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Towards a Science of Cities: City Observation and Formulation of a City Theory

by

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ABSTRACT

This paper proposes a conceptual framework of the interactions present in the settlement-transport system. This framework has been inspired by the database on 46 world cities which has been compiled at Murdoch University in Western Australia. It is postulated that there are three key factors that undergird the settlement-transport system and explain many of the observed differences in the working of cities around the world: constant travel time budgets, transport infrastructure and urban form. Analyses, mostly based on the cities data, reveal strong and systematic relationships between the various dimensions that can be used to describe these three factors. The strength of many of these relationships, with correlation coefficients in excess of 0.85 are perhaps surprising, especially given the scope in data collection methods between cities. They do however suggest that much of the observed difference between cities in car use, public transport use and other key performance indicators are physically driven and amenable to direct physical planning policy intervention on a metropolitan scale.
This conclusion is in contrast to those who contend, that wealth is the primary determinant of automobile dependence. It is suggested that this framework could form a basis for developing a scientific understanding about the processes that occur in the settlement-transport system.

Introduction

Recent research comparing transport characteristics, land use and economic indicators across 46 international cities reveals systematic relationships between many of these variables (Kenworthy and Laube et al, 1999; Newman and Kenworthy, 1999). These results are supported by findings from other studies that make whole city comparisons (Thomson, 1977; Zahavi, 1976; Goldberg and Mercer, 1986). To explain these strong and consistent patterns, one arrives at the inevitable conclusion that a set of universal factors is at work where the physical structure of cities becomes the primary determinant of transport consumption patterns rather than cultural differences or levels of affluence.

These systematic relationships appear to constitute what might be called 'universal factors' and seem to be firmly anchored in aspects of the physical urban environment. From research presented in this paper, 85% of urban mobility can be explained in terms of variables describing urban form and infrastructure provision. This runs contrary to some arguments that claim economic progress is the key driver and that socio-political conditions and cultural preferences are the key secondary variables which explain travel choice (Lave, 1992).

This paper attempts to set out in more detail what these universal principles surrounding the function of urban regions might be. It attempts to show how these principles can be enunciated using the large international database referred to above for 46 cities in the USA, Canada, Australia, Europe and the wealthy and developing parts of South East and East Asia. The cities used in this paper are listed in Table 1 along with their 1990 populations and urbanised land area.

Cities	Population	Urbanised land area
American cities		
Boston	4,056,947	230,820
Chicago	7,261,166	410.380
Denver	1,787,928	118,840
Detroit	3,912,679	289,940
Houston	3,462,529	304,930
Los Angeles	8,863,164	370,878
New York	18,409,019	958,372
Phoenix	2,122,101	191,940
Portland	1,174,291	100,490
Sacramento	1,355,107	86,470
San Diego	2,498,016	178,750
San Francisco	3,686,592	226,390
Washington	3,559,604	244,660
Australian cities		
Adelaide	1,023,278	87,045
Brisbane	1,333,773	136,338
Canberra	277,930	28,803
Melbourne	3,022,910	202,698
Perth	1,142,646	107,463
Sydney	3,539,035	210,407
Canadian cities		
Calgary	710,677	34,173
Edmonton	823,163	20,589
Montreal	3,119,570	92,390
Ottawa	907,919	29,023
Toronto	2,275,771	54,868
Vancouver	1,542,933	74,115
Winnipeg	641,850	30,146
European cities		
Amsterdam	804,711	14,392
Brussels	964,285	12,872
Copenhagen	1,711,254	59,928
Frankfurt	634,357	16,609
Hamburg	1,652,363	41,497
London	6,679,699	157,829
Munich	1,277,576	23,844
Paris	10,661,937	231,085
Stockholm	674,452	12,694
Vienna	1,539,948	22,547
Zurich	787,740	16,731
Wealthy Asian cities		
Hong Kong	5,522,281	18,380
Singapore	2,705,115	31,160
Tokyo	31,796,702	448,000
Developing Asian cities		
Bangkok	7,639,342	42,580
Jakarta	8,222,515	48,129
Kuala Lumpur	3,024,750	53,242
Manila	7,948,392	40,135
Seoul	18,586,128	32,462
Surabaya	2,473,272	13,983

Table 1. Population and urbanised land areas in 1990 for the cities used in the research.

To begin, we will outline a conceptual framework that sets out these factors. We will then address each component of the theory in turn, drawing on the international city data and some of the literature to show why we believe there are a set of key factors that undergird the urban settlement-transport system. Finally, the paper will discuss some of the human and economic outcomes which we believe flow from the beginnings of this 'city science'.

Conceptual Framework

Figure 1 provides a summary of the relationships identified in the empirical analysis of the 46 cities. It suggests that there are essentially three factors which work together to explain the bulk of travel patterns in cities and aggregate travel behaviour. These factors, and the synergies between them, in turn culminate in the degree of access experienced in cities. The factors are:

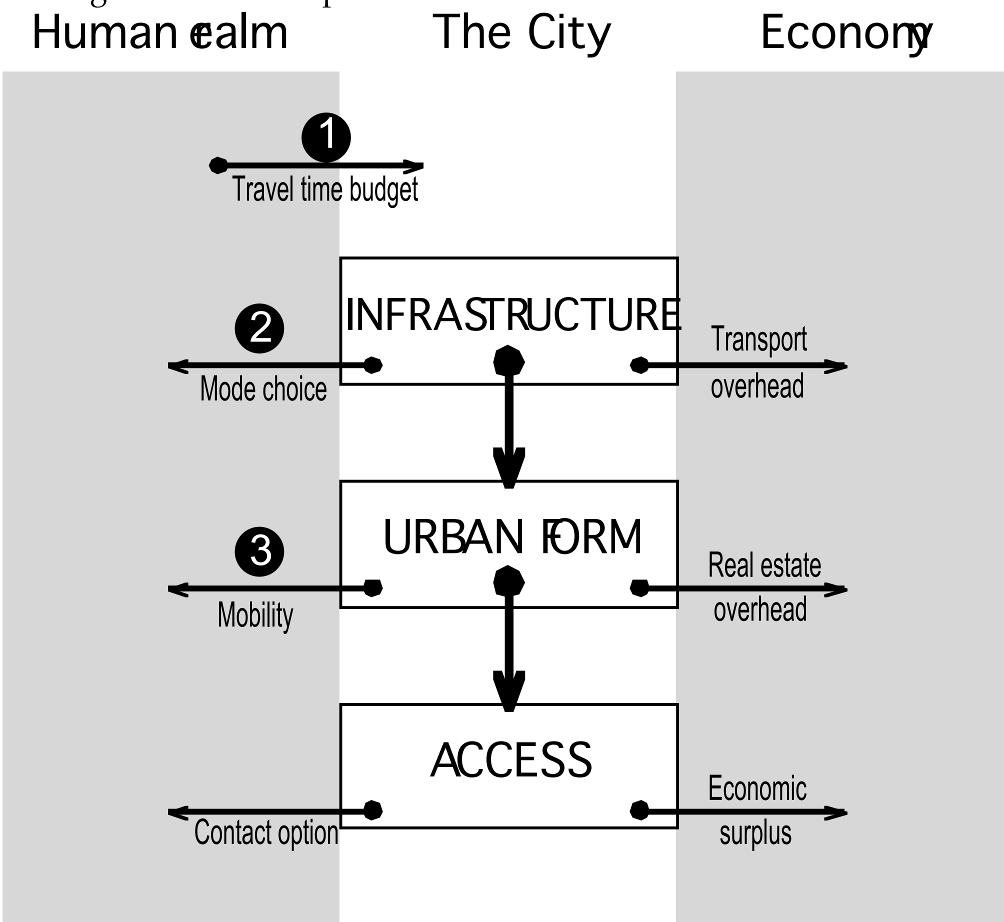

Figure 1. Model of the settlement-transport system.

Notes:

(1) Item 2 shows a transport overhead as the economic implication flowing from infrastructure. This is reflected in a number of ways, as is shown later in the paper in some efforts at direct quantification. However, a transport overhead is not the only economic implication flowing from infrastructure. Essentially, all major infrastructure in cities follows road networks (water mains, main drainage, sewer systems). The more sprawling and roads-orientated a city is, the higher generally will be the costs for these items due simply to the length required per capita to service all developed land. No data are presented in this paper on these other overheads, but they are certainly worthy of further research and flow from a city's transport orientation.
(2) The real estate overhead shown as an economic implication of urban form refers to all the land consumption costs and cost of buildings from different forms of urban development. Again, no data are presented in the paper specifically on these aspects. This again is worthy of more detailed comparative urban research and overlaps with land economics.
(3) "Contact option" shown under "access" flows from the type and quantity of transport infrastructure in a city and its urban form. It refers to the number and diversity of urban activities potentially accessible per expenditure of a given unit of wealth.

(1) Travel time budgets
(2) Transport infrastructure
(3) Urban form

All these factors come into play on a city-wide level and have both human and economic consequences. Each is distinguished by its physical nature, and can be described by 'natural' constants.

The human aspects are manifested in mode choice, mobility and contact options experienced by residents and workers, and the economic dimensions appear as the transport and real estate overheads which the city must bear and economic surplus which may accrue to it.

This conceptual model is now explained and substantiated through empirical comparative urban research that looks at each aspect in turn.

Results

Travel time budgets

Travel time budgets refer to the amount of time individuals are willing to spend travelling on a daily basis. The cross-section of cities examined reveal that mean travel times for the journey-to-work are remarkably similar. These are summarised in Table 2. On average, individuals living in the 46 cities examined are budgeting somewhere between 25 to 30 minutes for the journey-to-work. These results are supported by other research on travel times for the journey-to-work, including Szalai (1972), Manning (1978), Pederson (1980) and Hodges (1993). SACTRA (1994) has shown how journey-to-work times in the UK have held constant at around 30 minutes for some 600 years.

Cities	Average journey-to-work trip time (mins)
American cities	26.1
Australian cities	26.4
Toronto	25.3
European cities	28.2
Asian cities	34.0
Average all cities in study	**28.9**

Table 2. Journey-to-work trip times in a large sample of global cities (1990)

In addition to the regularity in travel times for the journey-to-work, data for travel time budgets that include all daily travel, also reveal a high degree of consistency. In aggregate, urban populations tend to spend 1.1 hours per day travelling (Schafer and Victor, 1997). This regularity appears to occur irrespective of the vastly different transport technologies, levels of wealth, degree of industrialisation or cultural norms that prevail in the cities studied. Marchetti (1994) suggests that throughout history, cities have always been about "1 hour wide".

Explanations for why this occurs have been put forward by numerous researchers. These are summarised in Kirby (1981). Generally, there seems to be agreement with the line of reasoning which says that in practice individuals are constrained in the amount of time they can budget to spend in urban travel. The hours in the day are finite, as are the hours that can be directed to potentially productive activity. Time spent travelling is not in itself productive. Exchanges individuals make at their destinations provide the real value and rationale for travel. Spending more than, say, 70 minutes per day travelling, reduces an individuals ability to carry-out essential daily tasks, so that travel becomes counter-productive.

Interest in travel time budgets on the part of researchers began in earnest with CJ Tanner's paper—"Factors affecting the amount of travel" (Tanner, 1961). In the years that followed, considerable effort was made to collect and collate empirical data sets aimed at investigating the degree of 'stability' in travel time budgets. Although aggregated travel time budgets are generally similar, there is a high degree of variation in cross-sectional groups that make up the sample populations (Gunn, 1981). For example, cross-sectional groupings by gender, age, and employment status, show degrees of variation in their travel time expenditure. In many of the sets, data indicate that men spend more time travelling than women, younger people more than elderly people and individuals classified as employed, spend more time travelling than those classified as unemployed. This suggests that the need to travel alters in accordance with changes in the "stage in the family cycle" (Heggie, 1978).

Differences in urban density, however, appear to have little effect on travel times (Gunn, 1981 and Goodwin, 1981). Similarly, travel times appear to be little affected by relative location to the CBD (Hodges, 1993).

In some data sets for developing cities, travel time budgets systematically alter in accordance with income (eg. Roth and Zahavi, 1981). That is, individuals on high incomes appear to spend more time travelling than those on low incomes. However, it is admitted that only motorised trips are included in such sets. This suggests that the data are actually indicating that poorer people walk more than those who can afford motor vehicles. Indeed in other sets where walking is taken into account, this has been found (eg. Szalai, 1972).

This raises the issue of variations in data collection methods and the degree to which these cause variations in the results. It is not possible to assess all of these in total, but it is worth pointing out that variations within these sets in most cases comprise only a few minutes. A more detailed discussion of these issues can be found in Zeibots (1999a).

If we take into account changes in the stage in an individuals life-cycle and the consistency in empirical results, on balance, it seems reasonable to accept the idea that a degree of constancy exists in the amount of time people are willing to spend travelling. Therefore, the idea of a constant travel time budget, both for the journey-to-work and all trips, appears reasonable in and of itself. However, the idea conflicts with key aspects of urban transport policy and assessment methods. As UK researcher Phil Goodwin has said: "[T]here has been some concern that if travel time outlay is constant, this invalidates the whole idea of valuing time savings" (Goodwin, 1981, p.99).

The whole history of planning around the automobile since the Second World War has been based on the notion that major new roads, especially freeways, return a net economic benefit to societies precisely for the reason that they save time. If aggregate travel times essentially remain constant, then the result of new infrastructure will not be shorter travel times but increased travel distances and increased trip numbers. The economic benefit of this in itself is unclear, suggesting that current justification methods may be erroneous. This concern has been expressed by researchers such as Manning (1981) and Marchetti (1994), commentators such as Donovan (1994) and the UK government committee findings contained in SACTRA (1994).

But irrespective of these concerns, which also seem to underscore many of the uncertainties about accepting the empirical results, the constancy of travel time budgets appears to be a central factor of transport behaviour. Or as Mills (1994) has said, "Time constancy goes to the heart of the urban transport problem" (Mills, 1994, p.1). We therefore suggest that:

The constant travel time budget is one of three universal factors that underpin the settlement-transport system.

This is indicated in Figure 1 by the number 1.

If the idea of a constant travel time budget is accepted, then several implications arise from this. Firstly, the average distance travelled per capita (private and public transport) will be a product of the travel time budget and the absolute speed of the transport network. Empirical data for this from the 46 cities in this study show a positive correlation coefficient of + 0.84 (or an r-squared value of 71%) between total person kilometres and travel speed across cities, as shown in Figure 2. This is a good result given the number of cities and wide range in data collection systems involved in producing the data set. The city's spread, measured in terms of its urbanised area is then a direct product of the travel speeds experienced on the city's infrastructure and the constant travel time budget.

These two factors—the relative constancy of travel times in combination with the physically fixed nature of transport infrastructure—have implications for mobility generally and the choices available to individuals specifically. These are discussed in the next section.

Infrastructure

Travel speed is dependent on the operational aspects of the infrastructure available to users. In this factor there is a degree of choice available to the community via the administrations of transport bureaucracies in that a conscious decision must be made as to what modal mix of infrastructure will be provided. The infrastructure factor is shown in Figure 1 by the number 2.

In our data, we can see evidence of the effect infrastructure provision and travel speeds have on mode choice. For example, the length of road per person is strongly associated with the overall road traffic speed (24hr/7day). The more road facility available per person, the higher the speed and this is shown in Figure 3 (r = +0.82, r-squared = 67%).

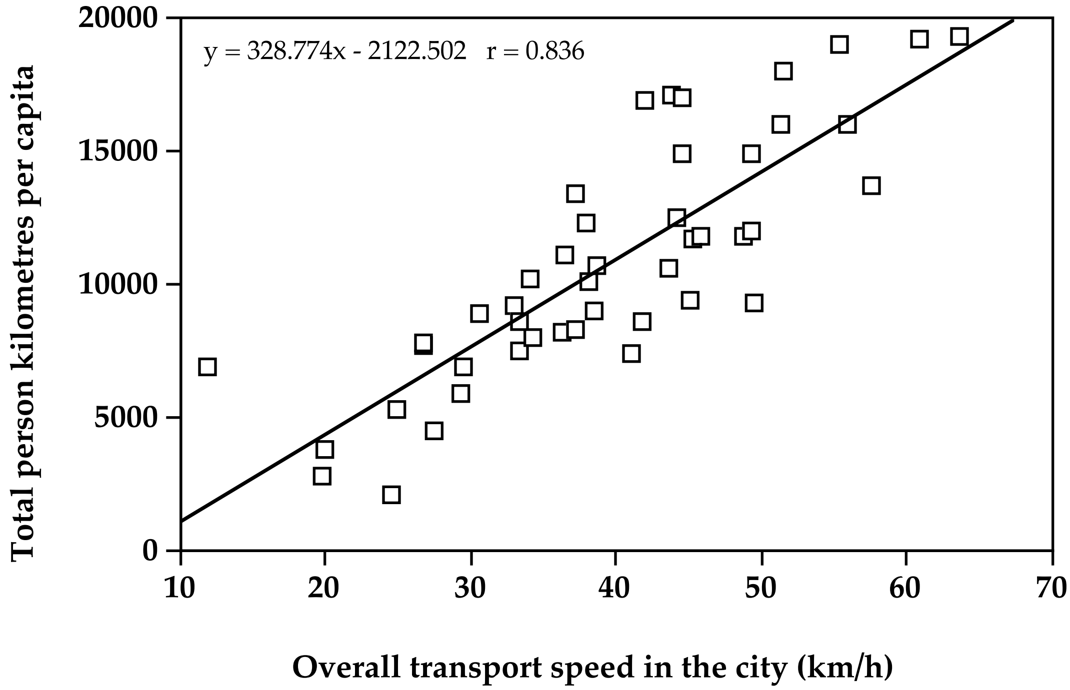

Figure 2. The relationship between total per capita person kilometres travelled and the overall average speed of the city transport system in a large sample of global cities (1990)

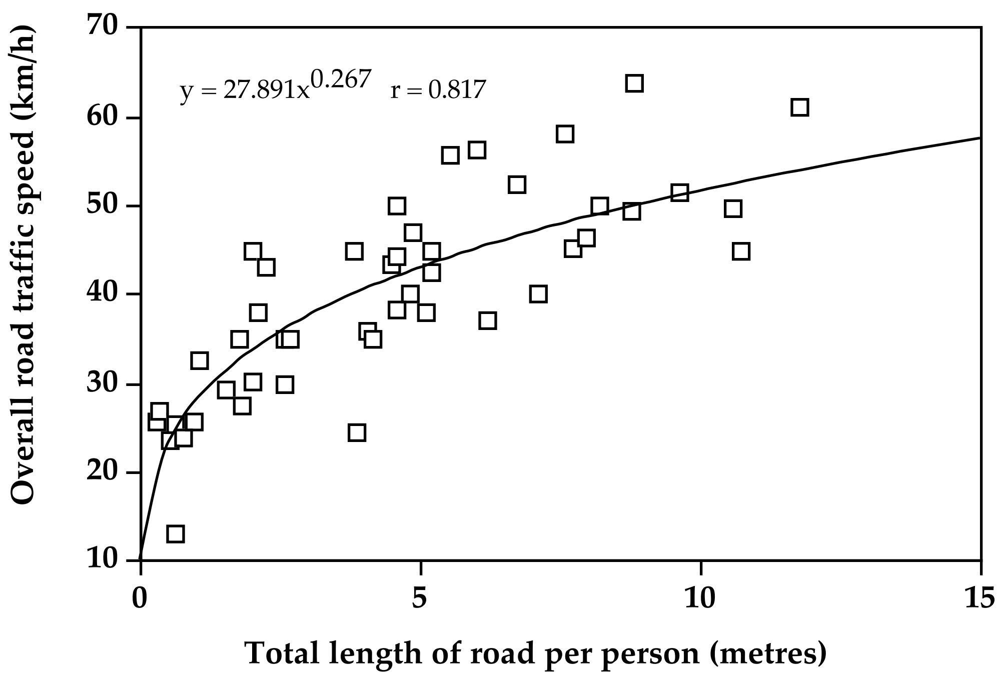

Figure 3. Total length of road per person versus the overall road traffic speed in cities (1990)

Likewise, there are further strong associations amongst transport infrastructure items that have a bearing on travel speed. For example, the length of road per person is significantly correlated with the amount of parking space provided in city centres (central business districts or CBDs: r = +0.646) and CBD parking per 1000 jobs in turn is strongly correlated with average road traffic speed (r = +0.644).

The effect of infrastructure provision on speed can also be seen within the public transport system. Where extensive rail systems exist, and service frequencies are high, the higher will be the average speed of the public transport system as a whole. This is because, as a rule, rail enjoys segregated rights-of-way that allow for unhindered movement of public transport vehicles. Evidence for this is shown in Figure 4 with a strong correlation between the annual rail car kilometres of service per person and the overall average speed of public transport in cities (r= + 0.85, r-squared = 72%).

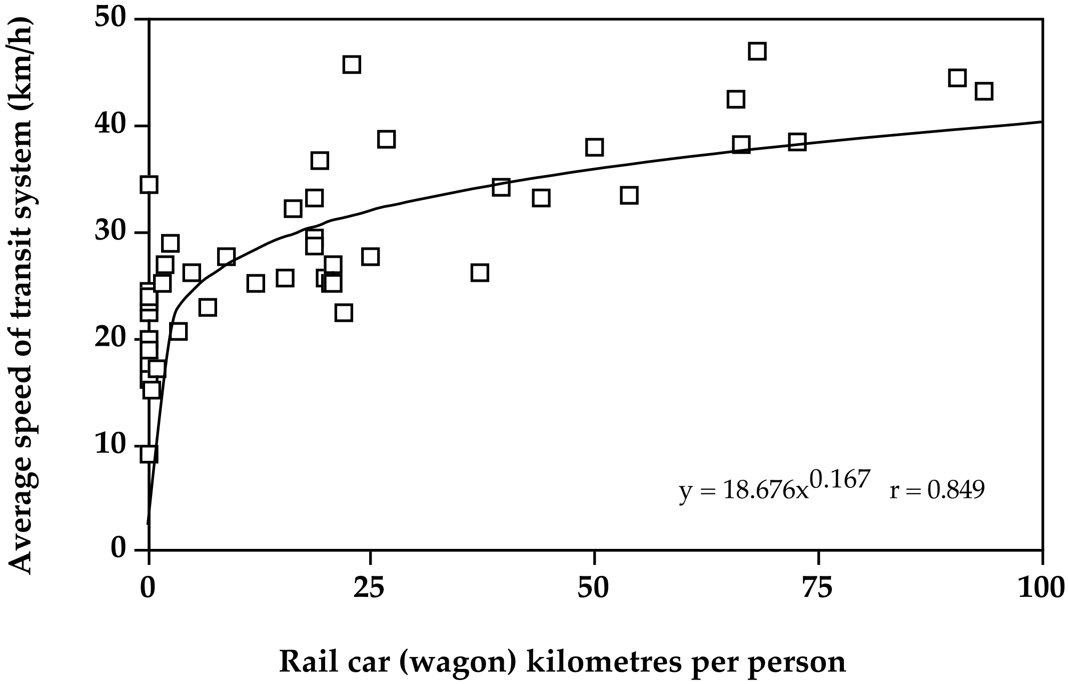

Figure 4. The relationship between the supply of rail service and the speed of public transport in cities (1990)

Bus systems are also the beneficiaries of high levels of infrastructure provision. The correlation between length of road per person and bus average speed in cities is positive and statistically significant (r = +0.617), though not as marked in its effect as that of rail infrastructure supply on the overall speed of the public transport system.

It has thus been shown that infrastructure provision has a marked effect on travel speeds in cities. More significantly it can also be shown that infrastructure and relative travel speeds have a significant effect on mode choice. If we accept that faster modes have an advantage over slower modes because faster modes potentially increase the area of city that falls within an individual’s travel time budget, then we can examine the effect that relative differences in public and private transport speeds have on mode choice. Figure 5 shows a very strong association between the ratio of system-wide public and private transport speeds and the utilisation of public transport expressed as annual passenger kilometres per person (r = +0.83, r-squared = 69%). In other words, people tend to choose whichever mode is fastest. This notion is also supported by the fact that when the speed weighted public transport service provision per hectare[1] is correlated with the overall motorised mode split in cities (ie the proportion of total motorised passenger kilometres on public transport), the results are extremely strong (r = + 0.97, r-squared = 94%; Figure 6).

Clearly, policies that favour the provision of public transport infrastructure in cities, while giving less emphasis to road infrastructure and private motor vehicle use, will positively influence mode split in favour of the more sustainable mode.

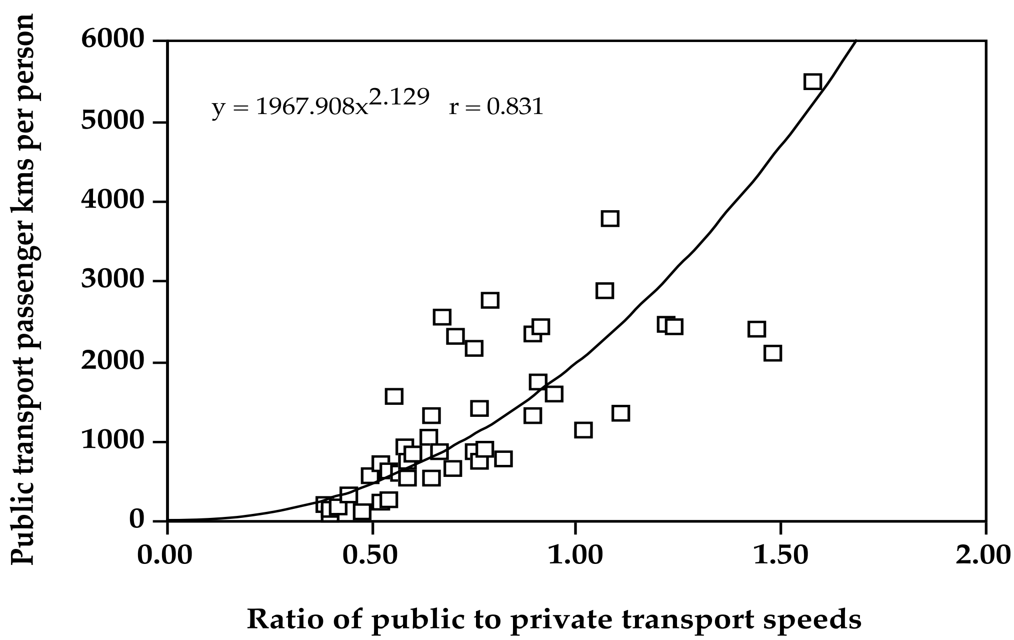

Figure 5. The relationship between the relative speed of public and private transport and the use of public transport in cities (1990)

[1] The speed-weighted public transport service per hectare is calculated by multiplying the ratio of public to private transport speeds (this is >1 if public transport operating speeds are higher than the road network speed) with the public transport vehicle kilometres of service. This is then normalised over the urbanised surface area of the city. The resulting indicator contains a factor of comparative modal advantage as well as absolute availability of public transport. It hence reflects the way the transport choice is viewed by the user.

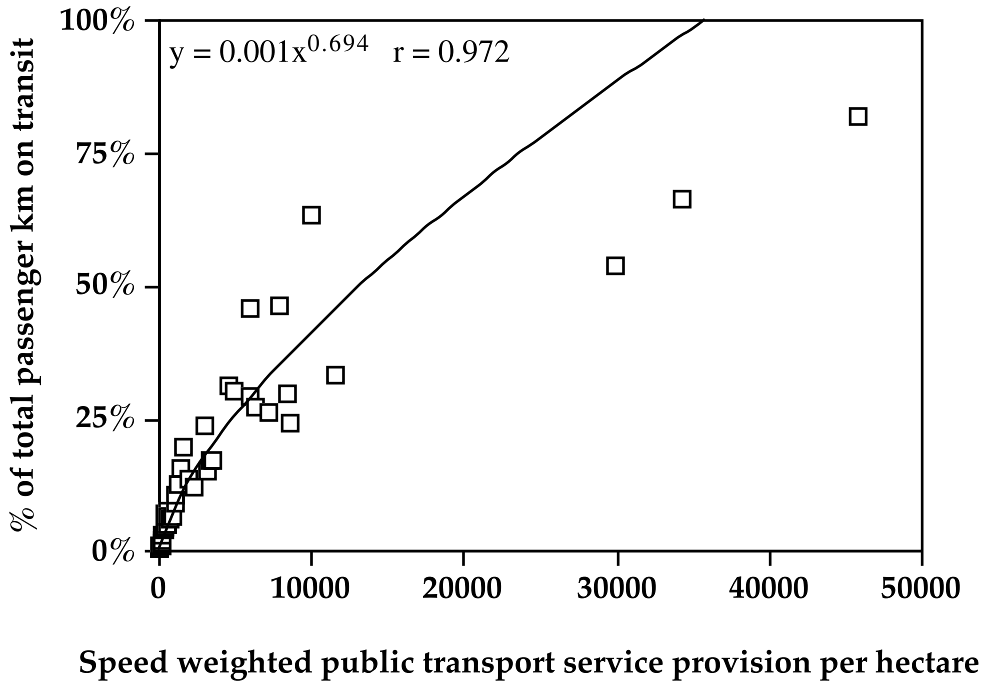

Figure 6. The relationship between the speed weighted public transport service per urban hectare and overall motorised modal split in cities (1990)

Overall in the international city data we can see that the relative provision for the various modes is strongly related to the mode choice made by individuals. In other words, mode choice is most strongly determined by the options available. For example, the empirical data show a correlation coefficient of 0.92 (r-squared = 85%) between public transport supply expressed as annual vehicle kilometres of service per person and public transport use expressed as annual passenger kilometres per person (Figure 7). In the same way, greater road provision and more generous parking supply in the CBD are strongly associated with higher car use per capita expressed as annual car kilometres per person (r = + 0.870 and r = + 0.735 respectively).

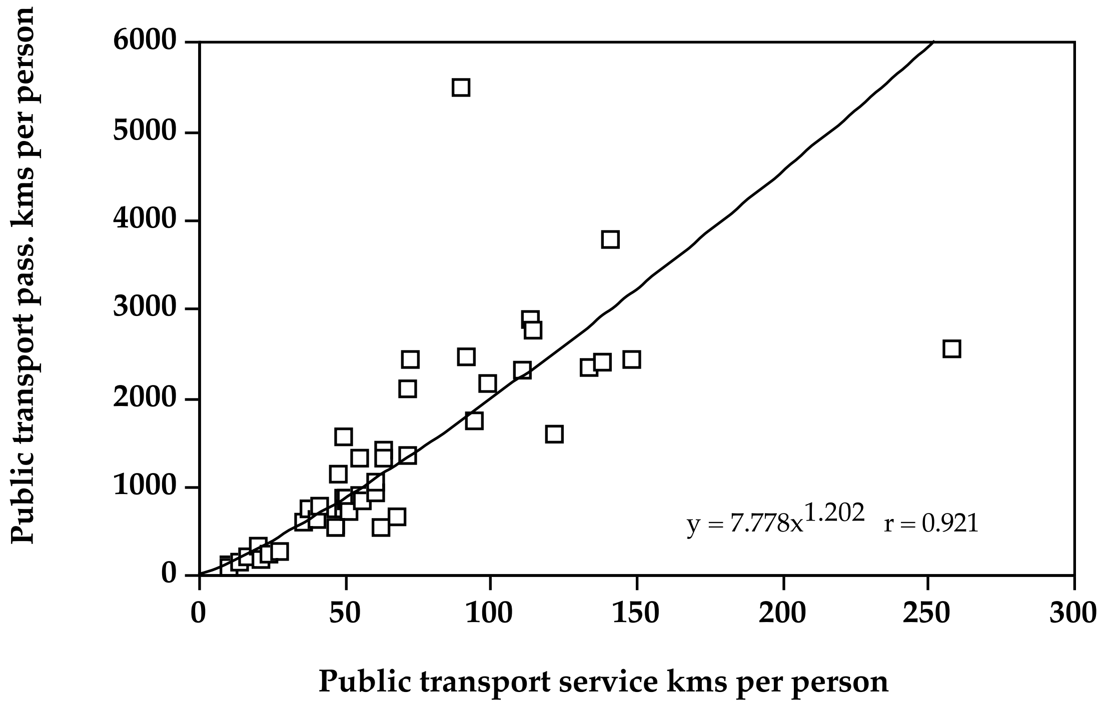

Figure 7. The relationship between public transport provision and use in cities (1990

The second universal factor in the settlement-transport system is that infrastructure will be used in accordance with its availability and the relative speed advantage that it offers, or conversely, if a particular mode is not provided it will not be used.

This tap-on, tap-off aspect of transport infrastructure usage has been the subject of many 'before and after' studies of road constructions aimed at investigating the existence of positive system feedback, or what has become known as induced traffic growth. Studies of this kind include Wirz (1992), Hansen and Huang (1997) and the many authors cited in an extensive literature review by Pells (1989). The opposite has also been shown to take place, that is, when road capacity is reduced, traffic volumes over the relevant area are also reduced (Cairns et al, 1998). In line with these empirical findings, time series analysis of changes in aggregate levels of private motor vehicle travel and road capacity for cities, have shown increases in line with capacity increases (Noland, 1999). These relationships were also the subject of extensive investigation by SACTRA (1994).

Urban form
It has been shown in the previous section that the scale and type of transport infrastructure is a key determinant of both the magnitude and kind of mobility experienced in a city. Furthermore, through infrastructure's links with the speed of travel in a city and modal split, there is also a very strong link to urban form, given a constant travel time budget. It can be argued that in the transport-land use conundrum, it is changes in transport infrastructure that tend to drive changes in urban form in various directions, rather than the other way around. This is apparent, for example, in the evolution of cities from walking through to transit and then automobile dominated systems (Marchetti, 1994).As the

dominant transport mode became faster, land uses gradually became less mixed and lower in density (Newman and Kenworthy, 1996).

In turn, we can also see that the mix of mobility in a city is strongly associated with urban form, with urban density being used as the key indicator. Figures 8 and 9 show respectively how car use per person declines dramatically with increasing urban density (r= - 0.924 and r-squared = 85%) and how the relative proportion between travel by car and public transport is highly positively correlated with urban density (r= + 0.870 and r-squared = 76%).

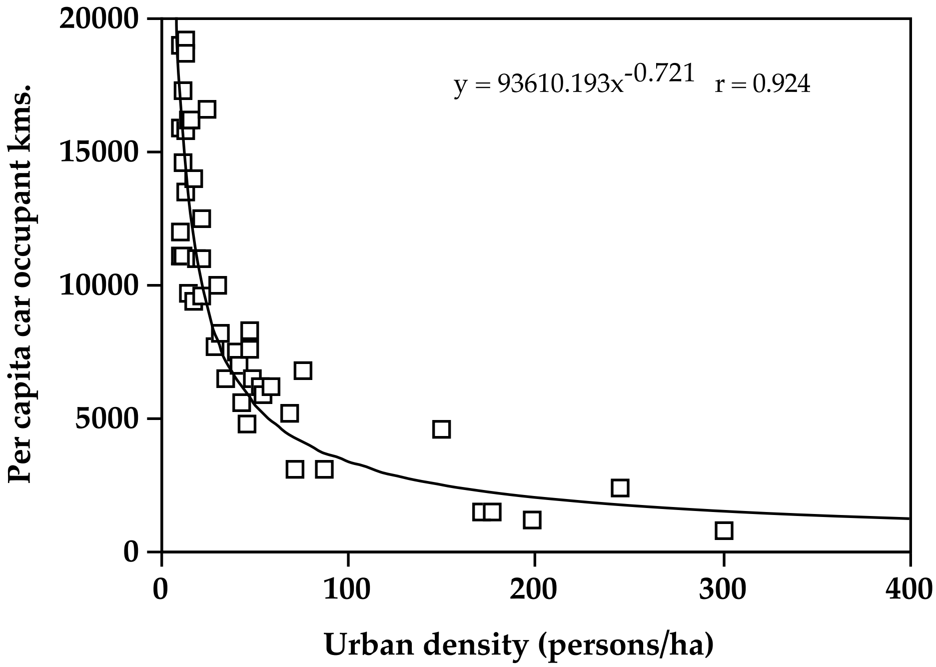

Figure 8. Urban density versus per capita car use in cities (1990)

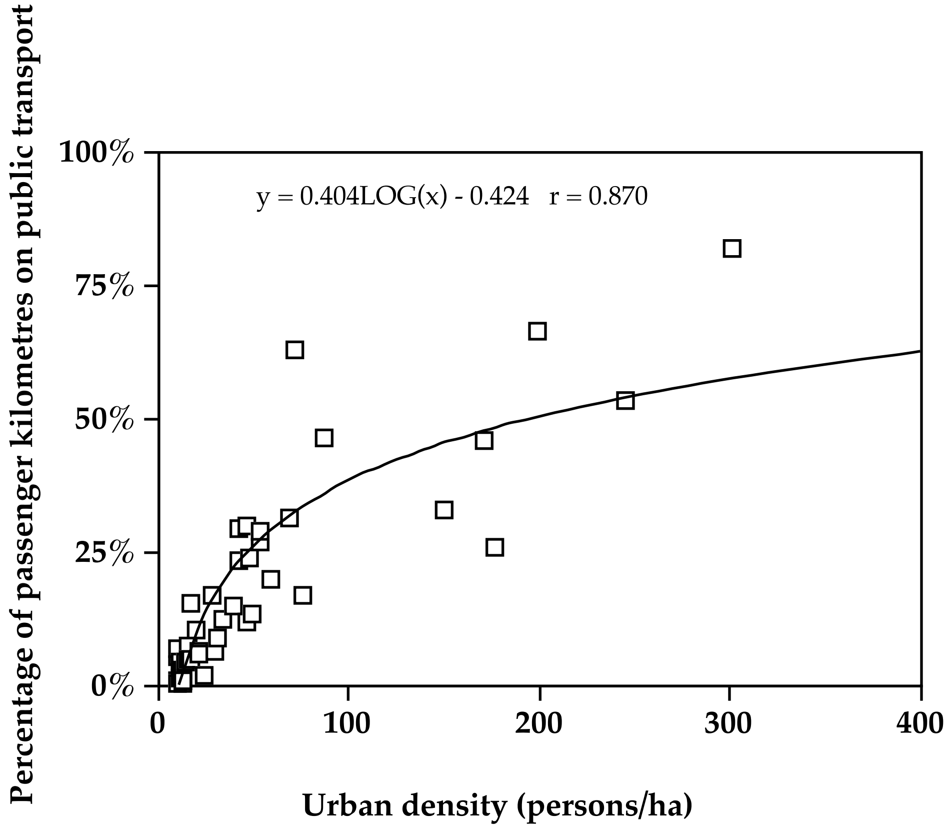

Figure 9. Urban density versus the proportion of total motorised travel on public transport in cities (1990)

Our conceptual model thus suggests that it is the combination of infrastructure and urban form that in turn determines the degree and type of mobility that occurs in a city. Disentangling the close linkages that exist between infrastructure and urban form is not easy, but as suggested above, the type of transport infrastructure appears to have a direct leading effect on the evolution of urban morphology or urban form, as it has been called in Figure 1.

One of the most surprising insights yielded by this systematic international study of cities is that mobility per unit urban area is constant. (mobility here is measured as vehicle kilometres in cars). The same result is evident for total vehicle travel, including commercial and freight traffic. Figure 10 provides a clear picture of this phenomenon with an extraordinary correlation between total urbanised land area of each metropolitan region and car vehicle kilometres (car VKT) which explains 91% of the variance. The same relationship using total VKT is almost equally strong (r = +0.942, r-squared = 89%).

All these results have wide-ranging implications for city policy. They mean that more compact cities show less private travel on a per capita basis and a much greater role for public transport (Figure 8 and 9). This entails less environmental impacts and resource consumption, but also ultimately results in lower operating costs on a per capita basis. It suggests that a city can add new development and grow in population size without increasing its total level of private vehicle travel, provided this growth is within existing urban boundaries and does not extend the urban land area. This of course means increasing urban density.

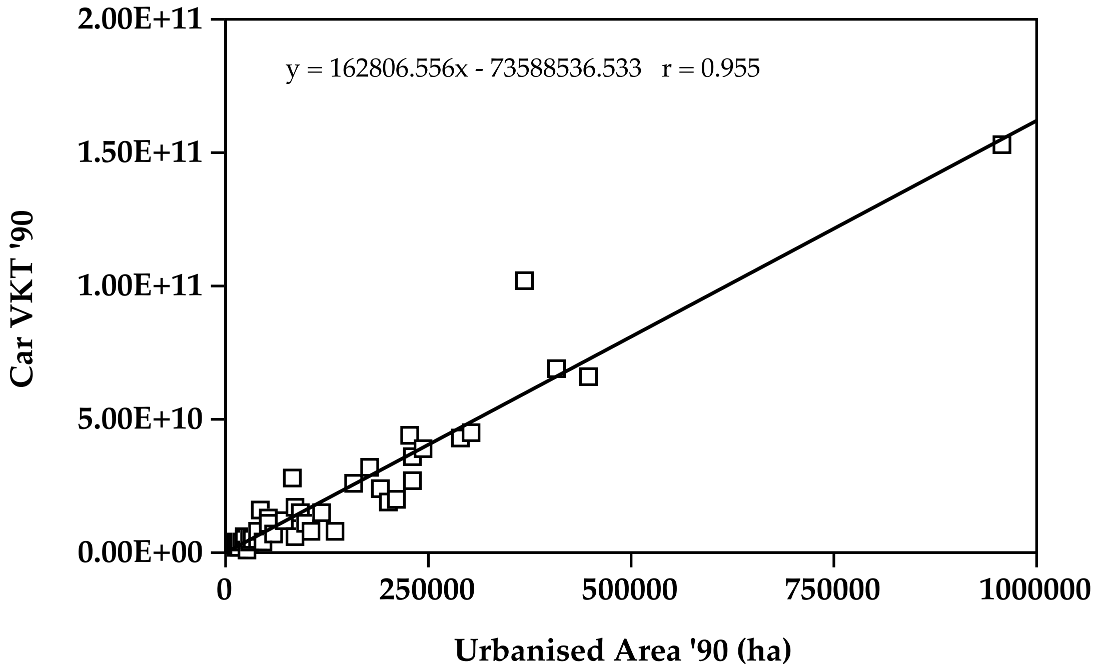

Figure 10. Urbanised land area versus travel in cars in cities (1990)

It needs to be recognised of course that travel in cars is not total mobility. The most practical way to measure total mobility is to combine the passenger kilometres in cars with those in transit. There is naturally very important mobility afforded by foot and bicycle traffic that is extremely important for the overall health and functioning of the city (especially in cities such as those in The Netherlands, Denmark and China). However, the total passenger kilometres by these modes compared to motorised modes would in most cases be very small (and extremely difficult to get numbers on) and in all likelihood, would not affect the results significantly by their absence.

If we accept this and repeat the exercise in Figure 11 using total private and public transport passenger kilometres, the result is still very strong (Figure 11). It shows the r value has dropped to + 0.853 (73% of variance explained), with a major contributing factor in this drop from two cities above the line (Tokyo and Seoul). The result means that even though more compact cities built around public transport have less private mobility, as shown previously, this is not generally compensated for by extra mobility on public transport. The cases of Tokyo and Seoul, where total mobility is considerably higher than we would have predicted, have in common that they are very strongly rail oriented and as a result public transport passenger kilometres actually exceed those in private transport, which makes them rather unique. Rail public transport is of course very spatially efficient and may be allowing these cities to break through certain barriers set in other cities by the spatial limitations of more space-hungry private transport. This anomaly, however, may in fact be quite pivotal to the theory being postulated in this paper and clearly needs further investigation.

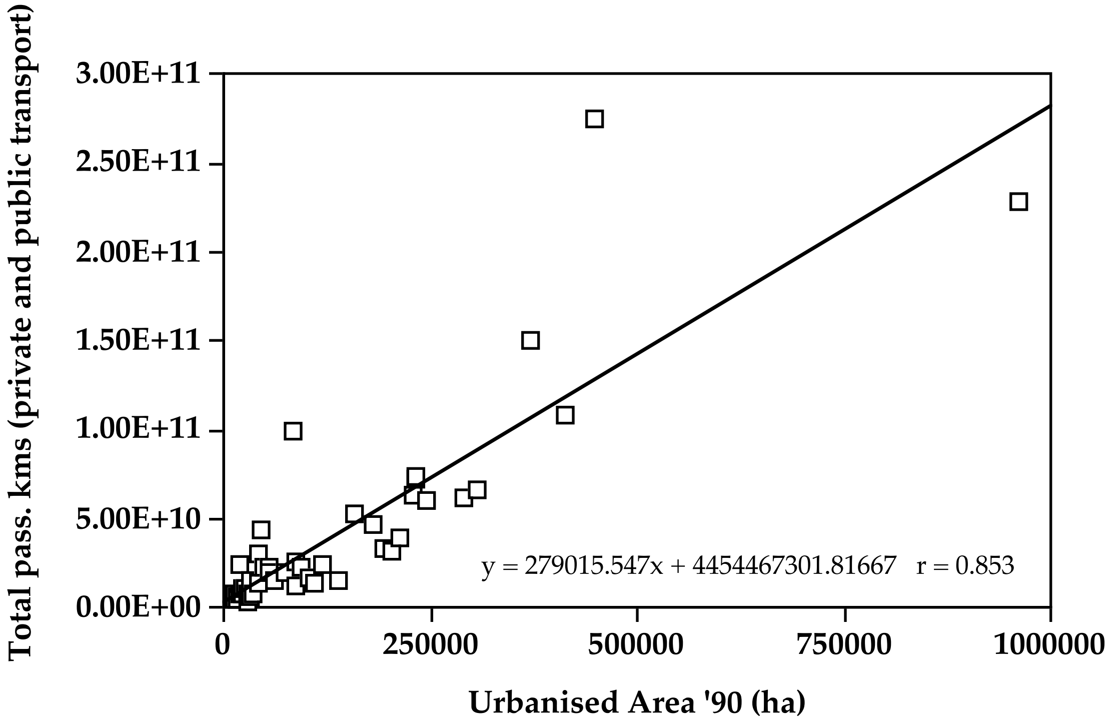

Figure 11. Urbanised land area versus total passenger travel in cities (1990)

We postulate that urban form is the third universal factor in the settlement-transport system,

This is indicated by the number 3 in Figure 1.

The outcome of the three universal factors we have just outlined is the level of access afforded to those who live and work in a city. Access is of course different to mobility in that it is a measure of the number and diversity of goods and services available to an individual given the range of the transport system that falls within the travel time and operating cost constraint. It is important to stress the difference between mobility and access, because greater mobility in and of itself does not necessarily entail greater access. As will be discussed later, it is ultimately access, not mobility, that benefits a city's general economic performance.

Human and economic implications
Having established the basis of what we believe points to the beginning of a "science of cities", it is important to explore the human and economic implications of this model.

Contact options
To do this we will first examine the ultimate human purpose of the settlement-transport system – the contact options it provides. A city provides contact options through the degree of access it provides for its citizens.
It would appear intuitively obvious that in cities where urban density is high (both in population and job terms) and where, land use is more mixed that

contact options would tend to be greater. Our comparative international data do in fact show that in cities that are denser, access is higher. Figure 11 shows this for the developed cities in the sample for which access has been calculated (r = +0.833, r-squared = 69%). The density term is the number of people and jobs per unit of urbanised land. Because the access calculation involves a wealth factor (in fact access here is measured by the number of people and jobs accessible per unit expenditure of wealth[2]), the six developing cities in the sample somewhat confound this picture. This is because they have, at the same time, very low wealth compared to the other cities, but are also very dense. Their low wealth means that the financial capacity of their residents to travel is greatly inferior to that of developed cities and this has a negative effect on the level of access in the city. Hence the developing cities have been eliminated from this correlation. If they are included, however, the correlation in Figure 11 is still highly significant (r = + 0.785), though there is more scatter (r-squared drops to 62%).

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[2] Mathematically, access is defined here as the total activities within reach of a radius equivalent to the length of the mobility distance as defined below in percent of GRP divided by 1,000,000. The unit thus works out to 1,000,000 activities within reach per percent of gross regional product spent. The city in this context is assumed to be of infinite size at uniform density, without any gaps in the urbanisation. The formula for access thus is:

$$Access = \frac{2 \bullet M^2 \bullet \pi \bullet d_A}{1{,}000{,}000}$$

M = Mobility

d_A = Activity density

π = pi

Mobility is defined as the distance that can be travelled, using motorised modes of transport, per percent of gross regional product. The costs that are taken into account are the user costs of private and public transport as well as the time cost while travelling at average speed (ie road network speed for private transport, average overall public transport speed for public transport), as recorded in the original set of data. The split between private and public modes of transport is assumed to be equal to that measured by the percentage of total motorised passenger kilometres on public transport. The resulting unit is km per % of GRP. The formula below further clarifies the calculation involved:

$$Mobility = \frac{GRP}{\left(\frac{D_C}{D_C + D_t}\left(C_C + V_C + \frac{C_{tt}}{S_C}\right) + \frac{D_t}{D_C + D_t}\left(C_t + \frac{C_{tt}}{S_t}\right)\right)} \div 100$$

Where:

C_t = public transport fare per passenger kilometre

GRP = GRP per capita

C_{tt} = travel time cost per hour

D_c = Car passenger kilometres per capita

C_c = car capital cost/km

D_t = Transit passenger kilometres per capita

V_c = car variable cost/km

S_c = Average road network speed

S_t = Average public transport speed

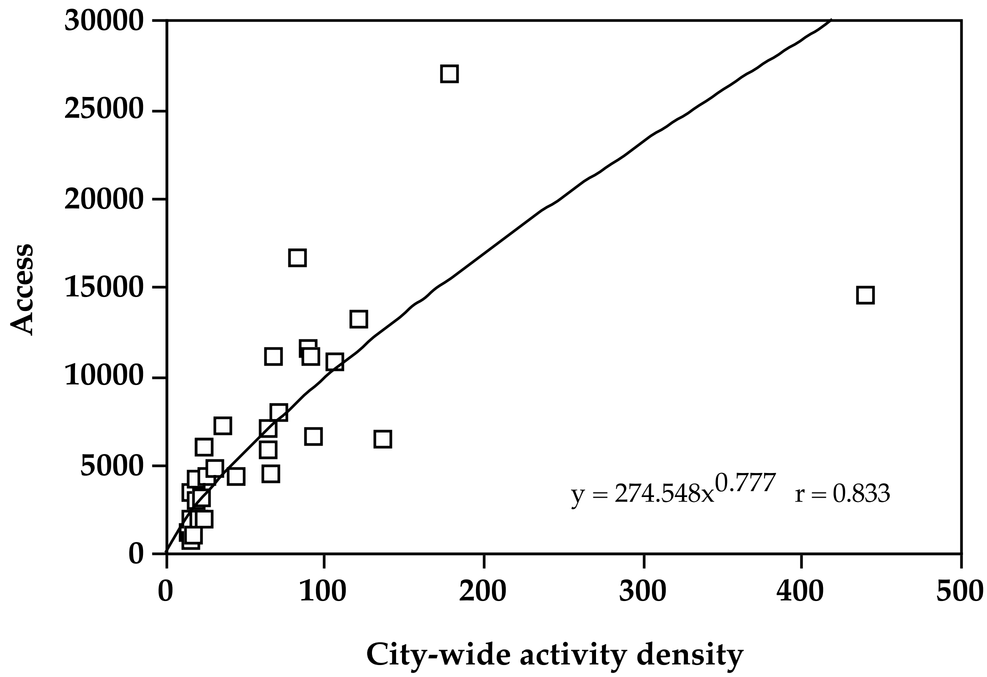

Figure 11. City-wide activity density versus the level of access in developed cities (1990)

Of course, in dense cities we have already shown how the use of public transport is much higher and it would be expected that the degree of access in a city, as measured by contact options, would tend to be higher where public transport is a bigger player in the city's transport system. This would also be because, as a rule, public transport is generally a cheaper travel option for the user which will naturally reduce the amount of wealth that has to be expended for access and this will improve our access measure.

The international data support this position. Figure 12 shows how as public transport passenger kilometres per person rises, overall access in developed cities also rises (r = +0.794, r-squared = 63%). Likewise, the proportion of total motorised passenger kilometres on public transport is positively correlated with access (r = +0.705).

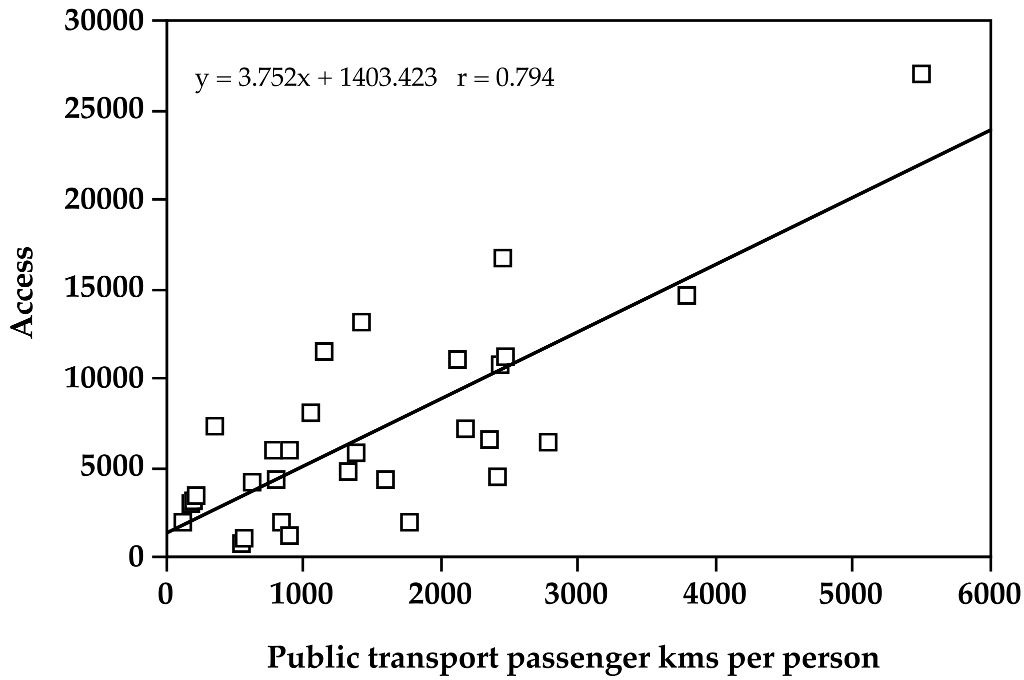

Figure 12. Public transport mobility versus the level of access in developed cities (1990)

Before closing the discussion of access and contact options, it is worth pointing out that per capita car use is significantly, but negatively, correlated with access, suggesting that more car-oriented cities actually provide inferior access and contact options to their residents than less car-oriented cities. The correlation is not as strong (r = -0.573), but it is statistically significant and its negative direction is highly relevant. Car use is a relatively expensive mode to the user compared to public transport (and of course much more expensive than walking and cycling). Thus cities optimised for the use of cars will tend to spend a lot more of their wealth in facilitating basic access to activities (see section on transport overheads to follow). Linking this to the infrastructure section, we also find that the length of road per person is likewise negatively associated with access and not positively, as would be the normal intuitive reaction (r-squared = - 0.779).

Mode choice and mobility

Figure 1 shows mode choice as being the human outcome of infrastructure and mobility as the human outcome of urban form. These aspects have really already been explored in the previous sections that elucidate the basic model, showing how the level and type of transport infrastructure dramatically affects the modal choice available in a city and the actual modal patterns experienced. Likewise, urban form has also been shown to have a major impact on the absolute level and type of mobility in cities, with higher density cities experiencing much lower per capita levels of private mobility and higher levels of mobility on public transport.

There are of course many, complex aspects of mobility and lifestyle choices which spin off from this, and, through social, commercial and political processes, feed back into the basic transport-land use system. While they are not outlined here, we do believe the conceptualisation presented in this paper provides a framework that can help explain many of the interactions between social and political processes and the physical urban environment.

This then completes the discussion of the human aspects of the model we are proposing. It remains now to discuss the economic outcomes of the model in some more detail. Figure 1 shows that at each level of the settlement-transport system, there are economic implications. It is suggested that transport infrastructure determines the city's transport overhead, its urban form determines its real-estate overhead, and the total cost of access determines the economic surplus available for development. We will now define the terms of each of these and their implications.

Transport overheads

There are a number of pieces of data we have collected on the economic functioning of cities and their land use-transport system which are indicative of a close link between transport overheads and infrastructure. These data all point to higher overheads in more auto-dependent regions. The three items that will be examined here are:

(1) Expenditure on roads (construction and maintenance costs)
(2) Public transport cost recovery
(3) The proportion of wealth a city spends on operating its total passenger transport system.

(1) Road expenditure (as measured by the proportion of city wealth spent on this factor), when correlated with the extent of the road system (per capita road length), shows a significant positive relationship amongst developed cities in the sample (r = + 0.613). Furthermore, the higher the use of private vehicles (as measured by total vehicle kilometres of travel per person), the higher the expenditure on roads (r = +0.678). Developed cities only are used here for the same reasons as described above for access (their profoundly lower wealth means that road expenditure expressed as a percentage of a city's gross regional product (GRP) becomes very high and inconsistent with cities with more comparable GRPs). It can be concluded that auto-dependent cities are incurring considerably higher costs for road infrastructure than less auto-dependent cities. For example, Phoenix, the highest spender consumes 1.9% of its GRP on roads or more than 6 times higher than Brussels, Hamburg, Munich, Vienna and Tokyo which share the lowest expenditure at only 0.3% of GRP.

(2) The recovery of public transport's operating costs is another factor associated with the level of transport overheads in a city. We have already seen how public transport performs a bigger role in cities that provide better for it in terms of infrastructure and service and which have an urban form more conducive to high levels of use (ie less sprawling cities). Based on the very detailed financial data we have collected on all public transport operators in all cities it is possible to reliably compare their performance in terms of their recovery of operating costs from the farebox. Farebox recovery is a very emotional subject in most cities where critics of public transport are only to eager to point out the subsidies to public transport.

The international data show that public transport cost recovery improves as the city's infrastructure becomes less oriented to private transport and its urban form becomes denser. Figures 13 and 14 depict this very clearly by correlating cost recovery first with the length of road per person (r = - 0.791) and then with urban density (r = + 0.792).

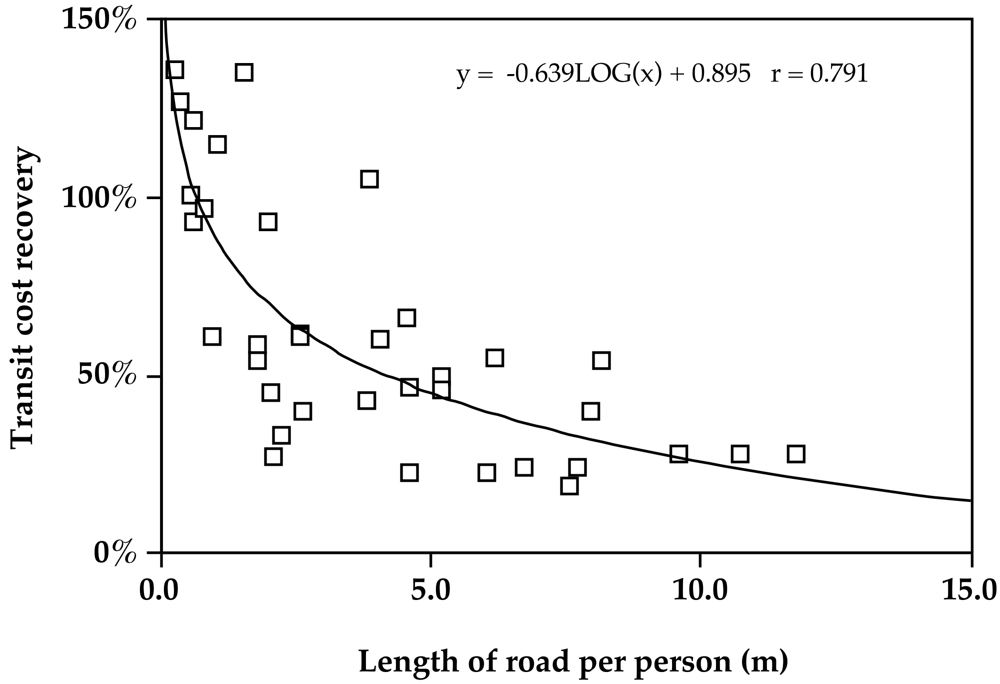

Figure 13. Length of road per person versus public transport cost recovery in cities (1990)

Other relationships show that cost recovery also naturally improves with higher levels of use. Public transport passenger kilometres per capita has a positive correlation with cost recovery of 0.676. Cost recovery of public transport also improves with the higher level of service provided to it (public transport vehicle kilometres per capita has a positive correlation with cost recovery of 0.646).

Overall it can concluded from the data here that reducing public transport operating subsidies is most effectively tackled on a system-wide basis. This can be done in terms of actually building up the level of infrastructure involved, improving services, reducing the emphasis on roads and gradually building a city more conducive to public transport operations. No data suggests that cost recovery can be improved by cutting back public transport services, nor by using cheaper bus systems (the 'bus-only' cities in the US have the worst cost recovery of all cities).

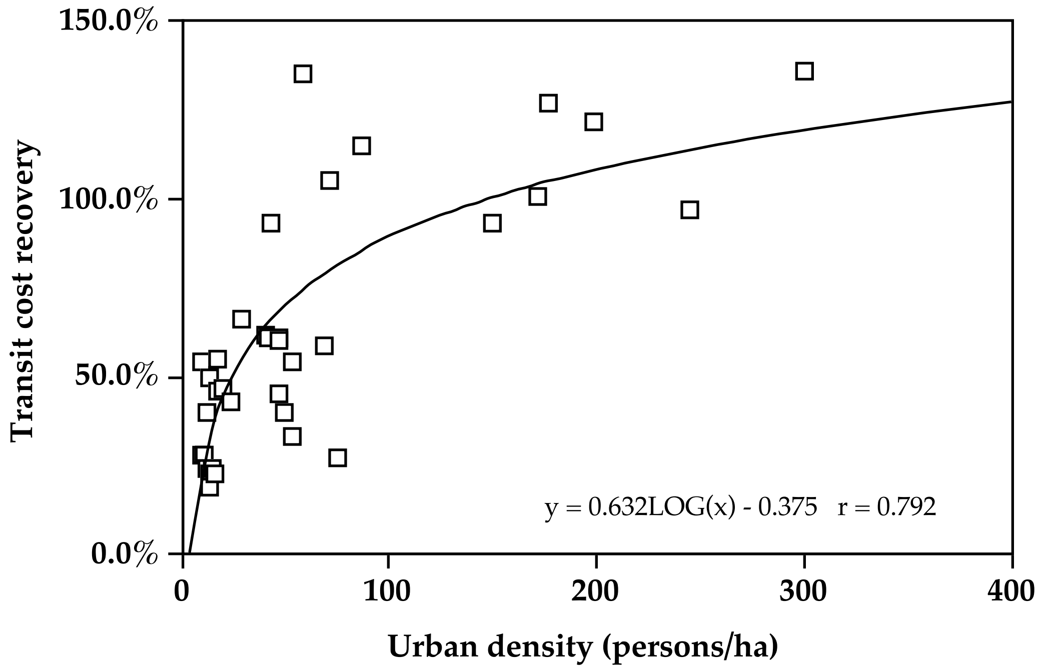

Figure 14. Urban density versus public transport cost recovery in cities (1990)

(4) The proportion of wealth a city spends on operating its total passenger transport system brings together the major transport expenses in a city and allows us to see in real terms how much a city is having to spend on what is, in itself, a non-productive activity. The data here suggest very clearly that transport overheads are bigger in more auto-orientated environments than in more public transport-oriented ones. This is depicted in Figures 15 and 16 which show how the proportion of wealth spent on operating passenger transport varies with the city-wide motorised modal split and urban density within developed cities (developing cities eliminated for these relationships for reasons already discussed).

The data suggest that as cities with reasonably similar levels of wealth become more public-transport oriented, the less of their wealth has to be spent on passenger transport ($r = -0.840$, r-squared = 71%). Linked to this relationship we find likewise that denser cities are more effective in the dollars they spend on passenger transport. Essentially, the low density auto-oriented cities are spending up to around 17% of their wealth compared to as low as 3% in Tokyo with its massive rail system and huge public transport mobility.

The only reasonable conclusion that can be drawn from these data is that automobile dependence creates the biggest transport overheads in a city while greater provision for and use of non-auto modes will reduce this factor. By providing a more cost-effective use of passenger transport expenditure, non-auto modes are providing cities with a comparative advantage.

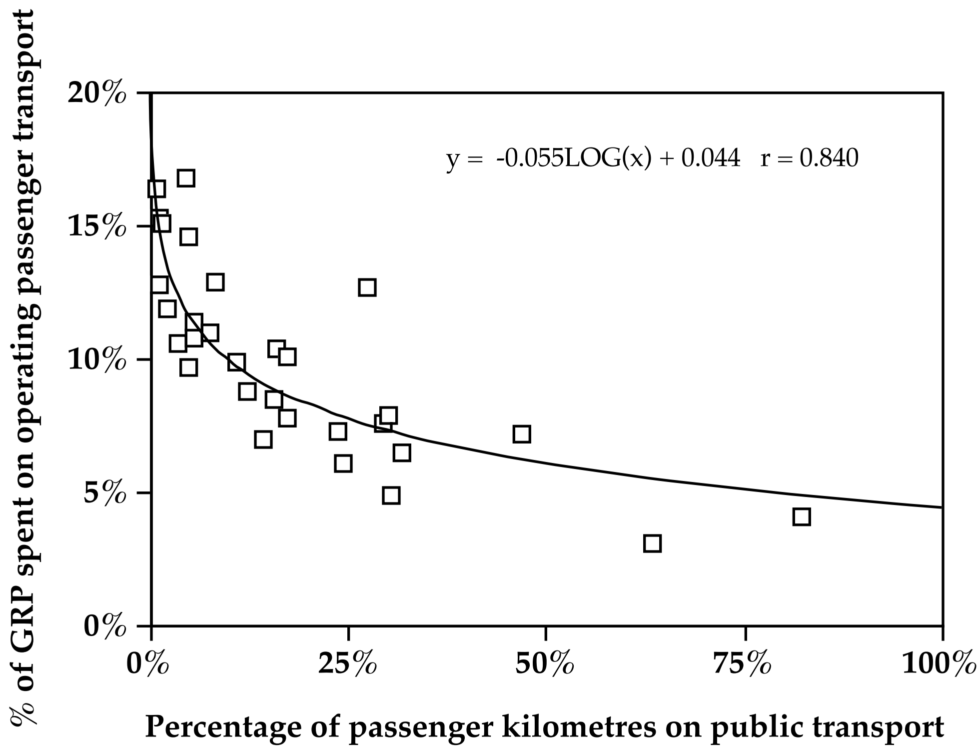

Figure 15. Motorised modal split versus the proportion of city wealth spent on operating passenger transport in developed cities (1990)

Real estate overhead

The relationship between real estate values and infrastructure is well documented. For example, when a new transport infrastructure is introduced to a previously poorly serviced district and changes in the travel times alter the accessibility balance, then the value of locating in such a district becomes greater. Residents of such areas now have access to a greater deversity of contact options. This has the effect of pushing up land prices (eg. Abelson, 1993), thus creating another process of system feedback and interaction that is the subject of land economics.

In terms of the present analysis, it is difficult to make any assessments about how this factor will respond to different types of private and public transport infrastructure and how it will operate in an overall urban system sense. So far all the data presented point to higher density, transit-oriented environments being more efficient and convenient places to live and to conduct business. Accessibility is better and transport overheads are lower and this appears to give such cities a comparative advantage. It is possible, however, that in transit-oriented environments where accessibility is high and physical expansion of development is limited, that real estate overheads may be higher. On the other hand, in auto-orientated environments where freeways lead to the constant opening up of new, accessible land, the real estate overhead could be lower. Then, of course, the factor of servicing new development with essential physical infrastructure such as water, sewerage, energy and telecommunications systems comes into play. Others have shown how these costs tend to be higher in new low density locations opened up by high capacity road systems, than in established urban areas with spare infrastructure capacity (eg Voran Consultants, 1991; Kenworthy

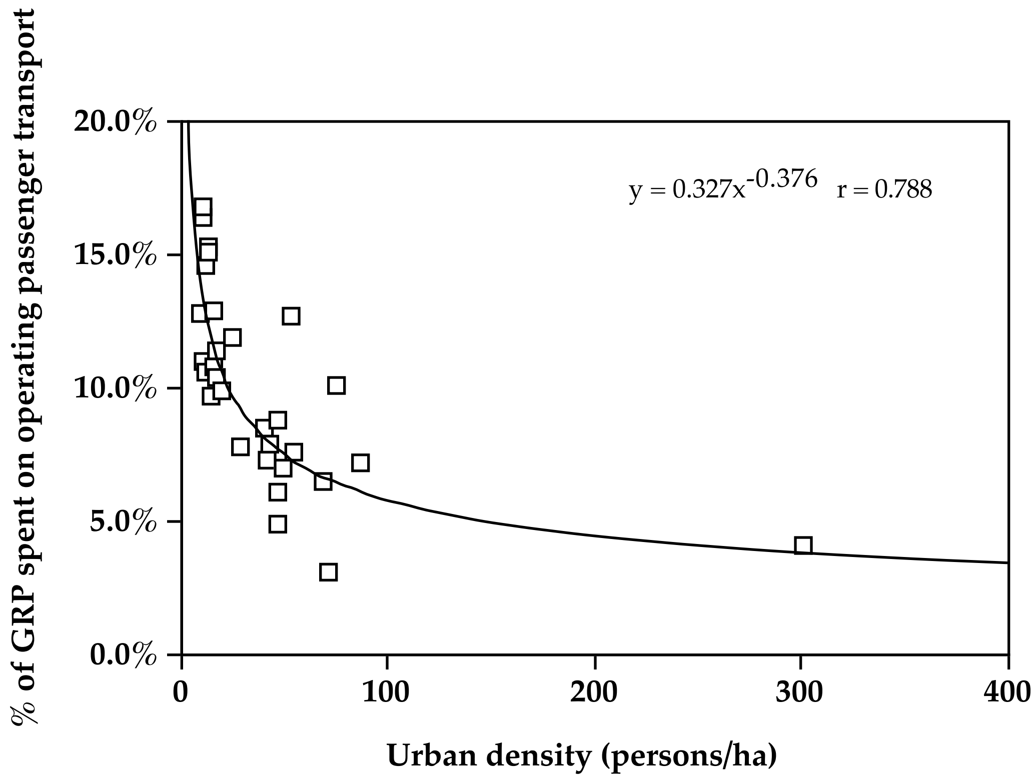

Figure 16. Urban density versus the proportion of city wealth spent on operating passenger transport in developed cities (1990)

and Newman, 1991). This has been shown to be particularly true of central business districts where huge infrastructure savings are possible compared to newer locations (eg Building Owners and Managers Association, 1991).

Without good comparative urban data to examine this and to look closely at the many feedback loops and other factors involved, this remains an important question for further research.

Economic surplus

The economic surplus loosely refers to the wealth generated by the combination of production factors located within the city, minus the operating costs of the city. In this sense, infrastructures comprise the operating costs, or inputs to production. By facilitating the production of goods and services produced by the industries and businesses located in the city, infrastructure does not directly earn an income for the city.

To illustrate this point more clearly, a city cannot, for example, sustain itself economically by simply expanding its infrastructure networks. Without activities that produce tradeable goods and services, a city cannot earn an income.

With this in mind, we consider infrastructure to be an operating cost or input from the perspective of a city's overall economy—a macroeconomic perspective. This is because, as a factor of production, infrastructure is city specific and can only be used to facilitate production located within the city that it supports. Hard infrastructures are immobile and so cannot be traded between cities. Even if a hard infrastructure like a toll road or an electricity grid can be sold to a foreign entity or corporation not located within the same city, payment for the infrastructure use is ultimately made by the local businesses and residents.

Figure 17 lists many of the basic factors of production in accordance with their degree of mobility. Those factors at the top of the ladder can be traded easily. Those at the bottom cannot. Of particular importance is the line marked 'mobility divide'. This attribute—the ability to move—differentiates between inputs and outputs for the city economy. Many of the factors in the upper sectors contribute towards what can be called infrastructure activities, however they are listed above the line because they can potentially move between cities, or trading units that are in competition with one another. Consequently, they are a potential output. Those below the line will always act as inputs.

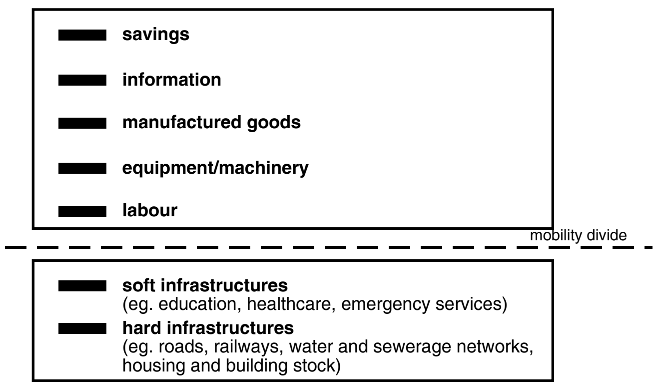

Figure 17. Ladder of mobility. ***Adapted from Prud'homme (1994)***
Source: Zeibots (1999a).

Figure 18 portrays these factors simply in terms of resource flows between industrial production sectors and supporting infrastructure sectors. It is important to note that resources that flow though the infrastructure sectors do not directly contribute to potential income earning output or economic surplus. How these conceptions have been derived, and how they fit within the framework of macroeconomic analysis, is covered in more detail in Zeibots (1999b).

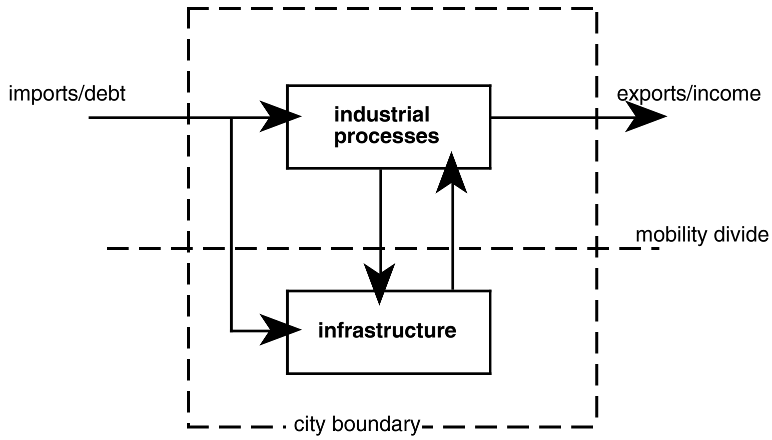

Figure 18. Inverse flow of resources through urban industrial and infrastructure sectors. Source: Zeibots (1999b).

From the data presented in this paper, it can be readily seen that there is considerable variation in the urban structure, or densities of cities. With this variation in urban form comes variations in infrastructure operating costs for the network of cities that are the global economy. Those cities with low urban densities have comparatively higher operating costs on a per capita basis because the distances between their internal operating units are greater and therefore more costly to service. An important question to ask at this point is: To what degree does a city’s infrastructure impose a comparative advantage, or disadvantage, to those firms and industries located within it who are competing in the global marketplace? And further: How does a city’s infrastructure system dovetail with the operations of firms and workers to enhance general productivity?

In our view, sprawling auto-dependent cities are put at a comparative disadvantage in two ways. Firstly, their operating costs on a per capita basis are generally higher than those of more compact, transit orientated cities. Secondly, accessibility, or contact options, are reduced, even though the cost of the infrastructure which produces the inferior contact option, is greater.

This first aspect was covered in the section dealing with transport overheads. It is important to mention it again here, because as was outlined at the start of this section, the general economic surplus is in part defined by the operating overhead. The second aspect—accessibility—is less obvious. Recent work by Prud’homme and Lee (1998) has investigated this link. They have defined accessibility in a slightly different way to our definition. In their analysis, accessibility is defined in terms of the number of jobs that fall within the range of individuals given the prevailing speed of the transport network and the travel time budget. Cities which have a compact morphology—which corresponds to our third universal factor called urban form—appear to have higher productivity levels in this analysis. This points to an emerging picture where cities that are big and dense, are also those cities that have a comparative advantage in an overall economic sense.

In this emerging picture it is easy to see the potential problems with sprawling cities, however, there are also important lessons for those compact cities that are currently undergoing the processes of industrialisation. In particular we would point to the cities of the South East Asia ’Tiger’ Economies region. New transport infrastructure projects that have the effect of increasing the speed of the transport network, but at the same time decreasing urban densities, or altering the urban form of a city in such a way that density and diversity are reduced, in actual fact undermine the net economic performance of these cities. Given the recent economic collapse of many of these cities, it is also easy to see that the rapid expansion of infrastructure sectors can be harmful. As was outlined earlier, infrastructure is an input to production and not an output. The rapid increase in input sector activities may be advantageous to some firms who's business this involves directly, but it is not necessarily advantageous to macro operations and activity overall. Indeed, much of the recent problems of South East Asia have been put down to an over commitment to "silly projects" as some commentators from the region point out (Patten, 1998).

Conclusion

The way urban infrastructure systems affect general economic performance is all pervasive. This is because most, if not all, activities undertaken in a city involve some use of infrastructure. With this in mind, we see the need for development of a more inclusive theory about cities, or 'science' of cities, as an important research program.

An important outcome of this will be a marked improvement in the tools we use to assess the wisdom of different policy options for city building and management. Before this can occur, however, it is important to understand the inherent nature of the object of such analysis—the workings of cities.

We postulate that there are three key factors that undergird the settlement-transport system and explain many of the observed differences in the working of cities around the world: constant travel time budgets, transport infrastructure and urban form. The analyses in this paper have revealed strong and systematic relationships between the various dimensions that can be used to describe these three factors. The strength of many of these relationships, with correlation coefficients in excess of 0.85 are perhaps surprising, especially given the scope in data collection methods between cities. They do however suggest that much of the observed difference between cities in car use, public transport use and other key performance indicators are physically driven and amenable to direct physical planning policy intervention on a metropolitan scale.

This conclusion is in contrast to those who contend, for example, that wealth is the primary determinant of automobile dependence - as wealth rises automobile dependence is inevitable (Lave, 1992). Analyses we have undertaken elsewhere show that in this data set, urban wealth measured as gross regional product per capita of each metro region, is simply unable to explain either transit use or car use (see Kenworthy et al, 1995; Kenworthy and Laube 1999).

Clearly more work is required to take this analysis beyond simple bivariate regressions into a full multiple regression analysis and other more sophisticated statistical interpretations. That this further work towards a 'science of cities' is worth pursuing, we hope we have established in this paper.

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