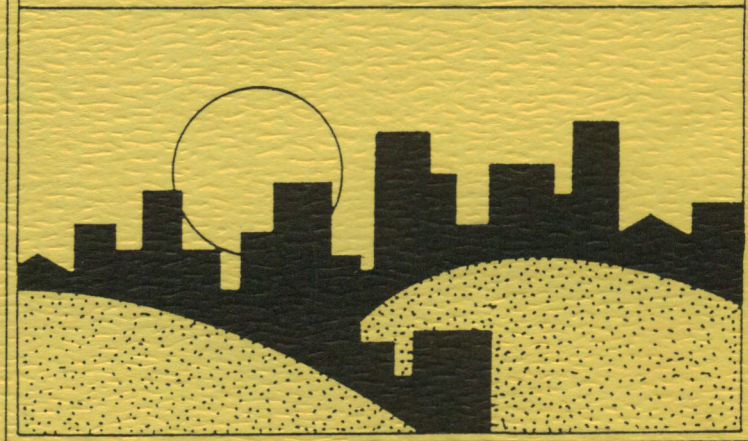


THE COSTS OF URBAN PHYSICAL
INFRASTRUCTURE SERVICES

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THE COSTS OF URBAN PHYSICAL INFRASTRUCTURE SERVICES

Max Neutze

The traditional methods of funding physical infrastructure – roads, public transport, water, sewerage, drainage, electricity, gas, telephones and garbage disposal – have involved varying combinations of loans amortised from current revenue, property taxes, user charges, access charges, developer charges, fuel taxes and subsidies from general tax revenue. These methods of funding have come under pressure in recent years for a number of reasons: shortages of government capital funds, pressures to reduce taxes, and attempts to make the funding systems more equitable and to use it to increase efficiency in the supply of these services and to reduce their adverse effects on the environment.

This Working Paper is one of the outcomes of a research project which aims to comprehensively review the funding system. The project examines the nature of these services, the objectives to be achieved through funding and the relative merits of the alternative funding sources. One of the early conclusions is that charges (prices) related to costs have efficiency and environmental advantages and are not necessarily less equitable than current financing methods. To appreciate the financial and other effects of prices related to costs, it is necessary to know the nature of the costs of infrastructure and the main factors which determine them. This paper focuses on the determinants of cost which influence the choice of appropriate charges. Other parts of the project examine alternative technologies, financial and jurisdictional issues and the relationship between infrastructure costs and financing and urban planning.

The unusual characteristics of infrastructure services are reflected in some unusual features in the cost of providing them. The paper deals with short and long-run costs and the question of economies of scale which affect the definition of marginal cost and the budgetary results of user charges based on marginal cost. It then looks at the complications introduced by the

existence of joint productions of different dimensions of services, and of the same services over time and in different locations. It considers the determinants of environmental (external) as well as financial (internal) costs and includes both volume of use of the service and other determinants such as the location and the time distribution of use. A final and minor determinant of costs of those services that charge individual customers, the cost of measuring the use by each customer and the administrative cost of charging for that use, is not discussed further.

1. Short and Long Run Costs and Scale Economies with a Single Product

(a) Short and long-run costs

In this section we assume that volume is the only product, an assumption which will be relaxed later. The short-run cost of providing a service at different levels is the cost, assuming that capacity is fixed; it can only be varied in the long-run. Since capacity costs are a high proportion of the total costs of many forms of infrastructure and expansion of capacity is very expensive, capacity is a more important constraint for many infrastructure services than for firms in most other industries. This is especially true of network services such as hydraulic services, roads, energy and telecommunications, but less so for bus services and garbage collection.

As the level of demand for a service approaches capacity, the costs of production and the costs to users, possibly through falling quality of service, is likely to increase. These increases are very evident in the case of roads where congestion results in slower trips, more collisions, more air pollution and, if heavy vehicles are involved, greater damage to the road surface. Because of the stochastic nature of demand for almost all of these services and of the supply of some, when demand approaches capacity there is an increased risk of being unable to meet demand rather than a particular occasion when, as in the case of storable commodities such as wheat, the warehouses become empty.

Examples of increased costs for other services are: the greater probability of an unsuccessful telephone call; reduced water or gas pressure; greater

probability of power cuts; greater probability of leaky sewers and those to which drains are illegally connected and sewage treatment facilities overflowing during rain storms; greater probability of flooding during rain storms; more standing on public transport; inability to get on to the chosen bus or train service; and reduced reliability of services; and the greater the probability of grid lock on congested roads. The severity of the effects of supply failure vary between services, from the mild effects on most users of reducing water pressure to the dramatic effects of grid lock and electricity cuts.

Various measures can be taken to extend the capacity of roads such as limiting left and right turns during peak hours, adjusting the phasing of traffic lights to limit cross traffic and limit entry of vehicles to congested routes at peak hours, and linking the phasing of lights on the main route to speed up the passage of platoons of traffic along congested routes.

Eventually, when capacity has been fully exhausted, the only way to accommodate greater use for one user is to deprive another user, so the short-run marginal cost becomes its opportunity cost: the value of the service to users whose supply is withdrawn. In the case of roads, the volume of traffic per hour on a section of road actually declines when too many drivers attempt to use it. Because demand is stochastic and rapidly fluctuating and the fact that most infrastructure services are provided by monopolies, rationing in the short term at least, is by queuing or cutting services rather than by price. Access to roads cannot usually be cut; the best that can be done is to warn people by radio where long delays are occurring. Neither service cuts nor queuing necessarily deprive supply to the users who place the lowest value on the service, whether that be measured by willingness to pay or some measure of need.

The long-run cost of providing a service is the lowest cost of providing a particular level of the service when capacity can be varied. At any given level of output, the optimal level of capacity will be that reflected in the long-run costs. If demand increases marginally beyond that for which this level of capacity was designed, there are (obviously) two alternative ways in which it can be met. The first is by increasing capacity, the cost of which is reflected in the long-run marginal cost. The second is by meeting the increase in demand within the existing capacity, the cost of which is

reflected in the short-run marginal cost. Since the optimal level of capacity is designed to minimise costs, short and long-run marginal costs must be the same at that level of capacity. Otherwise costs would be lower were there either more or less capacity.

The definition of long-run costs requires somewhat closer examination for urban infrastructure services. The long-run cost is really a planning cost: what would be the cost, including capacity cost, of providing this volume of services for a city or a suburb of a given size, in a given location and with given demand characteristics. In a normal industrial situation the long term is defined as the period long enough for the level of capacity to be varied. For some infrastructure assets, including most headworks such as dams, electricity generating stations, water and sewerage treatment facilities, the same kind of definition can be used.

For the networks of pipes, wires and roads that comprise a large part of the capacity of urban infrastructure, however, the planning cost, defined as the cost of capacity at the time an urban area is first developed, is generally lower than the cost of supplementing capacity at any later stage, for two reasons. First, the provision of these services itself increases the value of the land which will be needed for supplementing their capacity. This applies especially to roads and is known in the literature as 'the increasing supply cost of land'. Second, once a city is established, it is more expensive to install pipes and wires and to widen roads because of the cost of digging up existing roads and other public and private structures, and the disruption this causes.

To handle this problem it is useful to distinguish planning long-run costs from quasi long-run costs, the latter being the cost of expanding the capacity of infrastructure in an established urban area. If capacity is extended to cater for demand from an extension of the urban area on a green fields site, the two costs may not be very different, except to the extent that serving the new suburb requires increased capacity within established parts of the city. I will argue that it is quasi long-run costs as defined here that is important in thinking about charges for urban infrastructure services. The long-run costs as defined in textbooks can be achieved only when new settlements are built on green fields; they can never be achieved in the expansion of established urban areas.

(b) Returns to scale

Returns to scale determine the financial effects of marginal cost pricing: if there are economies of scale, long-run marginal cost will be lower than average cost and a charge set equal to long-run marginal cost will not cover the total cost of operation; if there are diseconomies of scale such a charge will produce a surplus. In this analysis the distinction between long-run and quasi long-run costs will be used: the first relates to whether costs increase or decrease in comparing plans for a larger or smaller city and the latter to the impact on costs as a city grows.

One of the accepted characteristics of many of the utility-type services that are provided by urban infrastructure is that there are economies of scale in their production. As a result long-run costs are assumed to decline with increases in production, and competition is grossly inefficient and unstable. Hence they are known as 'natural monopolies'. To demonstrate the economies of scale and the inefficiency of competition, one only needs to imagine the possibility of having the water mains of several competing suppliers running along each street. It is useful to consider headwork costs and network costs separately.

Headworks costs

Headworks costs including water harvesting and treatment, sewage treatment, garbage disposal and the production of electricity and gas are not essentially different from large industrial and mining operations. The average construction and operating cost of headworks per unit of output commonly falls as the scale of operation increases up to some level of production. Beyond that it is constant, though it may be lumpy since it is more efficient to make relatively large additions to capacity.

There is, however, one scarce input into the cost of headworks, the land and natural resources close to the city, which generally increases in cost as a city expands. This occurs for two reasons. First, good dam sites close to the city are scarce and as a result it is necessary to harvest water from more costly or more remote sites as a city's demand for water increases. Similarly it is necessary to draw from more costly or remote sources of natural gas.

Second the capacity of the natural environment in and close to a city to absorb pollutants is limited. As a result it is necessary either to treat water-borne city wastes to a higher standard of purity or to pipe them further from the city for discharge into the environment. This tendency to increasing costs applies to sanitary sewage, the wastes carried in stormwater, and to solid waste which must be transported further from the city as nearby landfill sites are exhausted.

Technological change is another factor affecting the cost of headworks as a city expands. A growing city can take advantage of new and more efficient technologies that are embedded in capital assets much more rapidly than a stagnant city which must wait for the replacement of the assets in which the old technology is embedded. In a growing city, the older equipment for provision of services such as electricity and water supply is used only in periods of peak demand or as emergency capacity for periods of drought or in the event of a breakdown. Scale of demand in a city also affects its ability to take advantage of lower cost technologies. For example, technological improvements in high voltage transmission have permitted cities to reap economies of scale from large scale generation on the coalfields.

Lumpiness in additions to capacity is a separate, but related cost characteristic which affects the cost of expansion. It is often cheaper per unit of capacity to install or add a large than a small amount of capacity, though the optimum size of increment needs to take account also of the cost of excess capacity while demand is growing to take up the large increment. At any given percentage rate of growth, demand for a service in a large city will grow by larger absolute amounts, so that such a city will be able to take advantage of the cheaper large lumps of capacity at lower cost.

In summary, the average cost of headworks capacity will tend to fall with urban growth up to the point where the city is large enough to use the capacity of the most efficient plant, and beyond that if it is growing quickly enough to make efficient use of large lumps of additions to capacity and to quickly make use of new technologies. The average cost will tend to increase because the limited capacity of the local environment causes increasing costs. In respect of headworks costs, therefore, there are not necessarily economies of scale as a city's demand increases.

Network costs

Economies of scale are unambiguously a feature of the network parts of infrastructure services only when scale is measured as the scale of *planned capacity*, and when that capacity will be used sufficiently soon that it is efficient to install it at the time of initial development. Increases in network capacity to meet increases in demand caused by normal growth in a city's demand may cost more or less than average cost: there are not necessarily economies of scale under this definition.

The argument can be illustrated with respect to water supply. The case is very similar for sewerage, gas and electricity. Let us distinguish four different kinds of expansion of demand. Unambiguous scale economies occur in only the first of the four cases.

1. Water supply is being planned for two different forms of development on a stand-alone 100 hectare site. In one form the demand for water will be 50 per cent greater than in the other. Because the cost of pipes increases roughly in proportion to their length and diameter but their capacity increases in proportion to their diameter to the power of about 2.6 (because the cross sectional area increases as the square of the diameter and because friction between the water and the pipe decreases with size), it will cost less per kilolitre to transport water to, and to distribute it within the development where the demand is greater.
2. Water supply is being planned for two stand-alone developments, one of 100 and one of 150 hectares, and the expected demand is proportional to the area. In this case we cannot be sure whether the cost per kilolitre may be higher or lower in the larger development. There are economies in transporting the larger volume of water to the larger development but the additional 50 ha may be closer to or further from source, and the pipes within the larger development will be longer as well as some of them being of larger diameter. Average cost in total may be lower or higher in the larger development.
3. The demand for water within an established urban area increases by 50 per cent. There is likely to be spare capacity in some of the mains bringing water to and distributing it within the area, but it is unlikely

that there will be spare capacity in all of the mains and pumping stations. Usually some will be bottle-necks. Increasing the capacity of mains in established areas requires replacing old mains with larger ones, or laying additional parallel mains, both of which are very expensive for reasons given above. Whether the marginal cost per kilolitre delivered will be above or below the average cost of supplying the original area can only be determined by examining individual cases. This is the quasi long-run equivalent of the genuinely long-run cost as defined in case 1.

4. An additional 50 hectares is opened for development adjacent to an established, similar, 100 hectare subdivision. The cost of supplying water to the second area depends on whether its development was foreseen and whether sufficient capacity was allowed in the bulk mains for the additional demand. If so it will be very similar to case 2, and there is no general presumption that the cost of supplying water to such a development will be above or below the cost of providing it to the first 100 hectare development. This may be seen as the short-run equivalent of case 2, but it is applicable for the same reasons as case 3. If the further development was not foreseen it is more likely that the cost of supplying the extension will be higher.

Cases 3, and especially 4, describe the ways in which demand for water in a city grows. As the city becomes larger spatially from type 4 growth, the supply lines within the built up area become longer and it becomes more likely that the marginal cost of increasing the distribution capacity to meet additional demand will be above average cost.

Roads

There is as yet no agreement on whether or not there are economies of scale in the provision of roads in urban areas. One of the peculiarities of transport infrastructure is that some costs are borne by users and some by suppliers. This feature, as we show later, leads to distinctive economic features of the costs of congestion. Some of the above arguments with respect to the network costs of pipe and wire services apply to roads, and of course the road system has no equivalent to the headwork costs of most of the pipe and wire services. There are also difficulties in deciding whether the unit of production of roads is the (weighted) number of

vehicles passing along a given link in a given time, or the (weighted) number of vehicles that can get through a road network from some distribution of origins to some distribution of destinations in a given time. Finally it needs to be recognised that the cost of road transport is shared between providers (pavement, right of way, maintenance, control, administration) and users (vehicle operating costs, time of occupants, risk of accidents) of roads; the costs to both need to be included.

There are economies of scale with increases in the width of individual sections of roads: two lanes in one direction can carry more than twice as much traffic at a given speed (cost to users) as one lane. Beyond a four lane road, capacity is close to proportional to the number of lanes, though the median strip, emergency stopping lanes and the buffer strip between the edge of a freeway and the edge of the right of way are 'overheads', which need only be provided once no matter how many lanes there are on a freeway. But in urban areas intersections are important components of costs of provision of roads, and of delays and hence user costs. For example the land occupied by an intersection increases as the product of the width of the two roads (the square if the two roads are of the same width).

The two best estimates are that average costs are either 1.03 (Keeler & Small 1977) or 1.19 (Kraus 1981) times marginal costs per unit of flow along a highway. The first is statistically indistinguishable from constant returns to scale and the second not much higher. Both are based on cross sectional data and provide estimates of planning long-run costs.

These above assessments of scale economies assume that flow along a road is the correct measure of output. In the case of pipe and wire services, however, the unit of output is delivered to a particular location. Just as these services produce access to water, electricity and so on, roads produce access between different parts of an urban area, something much more difficult to measure. Mohring (1976: 144-5) considers the situation in which the capacity of a freeway grid is doubled by converting it from a two mile grid to a one mile grid. The number of intersections between freeways increases as the square of the density of the grid. In urban areas the cost of construction of freeway intersections is quite high relative to the cost of the freeway. For arterial roads the equivalent cost of intersections is mostly the cost of delays. In both cases, consideration of the network

reduces the economies of scale relative to consideration of route capacity alone. In total there may be diseconomies of scale.

As cities grow spatially rather than through increasing density, journeys to provide access from all parts of the city to the employment and other opportunities it provides tend to become longer (Neutze 1965). Among other effects this increases the density of traffic in many areas and results in the network effects noted above. At the same time, however, employers and providers of services decentralise to suburban areas and drivers and travellers trade off the cost of long journeys against the greater range of opportunities, and make most of their journeys to places close to where they live or work so that journeys do not lengthen to the extent implied by the spatial growth. In recent years, while the average length of journeys to work in the CBDs of Sydney and Melbourne have lengthened, the average lengths of other journeys, and of all journeys have in fact become shorter

If the volume of traffic increases within an existing urban area, unless the growth has been anticipated and space reserved for road widening, the cost of increasing capacity is likely to be a good deal higher than the cost of providing wider roads at the time of original construction. The two alternative ways in which capacity and speed of flow can be increased are to widen existing roads or to build new roads to take some of the pressure off existing through-roads. The advantage of the latter is that, because frontages of arterial roads (but usually not freeways) attract high density activities, the cost of the land needed to widen them is generally very high. The cost of widening freeways depends more on the availability of space and of lengthening overhead bridges. Alternative routes are often a cheaper option, whether they involve widening minor roads or new routes through land that is not intensively used.

Because land in urban areas becomes more valuable as a result of the provision of roads and other urban services, the quasi long-run cost of increasing capacity in either of the above ways is higher than the planning long-run cost. The former is relevant for pricing, and provides relevant information about scale economies. Given the very modest economies of scale with increasing flow found by Keeler and Small (1977) and Kraus (1981) it seems certain that when the increasing cost of land is taken into account, there are decreasing returns to scale.

2. Costs in the Multiple Product Case

As argued in the first chapter, most infrastructure services provide more than one product. From this point of view a product is different from another if the two are not close substitutes from the point of view of consumers. Thus services provided at different locations are different products: water, sewerage and electricity connections in, or a road or railway that provides access to, an adjacent suburb are of little value to me in my suburb. The same can be said, though with less strength, about services delivered at different times: the fact that there is plenty of electricity available in the early hours of the morning is of little value if there are power cuts in the early evening which prevent me from cooking my dinner.

Dimensions of these services can also be thought of as different products. In the recent literature on the economics of roads there is clear recognition (especially in Small et al. 1989) that arterial roads produce two distinct products: durability (or strength) to carry heavy vehicles which is almost entirely used by trucks and buses, and capacity to carry a large number of vehicles which requires wide roads and which is very predominantly used by cars. The road system as a whole includes also local roads in both rural and urban areas whose major function is to provide vehicular access to properties. Unfortunately there is seldom a clear distinction between access roads and through roads, though at the extreme rural lanes and urban cul-de-sacs provide only access and freeways provide only for through traffic. All other roads provide, in varying proportions, for access and for through traffic.

To use conventional economic terminology, access, durability and capacity are joint products of most roads. This does not imply that they are always produced in the same proportion. It simply means that in many situations it is more efficient to have roads that provide two or all three products than separate roads providing for each. To use more recent terminology there are economies of scope in some places from providing roads that produce two or three of the products. Small et al. argue that there are diseconomies of scope in providing for heavy vehicles and cars on the same roads because this means that all roads have to be thick enough to

carry trucks and buses. If trucks were kept off some freeways, as they are on some American parkways, the pavements could be much thinner. This view is most relevant for roads which mainly provide for long distance through traffic. It is less persuasive for the majority of roads for which the provision of access is a major function.

Measurement of the durability and capacity provided by roads and assessment of their costs is not in principle difficult. Measurement of the amount of access they provide and the cost of providing more access is more difficult. One measure of access is the density of roads (excluding limited access roads) in an area: kilometres per square kilometre. On this measure the cost of providing greater access is the cost of greater road length. Providing access from through roads results in economies of scope, especially during periods when through traffic does not use the whole capacity. There may be diseconomies of scope when through traffic is close to capacity: vehicles entering or leaving the flow of traffic, and vehicles parking on the roadside while their occupants visit a property reduce their capacity. We might estimate these costs by measuring their effect on the capacity of the roads to carry through traffic.

As detailed by Small et al. (1989) the marginal cost of durability should be charged through mass/distance charges on trucks and buses and the marginal cost of capacity through congestion charges. How should the marginal cost of access be defined and charged? Its two elements can be defined as:

- 1 The increased congestion cost from additional vehicles exiting or entering a road between intersections and the cost, in terms of increased congestion or of providing the space, of roadside parking; and
2. The marginal cost of an additional km of access road within a given urban or rural area.

To anticipate a later chapter: since vehicular access to a property and the right parking space adjacent to a property are rights attaching to property fronting a road, it is appropriate that their cost should be recovered as a charge on the property to which they give access. It follows that optimal

charges for durability and capacity need not pay the total cost of the road system.

The example of roads provides a framework for general consideration of the different products provided by infrastructure services. Each infrastructure service can be seen as delivering three broad kinds of products.

1. Access to the service requires a network which usually links individual properties with a source of the service or with each other, but in the case of public transport, links larger localities. Access always requires a network of pipes, wires, roads, rails, bus routes or garbage collection routes. The denser the network or the greater the area over which the network extends, the greater the level of access provided. Thus the cost of providing more access is a greater length of pipes and wires etc.

Access permits the service to be used. It is valuable in its own right because it meets an option demand, irrespective of how much of the service is used. Also it has a cost which is independent of the volume of use. If volume is considered as the sole measure of output, the provision of access appears as an overhead cost. It is this simplification which is largely responsible for the view that there are economies of scale in the provision of infrastructure services, especially for services such as water and sewerage where access costs are a high proportion of the total cost.

2. Volume of use is the conventional 'product' of infrastructure services. Producing a given volume of a service requires that the headworks have the capacity to cope with the volume of demand and that the roads, pipes, wires etc have the capacity to provide the service at the locations at which it is demanded. In addition it requires expenditure on the operating costs of the services: fuel for energy and transport, including costs of pumping water and sewage, chemicals for treating water and sewerage, and the time of drivers and passengers.

For some purposes it is useful to subdivide the volume of service into different products depending on when it is produced. The time distribution has a major impact on the capacity costs of both headworks

and networks, especially for services which are expensive to store (water, gas, goods transport) or impossible (telecommunications, passenger transport). In general the level of capacity is determined by the peak level of demand, reduced to the extent that is efficient to store the product to meet some peaks.

3. Various quality dimensions such as durability of roads. They include the ability to draw water at a particular rate and a particular pressure which is important for fire fighting and for some industrial purposes. The fire fighting demand determines the size of and pressure in mains in residential and many commercial areas and thus has a significant influence on costs. The right to discharge particular trade wastes into sewers affects the cost of providing and maintaining sewers and the cost of treatment. The voltage at which electricity is supplied is inversely related to cost because of the cost and power loss in transforming to lower voltage. The frequency of public transport services may be independent of volume, especially outside peak hours. The frequency of garbage collections, the quality of water delivered and the comfort of travel on public transport are additional quality dimensions.

While these various products are not substitutes from the point of view of consumers they are generally produced together because they can be more cheaply produced together than separately. The extent of jointness is sometimes known as the economies of scope, S_c , and defined as the proportionate savings in costs from producing the products together rather than separately:

$$S_c = \frac{C(Y_1, 0) + C(0, Y_2) - C(Y_1, Y_2)}{C(Y_1, Y_2)} \quad (1)$$

where C is the cost of production, and
 Y_i is the amount produced of product 1 and 2

The level of economies of scope varies greatly between different infrastructure services and different products each produces. Providing access and volume of a particular service to a particular property are joint products, though they could be separated to some degree if some services

were provided more frequently by individual households. For example much of the water required for use within a house could be collected from its roof, but access would still be required for dry periods because it is cheaper to provide long term storage in large dams. Similarly much of the stormwater falling on a property could be stored or allowed to soak into the ground on a residential block but access to the stormwater drains would still be needed in heavy rain storms. The capacity of the dams, water mains and drains could be lower however.

While there are economies of scope in delivering services to adjacent properties they may not extend over the whole urban area; there have been different distributors of electricity, gas and water to different parts of a number of Australian cities, but those distributors have not been in competition with one another. For both sanitary and stormwater drainage there are economies of scope in serving the properties within a catchment. Despite these economies much stormwater drainage is the responsibility of municipalities whose boundaries seldom follow catchment boundaries.

There are many examples of diseconomies of scope where it is more efficient for the different products, or different combinations of products of individual services to be delivered separately. Small et al (1989) argue that there are diseconomies of scope in providing for heavy vehicles and light vehicles on all roads. Their reason is that the great majority of road space is required for cars and light vans, and roads for them could be made much thinner at considerable cost saving if heavy vehicles were confined to specially constructed roads. In addition car-only roads would have a higher capacity where there is only limited grade separation because the slow acceleration of heavy vehicles slows down other vehicles.

There is, of course, a cost of such a separation of functions which was not considered by Small et al. To get access to properties heavy vehicles need to be able to use most roads. Even if heavy vehicles were permitted to use 'thin' roads for access purposes only, the length of trips by heavy vehicles would be increased significantly. Nevertheless there are advantages, especially in improved safety, in prohibiting heavy vehicles from using residential streets except for access, though this can often be achieved by designing residential subdivisions so that they do not provide convenient through routes. The costs and benefits of urban freeways for light vehicles

only are worth investigating. There are car-only freeways (often called parkways) in the United States.

A similar case can be made for other services. Thus it may be worth providing a separate sewer for some kinds of trade wastes, especially if separation permitted cheaper treatment. The fact that local sewage treatment and local storage of stormwater can provide much cheaper water than fresh potable supplies makes it possible to provide dual distribution systems with the lower quality water being used for irrigation, and possibly for toilet flushing and fire fighting. Whether or not it is economic to do so depends in part on whether the resource rent charge for extracting fresh water reflects the environmental costs of the extraction. A final example of diseconomies of scope occurs in public transport: alternative services by train, tram, bus, express bus, mini-bus and taxi vary in speed, comfort, frequency, cost and the walking distance at each end of the trip.

One implication of the multi-product view of these services for economies of scale has been considered already: if services are seen as simply producing volume, the costs of providing access are an overhead. For a single product firm economies of scale can be measured as the ratio of average to marginal cost of production. The average cost of one product in a multiple product firm is not easily defined. In their survey article on multi-product industries, Bailey and Friedlander (1982) derive an equivalent to economies of scale for one product of a two-product firm as the ratio of average incremental costs (AIC) to marginal cost (MC), where AIC is defined as the increase in the firm's total cost because it produces product 1, per unit of that product produced:

$$AIC_1(Y) = [C(Y_1, Y_2) - C(0, Y_2)]/Y_1 \quad (2)$$

and economies of scale in the production of product 1 is

$$S_1 = AIC_1(Y)/MC_1. \quad (3)$$

Multi-product economies of scale are then the average of the economies of scale of the two products, weighted roughly by the share of each product in the marginal cost of total production and amplified according to economies of scope:

$$S_m = [wS_1 + (1-w)S_2]/(1-S_c) \quad (4)$$

Where $w = Y_1MC_1/[Y_1MC_1 + Y_2MC_2]$ (5)

If Y_1 was assumed to be the only output, single product economies of scale (S_s) would have been

$$S_s = [AIC_1(Y) + AIC_2(Y)]/MC_1 \quad (6)$$

Taking Y_1 as volume and Y_2 as access, a comparison of S_m and S_s will show under what circumstances recognition that services produce multiple products will reduce the estimated economies of scale. S_s will be larger, relative to S_m :

1. the lower S_c (economies of scope);
2. the higher the economies of scale in providing volume relative to the economies of scale in providing access;
3. the higher the average cost of access;
4. the lower the marginal cost of providing volume; and
5. the lower the share of variable costs incurred in producing volume (w in equation 5).

Conditions 2, 3, and 4 are related to one another in that a low average cost of access and a high marginal cost of volume will increase the economies of scale in providing access and reduce them in providing volume.

The results can be illustrated for water supply and roads. In general there seem likely to be few economies of scale in providing access if access is measured as the number of properties connected, though there may be lower costs if the properties are located closer together. In the case of water there are probably large economies of scope but all of the other conditions suggest that S_m is likely to be lower than S_s . Thus there are very large economies from providing increased volume for reasons given above, the average cost of access is high and the marginal cost of volume is low, and the cost of providing access is high relative to the cost of providing volume.

The economies of scope in the case of roads are much lower, as reflected in the common policy of providing for through traffic on freeways and arterials and providing for access as far as possible from separate roads. There are only minor economies from providing for larger volumes of traffic. If S_c is zero and $S_1 = S_2$, $S_s - S_m = AIC_2/MC_1$ which is always positive, though it might be small.

An intuitive explanation of the effect of taking account of an infrastructure service providing a product other than 'volume' is that it results in additional costs being regarded as variable and therefore reduces economies of scale in production unless:

- there are large economies of scope;
- there are large economies of scale in the additional product; or
- the additional product accounts for little of the cost of production.

Services delivered at different times of the day, the week and the year are joint products wherever sunk capital costs are a major cost of providing the service. Indeed jointness over time extends to much longer time periods because of the durability, specialisation and immobility of the capital invested in providing capacity of those services which provide physical headworks or networks. For these services an investment decision today must consider the expected demand and its location for many years into the future. This does not apply to bus services or garbage collection.

Considering peak and off-peak outputs as different products adds little to the conventional theory of peak period pricing. In that theory it is recognised that the marginal cost of meeting peak demands is much higher than in off-peak periods. When capacity is not a constraint at all in off-peak periods, they can be ignored in deciding on optimal capacity.

The jointness of supply over longer periods has important implications for costs, resulting from the lumpiness of investment in capacity: the inefficiency of making small increments. The first is that costs are sensitive to the accuracy of the estimates of future demands, their quantity and their distribution over time and space. An overestimate will result in excess capacity for too long a period after the investment and an

underestimate will result in forgoing some of the economies from making large increments to capacity.

Because capacity is used fully only during peak periods it can be argued that they are the only periods for which forecasts are needed. For financial reasons, however, it may be possible to cater more fully to peak demands the less peaked the demand.

For reasons already given, planning of networks requires forecasts of the location of demand as well as its volume and time distribution. This is an important efficiency argument for controls over the location of urban development. Such controls improve the ability of infrastructure authorities to forecast the location of future increases in demand.

The second is that it is more efficient if future increases in demand occur in limited parts of urban areas. Under these circumstances it becomes efficient to provide distribution capacity in larger lumps. Demand will grow more rapidly in the selected areas so that the spare capacity will need to be carried for shorter periods.

The third occurs where supply and/or demand fluctuate in an unpredictable way, for example with variations in rainfall or temperature, and when lumpiness is marked and the time required to plan and construct additional capacity is long relative to likely periods of shortage. Under these circumstances the amount of capacity needed, and hence the cost of providing the service, will be higher the greater the planned security of supply: the lower the frequency and severity of periods in which supply is permitted to fall short of demand. Where variability of supply and demand (sometimes in the opposite direction as in the case of water) are large, the cost of reducing the probability and severity of shortages can be very high.

The main services affected by climatic variation are water supply (droughts), sewerage and stormwater drainage (heavy rain causes overflows of sewers, by-passing of treatment facilities and flooding) and electricity and gas (temperature extremes cause high demands for heating and cooling). The costs of maintenance and replacement are higher if the probability of breakdown is to be low.

Environmental costs

In considering whether there are economies of scale in the provision of infrastructure services it was argued that as a city grows these costs become higher because of the limited capacity of the environment within and around a city to provide water and energy and to absorb its waste products. Among the services considered, all except telecommunications have very significant environmental costs, and with present technologies overhead telephone wires cause environmental degradation, though even this may be removed by new satellite technology.

The provision of access to some services causes environmental costs, for example roads and overhead electrical transmission and reticulation. The level of environmental costs, however, is determined mainly by the volume of use of the services. Thus it is the volume of water used which either produces a volume of sewage or causes run off carrying nutrients and other wastes into rivers and lakes, and requires the flooding of river valleys to supply urban demands. A greater volume of water as well as volume and composition of waste material in sewage increases the cost and difficulty of separating the wastes from the water prior to discharge. The volume of stormwater which runs off the hard surfaces in an urban area during rain storms determines the extent of flooding. Volume is the main factor determining air pollution from transport, and the emission of greenhouse gases, and the volume of electricity and gas consumed largely determines the greenhouse gases emitted.

The location and nature of development

The location of urban development affects costs in several ways. First, it is more costly to provide services on sites which are steep, at a high (or very low) elevation or rocky. Second, it is more costly to service locations which are some distance from established areas and the networks which serve them because of the length of the necessary connecting roads and mains. Even if it is simply a matter of development being 'out of sequence', the lumpiness of capacity costs requires that the connections be installed with sufficient capacity to cater for future demands when the intervening areas are developed. The costs of excess capacity will be higher the greater the volume of out-of-sequence development.

The cost of services on the site depends also on the nature of development of the site, in particular the greater the density of expected demand. While the total cost will increase the greater the volume demanded on a site, because of economies of scale in the distribution system, the cost per unit volume will decrease.

Summary

This paper argues that it is necessary to recognise the multiplicity of products of most infrastructure services in order to understand the factors affecting costs. This does not detract from the great importance of the volume of use of each service as the major determinant of the cost of supplying them. Volume of use is the main determinant of both financial costs and environmental costs. The costs of providing access are still very significant for some purposes. The arguments for and against separate charges for access and volume of use and different levels of charges for use at different times will be assessed in later work.

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