STREAMLINED LIFE CYCLE ASSESSMENT: A METHOD FOR CONSIDERING ENVIRONMENTAL IMPACT OF ROAD CONSTRUCTION

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The main advantage of Life Cycle Assessment (LCA) is in supporting decision-making with scientific data. Fully developed LCAs, however, are time-consuming and costly to prepare, limiting their viability during the procurement process. Streamlined LCAs, on the other hand, can be used more effectively as decision-making tools, due to the reduced level of data required. The inclusion of input-output data improves the completeness of streamlined LCAs, which are often severely abbreviated. This paper demonstrates the integration of input-output data with case traditional LCA data for a road system. It is shown that the use of input-output analysis greatly increases the completeness of the analysis, while the inclusion of traditional LCA data greatly improves reliability. Results for a road system are compared to typical buildings.

Keywords: construction, input-output analysis, life cycle cost, road.

INTRODUCTION

The fourth construction objective—the environment—must be satisfied if constructed facilities are to improve their overall performance (Ofori 1992). It is suggested that such improvement requires iterative evaluations during the various phases of the procurement process. Life cycle assessment (LCA) is a technique that can be used to evaluate the environmental implications of a product or activity. It has been stated that the main advantage of LCA is in supporting decision-making with scientific data (Häkkinen 1994). Fully developed LCAs, however, are time consuming and costly to prepare, which limits their viability during the construction process. Streamlined LCAs can be used to rapidly compare competing systems or design solutions because they require the collection of less case specific data (Jensen *et al.* 1997). Most previous streamlined LCA methods, however, have resulted in reduced completeness, even when apparently comprehensive LCA databases are used (Janssen 1998).

A convenient source of comprehensive LCA ‘inventory’ data is input-output tables (Lave *et al.* 1995). Input-output data are collected nationally, and are most commonly prepared for financial analysis. The Leontief inverse input-output matrix gives the sum of direct and indirect requirements for products, such as fuels Transactions are included across the whole economy and practically an infinite number of transactions upstream. Input-output data are thus systemically complete.

Input-output analysis has been used as the basis for LCAs by associating broad parameter LCA data to sectors of the economy (Lave *et al.* 1995). The input-output model thus provides a comprehensive inventory, while the national average LCA data provides the environmental information. However, the use of input-output data in

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traditional LCAs has not been developed. Despite the inherent errors associated with the application of input-output data to specific cases, they can be used for streamlined LCAs to improve completeness. The aim of this paper is to demonstrate the application of input-output data to the streamlined LCA of a road system.

BACKGROUND

The procurement of construction has a significant impact on the environment. Consideration to the extent to which construction impacts the environment is becoming a topical issue for construction researchers as natural resources are being depleted, fossil fuels emit damaging pollutants, and rainforests are being destroyed (Finch 1992). Numerous techniques for assessing the environmental impacts are available, all of which have their advantages and disadvantages (e.g. Cole *et al.* 1993). Each method developed to date has made significant contributions to the author's understanding of how construction affects the environment. However, there are several limitations with existing techniques, as they have a general objective of encouraging greater environmental responsibility within the construction industry, but not towards sustainability as a whole. For example, pollution associated with fossil fuels consumed in the manufacture of construction products is very rarely considered during the procurement process. Another limitation of many environmental assessment methods is the effort required to carry them out.

Traditional LCA

LCA is considered to be the only legitimate basis on which to compare alternative materials, components and services (Cole 1998). LCAs are used to assess the environmental impacts attributable to processes, incorporating those effects associated with processes in the upstream supply chain. In the case of a construction project, for example, LCA could be used to consider the pollution associated with the fossil fuels consumed in the manufacture of materials used in the construction process and in the ongoing operation of the facility.

LCAs attempt to assess the environmental 'loadings' and/or 'impacts' that are associated with a process. The term 'loadings' refers to a quantifiable activity for which the direct environmental consequences are currently unable to be measured (e.g. emissions of carbon dioxide)(Fossdal and Edvardsen 1995). The term 'impacts', on the other hand, refers to activities that directly affect the environment, such as damage to a habitat caused by the extraction of raw materials, which are more difficult to quantify and compare than environmental 'loadings'. Häkkinen (1994) stated that there are four steps required to undertake LCA:

- Goal definition (e.g., the life-cycle phases to be considered);
- Inventory analysis (quantifying inputs of energy and other products);
- Environmental assessment (classification and valuation); and
- Interpretation and improvement assessment.

Step 1 and the second part of step 3 (*i.e.* valuation) require value judgements (Häkkinen 1994). It has been stated that inventory analysis (step 2) and classification (the first part of step 3) are carried out based on verifiable facts wherever possible (Häkkinen 1994). In the selection of items for the inventory, however, intuition plays a role, because the full range of inputs is not known beforehand. It is therefore difficult to prioritize data collection, for the both inventory and environmental assessment phases. Some inputs are excluded without consideration, and in some cases without acknowledgement. Lave *et al.* (1995) stated that not even the inventory phase of LCA can be supported scientifically. Generally, only the inputs thought to be important are included. Some small inputs may be rejected because there were found to be unimportant in previous studies. However, it is more likely that most are simply ignored.

STREAMLINED LCA

Streamlined LCAs often use generic data—qualitative and/or quantitative—for basic materials, transportation systems and energy production systems (Jensen *et al.* 1997). The use of similar materials and components in a wide range of construction projects means that databases of LCA data could be useful as the basis for streamlined LCAs of constructed facilities. Buildings and facilities require basic materials and complex products for their construction and operation.

A typical level of incompleteness for a streamlined LCAs is demonstrated in Figure 1. Normally, only a fraction of the inputs to a process are considered, for example, the simple linear stream comprising 'Transport' into 'Cement' into 'Concrete' into 'Road construction'. A traditional LCA may not be much broader than this simple linear stream (Lave *et al.* 1995). Thus, the difference between a streamlined LCA and a traditional LCA is not definite, but a continuum that comprises different levels of detail (Janssen 1998).

Häkkinen (1994) asserted that LCAs can provide a basis for developing a system with lower impact on the environment. The authors do not agree with Häkkinen's assertion because competing systems may be assessed with frameworks of such widely differing completeness that to compare the results may result in invalid conclusions. This criticism applies particularly to streamlined LCAs.

Current LCA databases are unsuitable for construction projects inasmuch as they mainly comprise basic materials. Many LCA databases are proprietary, and are embedded in expensive software making them difficult to evaluate or modify. Smaller construction companies and consultants are unlikely to be able to afford such software, or have the time to apply them to individual construction projects. Therefore, a more available and affordable source of comprehensive LCA inventory data is required.

PURE INPUT-OUTPUT LCA

A convenient source of comprehensive LCA inventory data is input-output tables. Input-output data are collected nationally, and are most commonly prepared for financial analysis. The Leontief inverse input-output matrix gives the sum of direct and indirect requirements for products, such as fuels, across the whole economy and an infinite number of transactions upstream. Input-output analysis has been used as the basis for LCAs, by associating LCA emissions data to sectors of the economy (e.g. Lave *et al.* 1995). In the US, the SETAC database is useful for streamlined LCAs to some degree, due to its breadth across the economy but many larger and sensitive industries are not required to divulge information (Lave *et al.* 1995). In other countries, databases of economy-wide emissions data are generally not available.

Figure 1 only partially indicated the complexity of the input-output model, because it listed just the main inputs to road construction, concrete and cement. The inputs to other processes were not expanded, e.g. chemicals. Even if each node indicated in

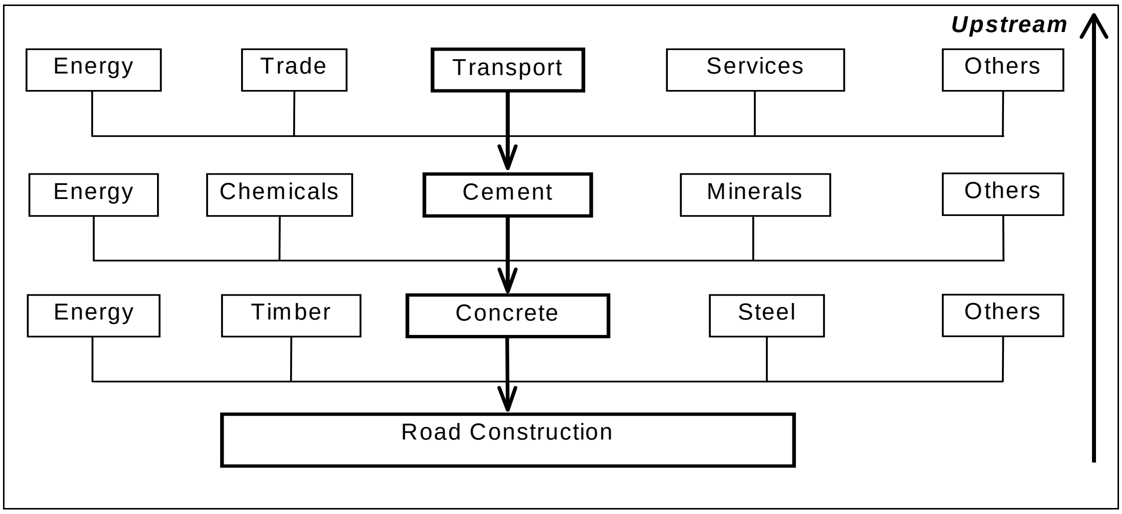

Figure 1: Direct and indirect suppliers to road construction

Figure 1 was expanded one further step upstream, however, this would only begin to approximate the systemic completeness of the input-output model (Treloar 1997).

STREAMLINED LCA FOR ROADS: A DEMONSTRATION

The streamlined LCA method is demonstrated below for an Australian road system using an energy input-output model. The method differs from pure input-output LCAs in that the inventory is derived using traditional LCA and input-output data is used to improve the completeness of the traditional LCA inventory. The use of national average input-output data provides a systemically complete system boundary for the items that are quantified in the inventory. In this example, the 'cumulative energy demand', or life cycle energy, will be the scope of the streamlined LCA. In Australia, road use dominates the transport industry, comprising 90% of passenger kilometres and one third of freight ton kilometres (Parikh *et al.* 1995). Road construction comprises 9.7% of Australian construction output annually, by cost (ABS 1996). The environmental impacts of roads relate initially to their construction and thereafter to their maintenance and use. Since the use of roads involves vehicles, the life cycle energy associated with vehicles was also included.

The road selected for analysis has been previously analysed in terms of life cycle cost by Porter and Tinni (1993), having the following attributes:

- trafficable width is 7 m with 2 m shoulders with a 1m verge;
- the sample 5 km length of comprised 333 m cut and 667 m fill (*i.e.*, 4 km is flat);
- design life of 40 years;
- rural Australian location; and
- traffic of 10 000 vehicles per day, comprising 90% cars and 10% trucks.

The pavement type was continuously reinforced concrete, comprising:

- base of 32 MPa reinforced concrete (1.33 m^3 per metre of road);
- reinforcement for 32 MPa concrete (133 kg of per metre length of road);
- unreinforced, lean mix concrete sub-base (1.39 m^3 per metre of road);

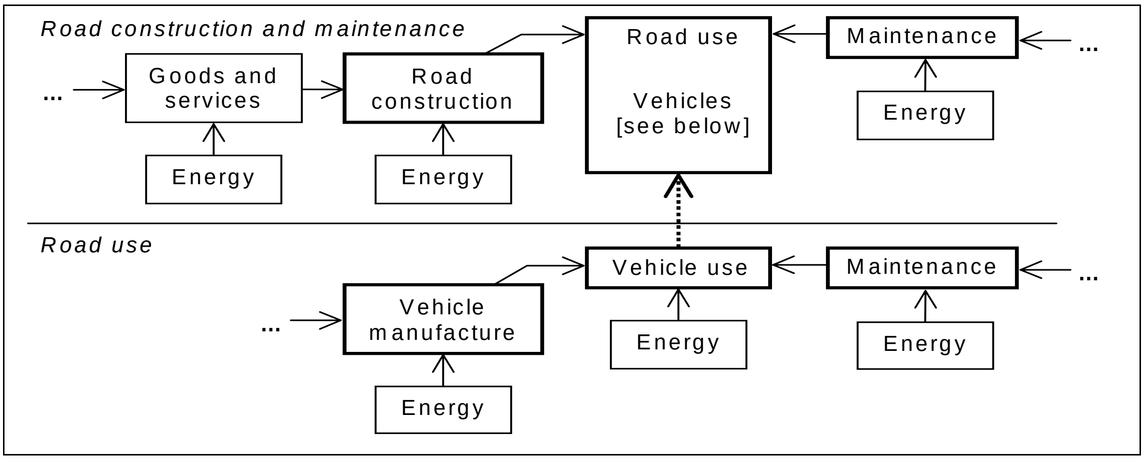

Figure 2: Conceptual model of life cycle energy use of a road, including vehicles

- plain concrete pavement finish (0.76 m^3 per metre length of road); and
- costing $602 per metre of road (Porter and Tinni 1993).

Porter and Tinni (1993) also analysed 14 other road types in terms of life cycle costing. They are not included here for the sake of clarity of the demonstration of the new streamlined LCA method. The selected type was the first on their list.

Method

The conceptual model for the life cycle of the road system, including cars, is depicted in Figure 2. The model is comprised of:

- road construction and maintenance; and
- road use, comprising vehicle manufacture, use and maintenance.

The initial embodied energy of the road, and other products requiring embodied energy data, was calculated using embodied energy rates for Australian economic sectors derived using an input-output model developed by Treloar (1998). In this input-output model, inputs to energy supply sectors were initially truncated, to remove the errors inherent to input-output analysis. The energy embodied in energy products was then reintroduced into the model through the application of primary energy factors. National average energy tariffs were used to convert purchases of energy in financial terms to energy terms. The life cycle energy model was conceptualized in primary energy terms. Energy use in Australia comprises mostly fossil fuels, thus the model relates directly to fossil fuel related environmental loadings. Electricity consumption, for example, is weighted to reflect the coal and other primary fuels used for its generation.

Incidental road system items, such as reflector posts, ‘cat eyes’, guard rails and lighting and communication systems were nominally included through the use of input-output data, but were not specifically quantified in the inventory. Road maintenance was simulated using a 4% linear growth factor.

Vehicle operation comprised consumption of liquid fuels. Over the next decade, improvements in car energy efficiency will likely be offset by energy used in the manufacture of new cars (Parikh *et al.* 1995). Thus, the 4% increase in traffic adopted by Porter and Tinni (1993) for the purpose of pavement performance simulation was not used herein for the purpose of LCA. The assumed average vehicle primary energy efficiencies were derived based on 10 km/l for a typical car (an estimate by the authors) and 3.63 km/l for trucks (equivalent to 10.49 mpg, quoted as a UK average for trucks by Boustead and Hancock 1979). Heat of combustion of liquid fuels was assumed to be 0.034 GJ/l (an average for petrol, Boustead and Hancock 1979). A primary energy factor of 1.4 was assumed for all liquid fuels (*i.e.* 1.4 GJ of oil and other fuels are required to make 1 GJ of petrol, Treloar 1997).

Associated with vehicle operational energy is the share of the energy embodied in the initial manufacture and ongoing maintenance of these vehicles. A 15 year life was used to model the life cycle of cars (after Parikh *et al.* 1995). This was extended to 18 years for trucks by the authors. The initial embodied energy was amortized over vehicle life, and partitioned to the distance travelled on the sample road (*i.e.*, 5 km).

Vehicle maintenance comprised the consumption of goods and services during the vehicle's life, for registration, tyres, servicing, insurance and interest. Similar assumptions applied for trucks. The annual interest payments were assumed only for the first four years of the vehicle's life. This is because some new vehicles are not financed, but some second-hand vehicles are financed; this is expected to even out over the road life cycle. The interest payment was assumed to represent the 'purchase' of a product from the banking sector. This technique does not work for savings, because interest accrued would erroneously indicate net energy production. Banking services used for administering savings, however, could be classified as a 'free' by-product of the finance industry, and no embodied energy need be attributed to them.

Results

Table 1 gives the details for the calculation of the initial embodied energy of the 5km stretch of road. The initial embodied energy of the road was found to be 26.0 GJ/m length of road, or 130 000 GJ for the 5km length. This amount comprised:

- 5.1% direct energy of the road construction process (pure input-output figure);
- 29.9% energy embodied in 32 MPa concrete;
- 35.1% energy embodied in steel reinforcement for 32 MPa concrete;
- 23.4% energy embodied in unreinforced lean mix concrete; and
- 6.5% energy embodied in other inputs of goods and services to road construction.

Assuming 4% linear growth per annum for road maintenance, the life cycle embodied energy of the road increased over the 40 year period to 601 000 GJ.

The road operational energy totalled 102 000 GJ per annum (Table 2), which was 22% less than the initial embodied energy of the road. Over the road's life cycle of 40 years, the vehicle operational energy totalled 4090 000 GJ.

The energy embodied in the vehicles was another factor in the life cycle energy use attributed to road activities (Table 3). For a car costing $30 000, the initial embodied energy was found to be 272 GJ, while a truck costing $120 000 was found to embody

Table 1: Initial road embodied energy

	Calculation (Australian economic sector)	Result (GJ/m of road)
Pure input-output embodied energy rate for 'Road construction'.	602 $/m x 0.618 GJ/$100* / 100 = ('Other construction')	3.7
Energy embodied in inputs of main materials to road construction, from the pure input-output model.	0.488* – 0.195* – 0.013* = ('Concrete slurry', 'Basic steel', and 'Cement and lime')	0.7
Subtract energy embodied in inputs of main materials from the input-output model for road construction.	3.7 – 0.7 =	3.0
Case specific - 32 MPa concrete.	1.33 m^3/m x 5.85 GJ/m^3* =	7.8
Case specific - steel reinforcement.	0.133 t/m x 68.6 GJ/t* =	9.1
Case specific – lean mix concrete.	1.39 m^3/m x 4.39 GJ/m^3* =	6.1
Sub-total - case specific quantities.	7.8 + 9.1 + 6.1 =	23.0
Add case specific values to modified pure input-output total for road construction.	23.0 + 3.0 =	26.0
Multiply metre rate by length of road.	26.0 x 5000 m =	130 000 GJ

*Derived using the primary energy input-output model for Australia described in Treloar (1998).
N.B. Values may not sum due to rounding. Units are in GJ/m of road, unless otherwise noted.

Table 2: Vehicle operational energy

	Car	Truck	Total
Number of vehicle trips per day for 5 km stretch of road	9000	1000	10 000
Assumed average vehicle primary energy efficiency (GJ/100 km)	0.476	1.311	-
Total primary energy per day (GJ)	214	66	280
Total annual primary energy (GJ)	78 200	24 100	102 000
Total primary energy over road life (40 years)	3130 000	957 000	4090 000

N.B. Values may not sum due to rounding.

Table 3: Energy embodied in vehicles

	Car	Truck
Assumed average price of new vehicle ($) (A)	30 000	120 000
Embodied energy rate for the 'Motor vehicles and parts; other transport equipment' sector from the pure input-output model (GJ/$100) (B)	0.906	0.906
Vehicle embodied energy (GJ) (A x B / 100) = (C)	272	1088
Number of vehicles per day (D)	9000	1000
Assumed total kilometres per week for vehicles (E)	210	2800
Assumed vehicle life (years) (F)	15	18
Vehicle embodied energy per annum (GJ, i.e., initial embodied energy is amortized over vehicle life cycle) (C x D x 5 / E / 7 / F)	27 200	800
Annual total for both types of vehicles (GJ)		28 000
Total primary energy over road life (40 years) for both types of vehicles (GJ)		1120 000

N.B. It is assumed that increases in vehicle use will be offset by improvements in energy efficiency. Values may not sum due to rounding.

1088 GJ. The energy embodied in vehicles, amortized annually, was 1120 000 GJ for the 40 year period.

A further factor was the energy embodied in the maintenance of vehicles (Table 4). Identical assumptions were made for trucks, based *pro rata* on the average vehicle price. Totalling only 15 200 GJ in the first year, the energy embodied in vehicle maintenance grew to 608 000 GJ over the 40 year road life cycle

Table 4: Annual embodied energy associated with car maintenance

Item	Price ($) (A)	Originating input-output sector	Total embodied energy (GJ/$100) (B)	Annual embodied energy (GJ) (A x B / 100) = (C)	15 Year life cycle energy (GJ) (C x 15)
Registration	410	Government administration	0.930	3.8	57
Tyres	250	Rubber products	0.745	1.9	29
Servicing	500	Mechanical repairs	0.340	1.7	25
Insurance	500	Insurance	0.255	1.3	19
Interest	1482	Banking	0.298	* 4.4	18
Total per car				9.8	148

*The assumed annual interest payment was only applied for the first four years of car life.
N.B. Values may not sum due to rounding.

The road system's life cycle energy over time is depicted in Figure 3. The relative importance of the various elements changed considerably over the 40-year life cycle. In the first year, the life cycle energy of the road (totalling 275 000 GJ) comprised:

- 47.2% initial road embodied energy;
- 37.1% vehicle operational energy;
- 10.1% initial embodied energy of vehicles; and
- 5.5% embodied energy of vehicle maintenance.

At the end of the 40 year period, the total of 6410 000 GJ comprised:

- 63.7% vehicle operational energy (initially ranked second);
- 17.4% initial embodied energy of vehicles (initially ranked third);
- 9.5% embodied energy of vehicle maintenance (initially ranked fourth); and
- 9.4% initial road embodied energy and maintenance @ 4% (initially ranked first).

DISCUSSION AND CONCLUSION

If the case specific data were not integrated into the input-output model for the materials concrete and steel reinforcement, then the initial road embodied energy would have been 89% lower. Road construction may involve greater quantities of energy intensive products than non-building construction in the 'Other construction' sector, involving both non-residential building and non-building construction (*i.e.*, including roads, ABS 1996). The pure input-output model for road construction was therefore extremely unreliable. However, it is estimated that the integration of input-output data into the traditional LCA model improved the completeness of the analysis by at least 50%, especially for the inputs of products from the 'services' type sectors (based on information from Treloar 1997).

The vehicle operational energy comprised two thirds of the life cycle energy for the road system, which was expected. However, the other life cycle energy components provided some interesting results. The embodied energy of cars has been previously

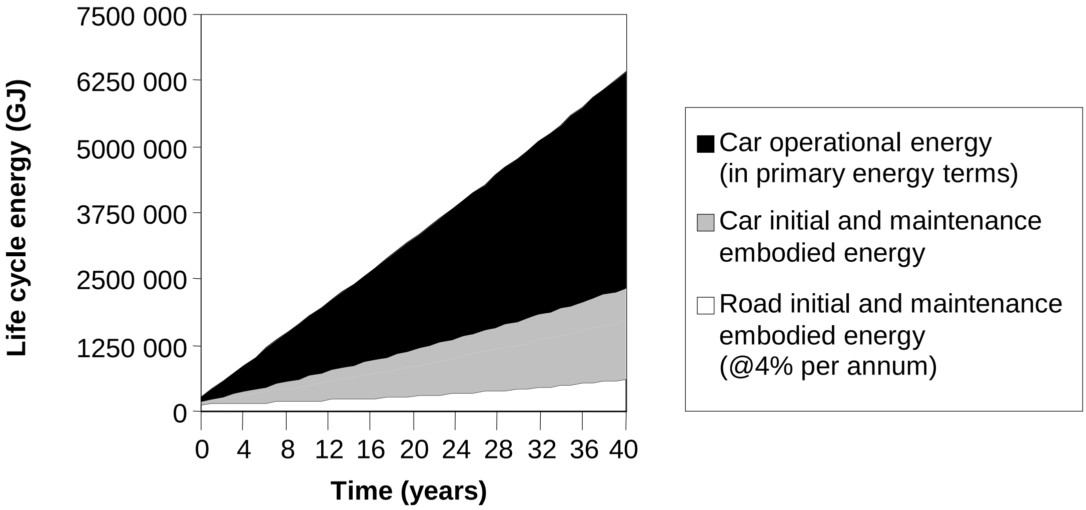

Figure 3: Life cycle energy attributable to road construction and use

estimated to be 273 GJ per car, using a pure input-output analysis method (Parikh *et al.* 1995). The pure input-output result obtained here is disturbingly similar, being only 0.3% lower, even though different Australian input-output tables and techniques were used. The vehicle maintenance items were also important (e.g. registration).

The relationship between capital and operational environmental impacts is important for the development and implementation of strategies for life cycle emissions abatement. Previous research conducted by Treloar (1996) suggests that for a building's life cycle, the ratio between the energy embodied in construction and the operational energy can be as high as 50:50. With a typical building having a life of 50 years, most buildings may use approximately two to four times more energy than its construction required. When the furniture and fittings of an office building are also considered, the embodied energy component of the life cycle may be greater than 50:50 (McCoubrie and Treloar 1998). This indicates that significant savings can be made though materials substitution, for example.

The relationship between capital and operational environmental impacts has yet to be established for road systems. The model presented in this paper, however, suggests that the ratio between road construction and operation may be much lower than for buildings. Thus, when a proposed road system is being evaluated, the scope should include the operational and maintenance implications of vehicles. Otherwise, the life cycle environmental impacts of the road system may be severely underestimated. This may be important in assessments of emissions reductions, for example. If all sectors of the economy are to achieve significant emissions reductions, then design consultants should be aware that an increase in one sector (e.g. road construction) could cause increases in another sector (e.g. automobile manufacture and use). This is not to suggest that the construction of a road immediately influences the manufacture of new automobiles, but regular and wide ranging increases in road construction may indirectly boost the automotive manufacturing industry, and liquid fuel use, over time.

Energy related emissions are the major component of environmental loadings attributable to car manufacture and operation (Parikh *et al.* 1995). Therefore, the life cycle model based on energy, as demonstrated here, may form an appropriate basis for a full LCA, based on a broader range of environmental parameters and indicators.

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