A Life-Cycle Analysis Model and Decision-Support Tool for Selecting Recycled Versus Virgin Materials for Highway Applications

Final Report for RMRC Research Project No. 23

Prepared for the RMRC
by

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Acronyms

AC – Asphalt concrete

CARB – California Air Resources Board

EIO-LCA - Economic input-output life-cycle assessment

EPA – Environmental Protection Agency

FIRE - Factor Information Retrieval

HTP – Human toxic potential

LCA - Life-cycle assessment

NIOSH - National Institute for Occupational Safety and Health

PAH - Polycyclic aromatic hydrocarbons

PaLATE - Pavement Life-cycle Assessment Tool for Environmental and Economic Effects

PCC – Portland cement concrete

RAP – Recycled asphalt pavement

RCM – Reclaimed concrete materials

RCRA - Resource Conservation and Recovery Act

RMRC – Recycled Materials Resource Center, University of New Hampshire

S-PAC - Sulfur-polycyclic aromatic compounds

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1. Background

The objective of this project was the development of a life-cycle assessment (LCA) framework and computer-based tool, which draws on environmental and economic parameters, and assists decision-makers in evaluating the use of recycled materials in highway construction and maintenance activities. The initial proposal suggested a list of tasks, and significant progress has been accomplished in each one.

Task 1. Develop a model of economic costs of using traditional highway materials.
Task 2. Develop a model of economic costs of using recycled materials for highway applications.
Task 3. Develop a model of environmental effects of using traditional highway materials.
Task 4. Develop a model of environmental effects of using recycled materials for highway applications.
Task 5. Develop a computer-based decision-support tool.

This report is organized according to the same division. Initially the report presents an overview of the tool. Next, the tool structure is introduced followed by a discussion of the environmental module, and a discussion of the economic module. The tool allows the comparison of traditional materials and secondary materials for road construction, and includes information on maintenance, recycling, and construction technologies. The final version of the model is highly comprehensive, but it is also amenable to future additions and expansions.

2. Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE)

The Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) utilizes a life-cycle assessment framework that draws on engineering, environmental, and economic information and data to evaluate the use of virgin and recycled materials in the construction and maintenance of pavements that use different percentages of virgin and recycled materials in the subgrade/subbase and wearing course layers. The tool takes user input for the design, initial construction, maintenance, equipment use, and costs of a roadway, and characterizes the life-cycle environmental effects and costs of a given project.

PaLATE is designed to assist decision-makers in evaluating the use of recycled materials in highway construction applications. It is implemented in MS Excel to provide a platform that is commonly found on any potential user’s desktop, and a software environment that is amenable to future changes and additions not just by the developers, but also by potential users. Calculations in the various modules are intended to be transparent, and formatting features enhance the user interface.

The tool takes the user through a series of input worksheets to gather information about:

- general design of the roadway
- initial construction materials as well as material transportation distances and modes
- maintenance materials, their respective transportation distances, and modes
- technology choices – e.g., on-site construction and maintenance equipment (e.g., asphalt paver), and off-site processing equipment (e.g., rock crusher)
- life-cycle economic costs
- period of analysis
- discount rate

PaLATE users may enter data about an existing, proposed, or hypothetical roadway to determine the environmental and economic effects of their decisions. Some example questions that the user may keep in mind when working with PaLATE are:

- For a particular roadway, which material is better for the environment: concrete or asphalt?
- Will changing the recycled material content in a particular pavement affect its environmental performance?
- Does sending demolished portions of a road to a processing plant or to a landfill make more environmental and economic sense?
- Which maintenance option(s) will minimize environmental and economic effects? For example, should full depth reclamation be performed instead of more frequent, smaller maintenance procedures?

- Will changing the type and/or capacity of equipment used on-site affect emissions?
- How much of a difference do materials transportation distance and mode make for a case study? For example, should materials from a local source be used to reduce emissions? Is it better to transport via rail or truck?

2.1 Modeling

PaLATE is built on extensive data collection, analysis, and modeling efforts at the initial stages of this research project. It uses the state-of-art LCA model, and it is a robust yet flexible modeling framework. Robustness is achieved through the inclusion of all relevant roadway engineering factors coupled to the most significant environmental variables known today. Flexibility is achieved through the design of the model and transparency of the programming and user interface.

Not just variables! While one intention with creating PaLATE was to provide a modeling framework that is independent of current or past technology and information that may become obsolete quickly, we have achieved to incorporate not just the crucial variables of the model, but also information and data that are as comprehensive as possible, as well as current and relevant. Our literature surveys have been incorporated into the determination of the actual values for the variables of the model. We provided default values for most of the variables in the model, but we left it open to the users to add their own numbers if they deem them more accurate or relevant than those provided by PaLATE.

2.2 Audience

PaLATE targets primarily pavement designers and engineers, transportation agency decision-makers, civil engineers, and researchers. Users should have a working knowledge of pavements and a desire to learn more about the environmental and economic implications of their choices.

2.3 User Interface

We have included with PaLATE a set of instructions that describes all modules of the software and details their use. Every step in the software is integrated with a help file. User input is needed on many variables, decisions need to be made many times during the software use, but this is the price of being comprehensive. The user is required to have familiarity with pavement construction activities in order to go through the set of options required in the analysis. However, the degree to which the user interacts with PaLATE varies, e.g., the tool provides a set of default parameters that may or may not be accepted by the analyst.

Web site: A dedicated web site explains the tool, its potentials, its structure, and its applications: www.ce.berkeley.edu/~horvath/palate.html.

2.4 Tool Structure

PaLATE uses an LCA approach to model the environmental effects of road initial construction and maintenance. The user defines the design of the pavement, which results in a given type and volume of construction materials and its source (hauling distance), a given combination of construction activities, and a set of prescribed maintenance activities. The framework comprises the major phases of the pavement (Figure 1).

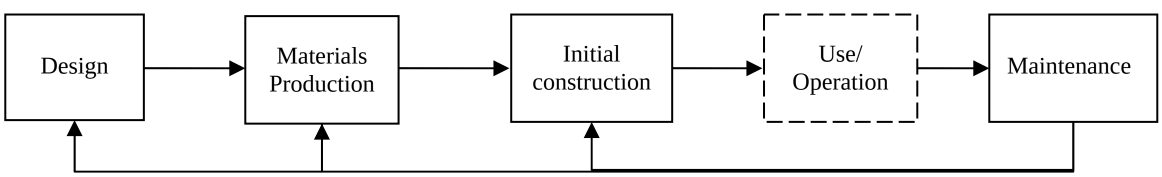

Figure 1: Life-cycle Phases of Pavements

Figure 1 implicitly represents the idea of perpetual pavements because there is limited end-of-life for roadways and its materials. That is, the maintenance box may represent major reconstructions of a road section that replaces the previous structure in that place. However, if part of the material is recycled and reused in the new structure, a part may also end up in a landfill. That is, pavements may be perpetual but the materials used in construction are not.

The first module in the spreadsheet is the design module where the user defines the dimensions of each layer, the density of the construction materials, and the period of analysis (Figure 2). The period of analysis is used for discounting purposes as part of the economic assessment. The volume of the layers combined with the density of the materials calculates the mass of each material, which is used to determine the regime of operation of the construction equipment.

Layer Specifications				
Layer	Width [ft]	Length [miles]	Depth [inches]	Volume [yd^3]
Wearing Course 1	24	1	3	1,173
Wearing Course 2	25	1	7	2,852
Wearing Course 3				0
Subbase 1	28	1	24	10,951
Subbase 2				0
Subbase 3				0
Subbase 4				0
Total			34	14,976

Period of Analysis [yrs] (40 yrs or less)	**40**

Material	Density [tons/(yd^3)]
Asphalt mix	1.78
Ready-mix concrete	1.79
Virgin Aggregate	1.8
Bitumen	1.81
Cement	1.83
Concrete Additives	1.84
Asphalt emulsion	1.00
RAP	1.85
RCM	1.88
Coal Fly Ash	1.89
Coal Bottom Ash	1.9
Blast Furnace Slag	1.91
Recycled Tires/ Crumb Rubber	1.92
Glass Cullet	1.93
Water	1
Steel Reinforcing Bars	1.94
Rock	1.95
Gravel	1.96
Sand	1.97
Soil	1.98

Figure 2: User Inputs in the Design Module

Environmental effects of using recycled materials depend on the characteristics of the equipment used to recover the materials, and the hauling of materials between processing facilities and the construction site. Energy use and air emissions are based on typical productivity, fuel consumption rate, and the engine size of the equipment used in each recycling activity. PaLATE allows for the selection of different equipment brand/models amongst the ones used in the various recycling activities (Figure 3). Besides the equipment used at the construction site, the tool includes choices for larger fixed equipment such as crushing and asphalt plants. The analyst is encouraged to enter his/her own values and/or equipment type for a given task whenever the default values are not adequate.

ACTIVITY	Equipment	Brand/Model	Engine Capacity	Productivity	Fuel Consumption	Fuel Type
Cold in Place Recycling	CIR recycler	Ingersol rand DD110	800 hp	1,713 tons/h	150.00 l/h	diesel
	Pneumatic roller	Dynapac CP134	100 hp	884 tons/h	25.1 l/h	diesel
	Tandem roller	Ingersol rand DD110	125 hp	285 tons/h	32.7 l/h	diesel
Full Depth Reclamation	Asphalt road reclaimer	Wirtgen WR 2500 S	670 hp	4,800 tons/h	120.0 l/h	diesel
	Vibratory soil compactor	Dynapac CA 262D	150 hp	1,832 tons/h	37.6 l/h	diesel
Hot In Place Recycling	Heating machine	Wirtgen HM4500	49 hp	256 tons/h	9.1 l/h	diesel
	Asphalt remixer	Wirtgen 4500	295 hp	208 tons/h	55.0 l/h	diesel
	Pneumatic roller	Dynapac CP132	100 hp	668 tons/h	26.1 l/h	diesel
	Tandem roller	Ingersol rand DD110	125 hp	285 tons/h	32.7 l/h	diesel
Rubblization	Multi head breaker	Badger MHB Breaker	350 hp	520 tons/h	76.5 l/h	diesel
	Vibratory soil compactor	Dynapac CA 262D	150 hp	1,832 tons/h	37.6 l/h	diesel
Milling	Milling machine	Wirtgen W1900/60	400 hp	300 tons/h	87.4 l/h	diesel
Concrete Demolition	Multi head breaker	Badger MHB Breaker	350 hp	520 tons/h	76.5 l/h	diesel
	Wheel loader	John Deere 624E	135 hp	360 tons/h	35.3 l/h	diesel
Crushing Plant	Excavator	John Deere 690E	131 hp	225 tons/h	34.2 l/h	diesel
	Wheel loader	John Deere 624E	135 hp	225 tons/h	35.3 l/h	diesel
	Dozer	Caterpillar D8N	285 hp	225 tons/h	71.4 l/h	diesel
	Generator	John Deere 624E	519 hp	225 tons/h	98.4 l/h	diesel
Excavation, placing and compaction	Excavator	John Deere 690E	131 hp	315 tons/h	34.2 l/h	diesel
	Vibratory soil compactor	Ingersoll-Rand SD100D	125 hp	285 tons/h	32.7 l/h	diesel
Tire Recycling	Shredder + Granulator + Classifier + Aspirator System	Wendt Corporation	630 hp	3.00 tons/h	104.73 kWh/ton	electric
Glass Recycling	Hopper + Conveyor + Shredder System	Andela GP-05 Pulverizer	10 hp	1.00 tons/h	7.46 kWh/ton	electric
HMA Production	asphalt mixer	Uncontrolled Batch-mix		226.80 tons/h		oil

Figure 3: Equipment Details in PaLATE

Productivity values for the equipment used in the various activities and processes modeled by PaLATE were obtained from equipment manufacturers, and it is possible that actual values differ from the ones represented in the tool.

Hauling distances are key factors for the environmental effects arising from the use of recycled materials. PaLATE requires the analyst to identify the transportation mode and distances associated with every material used in the construction and maintenance activities. The selection of a given transportation mode combined with fuel efficiency and emission factors are used to calculate the environmental effects from materials transport.

PaLATE reports environmental effects disaggregated by initial construction and maintenance phases and by material production, transport, and processing. Figure 4 shows a graph from the environmental results worksheet of PaLATE featuring NO_x life-cycle emissions based on a case study.

The use phase of the road is not modeled by PaLATE. Currently, there are detailed traffic/technology-driven models that calculate user emissions such as the MOBILE 6.2 model from EPA that can be used to assess tailpipe emissions during the use phase of roads. But emissions from construction and maintenance activities require a distinct approach. PaLATE fills an important niche: it assesses pollution arising from construction and maintenance of pavements.

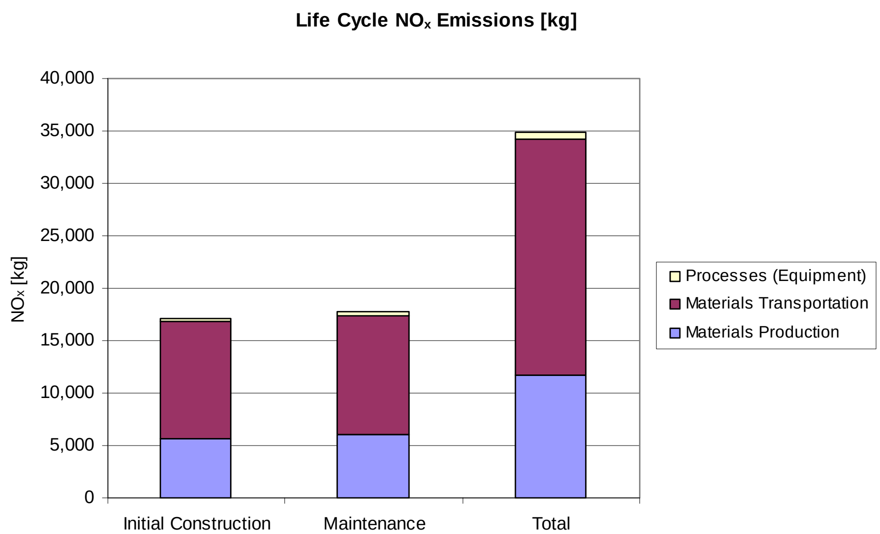

Figure 4: Life-cycle NO_x Emissions

2.5 Modeling Environmental Effects of Using Traditional Highway Materials Information

Different sources of information and analytical methods are used in PaLATE to characterize the environmental implications of alternative road construction projects.

The framework draws on two LCA procedures that capture impacts from every material and energy input during the service lives of civil engineering infrastructure, including raw materials extraction, manufacturing, on- and off-site construction, use, maintenance, and end-of-life. One is based on environmentally augmented economic input-output analysis (EIO-LCA), a Leontief general equilibrium model of the entire U.S. economy that has been used in a number of environmental and economic systems analyses [Pacca 2002, Hendrickson 1998]. The economy is divided into a square matrix of 480 commodity sectors. Each row and column represents a sector, and each cell represents the economic transactions in dollars between two respective sectors. Thus the matrix presents total sales from a sector to others, purchases from another sector or from the sector itself (circularity effects in the economy) to produce a dollar of output. The economic model is augmented by a number of environmental vectors in order to quantify energy (petroleum distillates, electricity, coal) and material (ore, fertilizer) and water inputs, as well as emissions (greenhouse gas, toxic, ozone depleting chemical, water) and wastes (hazardous). Input-output modeling is linear, so the effects of a $1,000 purchase from a sector are ten times larger than the effects of a $100 purchase from the same sector. Because EIO-LCA emission factors are available in metric tons per dollar of sector output, the present framework uses average U.S. producer prices in $/metric ton for each material (from [Means 1997] and other sources) in order to calculate emissions per mass of material used.

The tool calculates cumulative environmental effects such as:

- energy consumption
- water consumption
- CO_2 emissions
- NO_x emissions
- PM_{10} emissions
- SO_2 emissions
- CO emissions
- Lead emissions
- Mercury emissions
- Potential leachates
- RCRA hazardous waste generated
- Human Toxicity Potential (cancer and non-cancer)

Concurrently with assessing the environmental impacts of traditional and recycled materials, we have been working on assessing the uncertainty of the results and findings. The first step in this process was to catalogue the potential challenges of using the LCA method. Figure 5 shows sources of problems in LCA-based analyses.

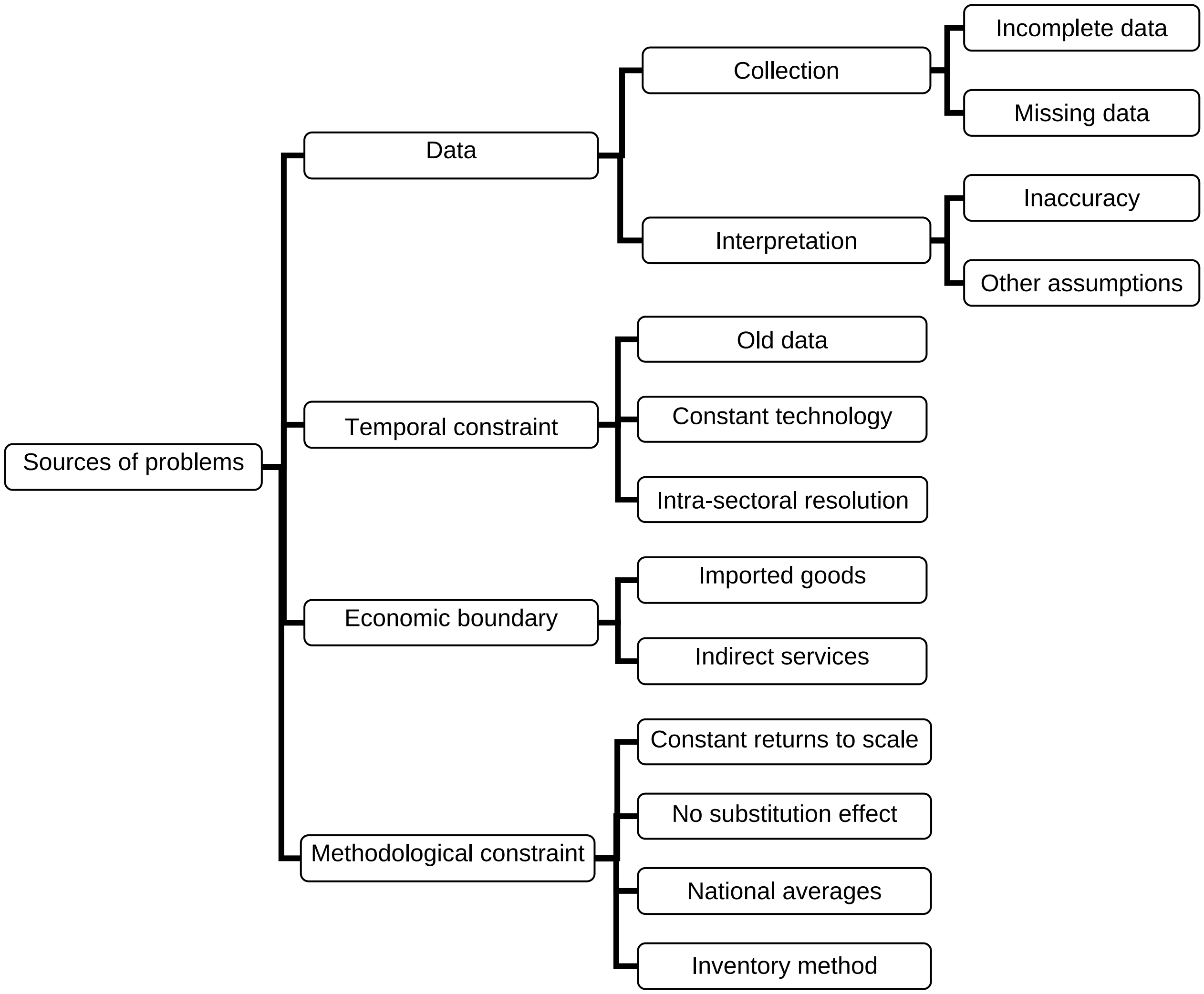

Figure 5: Assessing uncertainty in results due to LCA [Pacca 2002].

The EIO-LCA database is a source for several emission factors associated with material production. However, other sources are used for assessing environmental implications of other life cycle phases.

We have not found publications on the environmental effects of the different maintenance activities. Preliminary results of our research on various asphalt recycling technologies (cold in-place, hot in-place surfacing, hot in-place repaving, hot in-place remixing, and hot mix asphalt overlay) are presented in Table 1.

Maintenance Options	PARAMETERS					TOTAL EMISSIONS (g/m^2)					ANNUALIZED EMISSIONS (g/m^2/year)				
	Treated Depth (mm)	Overlay Depth (mm)	Emulsion Amount (% wght)	Serviceability (years)	Cost ($/m^2)	CO_2	NO_x	SO_2	PM-10	TOC	CO_2	NO_x	SO_2	PM-10	TOC
CIR	101.6	50.8	1.5	10	3.09	23,599	16	4	6	4	2,360	2	0	1	0
HIR-Surfacing	25.0			5		172	5	0.30	0.32	0.4	34	1	0.06	0.06	0.07
HIR-Repaving	25.0	25.0		8	4.28	11,695	10.1	2.0	3.1	2.1	1,462	1.3	0.3	0.4	0.3
HIR-Remixing	40.0	19.0		8	3.58	8,964	7.9	1.6	2.4	1.6	1,121	1.0	0.2	0.3	0.2
HMA-Overlay		25.0		6		12,323	27.1	3.2	4.3	3.5	2,054	4.5	0.5	0.7	0.6

Table 1. Comparison of Different Maintenance Options for Asphalt Pavements

PaLATE uses an alternative approach for assessing impacts from pavements construction and maintenance, which is based on the productivity and environmental implications caused by different types of equipment and materials.

A database that served as an information source for PaLATE was EPA’s Factor Information REtrieval (FIRE)[1]. FIRE is a database containing EPA’s recommended emission estimation factors for criteria and hazardous air pollutants. Using data from FIRE, emissions of particulate matter with a diameter smaller than 10 µm (PM_{10}) from loading and unloading trucks, as well as emissions of PM_{10} from transport, which are not fuel related, have been included in PaLATE.

PaLATE calculates PM_{10} emissions for aggregates unloading from trucks during the initial construction and maintenance phases. In addition, calculations for truck loading are carried out for initial construction and maintenance for the following materials:

- Virgin aggregates
- RAP transportation
- RCM from concrete plant

[1] http://www.epa.gov/ttn/chief/software/fire/

For the initial construction and maintenance phases, PaLATE calculates PM_{10} emissions from truck loading and truck unloading for the following activities:

- RAP to recycling plant
- RAP from recycling plant to site (crushing)
- RCM to recycling plant
- RCM from recycling plant to site
- RAP from site to landfill
- RCM from site to landfill

Hauling distances are key factors for the environmental effects arising from the use of recycled materials. PaLATE requires the analyst to identify the transportation mode and the distances associated with every material. In addition to emissions from fuel combustion, emissions of PM_{10} due to truck hauling are assessed as well. Most particles in this case are generated due to the friction between the truck wheels and the pavement. Therefore, independently of the material hauled, particles are always produced and included in the assessment. The emission factor used assumes average values and 90% of control.[2]

In addition to particles produced due to fuel combustion, which are calculated using EPA's AP-42 and CARB's offroad emissions model, other emissions are also part of the material production phase. In the case of sand and gravel production, the following emission factors from FIRE were aggregated and included:

- aggregate storage - construction sand and gravel
- material transfer and conveying - construction sand and gravel
- pile forming stacker - construction sand and gravel
- bulk loading - construction sand and gravel
- screening - construction sand and gravel

PaLATE includes health effects such as potential impacts of asphalt fumes. Such assessment is based on information collected at the National Institute for Occupational Safety and Health (NIOSH). NIOSH published a series of reports on emissions of asphalt fumes.[3] The reports contain emission factors and exposure estimates for the major air releases from asphalt storage and

[2] Department of Natural Resources. Bureau of Air Management. Nonmetallic Mining Guidance for the Development of the 1998 Air Emissions Inventory. Publication #: PUBL-AM-268-98. January 1998. Department of Natural Resources. Bureau of Air Management. State of Wisconsin. Madison, WI.
[3] http://www.cdc.gov/niosh/topics/asphalt/

handling. Fumes produced during asphalt paving are peculiar because higher temperatures increase the chemical complexity of the material, thus affecting the toxic releases. The way in which asphalt is handled affects the amount of emissions generated. Asphalt fumes collected during paving are reported in Table 2. Some polycyclic aromatic hydrocarbons (PAH) such as benz[a]anthracene and chrysene are known carcinogens, and some sulfur-polycyclic aromatic compounds (S-PAC) may cause mutations.

	Tank fumes	Laboratory fumes	
	at 149 °C	149 °C	316 °C
Naphthalene	2.1	1.6	0.1
Acenaphthene	0.12	0.03	—
Fluorene	0.12	0.22	0.09
Phenanthrene	0.15	0.47	0.27
Anthracene	0.13	0.46	0.03
Fluoranthene	—	0.02	—
Pyrene	—	0.03	0.07
Chrysene	—	0.02	—
Benz[a]anthracene and chrysene	—	—	0.11
Methyl naphthalenes	4.90	5.2	0.4
Methyl fluorenes	0.17	0.36	0.16
Methyl phenanthrenes and anthracenes	0.22	1	1.4
Methyl pyrenes or fluoranthenes	—	—	0.15
Methyl chrysenes	—	—	0.11
Dibenzothiophene	0.09	0.57	0.24
Methyl dibenzothiophenes	0.15	1.1	0.72
“C2" alkyl dibenzothiophenes	0.17	1.3	1.1
“C3" alkyl dibenzothiophenes	0.1	0.88	0.85
Benzo[a]naphthothiophenes	—	0.03	0.12
Methyl benzo[b]naphthothiophenes	—	0.06	0.33
“C2" alkyl benzo[b]naphthothiophenes	—	0.04	0.35
“C3" alkyl benzo[b]naphthothiophenes	—	0.03	0.37

Table 2: Chemical analysis of storage tank and laboratory generated paving asphalt fume condensates, mg/ml per sample (Ref 3).

Another experiment measured the concentration of PAH in the breathing zone of pavers and manual workers. In order to have a control category, similar measurements were repeated in an office where the compounds have not been detected. PAHs were identified in less than 6% of the breathing zone of paving crew (Table 3).

PAH and number of rings	manual workers	pavers 1	pavers 2
Naphthalene (2)	90	84	88
Acenaphthene (3)	5	8	4
Phenanthrene (3)	3	7	7
Pyrene (4)	<1	<1	<1
Benz[a]anthracene (4)	<1	<1	<1
Benzo[b and k]fluoranthene (5)	<1	<1	<1
B(a)P (5)	<1	<1	<1
Dibenz[a,h]anthracene (5)	<1	<1	<1

Table 3: Median percentage of time-weighted average (TWA) concentrations of nine PAHs determined in personal-breathing-zone samples (Ref 3).

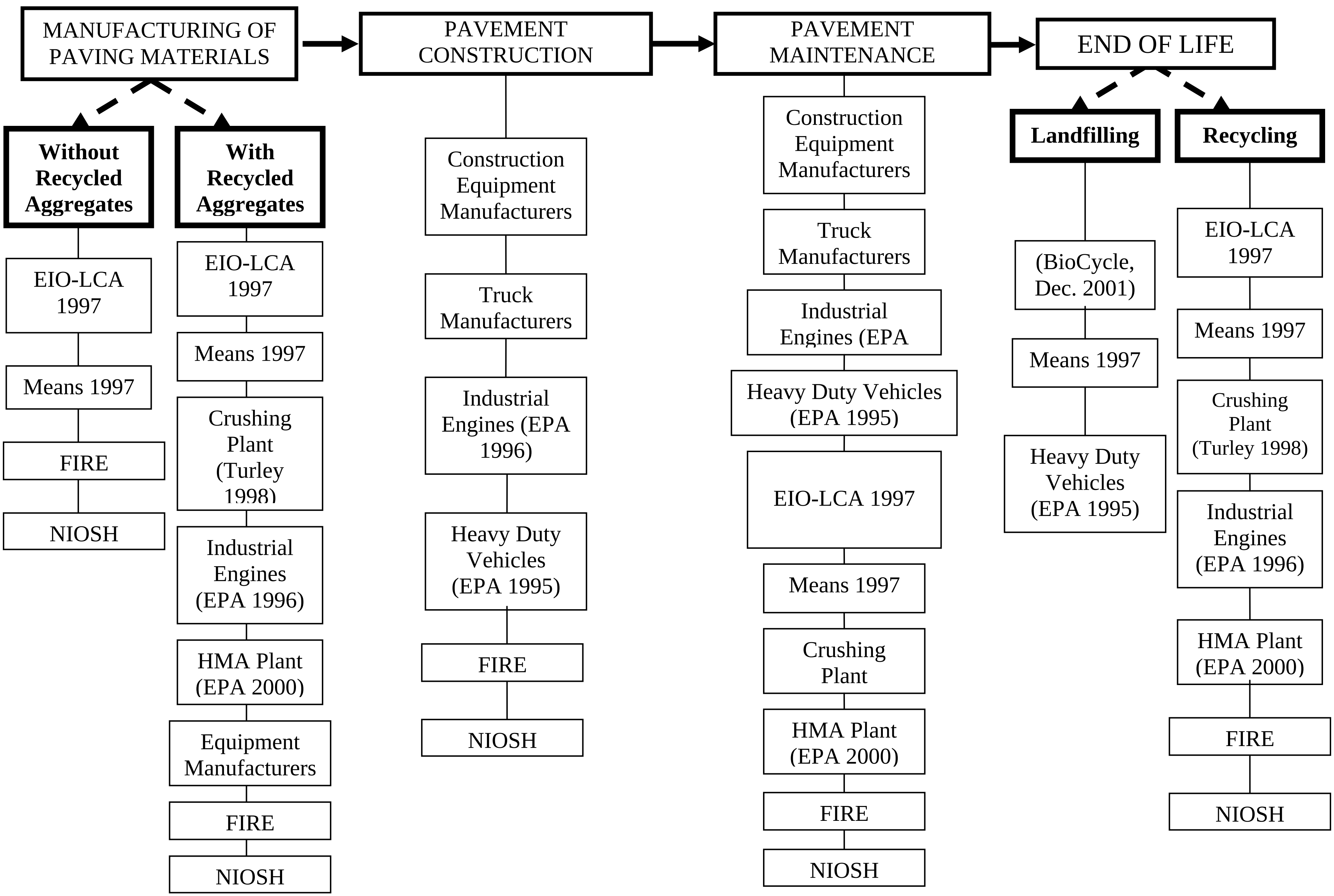

Figure 6 summarizes various sources of information for the air emission calculations in the LCA of pavements.

2.6 Modeling of Environmental Effects of Using Recycled Materials for Highway Applications

Aggregates constitute an important input into the production of pavements. About 95% by weight of asphalt concrete (AC) are aggregates, whereas 87% of portland cement concrete (PCC) by weight are aggregates [Wilburn 1998].

The use of reclaimed asphalt pavements (RAP) to substitute for virgin aggregates is a common practice in the U.S., and over 200 million metric tons are generated annually [USGS 2000]. Still, about 20% of all AC debris ends up in landfills and the rest is reused in AC pavements [Wilburn 1998]. PCC recycling is less typical and more than 50% of all debris is landfilled. Moreover, 85% of all debris that is recycled is used as road base, with minor amounts used in AC and fill material, which correspond to the initial use of the material [Wilburn 1998]. A survey indicated that the annual amount of substitution of crushed cement concrete for construction aggregates (95 million metric tons) is approximately 4.8% [Kelly 1998].

Figures 7 and 8 present a generic comparative energy demand for construction materials processing and transport:

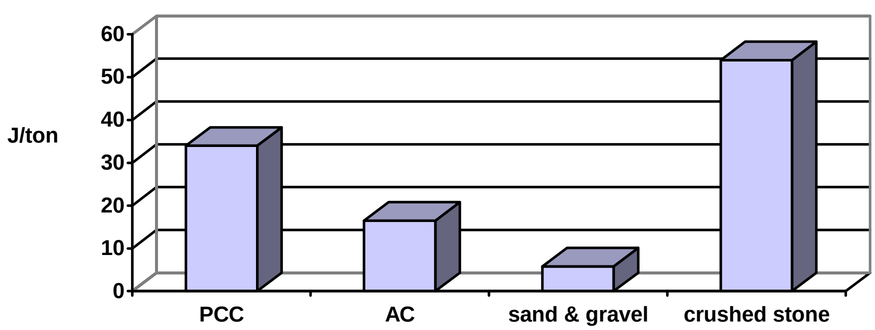

Figure 7: Processing Energy Demand for Road Construction Materials (electricity + fuel, excluding demolition and transportation) [Wilburn 1998]

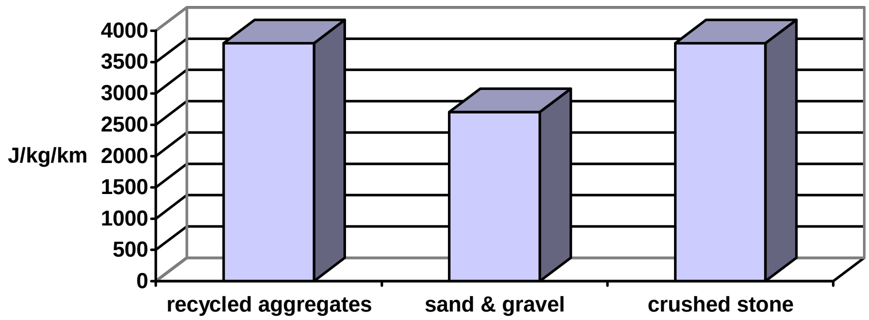

Figure 8: Energy Consumption for Road Construction Materials [Wilburn 1998]

Based on these data, crushed cement concrete requires the most energy of the four main choices for aggregate materials. The energy required for transporting sand and gravel is lower than that for recycled aggregates and crushed stone because of differences in the density. However, due to the significance of energy consumption during the transportation phase, it is fundamental to assess the local characteristics of each project.

Local conditions also affect the quality and use of aggregates. Therefore, it is important to consider the following characteristics when using recycled pavement materials [Dumitru 2003]:

- Limitations of recycled materials: variability in particle size/shape, contaminants, variability in quality, and failure to meet specifications
- Foreign materials
- Blending of recycled materials: durability and workability considerations
- Specifications
- Management of stockpiles: limit stockpile size to help ensure a consistent quality

The same sort of factors affect the economic feasibility of recycling as is presented in Figure 9, section 2.8. Besides the recycling of demolished pavement, PaLATE includes environmental and economic information on several industrial byproducts such as coal fly ash and bottom ash, blast furnace slag, glass, crumb rubber from tires, glass cullet, and foundry sand. The tool assesses the effect of choices and sensitivities of environmental and economic scenarios (e.g., use of a certain percent of fly ash in concrete in lieu of cement).

An extensive literature review has been done to characterize different industrial byproducts, which are relevant to the construction industry, and gather information to include in PaLATE. As an example, we show relevant information collected on foundry sand.

Every year 5.6 million metric tons of foundry sand are produced (Table 4). However, 2,300 foundries in the U.S. use 100 million tons of foundry sand, which is highly recycled within the industry [Hughes 2002a]. The sand that is potentially diverted to other uses, which can no longer be used to make molds, amounts to 2 to 15% of the total used in the sector. Such used foundry sand (UFS) volume is comparable to the apparent foundry sand consumption in Table 4.

		1998	**1999**	**2000**	**2001**	**2002[e]**
Industrial	Consumption, apparent	26,200	27,400	27,400	26,500	26,600
	Foudry sand apparent consumption[b]	5,502	5,754	5,754	5,565	5,586
	Price, average value, dollars per ton	18.19	18.64	19.58	20.64	20.2
Construction	Consumption, apparent[c]	1,070,000	1,110,000	1,120,000	1,130,000	1,130,000
	Price, average value, dollars per ton	4.57	4.73	4.81	5.02	5.14

[e] Estimated.
[b] About 21% of the U.S. tonnage was used as foundry sand.
[c] It is estimated that about 51% of the 1.13 billion metric tons of construction sand and gravel produced in 2002 was for unspecified uses. Of the remaining total, about 45% was used as concrete aggregates; 22% for road base and coverings and road stabilization; 13% as asphaltic concrete aggregates and other bituminous mixtures; 13% as construction fill; 2% for concrete products, such as blocks, bricks, pipes, etc.; 1% for plaster and gunite sands; and the remaining 4% for snow and ice control, railroad ballast, roofing granules, filtration, and other miscellaneous uses.

Table 4: Salient Statistics of Sand and Gravel in the U.S. (10^3 metric tons) [USGS 2003]

If all UFS is recycled in construction activities, that would account for only 0.5% of the total amount consumed by construction activities. In addition, the average value of construction sand in the U.S. is one quarter the average value of sand used by foundries. The use of UFS in construction activities has an enormous potential for diverting this industrial byproduct from landfills.

The use of UFS depends on the economic feasibility from processing and transporting the material plus the avoided disposal costs. Landfill tipping fees are estimated to be between $15-35 per ton or even higher in urban areas (see Table 11, section 2.8). A foundry company in Tennessee pays $4 per ton for brokering its UFS, and the price of the material needs to be competitive with the cost of traditional aggregates in the region [Hughes 2002b]. The average value of traditional aggregates in the U.S. is $5.14 per ton (Table 4). A tight profit margin demands low hauling costs to make the use of UFS competitive.

UFS can be used in road construction as filling material or as part of asphalt and concrete mixes. The use of UFS as a substitute for virgin aggregates in hot mix asphalt (HMA) has been proven, and states such as Pennsylvania, Michigan, and Tennessee allow such practice [Hughes 2002b].

Parameter	**ASTM[a]**	**Sand 1**	**Sand 2**	**Sand 3**
As received moisture content (%)	C 566	0.39	0.19	0.25
Unit weight (kg/m3)	R 29	1,840	1,730	1,784
Bulk specific gravity	C 128	2.43	2.38	2.44
Bulk specific gravity, SSD	C 128	2.47	2.50	2.57
Apparent specific gravity	C 128	2.52	2.70	2.79
SSD absorption (%)	C 128	1.00	4.90	5.00
Void (%)	C 29	25.00	33.80	34.80
Fineness modulus	C 136	3.57	2.33	2.32
Clay lumps and friable particles (%)	C 136	0.20	0.10	0.40
Soundness of aggregates (%)	C 88	10.00	10.50	54.90
Material finer than #200 (75 mm) sieve	C 117	1.40	0.17	1.08

Note: Sand 1 = regular concrete sand; Sand 2 = clean foundry sand (FS1); Sand 3 = used foundry sand (FS2).
[a]American Society for Testing and Materials (ASTM)

Table 5: Physical Properties of Sand [Naik 2001]

Despite presenting characteristics comparable to virgin sand (Table 5), USF is not a homogeneous material because it is collected at different places. Various processes in the foundry industry produce foundry sand. While casting forms produce a coarser product, baghouses, used to retain particles from exhaust air flows, produce much finer particles, which have the potential to reach the lungs, and cause serious health implications.

The use of foundry sand is constrained by its health and environmental implications. There are two basic concerns with the use of foundry sand in construction. First, foundry sand may be a source of air pollution [Afzal 2002]. Second foundry sand leacheates may contaminate watersheds with toxic materials [Tikalsky 2001, Naik 2001, Morse 2003]. This information is included in PaLATE.

An assessment of worker exposure from pavements constructed using foundry sand was carried out to check worker exposure to pollution. Because foundry sand is composed mainly of silica, there were concerns that it would be a precursor for silicosis and lung cancer [Afzal 2002]. Even if a preliminary health assessment was not conclusive, some management practices are recommended to reduce worker exposure to UFS fine suspended particles:

- Implementing a standard calling for the elimination of baghouse residues in UFS
- Wetting the material before its use,
- Wetting the material after its application and compaction,
- Using personal particles' collection devices to check workers exposure.

In addition, recent studies have published results from analyses of leachate properties of foundry sand. These studies are based on the Toxicity Characteristic Leaching Procedure (TCLP) used by EPA to estimate the amount of compounds that would leach if the material is placed in the landfill. Table 6 shows TCLP results for metals from 3 different references.

Parameter	Naik 2001	Tikalsky 2001	Morse 2003
Aluminum (Al)		0.74	2.017
Antimony (Sb)			0.00698
Arsenic (As)	0.001		<.025
Barium (Ba)	0.053	0.161	<2
Beryllium (Be)			0.00114
Cadmium (Cd)	0.0002	BDL	0.00146
Chlorides (CI)	3	1.7	
Chromium (Cr)	0.011	BDL	0.01187
Cobalt (Co)			<0.1
Copper (Cu)		BDL	<0.2
Fluoride (F)		0.1	
Iron (Fe)	0.93	0.3	
Lead (Pb)	0.015	BDL	0.01523
Magnesium (Mg)	0.01	2.225	0.12
Manganese (Mn)		0.012	
Mercury (Hg)	<0.0002	BDL	0.0127
Molybdenum (Mo)		BDL	0.06446
Nickel (Ni)		BDL	0.38355
Selenium (Se)	<0.001	BDL	0.1958
Silver (Ag)		BDL	<0.1
Sodium (Na)		7.84	<0.002
Sulfate (SO4)		5.2	<0.025
Vanadium (Va)		BDL	
Zinc (Zn)	0.03	0.044	0.236

BDL: below detection level

Table 6: Comparison of Results of Different Leachate Analyses (mg/l).

Besides metallic leachates, one reference also presents TCLP for other compounds (Table 7).

TCLP Property	number of tests	median value	90 Percentile	RCRA
Benzene	22	BDL	136	500
Carbon tetrachlorine	21	BDL	BDL	500
Chlorobenzene	21	BDL	BDL	100
Chloroform	22	BDL	BDL	6000
Cresol, meta	18	BDL	--	200000
Cresol, ortho	21	BDL	90	200000
Cresol, para	21	BDL	BDL	200000
Cresol, total	11	BDL	--	200000
Dichlorobenzene	21	BDL	BDL	7500
1, 2 - Dichloroethane	12	BDL	--	500
1, 2 - Dichloroethylene	12	BDL	--	700
Dinitrotoluene	21	BDL	BDL	130
Hexachloro - 1, 3 - butadienel	21	BDL	BDL	500
Hexachlorobenzene	21	BDL	BDL	130
Hexachloroethene	21	BDL	BDL	3000
Methyl ethyl ketone	22	BDL	2080	200000
Nitrobenzene	20	BDL	BDL	2000
Pentachlrophenol	21	BDL	BDL	100000
Pyridine	21	BDL	BDL	5000
Tetrachloroethylene	22	BDL	BDL	700
Trichloroethylene	21	BDL	--	500
Trichlorophenol (2,4,5)	21	BDL	BDL	400000
Trichlorophenol (2,4,6)	21	BDL	BDL	2000
Vinyl chloride	21	BDL	BDL	200

BDL: below detection level; RCRA: levels in the Resource Conservation and Recovery Act (RCRA)

Table 7: Summary of TCLP [Tikalsky 2001]

Results presented in Tables 6 and 7 are incorporated into PaLATE using the human toxicity potential (HTP) method. The HTP allows the comparison and aggregation of various releases from road construction and maintenance over different spatial and temporal scales. It expresses the potential harm of a unit of chemical released based on toxicity data coupled to generic source-to-dose relationships [McKone 1999]. The HTP assesses health impacts of both carcinogen and non-carcinogen compounds by normalizing emissions of different toxics to the effect of chemicals such as benzene (for carcinogens) and toluene (for non-carcinogens). The HTP converts toxic emissions from the transportation and construction phases in PaLATE into a common unit, and facilitates the judgment of analysts over different options and scenarios.

The same method is applied to emission factors from the EPA's FIRE database, and toxic releases from asphalt storage and handling.

The environmental modules of PaLATE represent an original contribution to the assessment of road construction projects. However, decision-making is mainly driven by economic appraisals. The next section deals with economic analyses of pavements.

2.7 Modeling of Economic Costs of Using Traditional Highway Materials

We have studied the life-cycle costing (LCC) framework for pavements. Based on literature review, we have found that LCC is still not the practice in every instance of decision-making about pavements. Decisions about whether to build asphalt or concrete pavements, how often to maintain them, and what maintenance technology to choose largely depend on first costs, experience of the local agencies, and local climatic conditions. We have not found nationally applicable, comprehensive, and robust models that would determine the life-cycle costs of using one pavement material versus the other. However, there are efforts to formalize LCC. For example, a comprehensive study has been published for Kansas [Cross 2002] that has described a regression-based model utilizing more than 30 years worth of first and maintenance cost data. Figure 9 shows that the model suggests somewhat higher costs for concrete pavements for the first 20 years of projects, and significantly different and increasing costs after about 20 years of usage of concrete pavements on the account of significantly higher maintenance needs than for asphalt pavements. Naturally, experiences in other states and municipalities may be quite different.

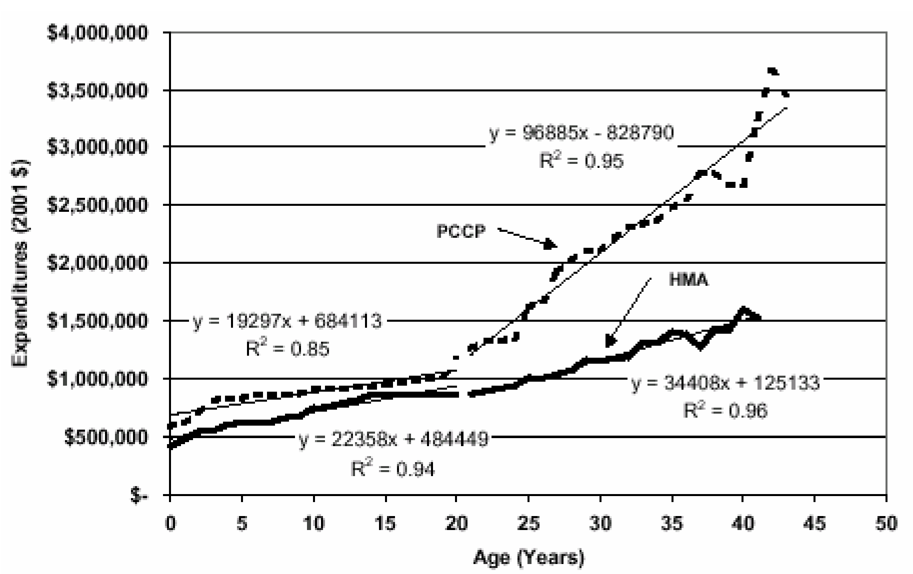

Figure 9: Average expenditures per 4-lane mile for rural interstate pavements in Kansas [Cross 2002].

PaLATE includes an LCC module. LCC frameworks for pavements combine the cost of the infrastructure, its maintenance, and salvage value (agency costs) with the cost of traffic delays, damage to vehicles, accidents, etc. (user cost). PaLATE has a module that calculates the net present value (NPV) of two pavement construction and maintenance alternatives and allows a comparison between two different discount rates. Because the periods selected by the analyst may differ, PaLATE also calculates the annualized cost for each of the alternatives.

The LCC framework integrated in PaLATE follows the recommendations of the Technical Bulletin of the Federal Highway Administration (Publication No. FHWA-SA-98-079). PaLATE suggests values surveyed in the literature for several items in the cost module (Tables 8, 9). Nevertheless, it encourages user inputs such as:

- Installed Asphalt Paving Cost
- Installed Concrete Paving Cost
- Installed Subbase & Embankment Construction Cost
- Hot in place recycling (HIPR) Cost
- Cold in place recycling (CIR) Cost
- Patching Cost
- Microsurfacing Cost
- Crack Sealing Cost
- Whitetopping Cost
- Rubblization Cost
- Full-depth Reclamation Cost

Layer thickness of typical 1.6-km length of 4-lane highway	Amount of material per kilometer of construction (tons)[1]	Average f.o.b.[2] price ($/ton)	Total material cost ($)	Transportation cost (56 km; $0.13/ton/km)	Total cost ($/ton)	Percent of total cost related to transportation
12.7 cm asphalt	8,700	$28.66	$249,000	$63,000	$312,000	20%
130 cm crushed gravel	14,400	$7.72	$111,000	$105,000	$216,000	49%
30 cm gravel	14,900	$5.51	$82,000	$108,000	$190,000	57%
15-61 cm sand	27,900	$5.51	$154,000	$203,000	$357,000	57%
Base course (borrow)	≤6,900	NA[3]	NA	NA	NA	NA
TOTAL	72,700	NA	$596,000	$479,000	$1,075,000	45%

[1] The term "tons" refers to the metric ton unit of 2,205 pounds.
[2] f.o.b., Free on board, processing plant.
[3] NA, Not available.
Adapted from Socolow, 1995.

Table 8: Cost Breakdown of Different Layers in a Roadway [Wilburn 1998]

Type of Natural Resource (Average Price in 1997)	Application Used for	Amount Utilized (million tons in 1997)	% of Use of Total Annual Production
Crushed and broken limestone and Dolomite ($4.16/ton)	Asphaltic concrete	4.08	5%
	Road construction/ Resurfacing	28.68	37%
Sand ($4.26/ton)	Asphaltic concrete	4.14	14%
	Road construction/ resurfacing	7.34	25%
Gravel ($4.26/ton)	Asphaltic concrete	3.00	10%
	Road construction/ Resurfacing	10.06	35%
Crushed Sandstone ($14.50/ton)	Aggregate	0.32	13%
	Construction	0.24	10%
Clay ($5.74/ton)	Construction	0.05	3%
Shale ($1.82/ton)	Lightweight Aggregate	0.24	8%
	Construction	0.03	1%

Table 9 Comparative Construction Costs in Ohio [Butalia 2003]

The literature search has convinced us that LCC is also a very important measure in the environmental characterization of pavements. For example, costs of maintenance may far outweigh the initial material and construction costs of pavements, especially for “perpetual pavements” where continuous maintenance is essential in extending the life-cycle of pavements.

2.8 Modeling of economic costs of using recycled materials for highway applications

The costs of recycling are not very clear in the literature, and usually some generic figures are available without detailed information about local conditions and the equipment used.

Entry into the aggregates recycling business requires a capital investment of $4 to $8 per metric ton of annual capacity. Processing costs for the aggregates recycler range from about $2.50 to $6 per metric ton [Wilburn 1998]. This average range fluctuates, and processing costs for aggregate recyclers range from $2.76 to $6.61 per metric ton [USGS 2000]. The average production capacity for a fixed site recycling operation is about 150,000 mt per year, and economies of scale affect its costs.

In Denver, the average price of recycled aggregates (ratio 60:40 asphalt – cement concrete) in 1996 was $5.23/ton [Wilburn 1998]. Transportation accounted for $0.13/ton/km, based on an average for 1995. Table 8 shows the cost breakdown of different layers in a roadway [Wilburn 1998]. Note the large percentage attributed to the cost of transportation.

Cold in-place recycling can be cheaper than more traditional rehabilitation methods. Table 10 shows the life cycle cost for CIPR [Murphy 2003].

	Rehabilitation Alternative[b]		
	Pulverize 200 mm 40 mm of HL 8, 50 mm of HL 3	Cold In-Place Recycle 100 mm[c], 50 mm of HL 3	Mill 40 mm, 65 mm of Recycled HL 8, 50 mm of HL 3
Initial Cost[d]	29,526	31,275	35,700
Present Worth of Maintenance Costs[e]	12,332	13,715	12,332
Present Worth of Rehabilitation Costs	22,478	8,706	22,478
Present Worth of Residual Value	(10,178)	(2,175)	(10,277)
Total Present Worth of Costs	54,158	51,521	60,233
Rank	2	1	3

a. Based on an interest rate of 8.0% and an inflation rate of 4.0% (discount rate of 3.85%).

b. Pavement rehabilitation alternatives based on equivalent overall granular base equivalencies. Existing conventional pavement structure consisting of 100 mm of asphalt concrete over 150 mm of granular base, granular subbase and native subgrade.

c. A granular base equivalency value of 1.8 was used for the cold in-place recycled material (CIP).

d. Initial cost of pavement sections includes pavement structure only. Additional work such as curb and gutter, drainage, pavement markings, etc. are not included. Initial cost based on average Ontario Ministry of Transportation (MTO) 1996 unit prices and typical in-place densities. Average MTO 1996 unit prices: Pulverize 200 mm depth $1.00/m2; CIP 100 mm $4.50/m2; Asphalt Removal (Mill) 40 mm $1.00/m2; HL 8 $31.60/t; Recycled HL 8 $30.00/t; HL 3 $32.00/t. In-place density of asphalt concrete mixes 2.4t/m3.

e. Maintenance and rehabilitation scheduling based on short term experience and estimated pavement performance for various asphalt concrete courses: pulverize/overlay 16 years to rehabilitation; mill/overlay 16 years to rehabilitation (reflection cracking); and, CIP/overlay 20 years to rehabilitation.

Table 10: Life-cycle Cost Comparison ($/lane-km) 30 Year Analysis Period [Murphy 2003]

The feasibility of recycling is strongly affected by material transportation costs and how such costs compare to the cost of new virgin material delivered to the construction site. When demolishing a pavement, both disposal cost of the material and its transportation cost should be considered. An important consideration in the cost model of recycled materials is the issue of avoided costs. If reclaimed pavement materials could be recycled into new applications, less would be spent on their disposal. Thus, we have collected landfill tipping fees from across the U.S. to provide data to decision-makers on the potential magnitude of avoided costs (Table 11).

State	*Number*	*Average Tip Fee ($/ton)*	*Remaining Capacity (years)*
Alabama	29	30	10
Alaska	275		0-100
Arizona	49	26.11	
Arkansas	23		30
California	175	35.14	18
Colorado	70	11	
Connecticut	2		3
Delaware	3	58.5	30
District of Columbia	0		
Florida	61	42.85	
Georgia	69	29.18	23.5
Hawaii	9	50	1-15
Idaho	29		
Illinois	52	30.68	15
Indiana	36	29.92	13.5
Iowa	61	33	60
Kansas	51		20+
Kentucky	26	27.24	15.2
Louisiana	23	22.85	
Maine	8	65	12-15
Maryland	23	49	>10
Massachusetts	21	67	<2
Michigan	54		15
Minnesota	22	40	7
Mississippi	20	25	20
Missouri	25	29.53	9
Montana			
Nebraska	23	25	
Nevada	24	18	>50
New Hampshire	15	66	8
New Jersey	12	55	12
New Mexico	44	32	20
New York	27		7
North Carolina	42	31	
North Dakota	14	25	20
Ohio	44	29	22
Oklahoma	40	20	20
Oregon	29	25	40
Pennsylvania	49		12
Rhode Island	4	40	10
South Carolina	19		>13
South Dakota	15	31	25-30
Tennessee	48	28.76	
Texas	227	25.46	32
Utah	37		100
Vermont	5	75	6.3
Virginia	67		20
Washington	21	49.79	51
West Virginia	18	42.37	30
Wisconsin	44	38	5
Wyoming	58		
Total	2,142		

Table 11: Municipal solid waste landfills by state, average tipping fee, and remaining capacity (BioCycle, Dec. 2001).

PaLATE suggests average landfill tipping fees for all U.S. states to give an idea of the costs arising from the disposal of demolished material. The total disposal cost is compared to the cost of demolishing and transporting the material to a recycling facility where after some handling and processing the material is ready to substitute for virgin materials. It is evident that the cost of recycled materials needs to be competitive with the cost of virgin materials.

Not only disposal costs but the objective and the technology used affect the economic performance of aggregates recycling. For example, reclaimed asphalt pavement (RAP) is processed differently depending on the type of facility and what the recycled aggregate will be used for. The following describes various recycling methods applied to road construction and maintenance [Chesner 2001]:

- <u>Hot Mix Asphalt (Central Processing Facility)</u>: Crushers, screeners, conveyors, and stackers produce and stockpile RAP. The RAP is later transported to a batch plant or drum-mix plant for use as an aggregate substitute in hot mix asphalt.
- <u>Hot Mix Asphalt (In-Place Recycling)</u>: Specialized heating, scarifying, rejuvenating, laydown, and compaction equipment is used in one or more passes. No processing is required before recycling begins. One pass can remix up to 2 inches of existing pavement.
- <u>Cold Mix Asphalt (Central Processing Facility):</u> Same as for hot mix RAP processing except the RAP is used in an aggregate substitute in cold mix asphalt.
- <u>Cold Mix Asphalt (In-Place Recycling):</u> Specialized plants or processing trains are used to mill the existing pavement surface up to 6 inches, mix with asphalt emulsion (or foamed asphalt), and place and compact in one pass. As with HIPR, no processing is required before recycling begins.
- <u>Granular Base Aggregate:</u> RAP is crushed, screened, and blended with virgin granular aggregate or reclaimed concrete material (RCM).
- <u>Stabilized Base or Subbase Aggregate:</u> RAP is crushed, screened, and blended with stabilization reagents (for increased strength when compacted).
- <u>Embankment or Fill</u>: RAP is rarely used for embankment or fill unless the stockpiled material has been stockpiled for a long time and would otherwise be disposed of in a landfill.
- <u>Full Depth Reclamation (FDR):</u> FDR penetrates the entire flexible pavement section and a predetermined portion of the base material, uniformly pulverizing and blending them together to produce a stabilized base course, and can correct deficiencies in the base as well as the bound asphalt layers [Landers 2001].
- <u>Rubblization:</u> This maintenance technique breaks concrete pavement into pieces and then overlays the road with Hot Mix Asphalt. The concrete is broken into pieces ranging from 2 to 6 inches by either a multiple head breaker or a resonant breaker. The former piece of equipment uses large hammers to strike the pavement surface, while the latter piece of equipment uses vibratory hammers to break up the pavement. Rollers are used to further break up the concrete, and then an asphalt overlay is placed. The process is relatively quick (up to one mile per day), and costs less than some other options. Environmental savings occur because the concrete is not landfilled and transportation during construction is less [APA 2003].

Different options for recycling of road construction materials are available. The cost effectiveness of such activities depends on a set of factors that should also include the cost associated with their respective environmental impacts. A detailed characterization of the cost determinants of aggregates recycling is fundamental for the evaluation of environmental costs. Figure 10 shows factors driving the cost of recycling and its environmental implications. Technology matters both in terms of material processing and transportation. Material quality determines its value and potential applications, whereas local characteristics such as DOT specifications, tipping fees, and transportation distance, affect the environmental economic feasibility of recycling. The use of virgin materials could be framed in the same way in order to assess the pros and cons of recycling.

Besides the assessment of recycled material from the demolished pavement, PaLATE also allows the assessment of various industrial by products that may be used in road construction and pavement mixes such as:

- coal fly ash
- coal bottom ash
- blast furnace slag
- foundry sand
- recycled tires/crumb rubber
- glass cullet

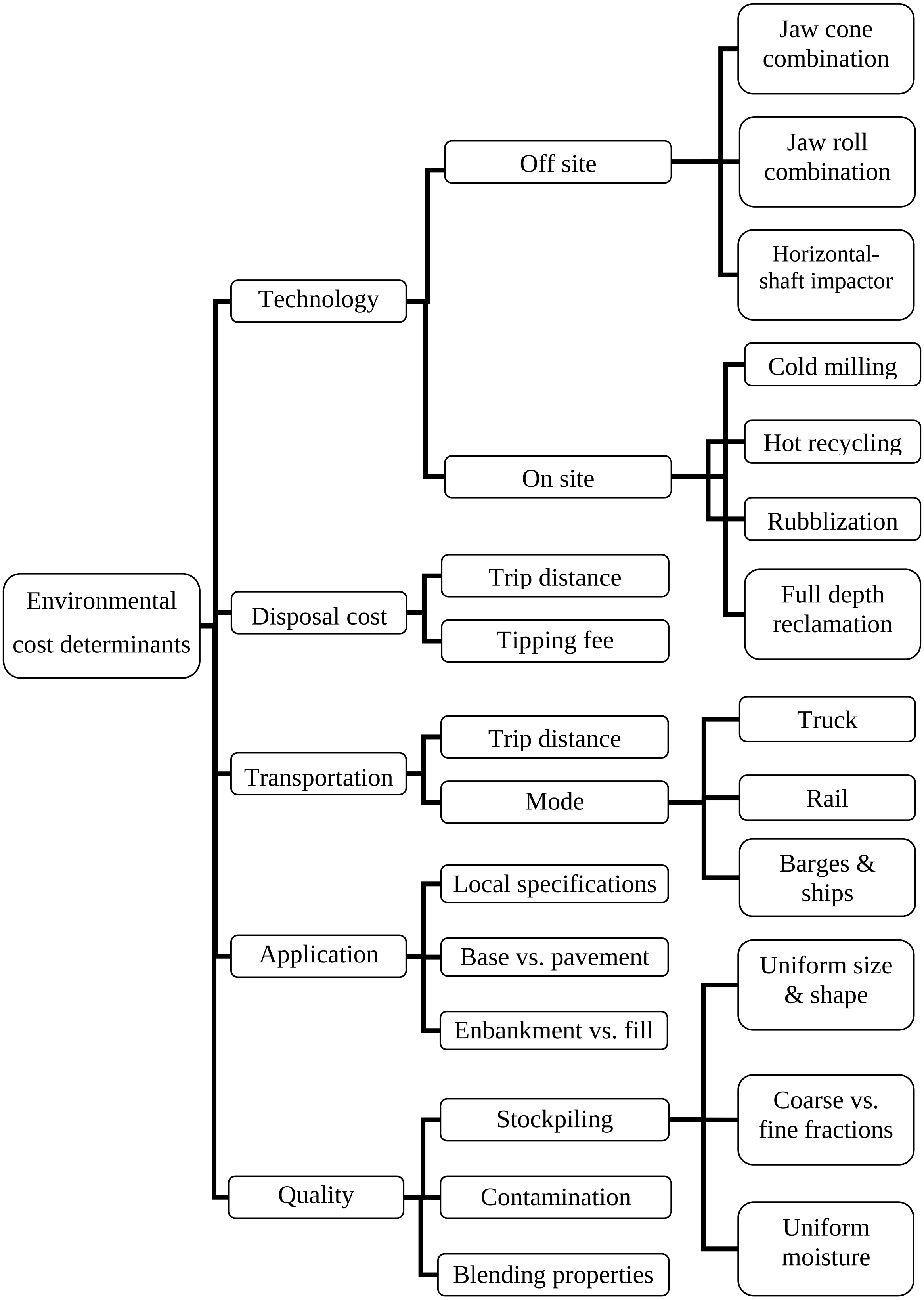

Figure 10: Environmental Cost Determinants for Aggregates Recycling

We have found that costs of recycled materials for highway applications vary greatly depending on the type of material and the location. For example, asphalt materials generally are in demand due to state requirements to include a certain percentage of RAP in new asphalt pavement materials. Conversely, while there is some demand for recycled concrete, it is generally lower than for asphalt, and most of the recycled concrete ends up in landfills. Of the alternative materials, coal fly ash is in increasing demand, and its costs have increased substantially over the last few years due to increased demand for fly ash by agencies that are required to substitute a percentage of fly ash for cement in concrete.

It is possible that the value of recycled materials increases in the future as local aggregate shortages are observed. For example, Table 12 shows the annual use rate of construction sand and gravel for several states compared to the national average (sand and gravel use from [Bolen 2000], population figures from [USCB 2001]). States such as Texas, California, Oregon, Michigan, Arizona, and Nevada use substantially more aggregates per capita than the national average and local shortages and increased procurement costs in California and Texas have been reported to us in personal communications.

Location (1)	**Use rate (tons/person-year) (2)**
U.S.	4.0
Texas	3.9
California	4.4
Oregon	4.8
Michigan	7.6
Arizona	11.5
Nevada	18.2

Table 12: Annual use rate of construction sand and gravel for several states compared to the national average (sand and gravel use from [Bolen 2000], population figures from [USCB 2001])

The challenging part was the quantification and inclusion of recycled materials into PaLATE. How much environmental "credit" should be given to recycled materials? Where should these credits be counted? How should transportation be counted in the model, and which life-cycle stage should it be assigned to? These were important and relevant questions for our work in order to generate realistic, robust and scalable models.

Environmental credit is given to recycled asphalt and pavement materials through the effects of their substituting for virgin material production by offsetting virgin material production by the amount of recycled materials used. The "life" of recycled pavement materials starts at breaking up the old pavement, followed by transportation to a depository place or asphalt/concrete plant, crushing, mixing of new pavement material, and transportation to the site of the new pavement.

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