26th Australasian Transport Research Forum
Wellington
New Zealand
1-3 October 2003

Cities, Area and Transport Energy

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1. INTRODUCTION

The issues relating to urban form, transport planning and energy consumption have been debated in detail over the past decade. This paper revisits this issue with particular emphasis on energy use in the context of urban areas.

This paper focuses specifically on transport energy use (subsequently generally referred to as 'energy'), urban area, and relevant population density (in this paper generally referred to as 'density'). The references provide further explanation of these parameters which is essential to the understanding of the issue.

2. BACKGROUND

The Council of the European Ministers of Transport (1989) resolved that:

> *"…good transport systems play a major positive role in the economies of all countries and in the lives of their citizens…that there exist growing environmental problems, globally, regionally and locally, for which the transport sector, inter alia, bears a significant responsibility and…that emerging scientific evidence points to the seriousness of the problems and gives an urgency to the need for action."*

While these principles are largely acknowledged and in many cases, implemented throughout the European Community, large western countries such as Canada, the United States and Australia who share a number of similarities (not the least of which include culture, a similar standard of living, lifestyles, transport systems and approaches to urban planning) have been less than diligent to embrace them.

Brunton and Brindle (1999) also observed:

> *"Urban form (the generalised shape of an urban region, and the disposition of its major components) is commonly represented … by two major characteristics: population density and the degree of mixture of land uses. There is some level of support, from theoretical and empirical studies, for the assumption that these variables are directly influential with travel choices such as mode, length and frequency of trips. The revival of concepts of 'neighbourhood' based on maximising local opportunities for trip satisfaction (exemplified by the current popularity of various forms of 'new urbanism') is justified at least in part on the expectation that the observed associations between trip making and urban form in older areas can be replicated in new areas – that is, there is actually a direct causation between urban form and trip making.*

> *But support for the assumed relationship between urban form and travel behaviour is neither unreserved nor unanimous. There are three cautions reflected in the literature: extrapolation from local to the regional scale (or, more commonly, vice versa) might not be valid; a potentially wide range of other variables, including non-physical variables, needs to be included; and (as ever) caution must be adopted when assuming that observed correlations imply causation (especially since the data are commonly cross-sectional rather than time series)."*

It should be noted that while the relationship of energy in the context of urban density has been touched on various discussions over the past decade, a detailed analysis and interpretation has not been undertaken. For instance, Newman and Kenworthy (1989) have dedicated years of research to establishing a causal relationship between energy consumption and urban density, they have not described the energy use per capita-density relationship. Brunton and Brindle (1998) noted the relationship between energy consumption and urban area, it has not been demonstrated or explored in any detail. Brindle (1994) noted that:

> *"…there is thus stronger evidence from this data for a policy of urban containment than there is for density increases per se…constraints on city growth would imply constraints on fuel use…thus, by implication more people in the same area (i.e. at higher density) would mean less fuel use per person…while this seems to provide encouragement for urban consolidation, it seems also to refute the present enthusiasm for higher-density new residential development in greenfields sites…"*

Hence, the reality is that further exploration is required to determine the relationship between energy consumption and urban area. This paper attempts to establish this relationship and establish a direct empirical link between total energy consumption and urban area by further exploring the relationship between urban density and energy consumption per capita.

3. DATA SETS

Three sets of transport and land use data were sourced and are summarised in the Table 1. Only those cities with transport energy use, population and area are included. Most data sets reported information for one of two adjacent years (eg 1970 or 1971). No distinction is made in this discussion between the two years which will be referred to by the decade year only (eg 1970, even if data is for 1971).

Dimensions and scale of parameters used in this discussion are summarised in Table 2.

Comparison of the cities reported suggests that data set 1 is the most homogenous and data set 3 is the most varied. Cities vary in many different descriptors including urban form, culture, affluence, development, region, transport systems, and so on. Given the range of variables and the extent of variation for each one it is not surprising that developing relationships between parameters is often difficult.

Newman and Kenworthy (1989) note for the density - energy use per capita relationship "*The correlation coefficients associated with these relationships range from 0.84 to 0.91, all very high values in any analysis of this kind*." Note that these correlation coefficients are 'R' values which then translate to R^2 values of 0.70 and 0.83 respectively.

Table 1: Data Sources

Author	Newman and Kenworthy (1989)	Kenworthy and Laube (1999)	UITP (2003)
Data set	1	2	3
Date published	1989	1999	2003
Date of data	1980	1960 1970 1980 1990	2000
Number of cities	32	19 - 46 (varies by year)	83
Regions	Australia, USA & Canada, Western Europe & USSR, Asia	USA, Australia, Canada, European, Asia (wealthy), Asia (developing)	Africa, Asia (developed), Asia (developing), Europe (Eastern), Europe (Western), Latin America, Middle East, North America, Oceania

Table 2: Data Information

	Dimension	Units	Scale
Transport Energy	Joules	(J)	$\div 10^{15}$
Urban Area	Hectares	(Ha)	$\div 10^{3}$
Population	Persons		$\div 10^{3}$
Urban Population Density	Persons per Hectare	(/Ha)	
Total Travel	Vehicle kilometres travelled		$\div 10^{9}$
Car Travel	Vehicle kilometres travelled		$\div 10^{9}$
Public Transport Travel	Vehicle kilometres travelled		$\div 10^{6}$

It is important to acknowledge that there are many inaccuracies in collecting the data. Acquisition of such a comprehensive range of information in different locations and cultures is a daunting task. The authors of the original data made every effort to minimise errors outside their control.

Possible errors include variations in definitions of parameters, estimations when measurements are not possible, errors of estimation when precise definitions are not possible, and so on. Therefore any relationships between parameters will be subject to additional error over and above what might normally be expected between parameters where there is good accuracy of measurement and consistency of definition. This is particularly true for city area which depends on the definition of a rather arbitrary boundary for the developed area of a city.

4. TRANSPORT ENERGY V CITY AREA RELATIONSHIP

In this analysis, simple linear relationships between area and a variety of independent parameters were investigated for each data set. Relationships were developed using simple linear least squares regression with R^2 being the qualitative factor.

It was found that New York was about twice the area of the next largest city and tended to disproportionately affect the relationship and the correlation factor. Therefore New York was removed from the analysis.

It was found that the constant in the equation was often close to zero and given the large numbers of measurement, relationships without a constant were also investigated. This is the estimate of energy when the city area is zero, or the number at which the relationship crosses the y axis. Therefore, the line of best fit was also calculated so that zero city area produced zero energy use, for all cases.

The equation of the line of best fit is:

$$\text{Total Transport Energy} = k \times \text{City Area} + c \qquad (1)$$

or when forced through the origin:

$$\text{Total Transport Energy} = k \times \text{City Area} \qquad (2)$$

Table 3 summarises the results of the relationships between city area and energy use which resulted for the 6 basic data sets. The first line for each data set gives coefficients for equation 1 and the second line gives coefficients for equation 2.

Table 3: Transport Energy - City Area Relationships

Data source	Data set	Number of cities	Data year	k	c	Correlation (R^2)
Newman and Kenworthy (1989)	1	31	1980	0.950	0.940	0.919
				0.910		0.916
Kenworthy and Laube (1999)	2/60	18	1960	0.824[1]	-13.7[2]	0.947
				0.746[1]		0.933
	2/70	25	1970	1.096[1]	-27.8[1]	0.943
				0.959[1]		0.919
	2/80	35	1980	1.028[1]	-15.6[3]	0.911
				0.961[1]		0.903
	2/90	45	1990	0.958[1]	1.28[3]	0.870
				0.963[1]		0.870
UITP (2003)	3	83	2000	0.808	0.099	0.844
				0.809		0.844

1. Significant at the 99% confidence level.
2. Significant at the 95% confidence level.
3. Not significant at the 90% level.

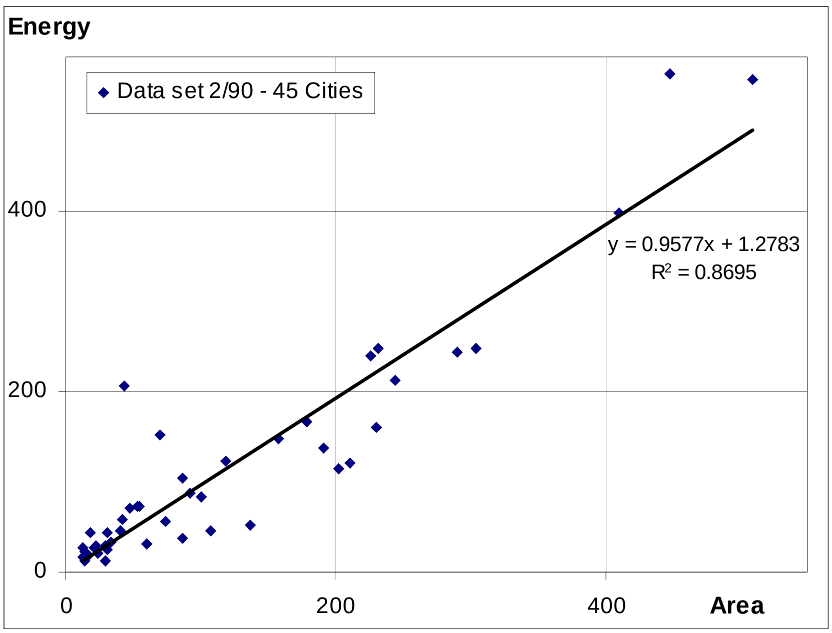
These results are important for two basic reasons:

- the correlation in the relationship (or the amount of variation which is explained by the relationship) is very high, and
- the results are consistent in the form of the relationship and the relationship values.

Data set 1 has the highest correlation, while data set 3 has the lowest correlation with a k value different to most other data sets. This variation is not unexpected due to the wide range of city types and the correlation is possibly higher than might be expected.

The relationship and data for Data Set 2/90 is shown in Figure 1.

Figure 1: Transport Energy - Urban Area Relationship



Cities highest above the line are the Asian cities of Bangkok, Seoul and Tokyo while cities furthest below the line include the Oceanic cities Brisbane, Perth, Melbourne and Sydney. These results suggest further investigation of urban density as an additional refinement could yield more sophisticated relationships. However urban density itself is not the principal determinant with respect to transport energy use since the majority of the observed variations in energy are described by city area alone.

The strong energy - area relationship means that cities would have almost the same energy use if they were all the same area. Total transport energy use is therefore almost independent of other city factors such as density, culture, development, affluence or location. Perhaps most importantly the relationship is relatively independent of transport system factors including amount of transport infrastructure (road or rail), parking supply and price, or car ownership. Cities highest above the line include Bangkok and Brussels while cities lowest below the line include Melbourne, Brisbane and Sydney.

5. TRANSPORT ENERGY USE - DENSITY RELATIONSHIP

The strong linear energy - area relationship results in a hyperbolic relationship between energy per capita and population density. A hyperbola has the mathematical form:

$$X \times Y = \text{constant}$$

In this case:

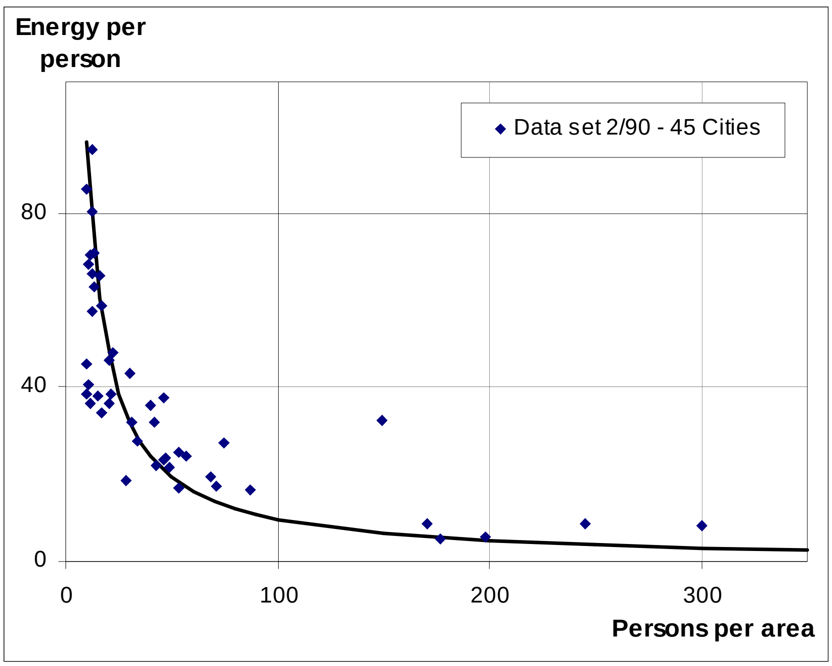
$$\text{Energy} = k \times \text{Area}$$

so:

$$\frac{\text{energy}}{\text{persons}} \times \frac{\text{persons}}{\text{area}} = k$$

The energy per capita - population density relationship for data set 2/90 is shown in Figure 2.

Figure 2: Transport Energy Per Capita - Urban Density Relationship



It is important to recognise that the relationship shown in Figure 2 is entirely due to the linear relationship between total transport energy and city area. This is not a line of best fit as such; it is the curve generated from the transport energy and city area relationship. This energy per person - density hyperbola indicates the locus where all cities would have the same energy use if they were the same area, all other things being equal.

While the shape of the curve is generally consistent with previous results it is not due to a fundamental relationship between the energy use per capita and urban density parameters. The hyperbolic form of the curve will occur with any third variable introduced as ratios to form new variables in this way (provided that the third variable is not itself otherwise correlated with transport energy or urban area). In this case population has been introduced as the additional variable, but other variables (such as buses, households, or anything else) would produce the same result.

6. RELATIONSHIP DESCRIPTION

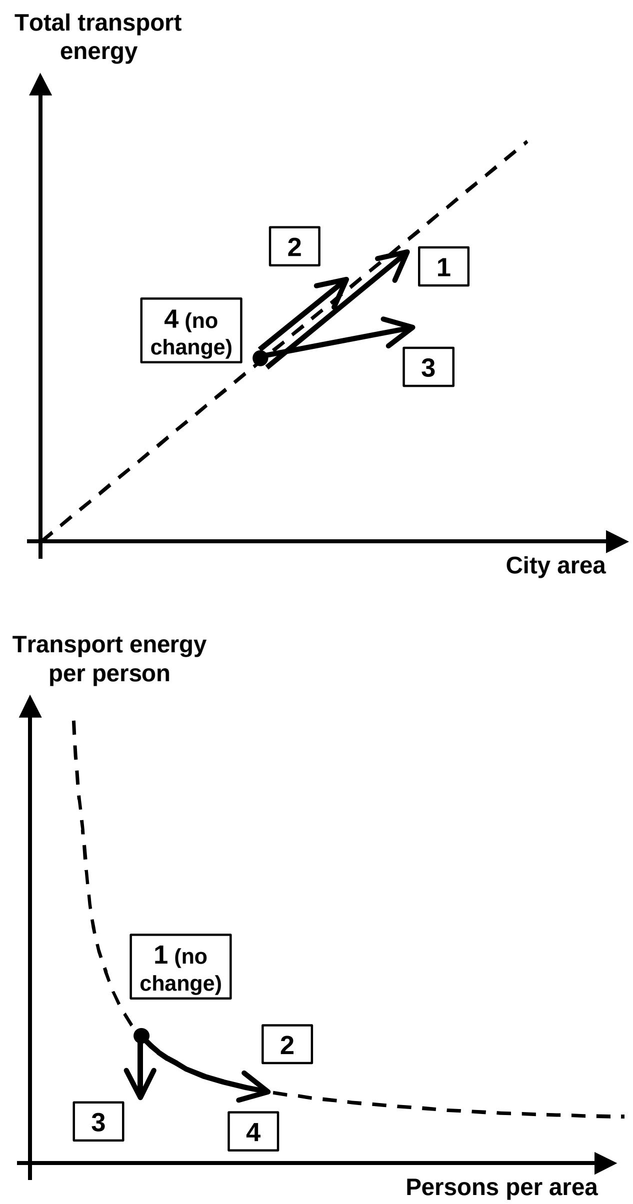
Increased energy efficiency can be observed in two ways:

- total city energy decreases, or
- energy per capita decreases

all other things being equal.
This is an important point because these differences can occur independently.

Figure 3 illustrates the connection between the energy - area relationship and the energy per capita - population density relationship.

Figure 3: Comparison of Different Changes in City Transport Energy



These relationships show that :
1. a city which increases in population at the same density will increase its energy use at the same linear rate, but its location on the energy per capita - population density relationship will not change.
2. a city which increases in population at a higher density will increase its energy use at a lower linear rate, but moves to a different point of the same energy per capita - population density relationship,
3. a city which keeps the same population and density but decreases its energy use (ie a move to a different energy - area relationship), will move to a different energy per capita - population density relationship, and
4. a city which increases in population within the same area will not increase its total energy use, and moves to a different point of the same energy per capita - population density relationship.

7. CHANGES OVER 3 DECADES

Data set 2 includes data for 4 decades, with increasing numbers of cities reported for more recent decades. Energy - area relationships were developed and are reported above, but some care should be taken in interpretation since the cities are not consistent for each decade.

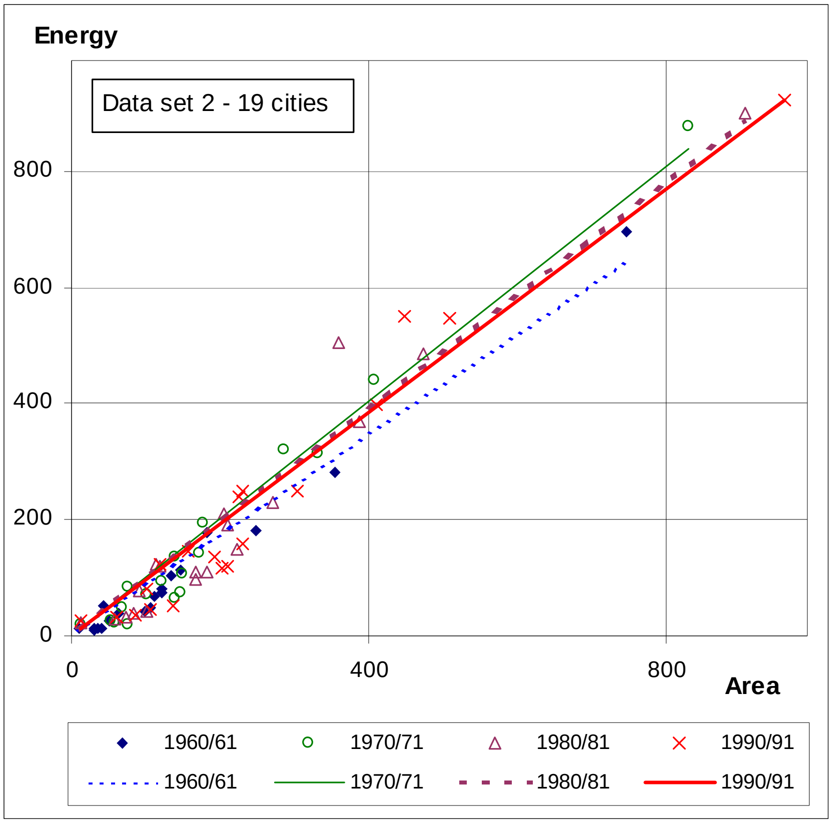
Nineteen cities in data set 2 had data for all four decades reported, which provides another view of changes in energy use over time. The relationships for these 19 cities are shown in Table 4 and the relationships are shown in Figure 4.

Table 4: Changes in Transport Energy Relationships Over Time

Data source	Data set	Number of cities	Data year	k	Correlation (R^2)
Kenworthy and Laube	2/60	19	1960	0.862	0.971
	2/70	19	1970	1.010	0.967
	2/80	19	1980	0.980	0.945
	2/90	19	1990	0.963	0.946

The results suggest that city energy efficiency deteriorated from 1960 to 1970 but subsequently stabilised. Little change is observed between 1970 and 1990 where energy efficiency shows marginal improvement.

Figure 4: Changes in Transport Energy Relationships Over Time



8. COMPARISON BETWEEN DEVELOPING AND DEVELOPED CITIES

Two data sets included information about 'developing' and 'developed' cities (Data sets 2 and 3) which were investigated. The first issue is how to decide whether a city is developed or developing so concepts need to be decided including:

- what are the categorisation characteristics - transport system cultural, economic, or other 'development';
- what is the threshold to decide whether a city falls into one category or other;
- how are changes over time considered (eg Data set 2 has three decades during which time a city, such as Seoul, has changed from developing to developed);
- how is a city categorised if it has major parts which are developed and others which are developing (eg Johannesburg).

These issues are not discussed in the sources of data sets.

Such issues are partly technical and partly psychological in the sense that they can be significantly affected by our personal values, culture and world view as we place a value judgement in the apparently good concept of 'development'.

Data set 2 has one category whereby 'developing Asian' cities are identified, however this includes cities such as Seoul and Kuala Lumpur which could perhaps be described as 'developed', and have changed over time. Data set 3 has several city groups which are either categorised or interpreted as developing. Some categories in

Data set 3 (such as Africa) are interpreted here as having cities which could be either developing or developed. Cities analysed in these categories are listed in Table 5.

Table 5: List of Developing Cities

Data Set 2	6 Cities	Data Set 3	24 Cities
Asia (developing)	Bangkok Jakarta Kuala Lumpur Manila Seoul Surabaya	Asia (developing)	Bangkok Beijing Chennai Guangzhou Ho Chi Minh City Jakarta Kuala Lumpur Manila Mumbai Seoul Shanghai
		Africa	Dakar Harare
		Europe (Eastern)	Budapest Cracow Prague
		Latin America	Bogota Curitiba Sao Paulo
		Middle East	Cairo Riyadh Tehran Tel Aviv Tunis

The results from two data sets are summarised in the Table 6.

Table 6: Relationships for Developed and Developing Cities

Data set	Number of cities	Data year	k	Correlation (R^2)
2/90 - developed	39	1990	0.951	0.916
2/90 developing Asian	6	1990	2.091	0.307
3 - developed	59	2000	0.964	0.944
3 - developing	24	2000	0.911	0.545

These results indicate the relationship between transport energy and city area apply to both developing and developed cities. However, the relationships between transport energy and city area are much more reliable for developed cities than developing cities. It is suggested that the structure of developing cities is much more diverse than for developed cities. A greater range of energy compared with area could therefore be expected in these locations. The energy per person relationship with population density is similarly diverse as a consequence.

9. ALTERNATIVE CORRELATIONS

Lyons et al (2003) identified a correlation between average daily car vkt (vehicle kilometres travelled) and urban area. Consequently several other correlations were investigated to consider which were more significant. Correlations of parameters with urban area for the 4 Kenworthy and Laube (1999) data sets are summarised in the Table 7.

Table 7: Alternative Transport Correlations with Urban Area

Data Set	Correlation with Urban Area (R^2)			
Parameter	**2/60**	**2/70**	**2/80**	**2/90**
Total vkt	.943	.934	.892	.885
Car[1] vkt	.925	.932	.955	.910
Public transport vkt	.157	.186	.067	.046
Private passenger energy use	.896	.848	.873	.820
Non passenger energy use	.157	.223	.233	.358

1. Also includes taxi, motor cycle and other private travel, where applicable.

These results indicate that total vkt, car vkt and private passenger energy use are highly correlated with urban area. However public transport vkt and non passenger energy use are poorly correlated with urban area. Also the previous correlations suggest that total energy is generally better correlated with urban area than other parameters, although car vkt has similar correlation. This result is expected since car vkt is generally the major proportion of total vkt and vkt is expected to be correlated with energy use.

Therefore city area is the fundamental parameter which directly affects travel demand and hence energy use. This parameter can be used for relationships to consider cities for a range of effects including total transport energy use, total vkt, car vkt and private passenger energy use.

10. IMPLICATIONS OF THE RESULTS

INTERPRETATION OF THE INFORMATION

The observed relationship between transport energy use and total urban area is perhaps counterintuitive to transport and urban planners. How could cities grow in population without there being an increase in energy use? This issue requires further separate investigation and consideration before being resolved.

In early stages of city growth there are few transport destinations and people, wherever they live, are required to travel to a few, distant locations. As more people move into the city (and increase the density) more destinations are built to service these people. As the numbers and locations of destinations increase, individuals can change their destinations to those that are closer.

This could be expected to occur if services and facilities also increase at a similar rate to population increases so the shortest distances to any type of destination decrease proportionally. Energy use could be expected to be directly related to travel distance which would then be constant. So, under these circumstances, transport energy use could be related to area as observed. The net effect is to reduce travel distances and so, globally, to maintain a certain level of energy use.

Allied to this effect are the many other minor effects that increasing density can contribute towards energy efficiency. Closer destinations result in shorter trips which encourages use of more energy-efficient modes such as walking and cycling. Public transport also becomes more energy-efficient when there are more people and destinations in a given area. The net effect could therefore maintain a certain level of energy use relative to area of the city.

Given the strength of the relationship between transport energy use and city area, other influences, sometimes considered important, pale into relative insignificance. Poor energy use has been blamed on everything from personal attitudes to highway engineers to the age of the city or some other fashionable concept. It is now clear that it is responses to consumer demand, which increase city size that results in increased transport energy use. This can be caused by land use policies, consumer demand, and construction of transport infrastructure (either road or rail).

POLICY CONSIDERATIONS

This work highlights the importance of city size in the sustainability debate from an energy use perspective. It would appear that there is value in constraining, in innovative and attractive ways, the physical extent of cities.

Finding ways of responding to consumer demand without increasing city area is more than challenging. The totalitarian response to implement a city boundary creates a scarce resource (land) which increases prices. This may be achievable, at least for a period in areas where there is vacant land suitable for development, or areas suitable for redevelopment. However, increasing density in already developed urban areas can waste existing assets (such as houses), increases construction costs and may require costly utility upgrades.

Few, if any cities, have managed to maintain a physical growth boundary but in part this may have been that there was little real evidence as to the value of decisions of this type. This finding may offer a bit more ammunition and contribute towards those cities that wish to reduce energy consumption per capita and to do this via constraining physical city size while increases are occurring in their populations.

Cities around the world are increasing in population due to both the attractiveness of cities and general population increases. Surprisingly, increasing population does not, in itself, dramatically degrade transport sustainability of a city. Cities can continue to grow in population and remain sustainable, provided the area of cities is contained.

Therefore the single most important issue to improve transport sustainability is the limitation of urban sprawl. Many other things can help, but nothing else is more important.

As a consequence, a major issue for sustainable transport is 'vital' urban development, which means a mixture of activities and mixed types of housing with a transport system to suit. Despite the promises of planners, it probably hasn't been achieved across large areas to any significant degree in cities since the widespread introduction of the motor car.

Another major issue is the poor quality of existing urban development in areas which have developed during the age of the private motor car. Dormitory suburbs dominated by residences are not sustainable in transport terms. The challenge is to change thousands of hectares of existing development. There is little evidence in the literature that this issue is recognised and almost no strategies exist to tackle it.

The final major issue is community perceptions and values. People are buying large blocks on the urban fringes because they can afford to choose a particular lifestyle. The challenge is to find ways to make development at higher densities attractive to buyers. Part of the challenge is to accommodate modern, affluent lifestyles which may require somewhere for a dog, a boat, a workshop or studio, a pool or a caravan.

11. CONCLUSIONS

There is a clear relationship between total transport energy use and city area:
- the relationship is linear,
- effectively the relationship has zero transport energy use for zero city area,
- the correlation coefficients are high indicating that transport energy use can largely be explained by city area.

So in general:

Total Transport Energy = k x City Area

The results are consistent:
- in the form of the relationship,
- in the values in the relationship,
- across data sets with substantial variation in city type, and
- across several decades.

The relationship is independent of other city land use, transport and cultural factors.

The form of the relationship between per capita energy use and population density suggested by Newman and Kenworthy (1989) is generally explained. However the transport energy - city area relationship provides a better understanding of the correlation than the population density - per capita energy use relationship (which represents a derived correlation from the fundamental relationship).

Both the transport energy - city area relationship and the population density - per capita energy use relationship provide valuable information about transport energy use.

Transport energy use has changed between 1960 and 1990, but there has been little change between 1970 and 1990. Energy efficiency degraded between 1960 and 1970 and became marginally better in the subsequent 20 years.

The transport energy - city area relationship provides an excellent relationship at least as good as other relationships describing global city transport factors. However total vkt, car vkt and private person energy use also provide strong relationships with city area. Therefore city urbanised area is the fundamental parameter which directly affects:
- total transport energy use,

- total amount of travel,
- car travel and
- total private person transport energy use.

12. REFERENCES

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