Hybrid Life-Cycle Inventory for Road Construction and Use

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Abstract: Life-cycle assessment (LCA) is a technique that is used worldwide by clients and their design team to assess the impact of their projects on the environment. The main advantage of LCA is in supporting decision making with quantitative data. LCA inventories can be either fully developed or streamlined. Fully developed LCAs are time-consuming and costly to prepare. Streamlined LCAs can be used as an effective decision-making tool when considering environmental performance during the design process, but with a loss of inventory completeness. Acknowledging the advantages and disadvantages of both types of LCA, this paper proposes a hybrid LCA method that uses input-output data to fill in those gaps routinely left in conventional LCA inventories. The developed hybrid LCA method is demonstrated using a life-cycle energy study of eight different road designs, including vehicle manufacture, maintenance, replacement, and operation. It was found that the road construction process was initially the most important, but in the long run the manufacture, use, and maintenance of vehicles using the road (which are an inevitable consequence of road construction) became paramount.

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Introduction

Life-cycle assessment (LCA) is a technique that can be used to evaluate environmental impacts during the construction procurement process. Accordingly, Häkkinen (1994) states that the main advantage of LCA is in supporting decision making with quantitative data. Fully developed LCAs are time-consuming and costly to prepare, limiting their viability during the construction procurement process. Streamlined LCAs require the collection of less case specific data and the use of more general data for commonly used products, requiring less time overall, and thus being more conducive to use during the construction procurement process. Previous streamlined LCA methods, however, have resulted in increased incompleteness, due to the narrowing in the scope of data collection (Treloar et al. 2000). Thus, the aim of this paper is to develop a hybrid LCA method using input-output analysis so as to provide a systemically complete framework for LCAs of road construction projects.

Construction Projects and Environment

Construction projects have a significant impact on the environment. Consideration of the extent to which construction impacts the environment is becoming a topical issue as natural resources are being depleted, fossil fuels are emitting damaging pollutants, and rainforests are being destroyed (Finch 1992; Zhang et al. 2000). The initial impact of a facility on the environment results from the energy and products consumed in its construction, and thereafter the facility continues to affect the environment throughout its operation, maintenance, refurbishment, and, finally, demolition. The use of energy for producing construction materials, be it directly or indirectly, contributes to air pollution and is a major factor in the overall environmental impacts of construction projects (Suzuki and Oka 1998). In Australia, for example, the construction sector—including construction of buildings and civil engineering projects—accounts for 10–20% of the nation's primary energy-usage and energy-related greenhouse gas emissions (Ballinger et al. 1995; Treloar 1996).

Numerous techniques for assessing environmental impacts are available—all of which have their advantages and disadvantages (Cole 1998). There are, however, several limitations with existing techniques, as they have a general objective of encouraging greater environmental responsibility within the construction industry, but not toward sustainability as a whole. For example, pollution associated with fossil fuels consumed in the manufacture of construction products is very rarely considered comprehensively, if at all, during the construction procurement process (Treloar et al. 2000). In other words, the impacts that the products used in construction have on the environment are not taken into account when considering the procurement of projects.

Life-Cycle Assessment

LCAs are considered to be the only legitimate basis on which to compare alternative materials, components, and services (Häkkinen 1994). LCAs are used to assess the environmental impacts attributable to processes and incorporate those effects associated with processes upstream in the 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 construction materials. Conventional LCA methods are too cumbersome for considering the environmental im-

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pact of design decisions. Therefore, a streamlined approach is required. Treloar et al. (2000) suggest the use of a hybrid LCA method that effectively streamlines the process using input-output data.

Hybrid Life-Cycle Assessment

The problem of missing or costly data for LCAs of construction projects can be at least partially overcome by using a hybrid method based on national input-output tables (Treloar et al. 2000). In the case of Australia, for example, this information can be obtained from the Australian Bureau of Statistics (ABS) (1996a). However, input-output data alone are not appropriate for LCAs, due to inherent errors in their black-box approach to deriving upstream requirements. Input-output LCA methods may be suitable for analysis of the national production of basic materials, where case-specific data may be unavailable for upstream companies due to industrial confidentiality. This is unlikely to be relevant for the whole upstream supply chain of a construction project.

Hybrid LCA involves the integration of more reliable LCA data into the comprehensive input-output model. Environmental loading data for specific processes can be associated with each important node in the upstream supply chain, as derived from the input-output data (Treloar 1997). Unimportant nodes in the upstream supply chain can then be left in the model using the input-output data, and case-specific data can be inserted for the most important nodes (Treloar et al. 2000).

A hybrid LCA method comprises the following steps.

1. Derive an input-output LCA model (perhaps using only embodied energy data).
2. Extract the most important pathways for the sector under consideration.
3. Derive case-specific LCA data for the facility and its components.
4. Substitute the case-specific LCA data into the input-output model.

Step 1 and Step 3 are described fully in other places (Treloar et al. 2000, 2001). For Step 2, the most important "pathways" from the inverse input-output model can be extracted using an algorithm (Treloar et al. 2001). The collection of data in Step 3 can be prioritized based on the ranked list of important pathways derived in Step 2. In Step 4, input-output data for the unimportant pathways are retained in the model by subtracting the initial values of the modified pathways from the total. Thus, the framework of the hybrid LCA method is as comprehensive as the input-output model.

The integration of conventional LCA data into an input-output LCA model improves the reliability of the modified components of the input-output LCA model. Only a fraction more of time needs to be spent for an input-output LCA model than for a conventional LCA. Furthermore, the conventional LCA efforts are more strategically targeted to processes deemed important in the initial input-output model.

Hybrid Life-Cycle Assessment for Roads

The key feature of the hybrid LCA method described earlier is the use of input-output data to fill in those gaps normally left in conventional LCAs. A financial system boundary is used to set the scope of the LCA within the comprehensive input-output framework.

The environmental impacts of roads relate initially to their construction, and thereafter to their maintenance and use. Road construction comprises 9.7% of Australian construction activity annually by cost (ABS 1996b). Since the use of roads involves vehicles, the life-cycle energy associated with vehicles should also be considered as part of the road system. This is analogous to considering the life-cycle energy of equipment used in a building as part of the life-cycle energy attributable to the building. In Australia, road use dominates the transport industry, comprising 90% of passenger kilometers and one-third of freight ton kilometers (Parikh et al. 1995). The full life-cycle energy implications of the manufacture, maintenance, and use of vehicles, in the context of a road, have not been articulated.

Road Designs Selected for Analysis

In addition to vehicle life-cycle energy, the life-cycle energy implications of different road designs were analyzed. The eight road designs selected for analysis were previously analyzed in terms of life-cycle cost by Porter and Tinni (1993). All cases had the following attributes:

Table 1. Road Designs Selected for Analysis (Data per Meter Length of Road)

Road type	Abbreviation	Base	Subbase	Miscellaneous
Continuously reinforced concrete	CRC	1.33 m^3 of 32 MPa concrete; with steel reinforcement, at 133 kg/m^3 concrete	1.39 m^3 of 5 MPa concrete	Shoulders: 0.76 m^3 of 32 MPa concrete
Plain concrete	PC	2.42 m^3 of 32 MPa concrete	1.39 m^3 of 5 MPa concrete	
Full-depth asphalt	FDA	3.0 m^3 of asphaltic concrete	1.70 m^3 of 5 MPa concrete	
Composite, asphalt and concrete	Comp	2.22 m^3 of asphaltic concrete	1.41 m^3 of 5 MPa concrete	
Deep strength asphalt	DSA	2.22 m^3 of asphaltic concrete	Compacted graded earth	
Granular	G	Compacted graded earth	Compacted graded earth	Sealed surface: 0.50 m^3 asphalt
Deep-strength asphalt on bounded subbase	DSAB	1.67 m^3 of asphaltic concrete	2.28 m^3 of 5 MPa concrete	
Asphaltic concrete on bounded subbase	ACB	0.55 m^3 of asphaltic concrete	3.28 m^3 of 5 MPa concrete	

Note: For Road Types FDA, DSAB, and ACB, the subbase of stabilized earth is assumed to be modeled adequately by 5 MPa concrete. No embodied energy is attributed to compacted graded earth, other than the amount of direct energy implied in the input-output model for the road construction process. Source=Porter and Tinni (1993).

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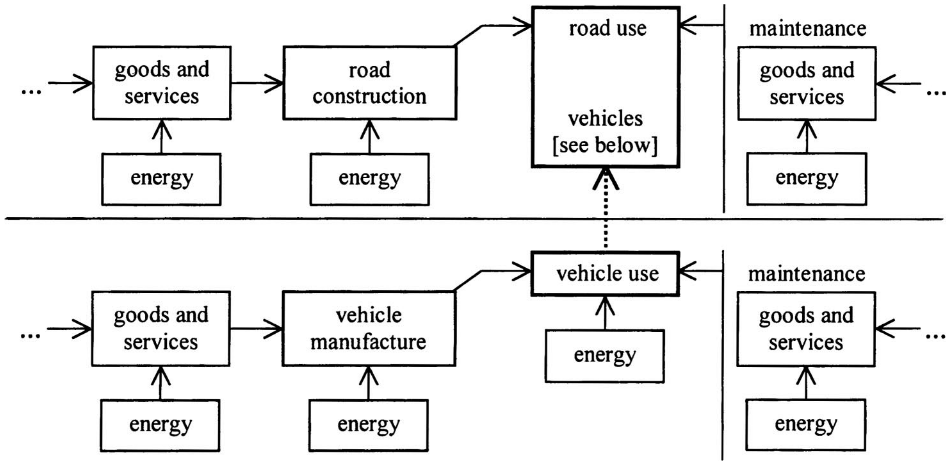

Fig. 1. Life-cycle energy model for a road, including vehicles

- Rural location,
- 5 km stretch,
- Maintenance requirements at 4% per annum, and
- 10,000 vehicles per day, comprising 90% cars and 10% trucks.

The specific attributes of each road type are described in Table 1.

Life-Cycle Energy Model

The life-cycle energy attributable to roads—including the share of the vehicles using the road—is depicted in Fig. 1, and comprises

- Road construction, use (i.e., vehicles), maintenance, and replacement and
- Vehicle manufacture, use, maintenance, and replacement.

The life-cycle energy model is conceptualized in primary energy terms. The model relates directly to fossil-fuel-related environmental loadings because energy use in Australia comprises mostly fossil fuels. Electricity consumption, for example, is weighted to reflect the coal and other primary fuels used for its generation.

The financial system boundary is greater than the traditional International Federation of Institutes for Advanced Study (IFIAS) levels of analysis (Fig. 2). Transactions rather than categories of inputs represent levels in the upstream tree. Thus, any activity can occur at any level, depending on the characteristics of the upstream supply chain for the process under consideration.

Derivation of Life-Cycle Assessment Data

The initial embodied energy of the first road design case was determined using embodied energy rates for basic materials and Australian economic sectors derived using an input-output model for 1992–1993 (Treloar 1998). The embodied energy rates used for basic materials are given in Table 2. Industry data for energy usage were substituted into this input-output model using the hybrid analysis method described previously, as described in Treloar (1998).

Nonmaterial inputs (such as financial services) and ancillary activities (such as administration) are included through the use of a financial system boundary (Treloar et al. 2000). The cost of

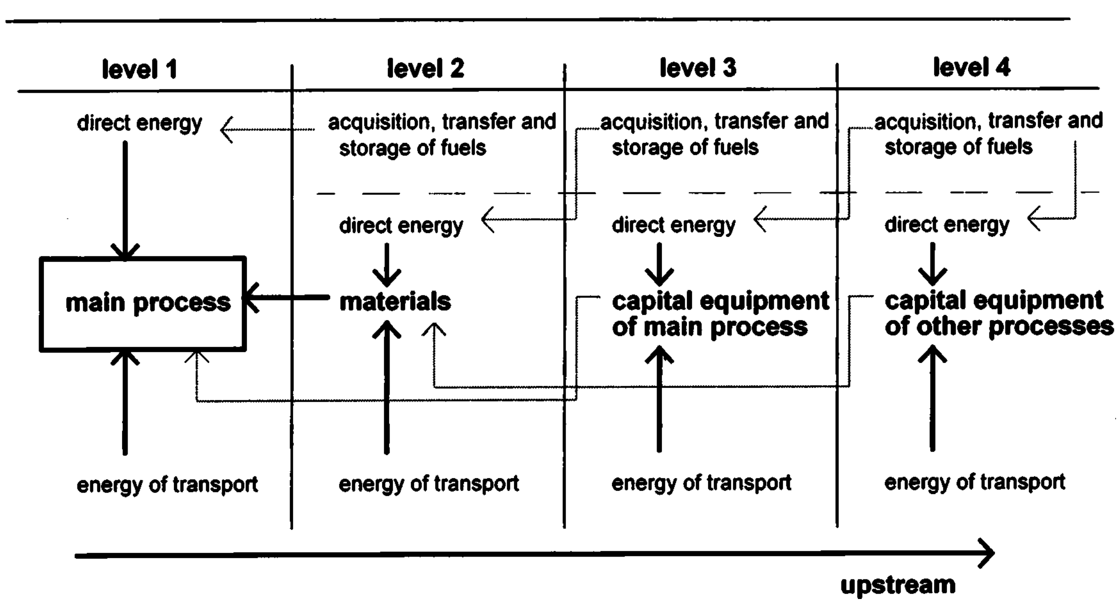

Fig. 2. Classification model for embodied-energy analysis (IFIAS 1974)

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Table 2. Embodied Energy Rates for Building Materials

Material	Unit	Embodied energy rate (GJ/unit)
32 MPa concrete	m^3	5.85
5 MPa concrete	m^3	2.03
Steel reinforcement	t	68.6
Asphalt	m^3	10.8

Note: Source=Treloar (1998).

these items was used as a mechanism to attribute embodied energy, facilitated by the initial derivation of energy intensities using the input-output model in units of energy per dollar of output. Embodied energy rates for Australian sectors as used for the analysis of products other than those listed in Table 2 are given in subsequent tables, along with the assumed costs for these items.

The assumed vehicle energy efficiencies were derived based on the assumption that cars average 10 km/L (an estimate) and trucks average 3.63 km/L [equivalent to 10.49 miles per gallon (mpg), quoted as a U.K. average for trucks by Boustead and Hancock (1979)]. Fuel heat of combustion was assumed to be 0.034 GJ/L (Boustead and Hancock 1979) and a primary energy factor of 1.4 was assumed for all liquid fuels, as it takes 1.4 GJ of oil and other primary fuels to make 1 GJ of petrol (Treloar 1997). It was assumed that future increases in vehicle efficiency will be exactly offset by increases in road use.

Associated with vehicle operational energy is the share of the energy embodied in the initial manufacture and ongoing maintenance of these vehicles. The embodied energy of the initial manufacture was modeled using the assumed average price of typical vehicles. Maintenance refers to the consumption of goods and services during the vehicle's life. The annual interest payment was assumed only for the first 4 years of the car's life. This is because some vehicles are not financed, so this is expected to even out over the vehicle life cycle. The interest payment is assumed to represent the "purchase" from the banking sector. This technique does not work for savings, because interest accrued would erroneously indicate net energy production. Similar assumptions are applied for trucks, based pro rata on the assumed vehicle prices.

Road maintenance was simulated using a 4% step. Data exist for a more comprehensive model for road maintenance, comprising estimates of materials used in maintenance activities (Porter and Tinni 1993). Such sophistication could be included in future research, but is not expected to significantly affect the results.

Results and Discussion

Table 3 identifies the calculations for the initial embodied energy of the 5 km stretch of road, for the continuously reinforced concrete (CRC) road type. Since the input-output analysis data were used as "background" in the hybrid analysis, this method is termed an "input-output-based hybrid analysis." First, a pure input-output result was obtained. Then the process analysis figures were derived for basic materials. Finally, these were integrated with the input-output results by subtracting the components of the input-output model that case-specific data were derived for (summing to 3.02 GJ/m). Components that were determined to not be relevant to road construction were also subtracted from the input-output model (e.g., glass is used in significant quantities in commercial building construction, but not in road construction). Initially, important pathways identified in the input-output model were not used to prioritize data collection because the initial values were so much lower than the case-specific values. This part of the method could be used to stimulate further research into the reliability of this study.

The initial embodied energy of the CRC road type was found to be 27.2 GJ/m per length of road, or 136,000 GJ for the 5 km length. Assuming 4% per annum for road maintenance, the em-

Table 3. Input-Output-Based Hybrid Analysis of Continuously Reinforced Concrete Road Type

Calculation step (description)	Calculation (Australian sector for energy intensity, GJ/dollars 100)	Cumulative result (GJ/m of road)
Input-output analysis		
Initial pure input-output embodied energy of road construction	602 dollars/m^2 [b] ×0.618 GJ/dollars 100[a]/100 =("other construction")=	3.7
Calculate energy embodied in inputs of concrete, steel, and cement to road construction in input-output model.	0.488[a]+0.195[a]+0.013[a]=("concrete slurry," "basic steel," and "cement and lime," respectively)=	0.7
Subtract energy embodied in inputs of concrete, steel, and cement from input-output model for road construction.	**3.7**−**0.7**=	3.0
Process analysis		
Case specific—32 MPa concrete	(1.33+0.76) m^3×5.85 GJ/m^3[a]=	7.8
Case specific—steel reinforcement	0.133 t×68.6 GJ/t[a]=	9.1
Case specific—5 MPa concrete	1.39 m^3×2.03 GJ/m^3[a]=	2.8
Case specific—miscellaneous	0.76 m^3×5.85 GJ/m^3[a]=	4.5
Subtotal—case-specific quantities	**7.8**+**9.1**+**2.8**+**4.5**=	24.2
Hybrid analysis		
Add case specific values to modified pure input-output total for road construction.	**24.2**+**3.0**=	27.2
Multiply meter rate by length of road.	**27.2**×5,000 m=	113,500 GJ

Note: Values may not sum due to rounding. Units are GJ/m of road, unless noted. Bold numbers are from earlier calculations in the table.

[a]Derived using the primary energy input-output model for Australia described in Treloar (1998).

[b]Porter and Tinni (1993).

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Table 4. Embodied Energy of Road Construction, and Assumed Life Cycles

Road type	Abbreviation	Initial embodied energy for 5 km length (GJ)	Assumed life cycle (years)
Continuously reinforced concrete	CRC	135,987	40
Plain concrete	PC	100,028	40
Full-depth asphalt	FDA	194,980	40
Composite, asphalt, and concrete	Comp	149,759	40
Deep-strength asphalt	DSA	135,419	40
Granular	G	42,204	20
Deep-strength asphalt on bounded subbase	DSAB	128,799	40
Asphaltic concrete on bounded subbase	ACB	78,271	20

bodied energy of Road Type CRC rose by a factor of 4.6 over the 40 year period to 628,000 GJ. Table 4 gives the initial embodied energy results for each of the eight road types, as well as the assumed life cycles (in years).

The road operational energy, comprising mainly liquid fuels used to run vehicles, totaled 102,270 GJ per annum, comprising 76.6% cars and 23.4% trucks (Table 5). Over the road's life cycle, the vehicle operational energy totaled 4,090,800 GJ. This figure was constant for each of the different road types.

The energy embodied in the vehicles was another factor in the life-cycle energy use attributable to road activities (Table 6). For a typical car costing $30,000, the initial embodied energy was found to be 272 GJ, while a typical truck costing $120,000 was calculated to have an embodied energy value of 1,088 GJ. For the projected road life cycle, the initial energy embodied in vehicles was amortized annually over 15 years for cars and 18 years for trucks, resulting in a figure of 1,087,751 GJ for the 40 year road life cycle. These figures were equivalent for each of the different road types.

A further factor associated with the use of cars was the energy embodied in the maintenance of vehicles. Assumptions for a typical car are given in Table 7. Similar values were assumed for trucks, pro rata by price. Totaling only 15,190 GJ in the first year,

Table 5. Calculation of Vehicle Operational Energy

Calculation step	Car	Truck	Total
Number of vehicle trips per day for 5 km stretch of road	9,000	1,000	10,000
Assumed average vehicle primary energy efficiency (GJ/100 km)	0.476	1.311	na[a]
Total primary energy per day (GJ/day)	214	66	280
Total annual primary energy (GJ/annum)	78,164	24,107	102,270
Total primary energy over road life (40 years)	3,126,560	964,280	4,090,800

Note: Values may not sum due to rounding.

[a]Not applicable.

Table 6. Input-Output Analysis for Vehicles

Calculation step	Car	Truck
Assumed average price of new vehicle (**A**)	30,000 dollars[a]	120,000 dollars[a]
Embodied energy rate for the "motor vehicles and parts; other transport equipment" sector [from input-output model developed by Treloar (1998)] (GJ/dollars 100) (**B**)	0.9065	0.9065
Vehicle-embodied energy (GJ) (**A**×**B**/100)=(**C**)	272	1,088
Number of vehicles per day (**D**)	9,000[c]	1,000[c]
Assumed total kilometers per day for vehicles (**E**)	30[a]	400[a]
Assumed vehicle life (years) (**F**)	15[b]	18[a]
Vehicle embodied energy expressed per annum (GJ; i.e., initial embodied energy is amortized over life cycle) (**C**×**D**/**E**×5/**F**)	27,194	755
40 year total	1,087,751	30,215

Note: Values may not sum due to rounding. Assume daily commuters only (i.e., 5 days).

[a]Assumed.

[b]Parikh et al. (1995).

[c]Porter and Tinni (1993).

this factor grew annually to 609,600 GJ over the 40 year road life cycle. Again, these figures were equivalent for each of the different road types.

The elements of the life-cycle energy attributable to the road are depicted in Fig. 3. The relative importance of the various elements changed considerably over the 40 year life cycle. In the first year, the life-cycle energy comprised

- 64% vehicle manufacture (not amortized annually),
- 21% road construction (for Road Type CRC), and
- 15% vehicle operation.

At the end of the simulated 40 year life cycle, the total of 6,571,635 GJ for Road Type CRC comprised

- 62% vehicle operation (initially third),
- 28% vehicle manufacture and maintenance (initially first), and
- 10% road construction and maintenance at 4% (initially second).

Initially, the most important phase of road use was the manufacture of vehicles. Energy-related emissions are the major component of environmental loadings attributable to vehicle manufacture and operation (Parikh et al. 1995). The embodied energy of a typical Australian car has been previously estimated to be between 221 and 273 GJ per car, using process-based hybrid analysis and pure input-output analysis, respectively (Parikh et al. 1995). The pure input-output result of Parikh et al. (1995) is similar to findings presented in this paper being only 0.3% higher.

Over the simulated 40 year life cycle, vehicle operation was the most important phase in life-cycle energy terms. Since the values were derived in primary energy terms, greenhouse gas emissions can be easily calculated using an average emission rate for fossil fuels of approximately 60 kg/GJ (in terms of CO_2 equivalent). This, however, would not include nonenergy greenhouse gas emissions, such as those from cement production (which are similar in magnitude to the energy-related emissions). The life-cycle phase "demolition" was not considered because

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Table 7. Life-Cycle Energy Use Associated with Car Maintenance

Category	Price (dollars) (**A**)	Australian sector (total energy intensity, GJ/dollars 100) (**B**)	Annual embodied energy (GJ) (**A**×**B**/100=**C**)	Life-cycle energy (GJ, over 15 years) (**C**×15)
Registration	410	Government administration (0.9298)	3.8	57.0
Tires	250	Rubber products (0.7449)	1.9	28.5
Servicing	500	Mechanical repairs (0.3400)	1.7	25.5
Insurance	500	Insurance (0.2526)	1.3	19.5
Interest	1,482	Banking (0.2984)	4.4[a]	17.6[a]
[Total per car]	—	—	9.8	148.1

Note: Values may not sum due to rounding.

[a]The annual interest payment was only applied for the first 4 years of car life.

existing rural roads are rarely demolished; they are most often maintained indefinitely into the future.

The road type with the lowest life-cycle energy, not including the life-cycle energy associated with vehicles, was ''granular.'' This road type, however, may not stand up well to marginal increases in truck traffic—a major determinant of road maintenance requirements—over time (Porter and Tinni 1993). Other road types found to have low life-cycle embodied energy may also have differential performance. The road type with the highest life-cycle energy, not including the life-cycle energy associated with vehicles, was ''full-depth asphalt,'' which is apparently quite common in Australia. Further research could identify implementation actions for selecting a road design that has lower life-cycle energy implications, but with equal or greater life-cycle performance in terms of the resistance to marginal increases in truck traffic. A broader hybrid LCA, considering environmental implications other than energy (for example, the environmental effects of construction waste), may result in the identification of a road design that may also reduce other environmental loadings and impacts. Performance characteristics and features that increase car efficiency and road safety would also need to be considered.

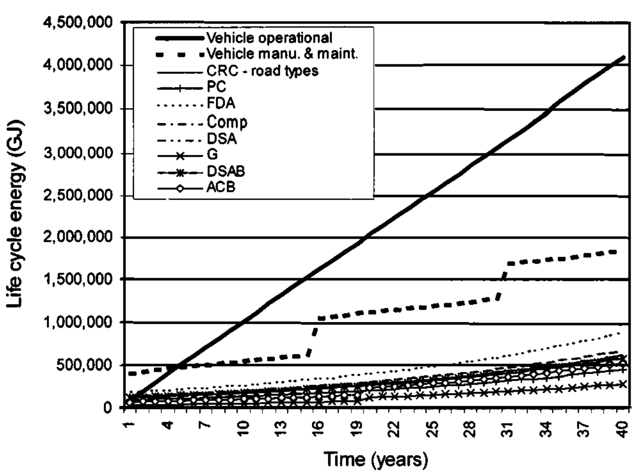

Fig. 3. Life-cycle energy attributable to road construction and use. The step jumps in the line for vehicle manufacture and maintenance represent complete vehicle replacement at 15 year intervals. Increases in road life-cycle energy are due to the energy embodied in materials used for maintenance. Continuously reinforced concrete, CRC; full-depth asphalt, FDA; deep-strength asphalt, DSA; deep-strength asphalt on bounded subbase, DSAB; plain concrete, PC; composite, asphalt, and concrete, Comp; granular, G; and asphaltic concrete on bounded subbase, ACB.

Conclusion

This paper suggests that the development of LCAs for road construction should focus on a hybrid approach, which uses national statistics to fill in those gaps not accounted for by conventional LCA data. Despite that the road construction was found to be small in embodied energy terms, the manufacture of vehicles was quite significant compared to the operational energy of the vehicles using the road. By adopting this approach, the writers argue that a more reliable comparison of products and systems can be undertaken more rapidly, and more strategically, which can more effectively support designers and engineers in their decision making. Similarly, the operational impacts can also be examined more effectively in a complete life-cycle context. Implementation actions for energy efficiency and conservation from the operational and construction/manufacture phases can be easily compared and prioritized.

References

Australian Bureau of Statistics (ABS). (1996a). ''Australian national accounts: Input-output tables.'' *Catalog No. 5209.0*, Canberra, Australia.

Australian Bureau of Statistics (ABS). (1996b). ''Australian national accounts: Input-output tables commodity details.'' *Catalog No. 5215.0*, Canberra, Australia.

Ballinger, J., Prasad, D., Lawson, B., Samuels, R., and Lyons, P. (1995). ''R & D of current environmental technologies in Australia.'' *Proc., Pan Pacific Symp. on Building and Urban Environmental Conditioning in Asia*.

Boustead, I., and Hancock, G. F. (1979). *Handbook of industrial energy analysis*, Ellis Horwood, Ltd., Chichester, England.

Cole, R. (1998). ''Emerging trends in building environmental assessment methods.'' *Build Res. Inf.,* 26(1), 3–16.

Finch, E. (1992). ''Environmental assessment of construction projects.'' *Constr. Manage. Econom.,* 10, 5–18.

Häkkinen, T. (1994). ''Environmental impact of building materials.'' Technical Research Centre of Finland (VTT), Espoo, Finland.

International Federation of Institutes for Advanced Study (IFIAS). (1974). ''Energy analysis workshop on methodology and convention.'' *Workshop Rep. No. 6*, Stockholm, Sweden.

Parikh, Y., Watson, H. C., and Charters, W. W. S. (1995). ''An overview of greenhouse emissions in the car's life cycle.'' *Proc., Int. Symp. on Energy, Environment and Economics,* E. J. Colville, ed., Univ. of Melbourne, Melbourne, Australia, 607–618.

Porter, K. F., and Tinni, A. (1993). ''Life cycle costing: Whole-of-life cost analysis for heavy duty pavements.'' *Rep. prepared for Australian Asphalt Pavement Association*, Statewide Roads Technical Management Ltd.

Suzuki, M., and Oka, T. (1998). ''Estimation of life-cycle energy consumption and CO_2 emissions of office buildings in Japan.'' *Energy*

J. Constr. Eng. Manage., 2004, 130(1): 43-49

Build., 28, 33–41.
Treloar, G. (1996). *The environmental impact of construction: A case study*, Australia and New Zealand Architectural Science Association, Sydney, Australia.
Treloar, G. J. (1997). ''Extracting embodied energy paths from input-output tables: Towards an input-output-based hybrid energy analysis method.'' *Econ. Sys. Res.*, 9(4), 375–391.
Treloar, G. J. (1998). ''A comprehensive embodied energy analysis framework.'' PhD thesis, Deakin Univ., Geelong, Australia.
Treloar, G. J., Love, P. E. D., and Holt, G. (2001). ''Using national input-output data for embodied energy analysis of individual residential buildings.'' *Constr. Manage. Econom.*, 19, 49–61.
Treloar, G. J., Love, P. E. D., Iyer-Raniga, U., and Faniran, O. O. (2000). ''A hybrid LCA method for construction.'' *Constr. Manage. Econom.*, 18, 5–9.
Zhang, Z. Y., Shen, L. Y., Love, P. E. D., and Treloar, G. (2000). ''A framework for implementing ISO 14000 in construction.'' *Environmental Management and Health*, 11(2), 139–148.

J. Constr. Eng. Manage., 2004, 130(1): 43-49