larger in absolute terms than one-year elasticities. Column 5 of Table 2 conforms to this expectation. Green of Oak Ridge National Laboratory studied 1966-through-1975 gasoline consumption and estimated the medium-term gasoline price elasticity to be -0.34 (5).

Both the one-year and the four-year elasticity estimates of scenario one conform the best to the findings in the literature. The four-year elasticity for New Jersey appears to be on a better methodological base than the one-year elasticity estimate. The four-year elasticity estimate of -0.28 means that with a 10 percent increase in the real price, automobile travel in New Jersey decreases by 2.8 percent.

FUTURE RESEARCH

Further research on the question of how the estimation method of this type of one-year elasticity can be improved is desirable. As noted above, taking out truck travel will result in a more correct and higher elasticity estimate in absolute terms.

ACKNOWLEDGMENT

I am indebted to R.L. Hollinger, Chief, Bureau of Transportation Systems Research, NJDOT, for his extensive advice and assistance with the computer work; to R. Barros, Senior Statistical Engineer, Bureau of Transportation Management Research, NJDOT, for his statistical assistance; and to A.W. Roberts, Chief, Bureau of Transportation Management Research, NJDOT, for his review of this paper.

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Publication of this paper sponsored by Committee on Social, Economic, and Environmental Factors of Transportation.

Land Use and Energy Intensity

HERBERT S. LEVINSON AND HARRY E. STRATE

This paper summarizes the energy implications of urban land use in the metropolitan Toronto area. It identifies the transportation and nontransportation energy intensities of various land uses, assesses the effects of population density on energy consumption, and suggests measures to improve energy efficiency. The annual energy requirements of various land uses, including transportation energy, were manufacturing, 40 percent; residential, 35 percent; commercial, 19 percent; and other, 6 percent. The total annual energy consumption of various types of residential development was computed by adding the annual transportation energy consumed to the annual energy required to build and operate buildings. Composite annual energy requirements were single-family attached—504 000 MJ/unit; single-family detached—376 000 MJ/unit; walk-up apartment—284 000 MJ/unit; and high-rise apartment—216 000 MJ/unit. Single-family residences consumed 50 percent more energy than did apartments on a per-unit basis. However, on a per-capita basis, apartments were found to be only 15 percent more efficient. Better land use planning to encourage compact urban development, increase residential densities, balance jobs and people, expand transit ridership, encourage ridesharing, and reduce per-capita space requirements would improve energy efficiency. These are desirable actions, especially in rapidly growing metropolitan areas. However, they appear difficult to achieve in view of public preferences and the incremental nature of implementing land use plans. Consequently, the greatest near-term gain in energy conservation probably will come from improving the operating energy efficiency of existing and new buildings and from improving transportation energy efficiency.

This paper summarizes the energy implications of urban land use in the metropolitan Toronto area (1). It overviews the state of the art, identifies the direct and indirect transportation and nontransportation energy intensities of various land uses, assesses the effects of population density on energy consumption patterns, and suggests measures to improve energy efficiency. It is based on a review of travel behavior and energy data for both Canada and the United States.

Much has been written on urban form, transportation, energy, and density; yet, many key parameters have not been quantified. There are differences of opinion among analysts regarding the effects of development density on energy consumption. Accordingly, the paper addresses two basic areas: (a) What are the energy requirements of various types of urban land? and (b) how does development density affect both transportation and nontransportation energy consumption?

STATE OF THE ART

The specific building factors that influence energy consumption include construction techniques, exposed surfaces, exposed surface-to-volume ratio, heating and cooling systems, insulation and fenestration, and climatological characteristics. However, most studies relate energy consumption to building types, age, and density, which may obscure many valid causative relationships. For example, a poorly insulated high-rise luxury apartment with spacious units may consume more energy per dwelling unit, per capita, or even per square foot, than a medium-density development of the same number of units per acre (2).

More study has been done of patterns of residential energy consumption than any other land use segment, and many of these findings are applicable to other land uses, such as commercial. For example, the cube minimizes the surface-to-volume ratio, thereby reducing heat-transfer potential; another example, shared walls, can reduce per unit energy consumption equally as well for retail establishments as for residential units.

Generalizations

From current literature, some generalizations may be made:

1. Higher residential densities relate to lower energy consumption;
2. Single-family detached homes consume more energy than low-rise, attached, and multistory housing;
3. Estimates for Ontario indicate that, for space heating, semi-detached houses require 25 percent less energy than single-family houses, and row houses require 50 percent less (3);
4. Decreasing exposed surface per enclosed volume minimizes heat transfer; surface can be minimized by creating cubical space or sharing common walls;
5. Landscaping and massing of buildings can serve as a shield to wind, sun, or other climatological extremes;
6. Increases in residential density may create opportunities to (a) increase efficiency of electromechanical systems through area heating and (b) minimize appliance use by sharing (e.g., washer-dryer);
7. Higher-density housing units tend to be smaller than single-family houses and thereby require less energy for heating and cooling; and
8. High-density living often means greater public transport use and lower automobile use.

Costs of Sprawl

The Costs of Sprawl study carried out for the U.S. Council on Environmental Quality attempted to isolate the variables of density from neighborhood age, obsolescent design, and low-income population, and to measure the most important consequences of urban form (4). Detailed estimates of the energy, environmental, capital, and operating costs were made of six hypothetical new communities--each containing 10 000 dwelling units, each housing an average urban fringe population mix, and each constructed in a typical environmental setting. The six communities varied by density (high, medium, low) and community design (optimal, typical). At the extremes were an optimally designed high-density community (19 units/net residential acre) and a typical low-density community (3.5 units/acre).

The analysis dealt with residential heating and air conditioning and with automobile use. The well-designed high-density community was found to be optimal with reference to all four key indicators examined, and the typical low-density community was least desirable with reference to all four. The overall consumption of the well-designed high-density community was 44 percent less than consumption in the typical low-density community.

In contrast, Altshuler (5) points out that many of the energy savings reported for high-densities dissolve on close examination. He indicated that the 44 percent savings in energy use for space heating and air conditioning reflected the different indoor space standards used:

> Overall, the high-density community had 34 percent less residential floor space than the low-density community and this accounted for five-sixths of the claimed energy savings....
>
> If one holds dwelling unit size constant and allows only 20 percent of the claimed auto travel savings (but still levies no charge for mass transit energy usage), the energy demand differential between the well-designed high-density community and the typical low-density community shrinks from 44 percent to 14 percent. If one compares the well-designed high-density community with the report's well-designed low-density community, moreover, the differential narrows to 6 percent.

Urban Form and Density

People living in cities with high population densities, concentrated employment in the city center, and extensive transit systems use substantially less gasoline per driver than those residing in low-density communities with dispersed employment. Each driver in New York and Chicago consumes less than 10 gal/week compared with some 15 gal consumed per driver in Los Angeles, Tucson, and Houston (6).

A few studies have modeled the future travel requirements associated with alternate urban development options over the past several decades. A study of five regional year-2000 plans in the Hartford, Connecticut, area showed that a balanced plan would have a work-trip length of 0.92 times that for the trend development. Corresponding ratios for linear development, satellite cities, and strong center plans were 0.96, 0.97, and 1.14, respectively (7).

A study on Energy, Land Use and Growth Policy: Implications for Metropolitan Washington analyzed six alternative 1992 development scenarios in terms of future energy consumption: wedges and corridor, dense center, transit oriented, wedges and corridors with income balance, sprawl, and beltway oriented (8). The dense-center scenario would consume about 8 percent less energy in the design year than with sprawl conditions.

STUDY APPROACH

Land use, transportation demand, and energy consumption are closely interrelated. Figure 1 illustrates this land use, transportation, and energy cycle and summarizes the steps followed in developing energy intensity factors: (a) the energy consumed in buildings and in operating various types of residential and nonresidential land was quantified, (b) the travel resulting from separations of various urban activities was estimated for various development densities, (c) composite energy intensity factors were obtained by adding the transportation and non-transportation energy, and (d) policy implications relative to energy consumption were identified.

The MTATES study assessed urban form, transportation, and energy relationships based on an earlier work by the Metropolitan Toronto Transportation Plan Review. Transportation system performance, based on assumed land use and transportation configurations, was tested by a number of criteria, including simulation of travel demand and performance. Three of the criteria used have direct bearing on energy consumption:

1. Average automobile trip length,
2. Average transit trip length, and
3. Mode split.

The selected systems tested and results of these evaluations are summarized in Table 1. Of the systems summarized, the Eglinton Corridor plan had the highest overall mode split at 47 percent. The shortest automobile trip length was achieved by the Metro Dispersion/Toronto Center plan--more than 0.5 mile less than the decentralized concept of regional dispersion.

Evaluating the energy consumption characteristics

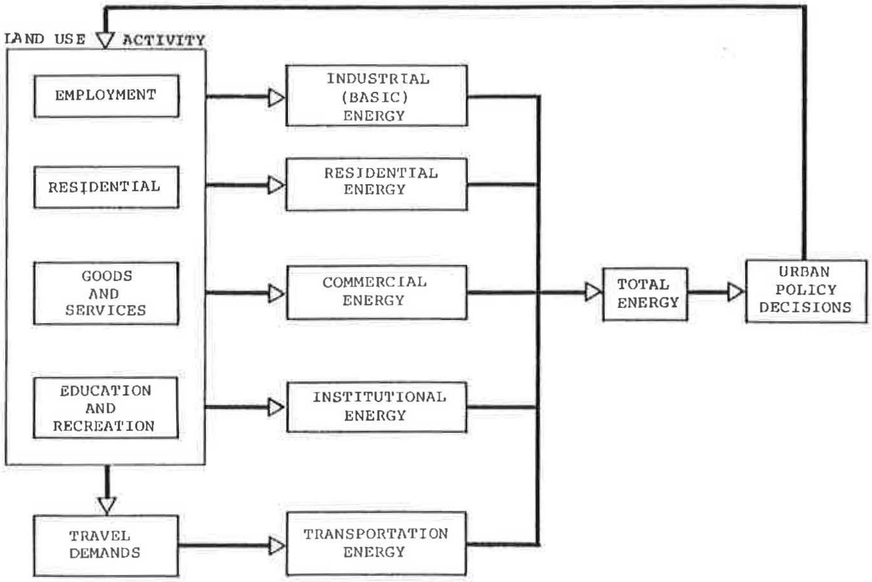


Figure 1. Land use energy cycle.

Table 1. Transportation performance of preferred land use and transportation combinations.

Development Designation	Description	Avg Automobile Trip (km)	Avg Transit Trip (km)	Mode Split (%)
Centralization (M3)	Highest level of central area growth	14.77	11.41	40
Binodal (O6)	Downsview Airport major center	14.51	11.09	39
Subcenter (D3)	Subregions at North York, Mississauga, and Oshawa	14.74	11.42	45
Corridor development				
(G2)	Eglinton corridor	14.69	11.39	47
(F1)	Lakeshore corridor	14.92	11.73	46
Metro dispersion (C3)	Toronto Center	14.42	11.13	38
Regional dispersion (L3)	Decentralization	14.95	11.89	39

Note: Data from Metropolitan Toronto Transportation Plan Review, Report No. 63, Jan. 1975.

Table 2. Influence of land use on transportation energy.

	Centralization[a]			Subcenter[a]			Regional Dispersion[a]			Load Factor Fix[b]		
Analytic Factors	Car	Bus	Total	Car	Bus	Total	Car	Bus	Total	Car	Bus	Total
Daily urban person work trips per household	1.39	0.92	2.31	1.27	1.04	2.31	1.41	0.90	2.31	1.31	1.00	2.31
Mode share	60.00	40.00	100.00	55.00	45.00[b]	100.00	61.00	39.00	100.00	57.00	43.00[c]	100.00
Avg trip length	14.77	11.41	-	14.74	11.42	-	14.95	11.89	-	14.95	11.89	-
Daily person kilometers	20.53	10.50	-	18.72	11.88	-	21.08	10.70	-	19.58	11.89	-
MJ/person kilometer	4.60[a]	0.70[a]	-	4.60[a]	0.76[b]	-	4.60[a]	0.70[a]	-	4.10[c]	0.60[c]	-
Total daily MJ/household	94.44	7.35	101.79	86.11	7.13	93.24	96.97	7.49	104.46	80.30	7.13	87.43
Total energy (MJ)			50 895 000			46 619 000			52 228 200			43 715 000
Equivalent gasoline (39.84 MJ/L)			1 461 000			1 338 000			1 499 000			1 255 000
Savings over dispersion (%)			2.70			10.90			-			16.40

Note: Data from Wilbur Smith and Associates.

[a] Assumes automobile occupancy of 1.36 passenger/vehicle and single value for all transit trips—subways, street cars, bus, etc.
[b] Assumes transit load factor increases 6 percent (ridership increase of 12 percent).
[c] Assumes transit load factor increases 5 percent (ridership increases 10 percent), and automobile occupancy increases 10 percent to 1.50.

of each, the subcenter plan that closely approximates the current Metro official plan consumes 10 percent less energy than the regional dispersion plan. As summarized in Table 2, subcenter even outperforms the centralization plan focused on the Toronto central business district (CBD).

Even more significant increases (11 percent) in energy efficiency can be achieved through strategies aimed at increasing automobile occupancy 10 percent and transit ridership 10 percent, as illustrated by the load-factor-fix scenario. These behavioral changes are not easy to obtain, yet hold potential for significant increases in efficiency. To illustrate, a 10 percent increase in automobile occupancy would require that one out of every eight drivers would no longer drive alone.

LAND USE AND ENERGY CONSUMPTION

The energy consumed by urban land use reflects the types, intensities, and spatial separation of the activities that take place. It includes the energy involved in construction and actual operation.

Energy Profile

The annual energy consumption profile of each region

Table 3. Relation of land use to travel and energy consumption.

Use	Distribution of Developed Land[a]	Person Destinations[b] (%)	Energy Consumed by Sector 1978[c] (%)	Transportation Energy Redistributed, Ontario	Energy Consumed with Transport Energy Distribution According to Columns 3 and 4
Residential	28.0	50.1	20.5	+14.7	35.2
Commercial	2.6	27.5	10.2	8.1	18.3
Manufacturing	5.7	8.5	37.7	2.5	40.2
Transportation, common, utilities	6.2	1.0	29.3	-29.1	0.2
Public and semipublic buildings and open space	29.9	12.9	2.3	3.8	6.1
Streets and alleys	27.6	-	-	-	-
Total	100.0	100.0	100.0	0	100.0

[a] Data from H. Bartholomew, Land Uses in American Cities, Harvard Univ. Press, Cambridge, MA, 1955.
[b] Data from TARMS, 1971.
[c] Data from Ontario Royal Commission on Electric Power Planning, 1978.

Table 4. Typical values for annual energy consumption in Buffalo and Toronto metropolitan areas.

Land Use	Annual Energy Consumed (MJ/m^2)			
		York[a]	Oakville[b]	Buffalo[c]
Residential				
Single-family detached (120m^2)		1540	-	1710
Single-family attached (110m^2)		-	-	1240
Multifamily low-rise (100m^2)		1470	-	1160
Multifamily high-rise (60m^2)		1470	-	1520
Composite residential (110m^2)		-	1420	-
	Annual Operating Toronto[d] (%)	Toronto[d]	Oakville[b]	Buffalo[c]
Commercial				
Hotel, motel	9	2320-1700	1700	1310
Office (large)		1940	1640	2290
Office (small)	47	1740	1640	1200
Shopping center	-[e]	-	2270	2040
Service station	10	3210	-	-
Store	23	2320	-	1620
Theater, auditorium	-	-	-	-
Composite wholesale	-	-	1700	-
Food store	11	4450	-	-
Total	100			
	Annual Total[d] (%)	Toronto[d]	Oakville[b]	Buffalo[c]
Institutional				
Clinic	-	-	2160	1460
Community center	-	-	-	1140
Gymnasium	-	-	-	1470
Hospital	32	4530	2160	3330
Nursing home	2	890	2160	1340
School, elementary[f]	17	1320	1360	1200
School, secondary[f]	19	1740	1360	1420
Community college	4	2130	-	-
University	24	2520	-	-
School administration building	2	-	-	-
Total	100			

[a] Data from Analysis of the Relationship between Urban Form and Energy Consumption. Ministry of State for Urban Affairs, Toronto, March 1979.
[b] Data from Energy Management at the Local Level. Royal Commission on Electric Power Planning, Toronto, 1975.
[c] Data from Federal Register, Vol. 44, No. 20, November 28, 1979.
[d] Data from Patterns and Levels of Commercial and Industrial Energy Consumption: A Case Study of Metropolitan Toronto. Ministry of Energy, Mines, and Resources, Toronto, 1979.
[e] See entry for stores.
[f] Ottawa school range = 970 to 1470 MJ/m^2. Data based on Energy Consumption in Schools. Ministry of Energy, Mines, and Resources, Toronto, 1979.

or municipality will vary, depending on the economic base and mix of activities. The annual energy consumption within the metropolitan Toronto area was estimated to be the following (9):

1. Residential, 20 percent;
2. Commercial, 11 percent;
3. Institutional, 2 percent;
4. Industrial, 38 percent; and
5. Transportation, 29 percent.

The composite annual energy requirements by land use were estimated by redistributing the energy involved in transporting people to each type of use. The resulting estimates of the overall energy consumed in the Toronto metropolitan area by sector are shown in Table 3. Estimates were derived as follows:

1. The distribution of developed land by type of use was based on Harlan Bartholomew's classic study of developed land in North American cities (column 1);
2. The distribution of person-destinations by land use was based on 1971 data for the Toronto area regional model study (column 2);
3. The distribution of energy consumed by sector was based on Ontario energy consumption for 1978 (column 3);
4. The transportation energy consumed was redistributed to the various types of use in accordance with the distribution of person trip generations (column 4) (for example, 50.1 percent of the 29.3 percent transportation energy, or 14.7 percent, was reallocated to residential land use); and
5. The composite energy consumption (column 5) represents the sum of columns 3 and 4.

The results are as follows:

1. Residential land occupies about 28 percent of the total developed land and consumes about 35 percent of the total energy,
2. Manufacturing consumes about 6 percent of the developed land and consumes about 40 percent of the total energy, and
3. Commercial activities consume about 3 percent of the developed land and 19 percent of the energy.

Changes in the distribution and density of residential land would involve about one-third of the area's total energy. If residential energy consumption could be reduced by half, it would result in about a 17 percent reduction in areawide energy consumed.

Building Operating Energy

The annual building operating energy requirements for the various land uses in Buffalo, New York, and in the Toronto metropolitan area are shown in Table 4. (Buffalo has similar climatic conditions to Toronto, and thereby provides a good data source where Toronto specific data are unavailable.)

1. Single-family detached homes have the highest residential consumption rate. They consume nearly 50 percent more energy than a multifamily, low-rise unit. Multifamily, low-rise units are the most efficient of the four types or residential forms with 1160 MJ/m^2 annually.
2. Among commercial establishments, foodstores consume the most energy each year, i.e., 4450 MJ/m^2. Hotels, motels, and office buildings consume about 2000 MJ/m^2 annually.
3. Hospitals represent the most energy-intensive institutional use; they consume more than 4500 MJ/m^2 annually.

Building Construction Energy

The total direct and indirect energy consumption involved in new building construction is shown in Table 5. The total construction energy is highest for hospitals (19 540 MJ/m^2) and office buildings (18 530 MJ/m^2) and lowest for residential construction (7100-8400 MJ/m^2).

Table 5. Typical values for construction energy.

Land Use	Direct Energy for Actual Construction (MJ/m^2)	Other Manufacturing, Component Parts, etc. (MJ/m^2)	Total
Residential			
Single-family, detached	990	6 970	7 960
Single-family, attached	1170	5 920	7 090
Garden apartments (low-rise)	1320	6 030	7 350
High-rise residential	1710	6 640	8 350
Commercial			
Hotel, motel	2790	10 020	12 810
Office building	4110	14 420	18 530
Garage, service station	1740	7 010	8 750
Store, restaurant	2500	8 080	10 580
Miscellaneous	3560	12 880	16 440
Institutional			
Dormitory	3720	11 520	15 240
Religious building	2830	11 440	14 270
Educational	3020	12 700	15 720
Hospital	4020	15 520	19 540
Miscellaneous	3560	12 880	16 440
Industrial			
Industrial building	1120	9 920	11 040
Warehouses	880	5 950	6 830

Note: Data from Energy Use for Building Construction, U.S. Energy Research and Demonstration Administration, 1967; and Center for Advanced Computation, Final Report, Energy Use for Building Construction–Supplement, C00-2791-4 CAC Document No. 228-A, Oct. 1977.

Total Building Energy Intensity

The total annual building energy intensity for various types of buildings was derived by annualizing the construction energy and adding it to the direct operating energy. The results are summarized in Table 6. A 30-year service life was assumed for warehouses, service stations, and single-family residences; a 40-year service life for apartments, hotels, and stores; and a 50-year service life for institutional and other commercial and industrial uses. Hospitals are the most energy intensive, consuming 4920 MJ/m^2 annually. Residential single-family detached buildings consume about 2000 MJ/m^2, compared with 1370 for garden apartments and 1760 for high-rise apartments. These values are subsequently used in assessing the total energy requirements of differing development densities.

TRANSPORTATION AND TRAVEL IMPACTS

The effects of population density on urban trip generation and travel modes have been well documented (10,11). These relationships provide a basis for deriving the transportation energy impacts associated with various types and densities of land use.

The generalized effects of population density on urban trip rates are shown in Figure 2. As population density rises, there is an increase in the total number of person trips, including pedestrian trips, and a corresponding decrease in the number of trips in vehicles. This is because many shopping, social, and school trips and some work trips are made by foot, and a greater proportion of the nonwalking trips are made by public transport in high-density environments. As a result, the number of automobile trips per dwelling unit reduces from about 10 at 3000 persons/mile^2 to less than two at 30 000 persons/mile^2 and even less at higher densities.

Residential trip generation rates derived by the Institute of Transportation Engineers were used to quantify the effects of residential density on travel demands and energy consumption. These trip rates are shown in Table 7. Total person trips were estimated, assuming an occupancy of 1.4 persons/car, and modal-split characteristics observed in Toronto and other large urban centers.

COMPOSITE RESIDENTIAL ENERGY REQUIREMENTS

The estimated effects of various types of residential developments on annual energy consumption in

Table 6. Total annual energy consumption.

Structure Type	Construction Energy (MJ/m^2)	Service Life (MJ/m^2)	Annual Energy (MJ/m^2)		
			Construction[a]	Operating	Total
Residential					
Single-family, detached	7 960	30	260	1710[b]	2000
Single-family, attached	7 090	30	240	1240[b]	1510
Garden apartment (low-rise)	7 350	40	180	1160[b]	1370
High-rise residential	8 350	40	210	1520[b]	1760
Commercial					
Hotel, motel	12 810	40	320	2000	2320
Office building	18 530	50	370	1900	2270
Garage, service station	8 750	30	290	3210	3500
Store, restaurant	10 580	40	260	2320	2580
Institutional					
Dormitory	15 240	50	300	2000	2300
Religious building	14 270	50	280	2500	2780
Educational	15 720	50	310	2000	2310
Hospital	19 540	50	390	4530	4920
Industrial					
Industrial building	11 040	50	220	NA	NA
Warehouse	6 830	30	210	910	1120

[a] Rounded to the nearest figure.

[b] Add 30 MJ/m^2 for delivery of municipal services to obtain total energy.

Figure 2. Generalized effects of density on urban trip rates.

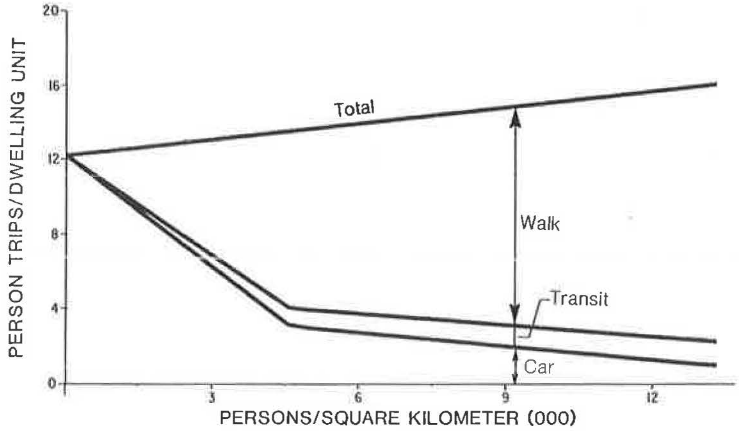


Table 7. Trip rates for dwellings.

Type of Dwelling Unit	Units per Net Acre	Avg Weekday Vehicle Trip Ends per Unit	Car Trips (1.4 persons/car)	Assumed Car Trips as Percentage of Total	Assumed Total Person Trips[a]
Single-family, detached	3.0	10.0	14.0	95	14.7
Single-family, attached	6.0	7.9	11.0	90	12.0
Low-rise apartment	15.0	5.4	7.5	80	9.0
High-rise apartment	30.0	3.7	5.2	65	8.0

Note: Data from Trip Generation–An Institute of Transportation Engineers' (Washington, D.C.) informational report, 1976.

[a] Rounded to the nearest figures.

Table 8. Estimated energy intensity of residential land use.

	Single-Family Home			Single-Family Attached			Apartment Walkup			Apartment High-Rise		
Item	Car	Transit	Total	Car	Transit	Total	Car	Transit[a]	Total	Car	Transit	Total
Transport												
1. Person trips (%)	95	5	100	90	10	100	80	20	100	65	35	100
2. Daily urban person trips/ dwelling unit	14.0	0.7	14.7	11.0	1.0	12.0	7.5	1.5	9.0	5.2	2.8	8.0
3. Avg trip length[b]	10.5	11.3	-	10.5	11.3	-	10.5	11.3	-	10.5	11.3	-
4. Daily person kilometer (2x3)	147.0	7.9	-	115.5	11.3	-	78.8	17.0	-	54.6	31.6	-
5. Annual person kilometers (4x300 days)	44 100	2370	-	34 650	3390	-	23 640	5100	-	16 380	9480	-
6. MJ/person kilometer[a]	5.9	1.5	-	5.9	1.5	-	5.9	1.5	-	5.9	1.5	-
7. Total annual transport energy (MJ/s/unit) (5x6)	260 190	3555	263 745	204 435	5085	209 520	139 476	7650	147 126	96 642	14 220	110 862
Nontransport												
8. MJ/m^2			2 000			1 510			1 370			1 760
9. m^2/unit			120			110			100			60
10. Total annual MJ/unit (8x9)			240 000			166 100			137 000			105 600
11. Total annual MJ/units (7-10) (000s)			503 745			375 620			284 126			216 462

Note: Data from Wilbur Smith and Associates.

[a] Mode used. [b] TARMS, 1971.

the Toronto area are shown in Table 8. These computations reflect the preceding estimates of direct and indirect residential energy construction, and the trip rates and modal split.

This table also reflects the following additional assumptions:

1. Average trip lengths of 10.5 km for car trips and 11.3 km for transit trips, based on the Toronto area regional model study (July 1971).
2. The total direct and indirect energy for automobiles, assumed at 8.28 MJ/vehicle-km, based on a specific analysis of energy consumption in Toronto. This translates into 5.9 MJ/person-km (12).
3. The total direct and indirect energy for public transport, assumed at 21.01 MJ/vehicle-km. In 1978, the Toronto Transit Commission averaged 13.96 passenger-km/bus-km. This corresponds to 1.5 MJ/person-km.
4. The square meters per residential unit for various types of residential construction, based on Ontario conditions.

The results of these computations are summarized in Figures 3 and 4. They are as follows:

Building Type	Annual Energy Consumption per Unit (MJ)	Index
Single-family home	503 745	1.00

Building Type	Annual Energy Consumption per Unit (MJ)	Index
Single-family attached	375 620	0.75
Garden apartment	284 126	0.56
High-rise apartment	216 462	0.43

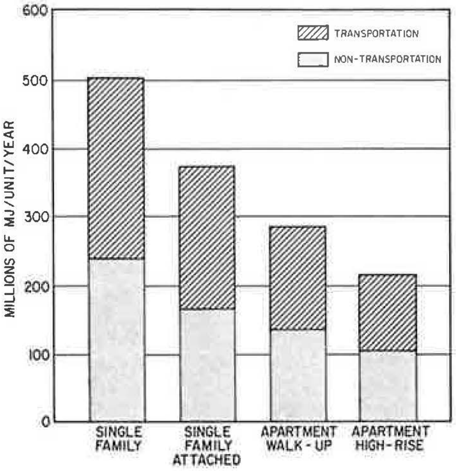
Several qualifiers should be taken into account in evaluating these results:

1. A large part of the energy savings associated with multifamily units results from the smaller amount of space they occupy.
2. There is a tendency for the number of persons per dwelling unit to decrease as density rises.

Assuming an approximate uniform amount of square feet occupied per person, the following indices of energy efficiency on a per-capita basis are obtained:

Building Type	Assumed Persons per Unit	Annual Megajoules per Person	Index
Single-family home	4.0	125 936	1.00
Single-family attached	3.3	113 824	0.90
Apartment walk-up	2.6	109 279	0.87
Apartment high-rise	2.0	108 231	0.86

Figure 3. Estimated annual energy intensity of residential land use.



These figures imply that a 15 percent energy savings on a per-capita basis would result from apartment development--gains that fall within the range identified by Altshuler. Equally as significant, the analysis shows the sensitivity of energy consumption estimates to the assumed number of persons per dwelling unit.

LAND USE IMPLICATIONS

The preceding analysis suggests several land use implications and future directions. Some of these are briefly noted below.

Land Use Planning

There are major savings in energy consumption as population density rises. Land use planning to achieve compaction, increase densities, relate people to jobs, coordinate public transport with jobs, and encourage transit ridership and ridesharing is desirable from an energy perspective.

1. Gains in energy efficiency can be achieved by better arrangement of urban activities, by encouraging higher development densities, and by limiting single-family construction. These gains could reduce total residential energy consumption by about 50 percent on a per-dwelling-unit basis and about 15-20 percent on a per-capita basis. They would be accompanied by savings in the commercial sector--since high-density developments would reduce transport requirements to shopping and work areas and encourage clustering and building efficiency.
2. While it is difficult to model, energy gains could likely result from reducing the journey to work by increasing self-containment of new communities and/or by creating a better balance between employment and population. (Quantifying these efforts remains an essential research project.)
3. Without any overall increase in gross density, clustering and associated modifications in street layout can reduce the length of streets and utility installations. Energy is saved in the construction and, later, in the maintenance of streets, transmission of electricity and water, and provision of services like garbage collection.
4. At the community level, higher density and mixed zoning (a) can potentially reduce travel distances and make transit more feasible by locating home and work places closer together and (b) bring major traffic generators near to each other. Inten-

Figure 4. Estimated effect of residential density on energy consumption.

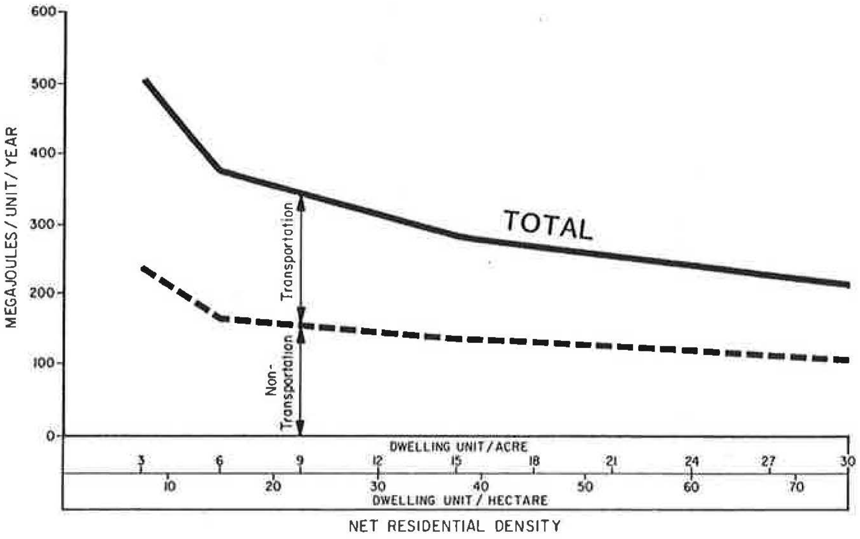


Table 9. Impact of conservation design on energy use and construction costs.

Structure Type	Reduction in Energy Consumption with Conservation Design (%)		Change in Construction Cost with Conservation Design (%)
	Northeast United States	North Central United States	
Single-family	30	30	+1
Single-family	15	15	+0
Low-rise apartment	51	32	-2
Office building	62	61	-2
Retail store	42	43	-1
School building	46	44	-2

Note: Data from D. Elliot Wilbur, Jr., Energy Conservation and New Technologies in Building, California Energy Seminar, May 10-11, 1977.

sifying land use along transportation corridors can encourage the use of public transit and give people a choice of travel modes--a valuable option whenever shortages arise.

5. Reducing the per-capita space requirements of new residential construction would substantially reduce energy consumption over the long run. However, this runs contrary to the trend and desires to increase space as incomes rise.

In sum, an energy-conservant transportation and land use strategy should:

1. Provide residential densities in all parts of the region that can support transit;
2. Concentrate new urban development along major transit corridors and around suburban centers;
3. Increase multifamily residential construction throughout the metropolitan area;
4. Improve the balance between people and jobs in all parts of the metropolitan area;
5. Increase the mix and integration of land use;
6. Provide closer residential developments on smaller lots and locations where houses can be served by public transport;
7. Encourage infilling of vacant parcels within the central city and its surrounding suburbs, especially with uses that enhance functional integration; and
8. Encourage mixed-use buildings where large office, shopping, and residential complexes are combined into single structures (for example, Eaton Center, Toronto; Water Tower Place, Chicago; and Peachtree Center, Atlanta).

These are important actions, and urban development policies should provide necessary incentives and controls to help achieve them. At the same time, it should be realized that attainment in many metropolitan areas will be difficult because (a) implementation of land use plans has not been effective, (b) much of the future metropolis is already in place today, and (c) people continue to increase their space requirements, especially as their incomes rise. Consequently, only limited gains can be anticipated from these land use measures over the near-term future in many metropolitan areas, even though they represent a desirable public policy direction.

Building Improvements

The greatest gains in future energy conservation, therefore, will probably come from two other sources: (a) improving the gasoline mileage efficiency of private automobiles and (b) increasing the operating energy efficiency of existing and new buildings. These gains will probably exceed those associated with land use planning per se, since they can be applied on a metropolitan basis. They will be especially desirable in those metropolitan areas where population has stabilized and little growth is anticipated.

Efforts should be directed toward improving space-heating efficiency since this accounts for more than two-thirds of the annual building energy consumption; and energy-conservant design represents another important way to save 30 to 50 percent of energy in new building construction. The potential savings from adhering to the standards developed by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) are shown in Table 9. These standards have been adopted by all the model building codes.

Extension to Other Areas

The research methodology outlined in this paper has been applied to the metropolitan Toronto area. Similar procedures can be used to estimate the energy impacts of various land uses in other North American cities. These efforts should reflect variations in population density, city size, transit use, and rates of growth. Thus, a broader cross section of relationships and implications can be derived to provide a sound basis for establishing energy-conservant transportation and land use decisions.

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Publication of this paper sponsored by Committee on Transportation and Land Development.