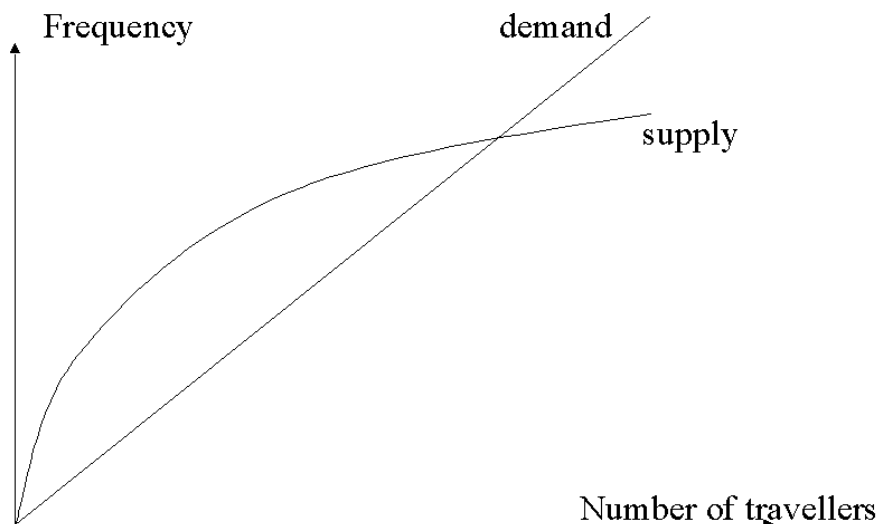


Figure 1. The relationship between capacity and travel demand according to the square root principle.

Using computer simulation techniques, Glaister (1986) analysed the potential consequences of deregulation of public transport in the city of Aberdeen based on the assumption of loss minimising operators, and where also bus fares are taken into account. His conclusions are comparable to those of Jansson that at that time frequencies were too low. Although deregulated bus companies would not take into account directly the user costs of travellers, they may yet benefit from higher frequencies when travellers are prepared to pay higher fares. A difference with earlier studies is that Glaister concludes that busses are too small, whereas Jansson finds that they are too large. This can be explained by the differences in the underlying assumptions and model parameters. One of the issues Glaister raises is the possible emergence of differentiated services for different types of travellers, a point that has been investigated in more detail by Gronau (2000) who analyses optimum diversity in terms of service frequencies and vehicle size.

Oldfield and Bly (1988) formulate a model with elastic demand where social benefits are maximised by using size, service frequency and price as control variables. Based on empirical data they find that both size and frequency vary approximately with the square root of demand. This underlines that also with much more complex models the square root principle seems to make sense.

Jansson (1993) formulates a model for a welfare maximising public transport authority that considers price and frequency. Two forms of schedule delay are distinguished: one where frequencies are so high that customers do not consult timetables when they use public transport, and another one where time tables are consulted. The two forms have rather different effects on schedule delay costs and hence may lead to local optima in the frequency choice problem.

In addition to these studies in the field of bus transport, issues of frequency and size have also been studied in aviation, especially in the context of deregulation. Important contributions can be found in Panzar (1979) Morrison and Winston (1986) Greenhut et al. (1991) and Schipper (2001). Schipper's contribution is of particular relevance for our purpose because he pays explicit attention to environmental aspects. He concludes that deregulation leads to increases in frequency and decreases in price, both having positive welfare effects. The consequences for the environment of these two are obviously negative. However, based on a cost-benefit analysis he demonstrates that the overall welfare effect is positive.

The literature surveyed above focuses on the bus and aviation sector. It is however equally relevant for rail transport. Given the nature of rail operations the number of constraints in the planning of network structures, timetables, vehicle capacities and crew and vehicle schedules tend to be more complex compared with those of bus companies (Daduna and Wren, 1988, Daduna et al., 1995). This may be an explanation why in the rail sector stylised models in terms of frequency and vehicle size only are not very common. Nevertheless, it may be argued, that although models in the tradition discussed above give a simplified picture of the optimisation of rail operations, they are useful to analyse the basic trade-offs faced in capacity management.

3. Choice of frequency and vehicle size by public transport operators. An in-depth analysis

Based on the approaches mentioned above four possible cases for the optimisation of vehicle size and service frequency by public transport operators are considered (see Table 1). Firstly, the dimension of elastic versus inelastic demand is considered. Secondly, operators according to the objective they maximise are distinguished: profits versus social surplus. This allows for investigating the implications of these various dimensions.

Table 1. Four choice contexts of frequency and vehicle size by public transport companies.

	Maximise social welfare	Maximise profits
Inelastic demand	I	II
Elastic demand	III	IV

Let demand for trips depend on generalised costs GC, where GC depends on the fare p , frequency F and other travel cost components tc (costs of in vehicle time plus costs of travelling to and from railway station)

$$GC = p + tc + a/F$$

Where a/F represents the scheduling costs as already explained in section 2. Demand also depends on other factors such as income, supply of competing modes, which are incorporated in a factor A . Thus, the demand for trips is:

$$Q = A.[p + tc + a/F]^z \quad (7)$$

where z is the generalised cost elasticity of demand ($z < 0$).

The costs of the production of transport services consist of various elements. Per passenger the costs of ticket counters, cleaning, and other personnel are equal to u . Another part depends on frequency; examples are the costs of drivers, and the cost of infrastructure use). Energy costs are proportional to frequency, but are subject to economies of scale: large vehicles are more energy efficient per seat than small vehicles. This leads to a formulation of energy costs such as $C_{\text{energy}} = wFS^b$, where b is smaller than 1⁴. In a similar way the capital costs of the driving stock are assumed to display scale economies, large vehicles are cheaper per seat than short vehicles: $C_{\text{driving stock}} = rFS^c$. Thus, total costs are equal to:

$$C_{\text{operator}} = uQ + vF + wFS^b + rFS^c \quad (8)$$

The costs of travellers have already been formulated in (2)

We assume that there are no restrictions on the size of the vehicles that the operator can purchase, neither are there restrictions on the frequency (thus, there is no public service obligation to have at least one train per hour, say). We impose the restriction that total capacity $F.S$ should be at least equal to demand Q . Note that if some combination of F and S is found that equals Q , an increase of S , keeping F constant would never be beneficial for travellers (their utility does not depend on S), whereas for the operator it would lead to higher costs. Hence in the present formulation we will always find that

$$F.S = Q \quad (9)$$

so that the occupancy rate $Q/[F.S]$ always equals 1 in these models⁵.

We will now discuss the four cases separately.

3.1 Maximise social welfare, inelastic demand.

This case can be considered as the direct extension of the Mohring model to the joint determination of frequency and size.

The optimal frequency F_1^* is the solution of:

$$F = [a.Q_0]^{0.5} / [v + w(1-b)Q_0^b F^{-b} + r(1-c)Q_0^c F^{-c}]^{0.5} \quad (10)$$

The optimal vehicle size follows as $S_1^* = Q_0/F_1^*$

The square root form can still be recognised in the equations, but note that F appears both at the right hand side and the left-hand side of the equation and that there is no analytical

⁴ The parameters w and r (below) are constants.

⁵ In the empirical part of this paper we will address the issue of occupancy rates that are lower than 100%.

solution for it. In the extreme case that scale economies in energy use and costs of vehicle stock are absent ($b=c=1$) we find again the exact square root formula where the only cost component that affects frequency is v , leading to a relatively high frequency.

When the scale economies in the costs of energy and the driving stock are relatively high (b and c are close to 0), it pays the operator to employ relatively large vehicles so that frequencies will be low.

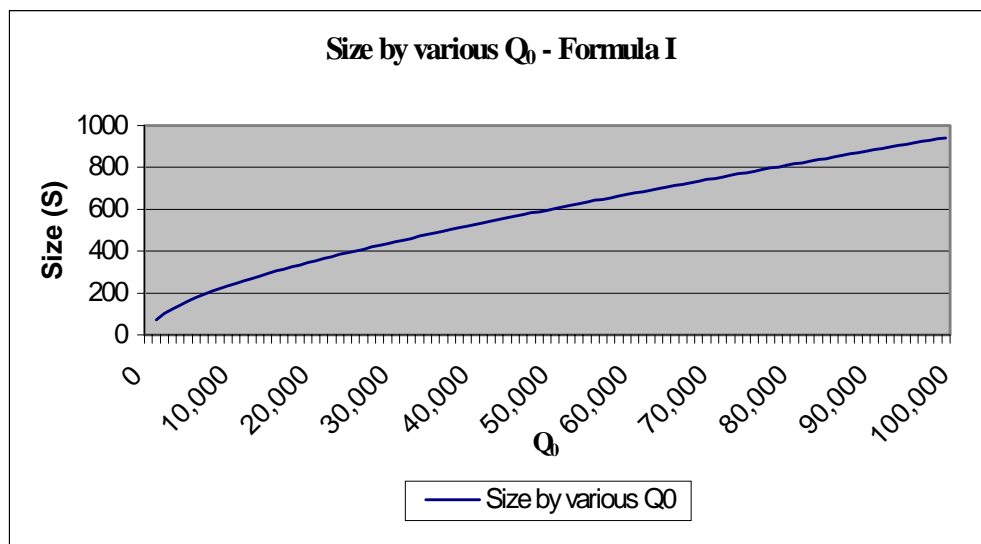
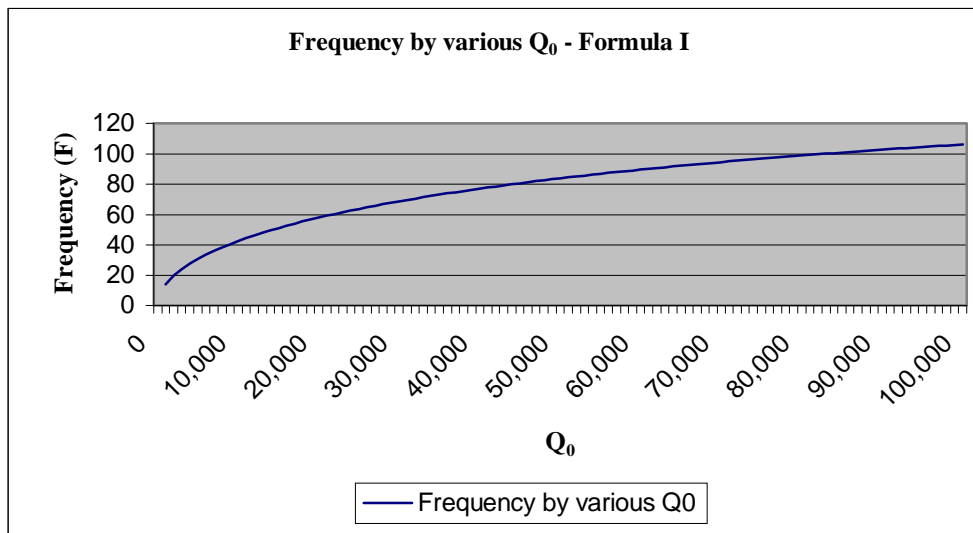


Figure 2. The relationship between travel demand, frequency and vehicle size (case I).

Note that since $F \cdot S = Q_0$, the elasticities of F and S with respect to Q_0 add to 1 by definition. The introduction of the size related elements in the cost function makes the supply of frequency slightly less elastic to changes in demand than in the base case. Figure 2 illustrates the relationship between demand and the optimal frequency level. The elasticity implied by

the figure is about 0.4⁶. The response of vehicle size with respect to travel demand is illustrated in the lower part of the figure. Thus the conclusion is that the introduction of the economies of scale in the cost function makes the frequency response with respect to changes in traveller demand slightly less elastic. The difference with the standard square root result is not large, however.

3.2 Maximise profits, inelastic demand.

The case of maximisation of profits under the assumption of inelastic demand is a trivial one. In this case the operator would minimise costs without paying attention to the interest of the travellers since consumer loyalty is not affected. This would lead to a choice of a very low frequency and a very large vehicle size.

3.3 Maximise social welfare, elastic demand.

The maximisation of social surplus with elastic demand means that the operator's objective can no longer be formulated in terms of costs, but that it should be in terms of consumer welfare (measured by means of consumer surplus) and costs. The inverse demand function is $GC = (Q/A)^{1/z}$. Thus, consumer benefits equal

$$CB = \int_0^Q [q/A]^{1/z} dq$$

In the case of welfare maximisation the objective is to maximise consumer benefits minus total costs of producing and consuming the services:

$$\text{Welfare} = \int_0^Q [q/A]^{1/z} dq - [tc+a/F]Q - uQ - vF - wFS^b - rFS^c$$

Note that with the given model formulation the size S of the trains equals Q/F since given any Q and F adding capacity by means of larger trains only leads to higher costs without any benefits for the operator or the consumer. Maximisation of total welfare with respect to price and frequency yields the following first order conditions:

$$(p-u) = w.b.A^{b-1} \cdot (p+tc+a/F)^{b.z-z} \cdot F^{1-b} + r.c.A^{c-1} \cdot (p+tc+a/F)^{c.z-z} \cdot F^{1-c} \quad (11)$$

and:

$$\begin{aligned} (p-u).A.z \cdot (p+tc+a/F)^{z-1} \cdot (-a/F^2) &= v - [a/F^2].A.[p+tc+a/F]^z \\ + w.b.z.A^b (p+tc+a/F)^{b.z-1} \cdot (-a/F^2).F^{1-b} &+ w.A^b.(p+tc+a/F)^{b.z} \cdot (1-b).F^{-b} \\ + r.c.z.A^c (p+tc+a/F)^{c.z-1} \cdot (-a/F^2).F^{1-c} &+ r.A^c.(p+tc+a/F)^{c.z} \cdot (1-c).F^{-c} \end{aligned} \quad (12)$$

Results for the optimal frequencies as a function of autonomous demand (A) are given in Figure 3. It appears that, although a rather complex model is used the elasticity implied by this figure is slightly above 0.5. Thus, the introduction of endogenous demand (being dependent on frequency) does not lead to elasticities that are very different from 0.5 as indicated in the original Mohring model. Note, that an increase in exogenous demand A has two effects on total demand: a direct and an indirect one. The direct effect is proportional according to equation (7).

⁶ The figure is based on the following combination of parameters: $Q_0=20,000$; $A=10,000$; $z=0.2$; $p=8$; $u=2$; $v=1000$; $w=0.8$; $r=3.2$; $b=0.7$; $c=0.9$; $a=200$.

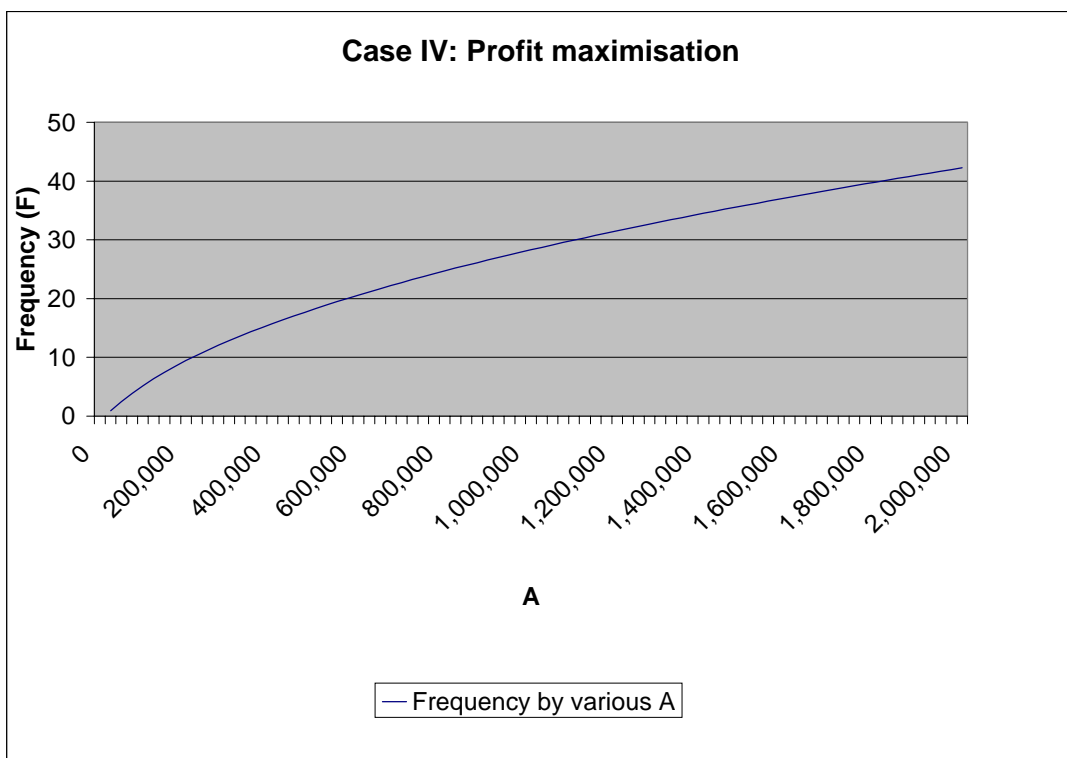
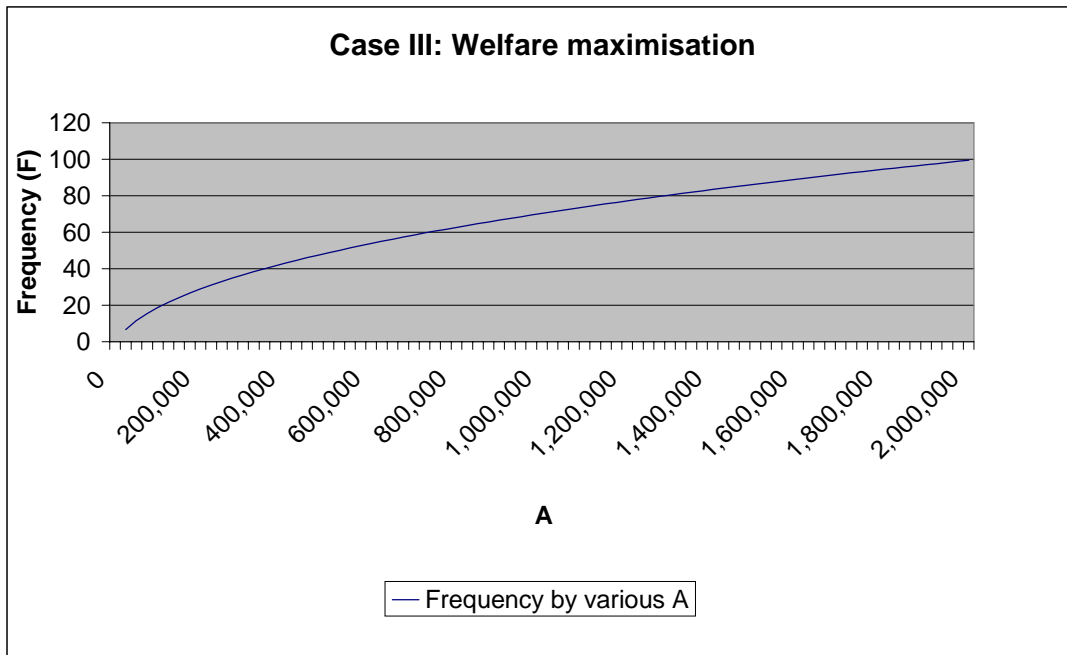


Figure 3. Relationship between travel demand and vehicle size under elastic demand, welfare maximisation (III) and profit maximisation (IV).

The indirect effect means that generalised costs decrease when frequency increases. Thus, when exogenous demand A increases with 1% total demand Q will increase with more than 1%. Since we assume in this section that total capacity $F.S$ is equal to total demand Q , the

conclusion is that the elasticity of frequency and size with respect to A are (slightly) higher than they are with respect to Q

3.4 Maximise profits, elastic demand.

Profits of the monopolist are equal to:

$$Z = (p-u)Q - v.F - w.F.S^b - r.F.S^c$$

Maximisation of profits with respect to price and frequency yields:

$$\frac{[p+tc+a/F]/z + (p-u)}{w.b.A^{b-1} \cdot (p+tc+a/F)^{b.z-z} \cdot F^{1-b} + r.c.A^{c-1} \cdot (p+tc+a/F)^{c.z-z} \cdot F^{1-c}} = \quad (13)$$

and

$$\begin{aligned} (p-u).A.z \cdot (p+tc+a/F)^{z-1} \cdot (-a/F^2) = \\ v + w.b.z.A^b \cdot (p+tc+a/F)^{b.z-1} \cdot (-a/F^2) \cdot F^{1-b} + w.A^b \cdot (p+tc+a/F)^{b.z} \cdot (1-b) \cdot F^{-b} \\ + r.c.z.A^c \cdot (p+tc+a/F)^{c.z-1} \cdot (-a/F^2) \cdot F^{1-c} + r.A^c \cdot (p+tc+a/F)^{c.z} \cdot (1-c) \cdot F^{-c} \end{aligned} \quad (14)$$

The difference between (12) and (14) is that consumer's surplus is not taken into account by the profit maximising operator. Ignoring consumer benefits of high frequencies will of course lead to a rearrangement of capacity F.S towards larger vehicles S and lower frequencies F. Note also that when z tends to zero in (14), also frequency will tend to zero, so that again the result of case II is found. Figure 3 demonstrates that in the case of profit maximisation the level of frequency is clearly lower compared with social surplus maximisation. Thus, a profit-oriented firm will run less (but longer) trains than a welfare maximising firm. Note, however, that there is not a large difference in terms of the elasticity of frequency with respect to changes in travel demand; in both parts of Figure 3 the elasticity is slightly higher than 0.5. We may conclude that the objective function of the supplier has important implications for the level of frequency, but not for its responsiveness with respect to changes in demand. Another conclusion from these models is that the square root principle following from Mohring's (1976) original model still approximately holds in more complex model contexts.

4. Empirical patterns of service frequencies and vehicle size

The above computations have been based on stylised facts about cost structures and demand functions in rail transport. One may wonder how the actual planning of frequencies and vehicle size compares with these theoretical results on optimal planning of operations.

To address this issue a sample of rail connections within The Netherlands has been considered. For 82 connections (46 stopping train and 36 intercity train connections) we obtained data of the number of passengers, the daily frequency and the number of seats.

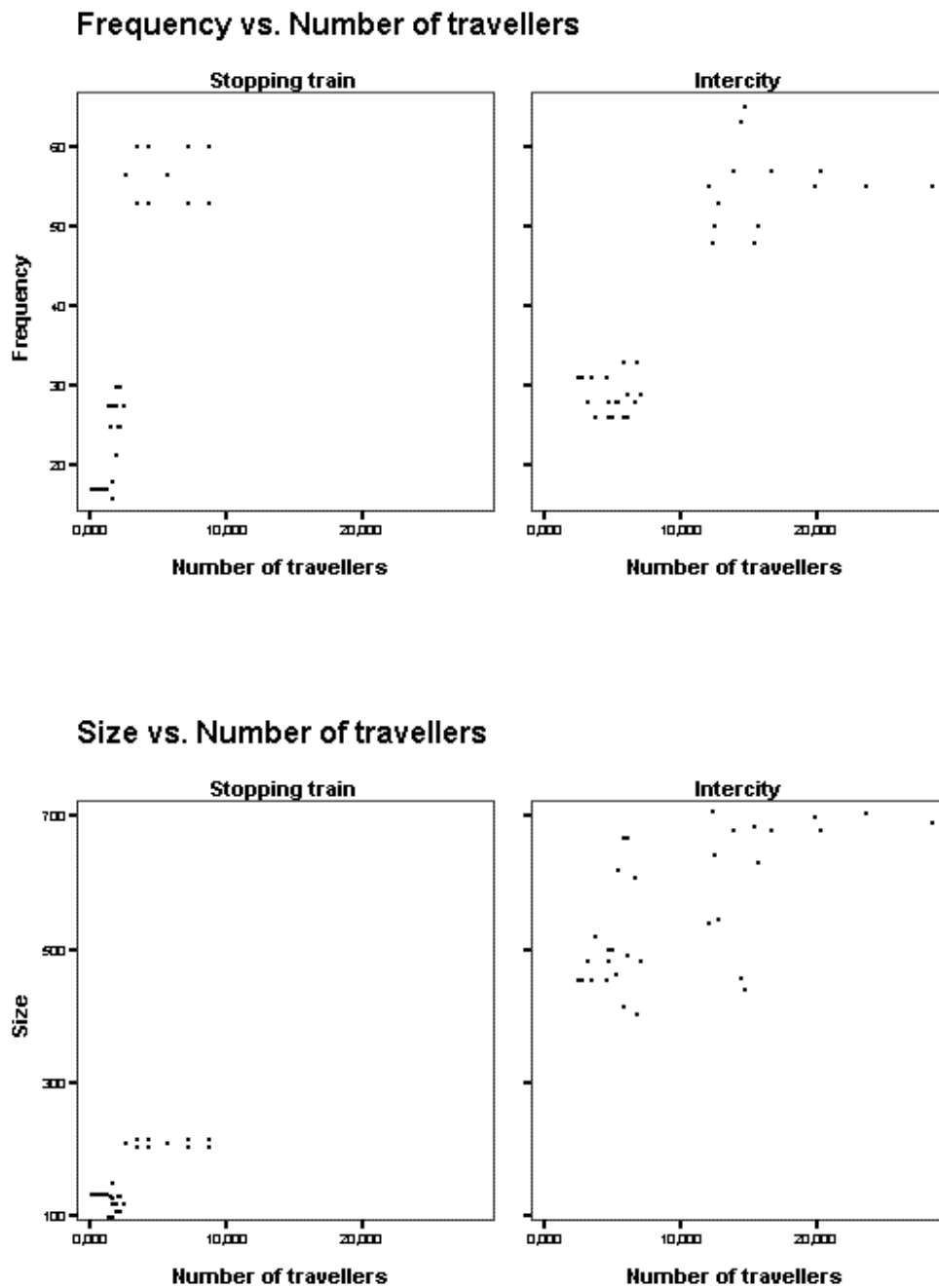


Figure 4. Service frequencies and number of seats per train for a sample of stopping trains and intercity trains in the Netherlands (off-peak, 1999).

Figure 4 presents the plots of service frequency and number of seats per train for the stopping trains and intercity trains during off-peak periods. It appears that in this sample the maximum frequency observed is about 60 trains per day (off peak). Based on an operational period of about 14 off-peak hours per day this means that there are 4 or 5 trains per hour. The basic pattern of 1, 2 or 4 trains per hour is clearly visible in the figure. Variations may occur since

in the early and late hours frequency may be lower. In addition, international trains may lead to some irregularity in the timetables. Low frequencies are clearly overrepresented in the stopping train segment. Most intercity trains have a frequency of 2 per hour. Also in terms of size there is a substantial difference between intercity trains and stopping trains, the maximum size of the stopping trains considered being about 200 seats, and that of intercity trains being 700 seats.

The empirical relationship between frequency and size supplied on the one hand and the number of passengers on the other is considered:

$$\begin{aligned} \ln F_i &= a_0 + a_1 \text{Dum}_{\text{int},i} + b_0 \ln Q_i + \varepsilon_i \\ \ln S_i &= c_0 + c_1 \text{Dum}_{\text{int},i} + d_0 \ln Q_i + \varepsilon_i \end{aligned} \quad (15)$$

Where $\text{Dum}_{\text{int},i} = 1$ when the link considered (i) is an intercity service, otherwise $\text{Dum}_{\text{int},i} = 0$. Estimation results of these relationships are reported in Table 2.

Table 2. OLS estimation results of dependence of service frequency and vehicle size on passenger demand (standard errors in brackets).

(a) separate analysis for stopping trains and intercity trains.

	frequency; stopping train	frequency; intercity trains	size; stopping train	size; intercity train	# of seats; stopping train	# of seats; intercity trains
constant	0.442 (0.352)	0.08867 (0.369)	3.924 (0.266)	4.661 (0.310)	4.365 (0.542)	4.750 (0.376)
Dum_{int}	-	-	-	-	-	-
$\ln Q$	0.387 (0.047)	0.396 (0.041)	0.138 (0.035)	0.183 (0.035)	0.525 (0.072)	0.578 (0.042)
R^2	0.609	0.730	0.256	0.449	0.547	0.847

(b) joint analysis for stopping trains and intercity trains.

	frequency; all trains	size; all trains	# of seats; all trains
constant	0.423 (0.248)	3.826 (0.193)	4.249 (0.360)
Dum_{int}	-0.282 (0.073)	1.118 (0.057)	0.836 (0.107)
$\ln Q$	0.390 (0.033)	0.151 (0.026)	0.541 (0.048)
R^2	0.678	0.926	0.870

The estimation results indicate that a 1% increase in passenger demand leads to a 0.4% increase in frequency and a 0.15% increase in the number of seats during off peak periods. Thus, when levels of demand vary, the railway company tends to respond more strongly in terms of frequency than in terms of size⁷. Note also that the overall elasticity of the railway company in terms of total capacity (F.S) with respect to passenger demand is about 0.55. This is clearly below the elasticity of 1 implied by the models in section 3. This result implies that

⁷ The estimates are based on cross-section data. The use of combined time series and cross section data would be preferable, because we are now forced to use the assumption that there are no line specific fixed effects. Unfortunately such panel data are not available to us.

occupancy rates tend to increase with passenger demand. We conclude that future theoretical work in this field of choice of vehicle size and frequency should pay explicit attention to various reasons why occupancy rates may be systematically below 100%.

An implicit assumption of the above analysis is that the correlation between the error term ε and the independent variable Q is zero in equations (15). In the present context it is probable, however, that the two are correlated. For example, as indicated in the theoretical model of section 3, there is a feed back of frequency on travel demand because waiting and scheduling times of travellers will be smaller. On those links where for some unknown reason frequency may be higher (via the error term) this may induce higher demand Q so that indeed the above-mentioned problem occurs. To correct for this an instrumental variable approach has been applied. The essence of this approach is that the number of passengers Q on the right hand side of the equations is replaced by an estimate of Q . This estimate is based on population totals of the municipalities involved, which are assumed to be exogenous so that the above mentioned correlation problem is removed. For details see Verbeek (2000). As demonstrated in Figure 3 this results in a frequency for elasticity that is somewhat lower (0.37 in stead of 0.39) and similarly a lower elasticity is found for train size.

Table 3. Estimation results of dependence of service frequency and vehicle size on passenger demand, making use of instrumental variables (standard errors in brackets).

	frequency; all trains	size; all trains	# of seats; all trains
constant	0.560 (0.392)	4.183 (0.312)	4.744 (0.578)
Dum _{int}	-0.247 (0.093)	1.189 (0.074)	0.942 (0.138)
ln Q	0.371 (0.052)	0.103 (0.042)	0.474 (0.077)
R ²	0.677	0.922	0.865

5. Implications for the environmental costs of transport

The above results have important implications for the marginal costs -and more in particular the marginal external costs- of rail transport. The external costs of various transport modes have been estimated in several studies (see for example CE, 1999, Mayeres and Proost, 1996, Kageson, 1998). An important factor appears to be the occupancy rate of vehicles since the emission per passengerkm of a train obviously depends on the number of passengers.

During the peak hours the occupancy rates are considerably higher than during the off-peak hours. This means that during the peak hours the emission per passengerkm is clearly lower than during the off-peak hours. Table 4 shows that during the peak hours the environmental performance per passengerkm of public transport is more favourable than that of the private car. During the off-peak hours the situation is less favourable since then the occupancy rate of the private cars tends to be higher and that of public transport is lower. For example, during the peak hours the capacity utilisation of trains is estimated to be 48% and during the off-peak hours it is only about 27%.

Table 4. Average emission per travellerkm for various transport modes during the peak (1998).

Transport mode	CO ₂ (g/tkm)	NO _x (g/tkm)	SO ₂ (mg/tkm)	PM ₁₀ (mg/tkm)
Petrol car, built-up area	232	.66	10.3	12.5
Petrol car, outside built-up area	166	1.45	7.3	9.3
Diesel car, built-up area	201	.47	61.1	154.7
Diesel car, outside built-up area	155	.65	47.0	102.3
Bus, built up area	26	.09	7.9	39.2
Bus, outside built-up area	39	.08	12.0	34.1
Tram	32	.04	13.0	.7
Metro	55	.07	22.5	1.3
Electric train, intercity	23	.03	9.3	0.3
Electric train, regional	35	.05	13.8	0.8
Diesel train, regional	53	1.00	65.5	n.a.

Source, SNM (2001)

However, a point that is often overlooked in this literature is that it is not the environmental burden of the average traveller that matters, but that of the additional traveller. Especially outside the peak an additional traveller in public transport could easily be accommodated without the need of adding capacity. This would bring the emission per additional passengerkm close to zero during the periods that there is ample capacity. During the peak period additional passengers will induce the railway company to supply more capacity in terms of frequency or vehicle size. It is here that Mohring's square root principle (or the refinements given in this paper) become relevant. An example of the computations is given in Rietveld (2002). The line of reasoning is as follows. An increase of passenger demand of 1% during the peak⁸ leads to an increase of capacity of about 0.5%. This can be decomposed in a frequency increase of about 0.37 % and a train size increase of about 0.10%. The ensuing increase in environmental burden appears to be slightly less (0.45%) because of the environmental economies of scale (Van den Brink and Gijsen, 2000) as introduced in section 3. Because of the overcapacity in the train system the marginal environmental burden of additional passengers could therefore be considerably lower than the average environmental burden.

However, a closer analysis of capacity management of the Netherlands Railways reveals that there is a complication. Frequency and train size vary hardly between the peak and the off-peak period. The background of this policy is the wish to maintain attractive frequencies outside the peak in order to reduce schedule delay times of passengers and thus attract more passengers. And train size is more or less kept constant because (de)coupling is considered to lead to extra costs and unreliability. The consequence is that an extra traveller during the peak hours leads to a modest increase of environmental burden of rail traffic during the peak, but since the total capacity is maintained during the rest of the day it obviously has a rather big adverse effect on total emissions. Since the peak lasts 4 hours per day and the rest of the

⁸ The estimated coefficients are based on data during the off-peak period. Unfortunately data on the peak period were not available. Therefore we base our calculation on the assumption that demand during the peak at the various line segments is proportional to demand during off-peak. This would imply that the coefficients estimated during the off-peak would also be valid for the peak period.

operations is carried out during about 14 hours per day, this leads to a considerably increase in total environmental burden. Based on estimates given in Rietveld (2002) the ultimate effect of an extra traveller during the peak is rather unfavourable for the environment: it is about 1.8 times the average burden of a peak traveller⁹.

For off-peak railway passengers the opposite holds true: their average emission is unfavourable due to the low load factors, but their marginal emission is zero. Thus, we arrive at a rather striking result (see Table 5). Taking the emission of an average peak passenger as a starting point (reference value = 100), the average emission of off-peak passengers is clearly higher (178) due to the low occupancy rates. But in terms of marginal burden the relationship is entirely reversed: additional peak passengers lead to a high burden whereas the burden of additional off-peak passengers is zero.

Table 5. Estimation of environmental effects of average and marginal railway passenger (index = 100 for average peak passenger).

	Emission of average passenger	Emission of marginal passenger
Peak	100	180
Off Peak	178	0

It must be emphasised that this result holds true for capacity management of the Netherlands Railways. It does not necessarily hold for railway companies in other countries or for other transport modes. In bus transport there seems to be less opportunity to change vehicle size, but bus companies tend to apply more flexible time tables during the day compared with railway companies. For each sector there is a clear need of an empirical analysis of Mohring's rule of half in terms of frequency and vehicle size adjustments.

6. Concluding remarks

The average environmental burden gives a misleading impression of the environmental friendliness of a transport mode. In stead, marginal values should be computed and therefore the behaviour of public transport suppliers in terms of choice of frequency and vehicle size has to be addressed. The theoretical and empirical work presented in this paper shows that the square root rule formulated by Mohring (1976), implying an elasticity of 0.5 of service frequency with respect to total demand is a reasonable first approximation in the case of railway services. However, in the empirical part of the paper slightly lower elasticities are found.

The structure of environmental costs is similar to that of operational costs of a railway company (see Rietveld and Roson, 2002). Thus, when there are environmental reasons to

⁹ This figure is based on duration of the peak of 4 hours and of the rest of the day of 14 hours. As indicated earlier a 1% increase of travellers leads to about 0.45% direct increase in environmental burden. Train size is about 5% lower during the off-peak and frequency is about 10% lower. Thus, an increase of 1% in railway travellers during the peak leads to an additional increase of environmental burden outside the peak of about $(14/4) (0.45) (0.9) (0.95)\% = 1.35\%$. Thus the total effect of 1% more peak travellers on the environmental burden is about $0.45\% + 1.35\% = 1.8\%$.

adjust capacity to demand during the off-peak period this also holds true from an operational costs perspective. This applies in particular for frequency of trains: frequency has a strong impact on both environmental effects and on labour costs. For the length of trains this cost similarity seems to hold to a lesser extent: a longer train implies low additional operational costs (compared with total operational costs) since it does not require more personnel, whereas the implications for energy use are substantial. It is true that operating with carriages that are unnecessarily large and with high frequencies offer advantages to the traveller in terms of more seating comfort and limited costs for scheduling and waiting time. These advantages do have their value for the traveller and may even invoke extra demand. The low occupancy rate during the off-peak hours, however, indicates that with the extra invited demand, the capacity in use is still ample.

Considering the very low costs of the off-peak traveller and the abundant capacity during the off-peak hours it is attractive for the Netherlands Railways to seduce travellers into taking the train during the off-peak by means of price policy, even more so than is the case at the moment. It would be in line with this policy to introduce a price increase of train tickets during the peak for the high-demand stretches and directions. Rietveld and Roson (2002) have investigated welfare implications of such a policy. When such a policy would be introduced it may be expected to reduce the gap between peak and off-peak demand. Peaks may still exist but they would be less and so would any environmental costs at both the margin and on average.

Further research in this field can take place in various directions. Taking into account spatial and temporal market imbalances in a more explicit way can refine theoretical models. This seems to be necessary to bridge the gap between theories in this field that assume full use of capacity and empirical results that show that occupancy rates are usually below 50%. Thus there is a need for models in this area that address this issue of low occupancy rates in a more explicit way. For empirical research the use of richer data sets is promising (combined time series and cross section data). Also the estimation of joint models of passenger demand and supply of railway services is recommended.

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