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Environmental Effects of Public Transport: On the Gap between Average and Marginal Costs

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Environmental Effects of Public Transport

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**Environmental effects of public transport;
on the gap between average and marginal costs.**

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Abstract.

Given the difference between peak and off-peak occupancy rates in public transport, the average emission per traveller kilometre is lower in the peak than during the off-peak period. For cars a reverse pattern can be observed. However, in this paper it is argued that it is much more fruitful to analyse environmental effects in marginal than in average terms. This calls for a careful analysis of capacity management policies of public transport suppliers that are facing increases in demand both during the peak and off-peak period. A detailed analysis of capacity management of the Netherlands Railways reveals that the off-peak capacity supply is mainly dictated by the demand levels during the peak period. Issues that receive attention in the analysis are the effects of frequency increases and size of vehicle increases on environmental effects. Also environmental economies of vehicle size are taken into account in the analysis. The main conclusion is that the marginal environmental burden during the peak is much higher than is usually thought, whereas it is almost zero at the off-peak period. Thus, one arrives at a pattern that is entirely reversed compared with the average environmental burden. The conclusion is that policies based on average environmental performances would lead to misleading conclusions.

Keywords: railways, service frequency, vehicle size, occupancy rate

1. Introduction.

The usual way to measure the environmental burden of public transport is the emission per vehicle kilometre. By applying a certain occupancy rate this can be translated into the emission per passenger kilometre. Note that both indicators are measured in average terms. It is conventional wisdom that the average environmental burden of a public transport user is lower than that of a car user. However, the gap seems to become smaller given the process of imposing sharper environmental requirements on cars. It is even sometimes stated that per traveller kilometre private cars perform better than diesel busses (see for example Table 1,

which presents summary indicators of the monetary values of environmental burden for various transport modes). On the other hand, during the peak, when occupancy rates are high in public transport, the mean environmental burden of all public transport modes is reported to be favourable compared with car use (SNM, 2001).

	Monetary value of emission in eurocent per travellerkm (European emission requirements 1992-2000)	Monetary value of emission in eurocent per travellerkm (European emission requirements 2001-2005)
Petrol car	1.0	0.8
Diesel car	1.4	1.3
LPG car	0.9	0.7
Diesel bus	2.2	1.2
LPG bus	0.8	0.8
Diesel touring car	0.4	0.3
Electric train	0.2	0.2
Diesel train	0.7	0.7
HST	0.2	0.2

Source: CE (1999)

Table 1. Monetary value of mean emission costs in eurocent per traveller-km for various modes of transport (the Netherlands, 1999) for various European emission requirements.

In this contribution I would like to engage in another point of discussion. The level of the *average* environmental burden of public transport per traveller is not the issue here, but the environmental burden of the *additional* traveller. After all, in discussions about the consequences of public developments or government policy on the environmental burden the focus is on changes in the environmental burden, so information about marginal effects is needed and not about averages. After a brief summary of a few issues I will give an estimate of the marginal environmental burden of an additional train traveller in the Netherlands.

2. Capacity management of public transport suppliers.

In public transport the environmental burden of an extra traveller may be small because often there is sufficient capacity in the carriages, especially during off-peak hours. This leads to a paradoxical situation. During off-peak hours the low occupancy rate has an adverse effect on the average environmental performance of public transport, but the marginal score is considerably more favourable since there hardly seems to be a need for extra trains or busses to accommodate the extra demand. During the peak, however, the opposite takes place. Now the question arises *to what extent* these effects occur. For example, how do suppliers of public transport in reality react to an increase in demand? The suppliers of public transport have various ways at their disposal when extra travellers enter the system:

1. No supply of extra capacity
2. Increase of service frequency
3. Increase in size of carriages
4. Combinations of options 2 and 3

The following notation will be used to analyse these options.

- Q volume of passengers per day
 F frequency of service per day

- S size of vehicle used, measured as capacity in terms of maximum number of passengers
 OR occupancy rate: $OR = Q/[F.S]$
 E emission per trip
 ET total emissions: $ET = E.F$

Consider the following relationships:

The supplier increases frequency F when demand Q increases with an elasticity b :

$$F = a_1 Q^b \quad (1)$$

According to the well-known square root principle derived by Mohring (1976) the value of b equals 0.5. This means that when demand increases with 2%, frequency will increase with 1%. The result is based on several assumptions such as maximisation of social surplus by the public transport supplier and the absence of capacity constraints.

Another policy is that the supplier may increase the size of vehicles S when Q increases with an elasticity c :

$$S = a_2 Q^c \quad (2)$$

Note that total capacity $F.S$ equals $a_1.a_2 Q^{b+c}$. Assuming that the load factor does not increase with increasing demand for passengers this implies that $b+c < 1$. In this paper we assume that the total demand for transport Q is inelastic: demand does not respond to changes in frequencies, prices, comfort levels or travel times. Examples of other studies on this theme, some of them with elastic demand can be found in Jansson (1980), Glaister (1986), Oldfield and Bly (1988), Jansson (1993) and Gronau (2000).

We now turn to the environmental cost part of the problem. The emissions per trip depend on the size of the vehicle:

$$E = a_3 S^d \quad (3)$$

Thus, the parameter d is an indicator of economies of vehicle size in environmental terms. Then total emissions $ET = E.F$ are equal to:

$$ET = a Q^{b+c.d} \quad (4)$$

The formulations for the average and marginal emission per traveller (EA , EM) are :

$$EA = a Q^{b+c.d-1}, \quad (5)$$

$$EM = a(b+c.d) Q^{b+c.d-1}$$

Therefore, the relationship between average and marginal external cost is:

$$EM = (b+c.d) EA \quad (6)$$

Strategy 1 mentioned above implies $b=c=0$. Strategy 2 means that $b>0$, $c=0$ whereas in strategy 3: $b=0$ and $c>0$. In Table 1 some typical examples of the various strategies are presented.

Elasticity of frequency w.r.t. demand b	Elasticity of vehicle size w.r.t. demand c	Elasticity of environmental cost w.r.t. vehicle size d	Elasticity of environmental cost w.r.t. total demand b+c.d
1.0	0	1.0	1.0
0.75	0.25	1.0	1.0
0.75	0.25	0.75	0.94
0.75	0	1.0	0.75
0.5	0.5	1.0	1.0
0.5	0.5	0.75	0.88
0.5	0.25	1.0	0.75
0.25	0.75	1.0	1.0
0.25	0.50	0.75	0.63
0.25	0.50	0.50	0.5
0.25	0.25	0.50	0.38
0	0.5	0.75	0.38
0.35	0.15	0.70	0.45

Table 2. Possible outcomes for the elasticity of environmental costs of public transport as a function of total demand for various combinations of parameters (bottom row: observed values for railway services in the Netherlands).

Table 2 shows that only in very exceptional cases the elasticity of total environmental costs with respect to demand equals 1. This occurs when $b+c=1$ and at the same time $d=1$. Only when $b=1$ (implying $c=0$) the requirement that d should equal 0 can be removed. In many situations public transport will be characterised by lower values of b , c , and d , as given in the lower part of the table. In such cases considerably lower values of the marginal environmental costs of public transport will be found implying that the marginal environmental costs are clearly lower than the average costs. In the bottom row of the table we report some estimates for the values of the parameters b , c and d as found for the operations of the Netherlands Railways¹. From these parameters it is clear that a low responsiveness with respect to frequency ($b=0.35$) in combination with an even lower responsiveness with respect to vehicle size ($c=0.15$) and a reasonable degree of environmental economies of scale ($d=0.7$) lead to a rather low value for the elasticity of the environmental effect with respect to travellers. According to equation (6) this implies a considerable gap between average and marginal emission levels. The above figures relate to the peak period. In the next section I will analyse how capacity management takes place during the off-peak period.

3. Capacity management and occupancy rates: peak versus off-peak.

Given the many crowded trains during peak hours one would expect a high occupancy rate during that part of the day. Yet, in reality the average occupancy rate during the peak hours will be a lot lower than one would think. The reason is that demand may fluctuate a lot between parts of a longer stretch, and also because often the demand according to direction is not very well balanced. Table 2 illustrates. Consider, for example, the time table for services

¹ Details of the estimation can be found in Rietveld et al. (2001).

between A, B and C, and back again where during the morning peak the demand between B and C is twice as high as between A and B. For the opposite direction we assume the demand in the morning to be a quarter of the original direction. The public transport supplier usually shows limited flexibility in adapting the capacity to match the demand: disconnecting carriages might lead to loss of time, extra costs and even to unplanned delays². Furthermore, with double-deck trains it is of course not possible to remove the upper deck. It is clear that the introduction of double-deck trains has decreased to some extent the flexibility of the Dutch Railways in the management of its working-stock. Moreover, it is not easy to change the imbalance of demand in both directions (see Rietveld and Roson, 2001, for a summary of possibilities to amend this problem by means of price differentiation according to direction). Assuming that the capacity matches the demand on the busiest stretch (BC), then in this case the resulting occupancy rate for peak hours is remarkably low: less than 50%³. The conclusion is that even during peak hours it is difficult for public transport to achieve high average occupancy rates for the whole network.

	Demand during the morning peak (number of traveller-kms)	Capacity: seat-kms	Occupancy rate (%)
AB	500	1000	50
BC	1000	1000	100
CB	250	1000	25
BA	125	1000	12.5
Total	1875	4000	46.8

Table 2. Influence of variations in traveller demand (according to stretch and direction) on the occupancy rate in a simple network.

Another point that deserves attention is that the occupancy rate as computed here is based on available seats. Another way of looking at these figures is to compute them from the traveller's point of view. In that case the occupancy rate on the busy BC stretch of course gets the higher weight and that on the quiet BA stretch a very low weight. It is on this occupancy rate that the traveller will base his contentment. On the basis of these figures it is easy to compute that the *occupancy rate experienced by the passenger* equals 70.1%, much higher than the occupancy rate computed from the supplier's point of view. This provides an extra reason why during peak hours the occupancy rate probably is lower than many passengers might think.

No matter how stylised the example in table 2 might be, it gives a surprisingly accurate indication of the occupancy rate in train traffic during peak hours. In the Netherlands this appears to be roughly 48%. During off-peak hours the occupancy rate is about 27% (see Table 3). The extent of adaptation of capacity during off-peak hours is very small: predominantly trains during off-peak hours move in frequencies and numbers of carriages equal to those during the peak. During the 4 rush hours of the day (4/18=22.2% of the time)

² Another reason for the Dutch Railways to be reluctant in disconnecting carriages is that the stretches covered by a train can be rather long. In that case there is no point to disconnect after the morning peak because the timespan during which the train runs completely out of the peak is rather short. With slow trains this holds to a lesser extent, because they usually cover a shorter stretch.

³ Note that even in aviation with its reservation systems and yield management which enable a rather accurate tuning of capacity and demand it is not easy to achieve an occupancy rate higher than 70% on network level.

about 24% of the trains are running. During off-peak hours the number of trains per hour is hardly less than during the peak and the number of seats per train is not much smaller either. Apparently the costs per train for connecting and disconnecting carriages are that high that the Dutch Railways abandon the idea to do this on a large scale. This approach means that the marginal costs of an extra traveller during off-peak hours are close to zero.

	Peak hours (4 hrs per day)	Off-peak hours (approx. 14 hrs per day)	Total
Number of train-kms (shares in %, adding up to 100 per full day)	24	76	100
Number of seats per train (average index = 100)	103	98	100
Total capacity (seat-kms; shares in %, adding up to 100 per full day)	25	75	100
Demand (seat-kms; shares in %, adding up to 100 per full day)	37	63	100
Occupancy rate (%)	48	27	35

Source: NSR

Table 3. Global characterisation of the demand for transport and the use of capacity of train services in the Netherlands (2000).

From the above analysis I conclude that the Dutch Railways is very inflexible in adjusting its capacity during the off-peak period. As we already found in section 2, it is more flexible during the peak period: total supply of capacity increases with an elasticity of $b+c=.50$ with respect to demand. It is clear that the company is facing several barriers to adjusting frequency and vehicle size. For frequency the upper limit relates to the capacity of the railway lines, whereas for vehicle size the length of the 'platforms' is a limiting factor. One way to remove the last mentioned barrier is the introduction of double-deck trains.

An important consequence of the inflexibility of capacity during the off-peak season is that the extra materials used during the peak will remain in use in the off-peak during which it will continue to have its environmental impacts. Thus, the system of regular timetables of train services throughout the day, which obviously is attractive for the passengers, has adverse environmental implications.

4. Implications for environmental effects.

What then are the implications of the above for the environmental effects of rail traffic? First of all it is clear that the *average* environmental effect will be closely related to the occupancy

rates as reported in Table 3. From the above figures it can be derived that the average energy costs per peak traveller are 34% below the full-day average and that for the off-peak traveller a level of 20% above average is found (see Table 4).

Of more interest is the question how the *marginal* environmental effects are related. First of all, with a view to the provider's strategy for the use of capacity during off-peak hours, it is obvious that the marginal environmental effects will equal zero. For the peak traveller the following computation holds. With a view to the elasticities and the coefficient of economies of scale for large over small carriages reported earlier it follows that 1% extra travellers during the peak will according to equation (5) lead to approximately $(0.35 + 0.7 \cdot 0.15) = 0.45\%$ extra use of energy during the peak. This also means that the marginal value during the peak equals 0.45 times the average value during the peak (see equation 6) so that the marginal value is very low (30) in respect of the reference value of 100⁴. However, as indicated above, most of the extra train carriages will remain in service during the off-peak period. When we correct for this, it suddenly appears that the peak traveller's marginal environmental effects are rather high, approximately 121⁵.

	Emission by an average traveller	Emission by a marginal traveller
Peak	66	121
Off-peak	120	0
24-hour average	100	

Table 4. Estimation of environmental effects of the average and marginal traveller in public transport (based on the average 24-hour emission index).

It needs to be emphasised that these values are rough estimates. Further research could lead to more accurate results. Closer research would involve both the scale economies for various types of pollution and a more accurate analysis of the capacity reaction by providers of public transport during peak hours. In addition, it should be noted that for specific cases rather different figures might result. For instance, with a view to Table 2: an extra traveller on the BC stretch has a proportional effect on the capacity to be used, whereas an extra traveller on the other market segments has a zero effect.

5. Discussion.

One may wonder whether a comparable analysis applies to car use, since car-pooling and other forms of car sharing are well-known phenomena. With an average occupancy of approx. 1.5 persons per car (i.e. an occupancy rate of 35-40%) the car reaches an occupancy rate comparable to that of a train. A remarkable difference is that the occupancy rate of a car during the peak is lower whereas the occupancy rate of public transport is higher. It is obvious that the extra car traveller will lower the mean environmental burden per traveller. However,

⁴ The 30 score is computed as the product of the reduction factor .45 and the average peak period base level of 66 on a scale ranging from 0 to 100.

⁵ This score follows as the product of the marginal value 30 and the frequency correction factor to take into account the total number of trains during the full day $[(24+76)/24]$, taking into account the small decrease in size $(98/103)$ and the elasticity of scale: 0.7. This results in $30 \cdot (24+76)/24 \cdot (98/103)^{0.7} = 121$.

there is no indication that car sharing will lead to a gap between marginal and average environmental effects for car users. The reason is that in practice an extra car user does not lead to an increase in the occupancy rate. The opposite is more likely to happen. The trend towards a decrease in the average occupancy per house and the increase in second car ownership make one to expect that less car sharing will take place. In specific cases, however, it is conceivable that policy measures be taken to emphatically stimulate car-pooling. Not only could this lead to an amelioration of the average environmental burden, but also to lower marginal environmental effects. So, in specific cases such as the computation of the environmental effects of, for instance, a kilometre charge the assumption that the marginal and average environmental burden of car use are equal is not valid.

A comparison with other public transport companies results in remarkable differences in terms of both capacity and frequency of carriages. With urban and regional transport, variation in carriage capacity can be much less than is the case with railway companies. As regards frequency, bus and regional transport can be considerably more flexible: the variation in frequency between peak and off-peak is considerable as far as bus and tram transport is concerned and little with the railway company considered here.

The picture that emerges from these figures is that mean values provide the wrong basis for computing the environmental effects of train use. *Peak travellers are not less polluting than off-peak travellers, as is often believed.* The use of marginal values for prognoses and policy making draws a more relevant picture of the differences between modes of transport than the use of average values does.

6. Conclusion.

The occupancy rate plays an important role in analysing train transport's environmental burden. We have discussed a number of reasons why the occupancy rate is lower than often assumed. Another conclusion is that the occupancy rate as *experienced* by travellers is systematically higher than the *actual* occupancy rate of seats. This difference could easily be 25% which means that according to the traveller's perception bottlenecks start much earlier than appears from the official statistics.

A remarkable conclusion of this analysis is that during the peak the average environmental costs for train use are indeed below the full day average (66 vs. 100), but that the marginal costs are almost twice as high (121 vs. 66). The explanation is that the extra stock in use during the peak hours does not get disconnected during the rest of the day. And so it appears that a large peak in demand can lead to extremely high costs if the policy is directed at accommodating the demand during the peak.

The analysis explains too that a decrease in disconnecting costs can have positive effects for both the environment as well as for the railways' level of costs. It also emerges that the Dutch Railways maybe ought to have another look at the fixing of frequencies during off-peak hours: beforehand it is not clear that the benefits of higher frequencies during off-peak hours can be off-set by the costs (among which environmental costs). Attention should be paid to the fact that operating with carriages that are too 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 invite 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. With a view to the very low costs of

the off-peak traveller and the abundant capacity during the off-peak hours it is attractive for the Dutch 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.

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