Energy Requirements Associated With Highway Maintenance and Rehabilitation

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Energy requirements for typical pavement rehabilitation, maintenance, and construction operations are defined. Detailed energy requirements associated with equipment, production and manufacture of materials, hauling, laydown, and compaction are summarized. Energy requirements to construct, rehabilitate, and maintain pavements over a 20-year period are of the order of magnitude of 378.6 MJ/m^2 (300 000 Btu/yd^2) of pavement. About 0.1 percent of total energy used in the United States is consumed in routine highway pavement maintenance activities.

Transportation of goods and services required 25 percent of the total 95 EJ (90 quadrillion Btu) consumed in the United States in 1977 (1). This amount increases to 42 percent if one considers the total amount of energy required for (a) the production of raw materials used in transportation vehicles, (b) the manufacture of transportation vehicles, and (c) the production of materials for construction, rehabilitation, and maintenance of transportation facilities.

Estimates of the energy consumed in highway construction are of the order of 1.7 percent of the total annual U.S. energy demand; maintenance and rehabilitation operations are estimated to require an additional 1.5 to 2.0 percent (2). Information included here indicates that a reasonable energy estimate for routine pavement maintenance operations on the 6 129 032-km (3 800 000-mile) U.S. highway system is 0.1 percent. Even though this percentage of total energy consumption is relatively small, it is nonetheless important that engineers optimize these operations based on energy requirements just as they presently optimize operations based on cost.

Information given below defines energy requirements for operations associated with highway pavement maintenance and rehabilitation. Energy requirements for selected pavement construction operations are also included. These data can be used for a number of purposes, including

1. Defining energy requirements of selected maintenance and rehabilitation operations,
2. Identifying energy-intensive maintenance operations,
3. Identifying energy-efficient operations,
4. Assessing the impact of fuel allocation programs,
5. Defining energy associated with maintenance equipment operations,
6. Evaluating the energy demand of new maintenance operations,
7. Identifying areas in which fuel savings can be obtained from an operational standpoint, and
8. Determining total or equal annual energy requirements for various pavement and rehabilitation strategies for a 20- to 30-year period and thus allowing the engineer to select the most viable alternative based on both cost and energy.

ENERGY EQUIVALENTS

A wide variety of equipment and processes are used to produce, transport, and place materials associated with highway maintenance and rehabilitation activities. Typical equivalents for a wide variety of fuels associated with these operations are given in Table 1. It should be noted that, as the density of the petroleum product increases, the energy equivalent increases. Asphalt cement has relatively high density and thus a relatively large energy equivalent. It should also be noted that in this paper asphalt has not been considered as a fuel source but rather as a construction material. Thus, if asphalt cement, cutback asphalt, and emulsified asphalt are materials used as a part of the maintenance or rehabilitation activity, their energy equivalents as a fuel are not considered (3). The potential is there, however.

To aid the reader in conversion from one energy unit to another, the following is offered: A joule is a unit of work and energy in the SI system. To raise one gram of water 1°C, 4.186 J are required. A British thermal unit (Btu) is the quantity of heat required to raise the temperature of 1 lb of water 1°F when water is at or near 39.2°F.

In practice, energy is lost when fuel is converted into electrical energy or power. For example, the following energy conversions are not unlikely: 11.6 MJ (11 000 Btu) to generate 3.6 MJ (1 kW·h); 0.23 L (0.06 gal) of gasoline to generate 0.74 brake kW·h (1 brake hp·h) (the brake power of an engine is calculated by direct measurement by use of a dynamometer and takes into account system losses); and 0.15 L (0.04 gal) of diesel fuel to generate 0.74 brake kW·h (1 brake hp·h).

Table 1. Energy equivalents for fuels associated with highway maintenance and rehabilitation activities.

Fuel	Energy Equivalent	Source
Gasoline	34.8 MJ/L	Asphalt Institute (3)
Kerosene	37.6 MJ/L	Asphalt Institute (3)
Fuel oil		
No. 1 (API 42)	37.6 MJ/L	Asphalt Institute (3)
No. 2 (API 35) (diesel)	38.7 MJ/L	Asphalt Institute (3)
No. 3 (API 28)	39.8 MJ/L	Asphalt Institute (3)
No. 4 (API 20)	41.4 MJ/L	Asphalt Institute (3)
No. 5 (API 14)	42.4 MJ/L	Asphalt Institute (3)
No. 6 (API 10) (Bunker C)	43 MJ/L	Asphalt Institute (3)
Gas		
Natural	37.3 MJ/m^3	Asphalt Institute (3)
Propane	25.4 MJ/L	Asphalt Institute (3)
Butane	27.9 MJ/L	Asphalt Institute (3)
Asphalt cement	44 MJ/L, 44.3 MJ/kg	Bureau of Mines (4), Portland Cement Association (5)
Coal	27 MJ/kg	Portland Cement Association (6)
Petroleum coke	33.6 MJ/kg	Portland Cement Association (6)
Lignite	13.9 to 21 MJ/kg	

Note: 1 MJ/L = 3587.4 Btu/gal; 1 MJ/m^3 = 26.84 Btu/ft^3; and 1 MJ/kg = 429.83 Btu/lb.

Table 2. Energy required in operation of various types of vehicles used in highway maintenance and rehabilitation activities.

Type of Vehicle	Energy Requirement: Megajoules per Kilometer	Energy Requirement: Megajoules per Hour	Energy Requirement: Megajoules per Megagram Kilometer	Source
Automobile	4.74			Maryland DOT
Station wagon	5.09			Maryland DOT
Pickup	7.48			Arizona DOT
Maintenance truck				
Diesel	17.52	102.6		Maryland DOT
Gasoline	17.45	105.5		Maryland DOT
0.9-Mg	10.23			Arizona DOT
Two-axle	18.04			Arizona DOT
Distributor truck, gasoline	20.53			Arizona DOT
Truck tractor, diesel	19.94			Arizona DOT
Truck				
Two-axle, six-tire, gasoline			25.22	Asphalt Institute (3)
Three-axle, gasoline			9.79	Asphalt Institute (3)
Three-axle, diesel			8.71	Asphalt Institute (3)
Three-axle (combination), gasoline			17.06	Asphalt Institute (3)
Three-axle (combination), diesel			13.39	Asphalt Institute (3)
Four-axle (combination), gasoline			11.56	Asphalt Institute (3)
Four-axle (combination), diesel			7.5	Asphalt Institute (3)
Five-axle (combination), gasoline			6.64	Asphalt Institute (3)
Five-axle (combination), diesel			4.5	Asphalt Institute (3)

Note: 1 MJ/km = 526.5 Btu/mile; 1 MJ = 947.8 Btu; 1 MJ/Mg-km = 384 Btu/ton-mile; and 1 Mg = 1.1 ton.

Table 3. Energy required in operation of various types of maintenance and rehabilitation equipment.

Type of Equipment	Energy Requirement (MJ/h)	Source
Front-end loader		
1.53 m^3 diesel	7.33	Maryland DOT
1.15 m^3 gasoline	5.27	Maryland DOT
Loader for aggregates	923.2	Asphalt Institute (3)
Front-end loader, diesel	234.2	Arizona DOT
Motor grader, 10 431 kg diesel	7.33	Maryland DOT
Grader, diesel	395.65	Arizona DOT
Rollers	659.4	Asphalt Institute (3)
Roller	117	Arizona DOT
Striping machine, self-contained	131.88	Arizona DOT
Hand striping machine	65.94	Arizona DOT
Mower		
Roadside	131.88	Arizona DOT
Landscape	49.38	Arizona DOT
Tractor, farm type	395.65	Arizona DOT
Spreader, self-propelled	356.6	Arizona DOT
Broom, mechanical	131.88	Arizona DOT
Dozer, track type	439.96	Arizona DOT
Crushing-screening plant	733.28	Arizona DOT
Asphalt paver	660.48	Asphalt Institute (3)
Asphalt pot	211	AASHTO and Arkansas Highway Department (7)

Note: 1 MJ/h = 947.8 Btu/h.

Thus, the burning of fuel to generate electricity is about 31 percent efficient. The burning of fuel in engines to obtain power is approximately 34 and 46 percent efficient for gasoline and diesel engines respectively. In addition, since power equipment is ordinarily not operated at full rated power for a prolonged period of time, adjustments of the order of 67 and 75 percent of rated power (relative to continuous operation) are normally made for stationary and power vehicles respectively (3).

ENERGY REQUIREMENTS FOR HIGHWAY MAINTENANCE

Equipment

Energy requirements for various types of vehicles and equipment associated with maintenance and rehabilitation are given in Tables 2 and 3. Table 2 gives energy requirements for automobiles and trucks, and Table 3 includes various types of maintenance equipment.

Production and Manufacture

Energy requirements for the manufacture of asphalt products, portland cement, steel, and lime are given in Table 4. Energy associated with operations that involve the production of aggregates, asphalt concrete, and portland cement concrete is given in Tables 5, 6, and 7 respectively. In some cases, different values have been reported in the literature. These different values are given and referenced in the tables. Energy requirements for miscellaneous construction operations are given in Table 8.

Maintenance and Rehabilitation Activities

Energy requirements associated with the performance of specific routine maintenance and rehabilitation activities are given in Table 9. Energy required in manufacture and transportation of materials; production, transportation, and placement of mixtures; and compaction are included in the data. Assumptions as to the percentage of pavement area treated by the particular maintenance activity and the thickness or quantity of material applied are identical to those used for estimating maintenance costs. These data are based primarily on information obtained through correspondence with personnel of the Arizona Department of Transportation, the Nevada Department of Highways, the North Dakota State Highway Department, and the Texas State Department of Highways and Public Transportation.

Energy consumption for materials used in pavements (in place) is given in Table 10. The energy consumed includes the energy associated with manufacturing, mixing, hauling, placing, and compacting. Materials included are asphalt concrete, portland cement concrete, slurry seal, chip seal, fog seal, crushed stone base, and emulsified asphalt base.

A summary of the data given in Tables 9 and 10 is given in Table 11 with energy requirements per dollar (December 1975) for 10 maintenance and rehabilitation activities. If one assumes that the Federal Highway Administration estimate of $5 billion for 6 100 000 km (3 800 000 miles) of road for annual maintenance of highways and roadways is correct, and if it is assumed that on the average 21 MJ (20 000 Btu) of energy are required for each dollar expended on maintenance (Table 11), it can be concluded that about 0.1 percent of the total energy consumed in the United States is consumed in highway maintenance operations. This 0.1 percent of total energy represents 105.5 PJ/year (100 trillion Btu/year) or approximately 2 514 300 m^3 (15 800 000 bbl) of oil per year. The reader is reminded that this neglects the ap-

Table 4. Energy required in manufacture of materials used in highway maintenance.

Item	Energy Requirement			Source
	Megajoules per Liter	Megajoules per Kilogram	Gigajoules per Megagram	
Asphalt cement	0.698	0.698	0.698	Asphalt Institute (3)
Emulsified asphalt	0.558	0.558	0.558[a]	Asphalt Institute (3)
Cutback asphalt	0.698	0.698	0.698[b]	Asphalt Institute (3)
Portland cement		8.72	8.72	Asphalt Institute (3), Portland Cement Association (5)
		7.33	7.33	U.S. Department of Commerce and Federal Energy Administration (8)
Steel for tiebars, rebars		24.42	24.42	Asphalt Institute (3)
Lime		6.978	6.978	Asphalt Institute (3)
Polyhydrate		3.489	3.489	

Note: 1 MJ/L = 3587.4 Btu/gal; 1 MJ/kg = 429.83 Btu/lb; and 1 GJ/Mg = 859 840 Btu/ton.

[a] For equal quantities of binder, this is equivalent to 860.6 MJ/Mg (740 000 Btu/ton) (assumes 65 percent residual asphalt).

[b] For equal quantities of binder, this is equivalent to 872 MJ/Mg (750 000 Btu/ton) (assumes 80 percent residual asphalt).

Table 5. Energy required in production of aggregates.

Product	Operation	Energy Requirement			Source
		Kilojoules per Kilogram	Megajoules per Megagram	Megajoules per Cubic Meter[a]	
Crushed stone	Drilling and shooting	14	14	29	Asphalt Institute (3)
	Crushing	59.3	59.3	123.5	Asphalt Institute (3)
	Handling (cranes and bulldozers)	8.14	8.14	17	Asphalt Institute (3)
	Total	81.4	81.4	170	Asphalt Institute (3)
	Total	60.5	60.5	126	Nichols (9)
Crushed gravel	Crushing	40.7	40.7	84.7	Asphalt Institute (3)
	Handling (cranes and bulldozers)	5.8	5.8	12	Asphalt Institute (3)
	Total	46.5	46.5	97	Asphalt Institute (3)
Natural or uncrushed aggregate	Total	17.44	17.44	36.3	Asphalt Institute (3)

Note: 1 kJ/kg = 0.43 Btu/lb; 1 MJ/Mg = 859.84 Btu/ton; and 1 MJ/m³ = 724.6 Btu/yd³.

[a] Assumed unit weight of 2083 kg/m³ (130 lb/ft³).

Table 6. Energy required in production of asphalt concrete.

Operation	Energy Requirement			
	Megajoules per Megagram of Mix	Megajoules of Operation[a]	Equivalent Liters of Diesel per Hour	Equivalent Liters of Diesel per Megagram of Mix
Asphalt heating and storage	7.44	1 013	26	0.192
Cold feed				
Loader	5.1	693.2	17.8	0.129
Cold bins, vibrators, belt feeders	0.12	15.8	0.38	0.004
Belt conveyors	0.29	39.56	1.14	0.008
Total cold feed	5.51	748.56	19.32	0.141
Dryer				
Drive motor	1.46	198.3	4.9	0.037
Fuel pump blower	1.7	230	5.6	0.042
Exhaust fan	1.46	199.4	5.3	0.037
Secondary dust collector	0.93	126.6	3.4	0.025
Total dryer	5.55	754.3	19.2	0.141
Mixing plant				
Hot elevator	0.4	55.9	1.5	0.012
Screening	0.53	72	1.9	0.012
Asphalt pump	0.29	39.5	1.14	0.008
Mineral filler elevator	0.23	31.6	0.76	0.004
Pugmill	2.4	327	8.3	0.062
Compressor (discharge)	0.23	31.6	0.76	0.004
Storage conveyor	0.46	63.3	1.5	0.012
Total mixing plant	4.54	620.9	15.86	0.114
Drying and heating aggregate	271[b]	36 928	954.5	7
Total plant operation	294.04	40 064.76	1034.88	7.588
Paving machine	4.85	659.4	17	0.125
Rollers (three)	14.54	1 983.5	51	0.375
Total spreading and compaction	19.39	2 642.9	68	0.5
Drying and heating aggregate	323[c]	43 997	1136	8.3
Drying and heating aggregate	323[d]	43 997	1136	8.3
Drying and heating aggregate	380[e]	51 699	1337	9.8
Plant operation (excluding drying)				
Laying and compacting	48.5[c]	6 605	170.45	1.25
Laying and compacting	47.6	6 478	167	1.25

Note: 1 MJ/Mg = 859.84 Btu/ton; 1 MJ = 947.8 Btu; 1 L = 0.264 gal; and 1 L/Mg = 0.24 gal/ton.

[a] Operating at 136 Mg/h (150 tons/h).

[b] Five percent moisture removed and temperature raised to 148°C (300°F) for a mix that contains 94 percent by weight of aggregate.

[c] From Foster and Kloiber (10).

[d] From Bituminous Construction Handbook (11).

[e] Illinois data from the Asphalt Institute (3).

proximately 22 278 000 m^3 (140 000 000 bbl) of asphalt consumed each year as a pavement ingredient.

The American Association of State Highway and Transportation Officials (AASHTO) Maintenance Subcommittee, working with the Arkansas Highway Department, has compiled a list of highway maintenance activities, completion of which requires large amounts of energy. Table 12 (7) lists these activities in descending order of energy use. Based on these data, it is estimated that about 0.02 percent of the total energy consumed in the United States is consumed in routine maintenance on state-maintained highways (1).

TYPICAL ENERGY REQUIREMENTS FOR PAVEMENTS

As noted, one potential use of the data presented in this paper is to define the amount of energy required for various pavement construction, rehabilitation, and maintenance strategies over a 20- to 30-year period. For example, the energy and costs associated with the construction of a pavement in central Texas are given in Table 13. Plan 1 consists of construction of a pavement containing 15 cm (6 in) of lime-stabilized subgrade, 20 cm (8 in) of crushed stone base, and 5 cm (2 in) of asphalt concrete surfacing. Overlays are scheduled on 7-year cycles with routine maintenance as required. Plan 2 consists of constructing a pavement containing 15 cm of lime-stabilized subgrade, 20 cm of asphalt-treated base, and 5 cm of asphalt concrete. Overlays will not be required during the 20-year life cycle. Routine maintenance will be performed as required.

Based on present worth and uniform annual cost and an 8 percent rate of return, plan 1 is favored ($9.72 versus $10.16 and $0.99 versus $1.05). If a lower rate of return were used, plan 2 would be favored over plan 1. For example, 0 percent rate of return indicates that plan 2 is favored over plan 1. From an energy standpoint, plan 2 is favored over plan 1.

Table 7. Energy required in production of portland cement concrete.

	Energy Requirement			
			Equivalent Liters of Diesel	
Operation	Megajoules per Megagram of Mix	Megajoules per Cubic Meter of Mix^a	Per Megagram of Mix	Per Cubic Meter of Mix
Loader	5.1	12.24	0.133	0.322
Conveyor	0.3	0.76	0.004	0.015
Mixing and other plant operations	2.06	4.94	0.054	0.129
Total plant operation	7.46	17.94	0.191	0.466
Placing, consolidation, and finishing	3	7.23	0.079	0.188

Note: 1 MJ/Mg = 859.84 Btu/ton; 1 MJ/m^3 = 724.6 Btu/yd^3; 1 L/Mg = 0.24 gal/ton; and 1 L/m^3 = 0.202 gal/yd^3.

^{a}Assumed unit weight of 2404 kg/m^3 (150 lb/ft^3) (12).

CONCLUSIONS

Based on the data presented in this paper, it is possible to calculate energy requirements associated with various pavement construction, rehabilitation, and maintenance strategies. Since energy conservation is one method by which our existing fuel supplies can be extended, both cost and energy considerations should be considered in the decision-making process.

REFERENCES

1. S. E. Blake and K. E. Cook. Transportation and the Energy Crisis. TRB, Transportation Research News 55, Summer 1974, pp. 17-19.
2. W. J. Halstead. Energy Use and Conservation in Highway Construction and Maintenance. Virginia Highway and Transportation Research Council, Charlottesville, March 1978.
3. Energy Requirements for Roadway Pavements. Asphalt Institute, Miscellaneous Rept. 75-3, April 1975.
4. Btu Content of Materials. Bureau of Mines, U.S. Department of Interior, news release, March 13, 1974.
5. On the Subject of Energy. Portland Cement Association, Nov. 1975.
6. Energy Report for the U.S. Portland Cement Industry. Portland Cement Association, May 1975.
7. High Energy Use Maintenance Activities. AASHTO

Table 8. Energy required in miscellaneous construction operations.

	Energy Requirement				
				Equivalent Liters of Diesel	
Operation	Kilojoules per Liter	Megajoules per Megagram	Megajoules per Cubic Meter	Per Megagram	Per Cubic Meter
Spreading and compaction of granular and stabilized bases		19.8	42.75	0.508	1.104
Travel plant mixing in windrow		3.5	7.55	0.092	0.193
Blade mixing		9.1	19.6	0.233	0.510
Central plant mixing of stabilized base		8	17.3	0.208	0.445
Excavation					
Earth		46.3	81.6^a	1.192	
Rock		41.3	106^a		
Other		45.5	95^a		
Asphalt distribution					
Asphalt cement	164.3				
Cutback asphalt	124				
Emulsified asphalt	40.4				
Aggregate spreading for seal coats	2.62^b				
Rolling cold asphalt mixes	33.4^c				

Notes: 1 kJ/L = 3.59 Btu/gal; 1 MJ/Mg = 859.84 Btu/ton; 1 MJ/m^3 = 724.6 Btu/yd^3; 1 L/Mg = 0.24 gal/ton; and 1 L/m^3 = 0.202 gal/yd^3.
Assumed unit weight of 2163 kg/m^3 (135 lb/ft^3) except for excavation items. Data from the Asphalt Institute (3) except where noted.

^{a}From Highway Research Board (12). ^{b}11.9 kJ/m^2 (9.4 Btu/yd^2). ^{c}59.6 kJ/m^2-cm (120 Btu/yd^2-in).

Table 9. Representative energy requirements for routine highway maintenance and rehabilitation activities.

Maintenance Activity	State or Other Source	Energy Requirement					Total Pavement Area Treated (%)
		Energy Per Unit	Area Treated (MJ/m^2)	Megajoules per Square Meter-Centimeter	Gigajoules per Lane Kilometer[a]	Megajoules per Square Meter	
Fog seal							
Partial width	Arizona	2.93 MJ/L	1.32		2.43	0.66	50
	Nevada	3.37 MJ/L	1.41		2.59	0.71	
Full width	Arizona	4.49 GJ/lane-km	1.22		4.49	1.22	100
	Asphalt Institute (3)	2.16 GJ/lane-km	0.59		2.16	0.59	
Chip seal							
Partial width	Arizona	741 MJ/m^3	10.35		5.68	1.55	
	North Dakota	1.52 GJ/m^3	11.62		6.37	1.74	
	Nevada	1.38 GJ/m^3	7.57		4.13	1.13	
	Nevada	2.25 GJ/m^3	9.46		5.2	1.43	
	Nevada	1.60 GJ/m^3	10.22		5.64	1.53	
Full width	Arizona	20.13 GJ/lane-km	5.5		2.01	5.5	100
	Asphalt Institute (3)	18.23 GJ/lane-km	4.98		1.82	4.98	
Surface patch							
Hand method	North Dakota	2.35 GJ/m^3	56.78	22.36	5.24	1.44	
	Nevada	4.43 GJ/m^3	112.7	44.38	10.29	2.85	2.5 (2.5 cm thick)
Machine method	Nevada	1.21 GJ/m^3	30.92	12.18	11.28	3.09	10 (2.5 cm thick)
	Arizona	1.48 GJ/m^3	37.6	14.81	13.77	3.77	
	North Dakota	1.64 GJ/m^3	41.75	16.44	15.28	4.16	
Digout and repair							
Hand method	Arizona	2.21 GJ/m^3	224.6	22.1	16.39	4.49	2 (10 cm thick)
Machine method	Arizona	1.55 GJ/m^3	236	15.5	43.14	11.8	5 (15.2 cm thick)
	Nevada	1.12 GJ/m^3	170.4	11.8	31.14	8.52	
Crack pouring	Arizona	9.12 MJ/L			5.57	1.54	-[a]
	Nevada	16.9 MJ/L			10.5	2.88	
	Texas	9.34 MJ/L			5.7	1.55	
	North Dakota	8.17 MJ/L			4.98	1.36	
Slurry seal	Slurry Seal, Inc. (13)	6.16 GJ/lane-km	1.69		6.16	1.69	100
Asphalt concrete overlay	Asphalt Institute (3)	595.5 MJ/Mg	70.2	13.82	256.34	70.2	100 (5 cm thick)
	Highway Research Board (12)	620 MJ/Mg	72.94	14.36	266.83	72.94	

Note: 1 MJ/L = 3587.4 Btu/gal; 1 MJ/m^2 = 792.4 Btu/yd^2; 1 MJ/m^2·cm = 2012 Btu/yd^2-in; 1 GJ/lane-km = 1.525 million Btu/lane-mile; 1 MJ/m^3 = 724.6 Btu/ft^3; 1 cm = 0.39 in; and 1 MJ/Mg = 859.84 Btu/ton.

[a] Energy requirements for square meters of total pavement surface maintained; for example, surface patching by the hand method may have been applied over only 5 percent of total pavement surface area, but energy reported is for pavement area maintained on 1.6 lane-km of pavement.

Table 10. Energy requirements for pavement materials in place.

Material	Energy Requirement			Source
	Gigajoules per Megagram	Gigajoules per Cubic Meter	Megajoules per Square Meter-Centimeter	
Asphalt concrete	0.595	1.380	13.8	Asphalt Institute (3)
	0.620	1.435	14.4	Highway Research Board (12)
PCC				
Jointed nonreinforced	1.151	2.760	27.6	Portland Cement Association (14)
Jointed nonreinforced	1.407	3.381	33.8	Asphalt Institute (3)
Jointed reinforced	1.616	3.892	39	Asphalt Institute (3)
Continuously reinforced	1.884	4.527	45.3	Asphalt Institute (3)
Slurry seal			0.7[a]	Slurry Seal, Inc. (13)
Chip seal, emulsion, and crushed stone			2[a]	Asphalt Institute (3)
Fog seal			0.23[a]	Highway Research Board (12)
Crushed stone base	0.274	0.571	5.7	Asphalt Institute (3)
	0.253	0.527	5.27	Nichols (9)
Emulsified asphalt base	0.345	0.776	7.75	Asphalt Institute (3)
Cement stabilized base	0.678	1.518	15.2	
Polyhydrate-fly ash base	0.378	0.835	8.35	
Cement-treated subgrade	0.612	1.176	12	Halstead (2)
Lime-fly ash	0.478	0.994	9.94	
Lime-stabilized subgrade	0.727	1.176	12	

Note: 1 GJ/Mg = 859 840 Btu/ton; 1 GJ/m^3 = 724 600 Btu/yd^3; and 1 MJ/m^2·cm = 2012 Btu/yd^2-in.

[a] Treatments are not 2.5 cm (1 in) in thickness.

Table 11. Representative costs and energy requirements for highway maintenance and rehabilitation activities.

Activity	Cost[a]		Energy Requirement[a]			Total Pavement Area Treated (%)
	Dollars per Square Meter	Dollars per Lane Kilometer	Kilojoules per Square Meter	Gigajoules per Lane Kilometer	Per Unit Cost (MJ/$)	
Fog seal						
Partial width	0.05	199	656	2.426	12.34	50
Full width	0.07	261	1 212.5	4.491	17.1	100
Chip seal						
Partial width	0.07	261	837.5	3.081	11.8	15
Full width	0.18	932	2 562.5	9.441	10.34	100
Surface patch						
Hand method	0.12	435	NA	NA	NA	2.5 (2.5 cm thick)
Machine method	0.09	348	3 737.5	13.768	39.45	10 (2.5 cm thick)
Digout and repair						
Hand method	0.30	1093	4 450	16.390	15	2 (10 cm thick)
Machine method	0.24	870	11 687.5	43.139	49.3	5 (15 cm thick)
Crack pouring	0.14	528	1 525	5.573	10.8	-[b]
Asphalt concrete overlay	2.26	8323	69 500	256.343	31	100 (5.1 cm thick)

Notes: \$1/m^2 = \$0.84/yd^2; \$1/km = \$1.61/mile; 1 kJ/m^2 = 0.8 Btu/yd^2; 1 GJ/lane-km = 1.525 million Btu/lane-mile; 1 MJ/\$ = 947.8 Btu/\$; and 1 cm = 0.39 in.
NA indicates data not available.

[a] For square meters of total pavement surface maintained; for example, surface patching may have been applied by hand over only 5 percent of total pavement surface area, but costs and energy reported are for total pavement area maintained, or 1.61 lane-km (1 lane-mile).

[b] 75.7 m (250 linear ft).

Table 12. Energy requirements for various highway maintenance activities in Arkansas.

Rank	Function	Activity	Cost ($)	Energy (TJ)
1	435	Premix leveling	2 516 740	80.3952
2	444	Mowing	2 959 320	54.0239
3	436	Restoring gravel surface	527 819	35.0193
4	412	Premix patching	2 169 238	29.8588
5	414	Spot surface replacement (bituminous)	846 772	26.7710
6	417	Blading nonpaved surface	665 404	19.3293
7	432	Seal coat	380 017	16.9604
8	437	Restoring gravel shoulder	202 621	15.0913
9	433	Fog coat	176 690	15.0224
10	441	Cleaning and repairing minor drains	1 014 203	13.3660
11	431	Mudjack and underseal	115 486	13.2562
12	416	Gravel surface patching	541 008	12.5547
13	418	Blading nonpaved shoulders	422 318	10.2732
14	443	Machine ditches	305 711	8.1909
15	411	Surface treatment patching	217 966	5.0024
16	413	Joint repair and crack filling	297 680	4.9456
17	415	Spot surface replacement (concrete)	146 430	4.7204
18	446	Litter pickup	244 560	2.5795
19	531	Paint striping and edge marking	1 072 346	1.3227
20	532	Painting pavement	37 041	0.3017

Note: 1 TJ = 947.8 million Btu.

Table 13. Energy and costs associated with pavement construction, rehabilitation, and maintenance over a 20-year period.

			Cost ($/m²)			
	Energy (MJ/m²)		Present Worth		Uniform Annual	
Plan	Total for 20-Year Period	Uniform Annual Requirement	0% Rate of Return	8% Rate of Return	0% Rate of Return	8% Rate of Return
1	445	22.2	14.75	11.62	0.74	1.18
2	344.3	17.2	12.76	12.15	0.63	1.24

Note: 1 MJ/m² = 792 Btu/yd²; $1/m² = $1.196/yd².

Maintenance Subcommittee and Arkansas Highway Department, 1977.

8. Voluntary Industry Conservation Progress Report 5. U.S. Department of Commerce and Federal Energy Administration, July 1977.
9. F. P. Nichols. Notes on Energy Requirements for Crushing Stone. National Crushed Stone Association, Nov. 1975.
10. C. R. Foster and R. Kloiber. Fuel Conservation. National Asphalt Pavement Association, Jan. 1974.
11. Bituminous Construction Handbook. Barber-Greene, Aurora, IL, 1976.
12. Fuel Usage Factors for Highway Construction. HRB, Highway Research Circular 158, July 1974.
13. Slurry Seal a Block With Half a Gallon of Gasoline. Slurry Seal, Inc., Waco, TX.
14. Energy Conservation in Construction of Pavements. Portland Cement Association, 1973.

Discussion

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The paper by Epps and others represents a necessary step if maintenance organizations are to become fuel conscious. The authors have gathered together a comprehensive listing of energy requirements to run maintenance equipment, energy used in manufacture of materials used in maintenance, and energy required in various maintenance operations.

Initially, I was disappointed that no conclusions were drawn and that the reader was left with only the facts as represented by the tables. But it became clear that this paper must be considered a reference document that, taken together with other facts, will enable those managing maintenance to make decisions that will achieve the desired results in an energy-effective manner. A quick review of Table 10 would indicate that use of an asphalt concrete overlay would require seven times the energy required by use of a chip seal. The next reasonable step for a maintenance man to take would be to determine the age life of each treatment at a specific pavement location and under the exact conditions it would be used. If the overlay would yield an 11-year life and the chip seal only a 3-year life, the relative energy consumed would change. Assuming that the chip seal provided a negligible increase in the rideability index while the overlay yielded an increase of three points in the rideability index, we could expect fuel savings at a speed of 80.5 km/h (50 mph) of 0.045 L/km (0.0175 gal/mile) driven for every vehicle trip over the pavement if an overlay were used. Again, the relative energy consumed has been changed. It can be concluded then that the data contained in this paper become another resource to be used in the decision-making process to determine what corrective actions will be taken.

It is commonly thought that asphalt cements represent a by-product of the process that produces gasoline and fuel oils. This is no longer the case because oil companies now have the technology whereby nearly all that portion of crude oil that is used in asphalt cement can be used in the production of light fuels. This means that, when we put down a megagram of asphalt concrete, we are placing joules and not just using joules in its placement. Ultimately, this fact could have as great an influence in the choice of materials as price.

The fuel used can have a major impact on the choice of equipment to be purchased. Table 2 indicates the energy required to operate various pieces of equipment. In the past, the diesel engine had a significant advantage in the area of operating costs not only because the diesel engine is more efficient than the gasoline engine but also because in the past the price per liter of diesel oil was substantially below that of gasoline. This has changed since the onset of the energy crisis, and now diesel oil is more expensive than gasoline on a cost per liter basis. Our state contracts give us diesel oil at $0.115/L ($0.436/gal) versus $0.10/L ($0.39/gal) for gasoline. If these costs are calculated per 1.05 MJ (1000 Btu), the following applies (1 L = 0.264 gal, 1 MJ/L = 3587.4 Btu/gal, and 1 MJ = 947.8 Btu):

Item	Gasoline	Diesel Oil
Cost per liter, $	0.103	0.115
Megajoules per liter	34.8442	38.7467
Cost per 1.05 MJ, $	0.003 12	0.003 14

This would indicate that the price is providing equal cost per unit of heat. Naturally, the greater efficiency of the diesel engine still provides operating economy.

Now that the first step has been taken, there remains much more work to be done. Maintenance consumes great amounts of heating oil in buildings. As we replace our buildings, we should be using energy-efficient designs that will still meet our unique needs. Energy-efficient designs are not yet readily available. Fuel can be saved in existing buildings if money is invested in insulation, storm windows, and lower ceilings. Further research that relates the cost of each alteration to the energy (and dollars) saved is needed to convince legislators that such rehabilitation pays off. We need further research that integrates energy consumption with pavement management and maintenance management systems as well.

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