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"ENERGY IN ROADWAY CONSTRUCTION"

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Introduction

The purpose of this report is to address one aspect of energy with respect to highway construction. Major concentration will be upon the production of concrete and asphalt. It is hoped by this analysis that future highway work will be influenced to the point that more energy efficient construction will occur.

To aid in the understanding of the energy required to produce asphalt and concrete roadways, an example project, I 76–1(35), will be analyzed using two of the following five alternates:

Alternate No. 1 - 8" Concrete Main Line with 6" Bituminous Base
Alternate No. 2 - 8" Concrete Main Line with 6" Recycled Bituminous Base
Alternate No. 3 - 8" Concrete Main Line with 6" Lean Concrete Base
Alternate No. 4 - 8" Concrete Main Line with 6" Recycled Lean Concrete Base
Alternate No. 5 - 6" Hot Bituminous Pavement (HBP) with 6" Plant Mix Bituminous Base (PMBB)

Alternate 4 will be analyzed because the materials used consist of concrete. The base material is lean concrete made of both recycled and virgin aggregates. Over the lean concrete base a cover of concrete pavement will be placed. Future resurfacing of this pavement is expected to be done 15 years after construction using a grinder. Following this resurfacing, an overlay using Hot Bituminous Pavement is expected to be placed 30 years after initial construction. Similar to the grinding used 15 years after construction, a grinding of the existing concrete pavement surface is done to match the newly placed pavement.

Alternate 5 will be analyzed because the materials call for the use of asphalt cements. The construction of the new roadway would be done using Plant Mix Bituminous Base (PMBB) and a surface layer of Hot Bituminous Pavement (HBP). The current Main Line would be overlayed using HBP to match the newly placed pavement. Future resurfacing of this roadway will be done with other asphalt pavement overlays as shown by this list.

8 years after construction	=	1½" overlay
16 years after construction	=	1½" overlay
25 years after construction	=	2" overlay
30 years after construction	=	1" overlay
		6" Overlay Total

An asphalt crack filler is expected to be placed on the existing pavement before the initial overlay and before the overlay of the 16th year.

Concrete Quantities for Alternate No. 4

Present: A) Grind Main Line: 70,392 yd^2

B) Widening: Recycled Lean Base - 63,492 yd^2

New Lean Base - 41,650 yd^2

Total Base 105,142 yd^2 at 6" depth

8" Concrete Main Line - 105,142 yd^2

Future: A) Grind all of Main Line - 175,534 yd^2

B) 30th year 1" Overlay - (203,555 yd^2) (.055 ton/yd^2/1" thick) = 11,196 ton HBP

C) 30th year CSS-lh - (203,555 yd^2) (.05 gal./yd^2) = 10,178 gal.

Asphalt Quantities for Alternate No. 5

Present: A) 2" Overlay of Main Line - (70,392 yd^2) (.055 ton/yd^2/1") (2") = 7,743 ton HBP

B) Widening: $\frac{(70{,}831 \text{ ton} - 7{,}743 \text{ ton})}{2}$ = 31,544 ton HBP

$\frac{(70{,}831 \text{ ton} - 7{,}743 \text{ ton})}{2}$ = 31,544 ton PMBB

C) CSS-lh: 47,399 gal. - 25,935 gal. = 21,464 gal.

D) (18 ton) (.75) = 13.5 ton AC for crack filler

Future: A) Main Line Overlay: (203,555 yd^2) (.055 ton/yd^2/1") (6") = 67,173 ton

B) CSS-lh (203,555 yd^2) (.05 gal./yd^2) (4 times) = 40,711 gal.

C) Two crack fillers: (2) (13.5) = 27 ton A.C.

The difference in the square yards of area between the future grinding (Alternate 4) and the future overlay (Alternate 5) occurs because of the overlay method used on the existing I 70. (I 70 is a part of the I 76 project.) The present I 70 has shoulders which are not included as the area to be ground. For an overlay, the same shoulders are covered and hence a larger area evolves for the future 1" overlay than for the future area to be ground.

Present Concrete Construction

As shown by the breakdown, Alternate 4 calls for the grinding of the existing I 70. For an average grinding operation the following method of calculating the energy required may be used. All work will be done in terms of British Thermal Units (BTU), where one BTU is the energy required to heat 1 pound of water 1 degree Fahrenheit.

Using the values for fuel consumption per hour for the equipment and the average rate of production, the number of gallons of gasoline and diesel required to grind one square yard 1" deep may be calculated.

$$\left(\frac{\text{gal.}}{\text{hr.}}\right)\left(\frac{\text{hr.}}{\text{yd}^2}\right) = \frac{\text{gal.}}{\text{yd}^2}$$

These values can now be multiplied by the BTU per gallon of fuel for each fuel type being analyzed. This will give the BTU/yd^2 for any area being ground.

$$\left(\frac{\text{gal.}}{\text{yd}^2}\right)\left(\frac{\text{BTU}}{\text{gal.}}\right) = \frac{\text{BTU}}{\text{yd}^2}$$

Multiplication of this value by the area to be ground will give the energy consumed in the grinding of any area.

$$\left(\frac{\text{BTU}}{\text{yd}^2}\right)\left(\frac{\text{yd}^2}{\text{job}}\right) = \frac{\text{BTU}}{\text{job}}$$

For any grinding operation the following fuel consumption values and production rate may be used.(1)

Self Propelling Grinder	2.5 gal./hr	gasoline
Cat Engine	5.0 gal./hr	diesel
Vacuum	2.5 gal./hr	diesel
Vacuum Truck	4.0 gal./hr	diesel

Average production is 100 yd^2/hr.

For I 76-1(35) the area to be ground is 70,392 yd^2.

Calculations now give the following values.

$(2.5 \text{ gal./hr})(1 \text{ hr} / 100 \text{ yd}^2) = 0.025 \text{ gal./yd}^2$ gasoline

$(11.5 \text{ gal./hr})(1 \text{ hr} / 100 \text{ yd}^2) = 0.115 \text{ gal./yd}^2$ diesel

$(0.025 \text{ gal./yd}^2)(125{,}000 \text{ BTU/gal.}) = 3{,}125 \text{ BTU/yd}^2$ gasoline

$(0.115 \text{ gal./yd}^2)(139{,}000 \text{ BTU/gal.}) = 15{,}985 \text{ BTU/yd}^2$ diesel

$(3{,}125 \text{ BTU/yd}^2)(70{,}392 \text{ yd}^2) = 0.219975 \times 10^9 \text{ BTU}$

$(15{,}985 \text{ BTU/yd}^2)(70{,}392 \text{ yd}^2) = 1.125216 \times 10^9 \text{ BTU}$

$1.345191 \times 10^9 \text{ BTU}$

This value will be used as a part of the energy requirements for Alternate 4.

The major energy requirement of Alternate 4 evolves from the production and placement of both the concrete pavement and the lean concrete base. Each mix will be analyzed in four parts: the cement, aggregate, plant operations, and the placement. Both mix designs are for one cubic yard of concrete. The mix designs used will be the following:

<u>Concrete Pavement (1 yd^3)</u>

Cement	-	565 lb.
Water	-	250 lb.
Aggregate	-	3100 lb.

<u>Lean Concrete Base (1 yd^3)</u>

Cement	-	250 lb.
Water	-	290 lb.
Aggregate	-	3150 lb.

There are two major energy requirements involved with the production of cement. These two major requirements are the actual production requirements and the energy to haul the cement to its point of usage. The average production requirement for cement is 6,220,000 BTU/ton.(1) Following is a list of the three major plants in Colorado which produce cement and their estimated distance from the job site. (Cement for Denver comes from all three plants.)

Lyons: 40 miles to Denver
LaPorte: 71 miles to Denver
Canon City: 115 miles to Denver

The average haul distance is calculated at 76 miles. To establish the energy requirement for the haul, a five axle diesel powered truck is assumed to be the means of transporting the cement. The energy requirements for trucks is found in the following table.(2)

3 axle	3,800 BTU/ton/mile
4 axle	3,270 BTU/ton/mile
5 axle	1,960 BTU/ton/mile

Hence, using the average haul distance as calculated above, the energy required to truck the cement is:

(76 mile) (2 way trip) (1960 BTU/ton/mile) = 297,920 BTU/ton

As with cement, the production of aggregates for the use in concrete involves two major items, the removal and the haul of the aggregate. The removal and handling of natural, uncrushed aggregate has been estimated to require 15,000 BTU/ton.(2) For this analysis a six mile haul distance using large five axle trucks has been assumed for the aggregate. Using these factors, an estimated value for hauling the aggregate is:

$$(6 \text{ mile})(2 \text{ way trip})(1960 \text{ BTU/ton/mile}) = 23{,}520 \text{ BTU/ton}$$

The information for plant production of concrete is hard to obtain. The following figures for plant operations are from "Energy Requirements For Roadway Pavements" (ERRP).[2] The aggregate used in the concrete mixture is assumed to contain 5% water. This added water then requires the handling of a larger amount of aggregate than called for by the mix design. This amount of aggregate is calculated as the following:

$$\left(\frac{3100 \text{ lb.}}{\text{yd}^3}\right)(1.05) = \frac{3255 \text{ lb.}}{\text{yd}^3}$$

From ERRP the two major factors affecting the energy required to produce concrete aggregate are:

Loader	-	4,375 BTU/ton
Conveyor	-	275 BTU/ton
Total		4,650 BTU/ton

This gives $(4{,}650 \text{ BTU/ton})(1 \text{ ton}/200 \text{ lb.})(3255 \text{ lb/yd}^3) = 7{,}568 \text{ BTU/yd}^3$ for the handling of the aggregate at the plant.

The plant used for the mixing of the concrete is assumed to be a 195 Horsepower plant. This plant is assumed to be an electrical plant which operates at 67% efficiency. The production of electricity is assumed to be produced at 31% efficiency. Combining all of these factors with the production rate of 300 yd^3/hr will give the energy for producing a cubic yard of concrete.[2]

$$\frac{(195 \text{ hp})(.67)(2{,}547 \text{ BTU/hp})}{(300 \text{ yd}^3/\text{hr})(.31)} = 3{,}580 \text{ BTU/yd}^3$$

Haul and placement of the concrete is the last major factor affecting the energy for constructing roadways of concrete. Because there is a plant extremely close to the I 76 job site it is assumed that this plant will be used. Three-axle concrete mixing trucks are assumed to be the means of transporting the mixed concrete. This gives the following value for the haul[2].

$$(1/4 \text{ mile})(2 \text{ way trip})\left(\frac{1.96 \text{ ton}}{\text{yd}^3}\right)(3{,}800 \text{ BTU/ton/mile}) = 3{,}724 \text{ BTU/yd}^3$$

Placement of the concrete is assumed to be done with a slip form paver. Following are values obtained from a local contractor for running a slip form paver.

Consumption - 15 gal./hr of diesel

Production - 300 yd^3/hr

Calculations now show the energy requirements for the placement of concrete to be:

$$\left(\frac{15 \text{ gal.}}{\text{hr}}\right)\left(\frac{\text{hr}}{300\text{yd}^3}\right)\left(\frac{139{,}000 \text{ BTU}}{\text{gal.}}\right) = 6{,}950 \text{ BTU/yd}^3$$

Combination of this information on the production of concrete yields the amount of energy required to produce one cubic yard of mix. The bottom of Table 1 shows the calculations for the energy requirements of the I 76 job. The quantities used in this calculation come from the previous sections of study. The total shown will be used in a later comparison.

The Concrete alternate calls for the use of lean concrete base as a base material. A portion of this material has aggregate which consists of recycled material. No energy will be attributed to the lean concrete base for the removal of the old concrete because this material must be removed no matter where or how it is used. No haul of this material is calculated because the crushing is assumed to be done on the job site.

The crushing process for the recycled material is assumed to be the same as that for the crushing of aggregates. The most accepted value for this process is 35,000 BTU/ton. In addition to the energy for crushing, 5,000 BTU/ton is required for the handling and separation equipment. Together these values give a total for the energy required to produce recycled aggregate of 40,000 BTU/ton.(2) In the same manner as that used for the regular concrete pavement, the weight of the aggregate handled in the plant is:

$$\left(\frac{3150 \text{ lb.}}{\text{yd}^3}\right) (1.05) = 3307 \text{ lb/yd}^3$$

Using the same energy factor as previously used, the energy requirement is:

$$\left(\frac{4650 \text{ BTU}}{\text{ton}}\right) \left(\frac{1 \text{ ton}}{2000 \text{ lb.}}\right) \left(\frac{3307 \text{ lb.}}{\text{yd}^3}\right) = 7,689 \text{ BTU/yd}^3$$

All other values for the production of lean concrete base are the same as those for concrete pavement. These values are the production of cement, mixing of the concrete, and the haul and placement of the mix. These values are all combined again in Table 2 to show the energy required to produce lean concrete base with both new and recycled aggregate. Also at the bottom of the table the energy required to produce the lean base for the I 76 job is calculated.

Present Asphalt Construction

Alternate 5 calls for the use of an asphalt pavement and an asphalt base. The production of Asphalt Cement with a viscosity of 1000 poise (AC-10) has numerous values quoted for the energy requirements of its production. Because of these diverse values one will be estimated by working from several basic assumptions. First, AC-10

Table 1

Concrete Mix - Alternate #4

Item	Energy Values	
Produce Cement	6,220,000 BTU/ton	
Haul Cement	297,920 BTU/ton	
	6,517,920 BTU/ton	
Natural Stone	15,000 BTU/ton	
Haul of Stone	23,520 BTU/ton	
	38,520 BTU/ton	
Mix Composition ($1\ yd^3$)		
Cement (565 lb)	1,841,312 BTU	
Water (250 lb)	- 0 -	
Aggregate (3100 lb)	59,706 BTU	
	1,901,018 BTU	1,901,018 BTU
Plant Operations ($1\ yd^3$)		
Handle Aggregate	7,568 BTU	
Mixing	3,580 BTU	
	11,148 BTU	11,148 BTU
Haul and Placement ($1\ yd^3$)		
Haul Mix	3,724 BTU	
Place Mix	6,950 BTU	
	10,674 BTU	10,674 BTU
TOTAL PER CUBIC YARD OF MIX		1,922,840 BTU/yd^3

Job requirement:

$$\left(\frac{1{,}922{,}840\ BTU}{yd^3}\right)(105{,}142\ yd^2)(8\ inches)(1\ yd/36\ inches) =$$

$$44.926943 \times 10^9\ BTU$$

Table 2

Lean Concrete Base - Alternate #4

	New Aggregate		Recycled Aggregate	
Produce Cement	6,220,000 BTU/ton		6,220,000 BTU/ton	
Haul Cement	297,920 BTU/ton		297,920 BTU/ton	
	6,517,920 BTU/ton		6,517,920 BTU/ton	
Stone	15,000 BTU/ton		40,000 BTU/ton	
Haul Stone	23,520 BTU/ton		- 0 -	
	38,520 BTU/ton		40,000 BTU/ton	
Mix Composition: (1 yd^3)				
Cement (250 lb)	814,740 BTU		814,740 BTU	
Water (290 lb)	- 0 -		- 0 -	
Aggregate (3150 lb)	60,669 BTU		63,000 BTU	
	875,409 BTU	Subtotal	677,740 BTU	Subtotal
Plant Operations (1 yd^3)				
Handle Agg.	7,689 BTU		7,689 BTU	
Mixing	3,580 BTU		3,580 BTU	
	11,269 BTU	Subtotal	11,269 BTU	Subtotal
Haul and Place (1 yd^3)				
Haul	3,724 BTU		3,724 BTU	
Place	6,950 BTU		6,950 BTU	
	10,674 BTU	Subtotal	10,674 BTU	Subtotal
TOTAL PER CUBIC YARD	897,352 BTU/yd^3		899,683 BTU/yd^3	

Job requirement:

New aggregate base $\left(\frac{897{,}352\ BTU}{yd^3}\right)(41{,}650\ yd^2)(6\ in.)(1\ yd/36\ in) = 6.229118467 \times 10^9\ BTU$

Recycled Aggregate Base $\left(\frac{899{,}683\ BTU}{yd^3}\right)(63{,}492\ yd^2)(6\ in)(1\ yd/36\ in) = 9.520445506 \times 10^9\ BTU$

$- 15.749564 \times 10^9\ BTU$

is assumed to be a by-product of crude oil, thus, it can be considered as having no energy potential. Hence, the only energy attributed to AC–10 is the energy required to produce this product.

To estimate the energy required to produce AC-10, the specific heat of oil can be taken as 0.5 BTU/lb./^{o}F. The temperature rise required to produce AC-10 goes from 100^{o} F to 800^{o} F under pressure. These values then show the number of BTU/lb. required for the production of AC-10.[4]

$$(800^{o}\,F - 100^{o}\,F)\,(0.5\ BTU/lb./^{o}F) = 350\ BTU/lb.$$

$$\left(\frac{350\ BTU}{lb.}\right)\left(\frac{2000\ lb.}{ton}\right) = 700{,}000\ BTU/ton$$

This value is one that would apply if the process would occur at 100% efficiency. However, a more appropriate efficiency rate of 80% results in 875,000 BTU/ton. Other values have been found ranging from 587,500 BTU/ton[2] to 3,150,930 BTU/ton.[5] Because of this wide range in values, a median value of 1,000,000 BTU/ton has been chosen as the energy required to produce AC-10.

One method to obtain AC-10 in Denver is by truck from Wyoming. The trucks used are assumed to be large five axle diesel trucks. The distance from the average Denver plant to Sinclair, Wyoming is estimated as 275 miles. Calculations then show the following value to truck AC-10 to Denver and return to the point of departure.

$$(275\ mile)\,(2\ way\ trip)\,(1960\ BTU/ton/mile) = 1{,}078{,}000\ BTU/ton$$

The second method to obtain AC-10 in Denver is to pipe the crude to Denver and then refine it here to produce the AC-10. One pipeline pumping crude oil from Wyoming to Denver has the following characteristics:[6]

Number of pumps = 7
Pump type = electric
Pump horsepower = 1500 hp
Average flow = 1500 barrels/hr
Time run = 24 hr per day

The average percentage of AC-10 contained in a barrel of crude is between 22% and 35%.[4] Further calculations give the percentage of energy that is attributed to the production of AC-10 if the crude for the product is piped from Wyoming to Denver.

$$\left(\frac{1500\ barrels}{hr}\right)\left(\frac{42\ gal.}{barrel}\right)\left(\frac{ton}{235\ gal.}\right) = 268\ ton/hr$$

$$\left(\frac{(1500\ hp/hr)\,(7\ pumps)\,(.67\ pump\ efficiency)\,(2547\ BTU/hp)}{\left(\frac{268\ ton}{hr}\right)\left(.31\ efficiency\ for\ electricity\ production\right)}\right) = \frac{215{,}673\ BTU}{ton\ crude}$$

$$\left(\frac{215{,}673\ \text{BTU}}{\text{ton crude}}\right)\left(\frac{0.29\ \text{ton crude}}{\text{ton AC}}\right) = 62{,}545\ \text{BTU/ton of AC}$$

In addition to this value, an average 19 mile haul is included as the distance between the refinery and the asphalt plants in Denver. This haul is assumed to be done by five axle diesel trucks. This adds the following amount of energy to the AC-10 that is piped:

(1960 BTU/ton/mile) (19 mile) (2 way) = 74,480 BTU/ton of AC

Total of these two values gives:

62,545 BTU/ton
74,480 BTU ton
137,025 BTU/ton

This is the amount of energy required to obtain AC-10 at the asphalt plants in Denver.

The aggregate for this material is assumed to be a crushed aggregate. As previously established the handling and crushing of such aggregate requires 40,000 BTU/ton. The haul of this aggregate is based on local contractors and their haul distances from local pits by using a combination of small and large trucks. The average distance has been estimated to be four miles. The two truck sizes are the three axle and five axle trucks. Each truck size is assumed to be used one half of the time. Use of these values yields an approximate energy consumption for the trucking of the aggregate.

(4 mi.) (3800 BTU/ton/mi.) (2 way) (1/2) = 15,200 BTU/ton
(4 mi.) (1960 BTU/ton/mi.) (2 way) (1/2) = 7,840 BTU/ton
23,040 BTU/ton

The actual mixing of asphalt cements involves three separate functions which consume energy. These parts are the drying of the aggregate, heating of the aggregate, and the other continuing plant operations. For the drying and the heating of the aggregate several assumptions are first established.[2]

A) Aggregate moisture is 5%
B) Raise the aggregate temperature an average of 230°F.
C) Aggregate makes up 94.2% of the HBP mix
D) 28,000 BTU/ton/% moisture required for the removal of water
E) 470 BTU/°F/ton aggregate required for heating

Calculations give the following figures:

Drying: (28,000 BTU/ton/%) (5%) (.942 ton) = 131,880 BTU for HBP
(28,000 BTU/ton/%) (5%) (.95 ton) = 133,000 BTU for PMBB

Heating: (470 BTU/°F/ton) (230°F) (.942 ton) = 101,830 BTU for HBP
(470 BTU/°F/ton) (230°F) (.95 ton) = 102,695 BTU for PMBB

Other plant operations are the third part of mixing asphalt cements. The energy consumed in this part can be categorized as:

A) asphalt storage

B) cold feed

C) dryer and exhaust

D) mixing plant

Each of these parts has its own value of energy consumption. For further details reference (2) should be consulted. As given by this reference the following list shows the values for energy consumption of each part and the estimated total for the plant operations in an average asphalt mix plant:

A)	asphalt storage	-	6,400 BTU/ton hot mix
B)	cold feed	-	4,730 BTU/ton hot mix
C)	dryer and exhaust	-	4,770 BTU/ton hot mix
D)	mixing plant	-	3,920 BTU/ton hot mix
	TOTAL		19,820 BTU/ton hot mix

Once the asphalt mix has been completed at the plant it must be hauled and placed at the job site. An average distance of six miles is assumed between the plant and the job site. The local producers haul the mixes in large five axle trucks one half of the time and three axle trucks the other half of the time. Using this information, calculations for the haul of the mixes are:

(6 mi.) (1960 BTU/ton/mile) (2 way trip) (.50) = 11,760 BTU/ton

(6 mi.) (3800 BTU/ton/mile) (2 way trip) (.50) = 22,800 BTU/ton

TOTAL = 34,560 BTU/ton

Placement of an asphalt mix will normally involve one laydown machine and two rollers. The fuel consumption and production rate for these machines are:[3]

Lay down: 4 gal./hr of diesel

200 ton/hr average production

Rollers: 4 gal./hr of diesel (each)

2 rollers for one laydown

Calculations will now give an average rate of energy consumption for the lay down of asphalt mixes.

$$\left(\frac{4 \text{ gal.}}{\text{hr.}}\right)\left(\frac{1 \text{ hr.}}{200 \text{ ton}}\right)\left(\frac{139{,}000 \text{ BTU}}{\text{gal.}}\right)(3 \text{ units}) = 8{,}340 \text{ BTU/ton of mix}$$

Having found all of the related energy consumption values, Tables 3 and 4 show how the energy required to produce asphalt mixes is found. Two tables are used to show the difference between the values when the AC-10 is hauled or piped to Denver. Each

Table 3

Asphalt Mix - Haul AC-10 - Alternate #5

Item	HBP @ 5.8% AC			PMBB @ 5% AC		
Produce AC	1,000,000	BTU/ton		1,000,000	BTU/ton	
Haul AC	1,078,000	BTU/ton		1,078,000	BTU/ton	
	2,078,000	BTU/ton		2,078,000	BTU/ton	
Crushed Stone	40,000	BTU/ton		40,000	BTU/ton	
Haul Stone	23,040	BTU/ton		23,040	BTU/ton	
	63,040	BTU/ton		63,040	BTU/ton	
Mix Composition (1 ton)						
% AC	120,524	BTU		103,900	BTU	
% Aggregate	59,384	BTU		59,888	BTU	
	179,908	BTU	Subtotal	163,788	BTU	Subtotal
Plant Operations (1 ton)						
Dry Agg.	131,880	BTU		133,000	BTU	
Heat Agg.	101,830	BTU		102,695	BTU	
Other	19,800	BTU		19,800	BTU	
	253,510	BTU	Subtotal	255,495	BTU	Subtotal
Haul and Place (1 ton)						
Haul	34,560	BTU		34,560	BTU	
Place	8,340	BTU		8,340	BTU	
	42,900	BTU	Subtotal	42,900	BTU	Subtotal
TOTAL PER TON OF MIX	476,318	BTU		462,183	BTU	

Job requirements:

HBP: 2" overlay and widening $\left(\frac{476{,}318 \text{ BTU}}{\text{ton}}\right)(7{,}743 + 31{,}544 \text{ ton}) = 18.713105 \times 10^9$ BTU

PMBB: Widening $\left(\frac{462{,}183 \text{ BTU}}{\text{ton}}\right)(31{,}544 \text{ ton}) = 14.579101 \times 10^9$ BTU

TOTAL: 33.292206×10^9 BTU

Table 4

Asphalt Mix - Pipe AC-10 - Alternate #5

Item	HBP @ 5.8% AC		PMBB @ 5% AC	
Produce AC-10	1,000,000 BTU/ton		1,000,000 BTU/ton	
Pipe AC	137,025 BTU/ton		137,025 BTU/ton	
	1,137,025 BTU/ton		1,137,025 BTU/ton	
Crushed Gravel	40,000 BTU/ton		40,000 BTU/ton	
Haul Gravel	23,040 BTU/ton		23,040 BTU/ton	
	63,040 BTU/ton		63,040 BTU/ton	
Mix Composition (1 ton)				
% AC	65,948 BTU		56,851 BTU	
% Aggregate	59,384 BTU		59,888 BTU	
	125,332 BTU	Subtotal	116,739 BTU	Subtotal
Plant Operations (1 ton)				
Dry Agg.	131,880 BTU		133,000 BTU	
Heat Agg.	101,830 BTU		102,695 BTU	
Other	19,800 BTU		19,800 BTU	
	253,510 BTU	Subtotal	255,495 BTU	Subtotal
Haul and Place (1 ton)				
Haul	34,560 BTU		34,560 BTU	
Place	8,340 BTU		8,340 BTU	
	42,900 BTU	Subtotal	42,900 BTU	Subtotal
TOTAL PER TON OF MIX	421,742 BTU		415,134 BTU	

Job Requirements:

HBP: 2" overlay and widening: $\left(\frac{421{,}742 \text{ BTU}}{\text{ton}}\right)(7{,}743 + 31{,}544 \text{ ton}) = 16.568978 \times 10^9$ BTU

PMBB: Widening $\left(\frac{415{,}134 \text{ BTU}}{\text{ton}}\right)(31{,}544 \text{ ton}) = 13.094987 \times 10^9$ BTU

TOTAL: 29.663965×10^9 BTU

table has two columns to show both the Hot Bituminous Pavement (HBP) and the Plant Mix Bituminous Base (PMBB). At the bottom of each table calculations showing the energy required for the job can be found. Again, the quantites used are from the beginning of this report.

Alternate 5 uses asphalt as the roadway material. The use of this material then requires the use of emulsified asphalt between existing roadways as well as between new asphalt layers. The energy to produce emulsified asphalt has been found to consume 1980 BTU/gallon.[2] In addition to the production of the emulsified asphalt, the energy required to pipe the crude to Denver must also be considered. From the previous page on piping, and using the percentages of emulsified asphalt contained in a gallon of AC-10, the following energy can be calculated.

$$\left(\frac{62{,}545 \text{ BTU}}{\text{ton AC}}\right)\left(\frac{\text{ton AC}}{235 \text{ gal.}}\right)\left(\frac{.65 \text{ gal. AC}}{\text{gal. Emul.}}\right) = \frac{173 \text{ BTU}}{\text{gal. of Emulsified}}$$

A haul that requires energy is the daily travel distance between the job and the supplier. This distance has been estimated to be a total of six miles one way. It is estimated that two tankers per day will be used. The use of two 3 axle gasoline tankers which run on 4,270 BTU/ton/mile would then require the following energy.[2]

$$(4270 \text{ BTU/ton/mile})(6 \text{ mile})\left(\frac{\text{ton}}{241 \text{ gal.}}\right)(2 \text{ way trip}) = 213 \text{ BTU/gal. of emulsified}$$

Other trucking of the emulsified asphalt is done by the tanker when it sprays the emulsified asphalt between the asphalt layers. Estimates of the mileage covered in the process are as follows:

Widening	-	(5 passes) (4 coats) (1 mile) =	20 mile
Existing	-	(6 passes) (1 coat) (1 mile) =	6 mile
New	-	(12 passes) (4 coats) (1/5 mile) =	10 mile
			36 mile

Further calculation yields:

$$(4270 \text{ BTU/ton/mile})(36 \text{ mile})\left(\frac{\text{ton}}{241 \text{ gal.}}\right)(2 \text{ way}) = 1276 \text{ BTU/gal. Emulsified}$$

In addition to the trucking of the emulsified asphalt there are the energy requirements of the distribution system on the emulsified asphalt truck. Assumptions for this system are as follows:

A) 35 horsepower distributor at 75% efficiency
B) 10 gal./min./bar foot output
C) 12 ft. bar length
D) heating of 100 BTU/gal. required

Calculations now give the following BTU/gal. for the distribution of the emulsified asphalt:

$$\frac{(35\text{ hp})(.75)(.06\text{ gal./hp/hr})(125{,}000\text{ BTU/gal.})}{(10\text{ gal./min./ft})(12\text{ ft})(60\text{ min./hr})} = 27\text{ BTU/gal.}$$

Totaling all of these factors together, the BTU/gal. for the use of emulsified asphalt can be found.

Production	=	1980 BTU/gal.
Piping	=	173 BTU/gal.
Trucking	=	1489 BTU/gal.
Distributor	=	27 BTU/gal.
Heating	=	100 BTU/gal.
		3,769 BTU/gal.

Using the job estimate, the energy required for the I 76 job is:

(3,769 BTU/gal.) (21,464 gal.) = 80,897,816 BTU

A third and final aspect of the asphalt alternate to consider is the filling of all large cracks in the existing roadway. Initial estimates have shown that 18 tons of crack filler will be required to complete the job. This filler will consist of a mixture containing 75% AC-10 and 25% scrap rubber. Hence, for this mixture the only portion requiring energy will be that of the AC-10. This energy can be broken down into two different values depending upon how the AC-10 is obtained. These two values will then be entered into each separate analysis.

Haul AC-10: $\left(\frac{2{,}078{,}000\text{ BTU}}{\text{ton}}\right)(18\text{ ton})(.75) = 28{,}053{,}000\text{ BTU}$

Pipe AC-10: $\left(\frac{1{,}137{,}025\text{ BTU}}{\text{ton}}\right)(18\text{ ton})(.75) = 15{,}349{,}838\text{ BTU}$

This completes the analysis of present construction methods for both alternates. A factor which will enter into the entire outlook of each alternate is the need of future construction requirements. The normal time period of study for roadways is 35 years beyond the initial construction. This analysis will now use that same 35 year period for study of future construction estimates. The energy values and quantities used in this portion of the report come from the previous sections.

Future Energy Requirements

Concrete Alternate

Grinding: $(3{,}125\text{ BTU/yd}^2)(175{,}534\text{ yd}^2) = 0.54850 \times 10^9\text{ BTU}$

$(15{,}985\text{ BTU/yd}^2)(175{,}534\text{ yd}^2) = 2.805437 \times 10^9\text{ BTU}$

$3.353937 \times 10^9\text{ BTU}$

Future 1" overlay on 30th year using HBP. (take average of the haul AC and pipe AC values)

$$(11{,}196 \text{ ton}) \left(\frac{476{,}318 \text{ BTU/ton} + 421{,}742 \text{ BTU/ton}}{2} \right) = 5.02733988 \times 10^9 \text{ BTU}$$

Future CSS -lh on 30th year:

$$(10{,}178 \text{ gal.})(3{,}769 \text{ BTU/gal.}) = 38{,}360{,}882 \text{ BTU}$$

Asphalt Alternate

Haul AC:

$$(67{,}173 \text{ ton})(476{,}318 \text{ BTU/ton}) = 31.995709 \times 10^9 \text{ BTU}$$
$$(27 \text{ ton})(2{,}078{,}000 \text{ BTU/ton}) = 56{,}106{,}000 \text{ BTU}$$
$$(40{,}711 \text{ gal.})(3{,}769 \text{ BTU/gal.}) = \underline{153{,}439{,}759 \text{ BTU}}$$
$$32.205255 \times 10^9 \text{ BTU}$$

Pipe AC:

$$(67{,}173 \text{ ton})(421{,}742 \text{ BTU/ton}) = 28.329675 \times 10^9 \text{ BTU}$$
$$(27 \text{ ton})(2{,}078{,}000 \text{ BTU/ton}) = 30{,}699{,}675 \text{ BTU}$$
$$(40{,}711 \text{ gal.})(3{,}769 \text{ BTU/gal.}) = \underline{153{,}439{,}759 \text{ BTU}}$$
$$28.513814 \times 10^9 \text{ BTU}$$

These are the estimated values for the future construction on this roadway. These values will be used to find the total energy requirements of each alternate. The asphalt alternate will be analyzed in two parts to cover the differences between using the piped AC-10 or trucked AC-10. Three example companies will be used to illustrate that the factors affecting energy consumption in highway construction are numerous.

Example Contractors

The first of these companies is Western Paving Company. The two unique aspects of this company are the manner of hauling the aggregate and the placement of the mix. The first of these, aggregate haul, is accomplished by the use of a train from Lyons, Colorado. This train has the following characteristics:[7]

Haul: 3,000 tons/trip

Fuel: 380 gallons of diesel per round trip

Calculations now show the energy required per ton of aggregate.

$$\left(\frac{380 \text{ gal.}}{3000 \text{ ton}} \right) \left(\frac{139{,}000 \text{ BTU}}{\text{gal.}} \right) = \frac{17{,}606 \text{ BTU}}{\text{ton}}$$

This is the value to be used for the haul of stone by Western Paving.

A second factor affecting the energy requirements of Western Paving is the haul distance from the plant to the job site. This haul is assumed to be done using two truck types, three and five axle. Each truck type is assumed to haul one half of the time. The distance that has been estimated for Western Paving between the plant and job site is six miles. Calculations now give:

Table 5

Western Paving - Alternate #5

Item	HBP @ 5.8% AC		PMBB @ 5% AC	
Produce AC-10	1,000,000 BTU/ton		1,000,000 BTU/ton	
Haul Oil (AC)	1,078,000 BTU/ton		1,078,000 BTU/ton	
	2,078,000 BTU/ton		2,078,000 BTU/ton	
Crushed Stone	40,000 BTU/ton		40,000 BTU/ton	
Haul Stone	17,606 BTU/ton		17,606 BTU/ton	
	57,606 BTU/ton		57,606 BTU/ton	
Mix Composition (1 ton)				
% AC	120,524 BTU		103,900 BTU	
% Aggregate	54,265 BTU		54,725 BTU	
	174,789 BTU	Subtotal	158,625 BTU	Subtotal
Plant Operations (1 ton)				
Dry Aggregate	131,600 BTU		133,000 BTU	
Heat Aggregate	101,614 BTU		102,695 BTU	
Other	19,800 BTU		19,800 BTU	
	253,014 BTU	Subtotal	255,495 BTU	Subtotal
Haul and Place (1 ton)				
Haul 6 mi @ 2880	34,560 BTU		34,560 BTU	
Place	8,340 BTU		8,340 BTU	
	42,900 BTU	Subtotal	42,900 BTU	Subtotal
TOTAL PER TON MIX	470,703 BTU		457,020 BTU	

Job Requirements:

HBP: 2" overlay and widening $\left(\frac{470{,}703\ \text{BTU}}{\text{ton}}\right)(7{,}743 + 31{,}544\ \text{ton}) = 18.492509 \times 10^9$ BTU

PMBB: Widening $\left(\frac{457{,}020\ \text{BTU}}{\text{ton}}\right)(31{,}544\ \text{ton}) = 14.416239 \times 10^9$ BTU

AC for Crack fills: current & future $\left(\frac{2{,}078{,}000\ \text{BTU}}{\text{ton}}\right)(13.5 + 27\ \text{ton}) = 84{,}159{,}000$ BTU

Future overlays $\left(\frac{470{,}703\ \text{BTU}}{\text{ton}}\right)(67{,}173\ \text{ton}) = 31.618533 \times 10^9$ BTU

$$\frac{(3{,}800\ \text{BTU/ton/mile} + 1960\ \text{BTU/ton/mile})}{2} =$$

2880 BTU/ton/mile for one way

(2880 BTU/ton/mile) (6 mile) (2 way) = 34,560 BTU/ton/mile

Using all other established values the energy requirements for Western Paving can be found. It is assumed here that Western Paving obtains its AC-10 from a manufacturer who hauls the product to Denver. A comparison will show that all other values are the same as those which have been calculated in the general analysis. Table 5 shows the entire analysis for Western Paving.

Like Western Paving, the Asphalt Paving Company has special aspects which deviate from the general analysis. This company is assumed to use AC-10 which has been piped to Denver. With this energy cost, a haul of 16 miles must be included. This haul is assumed to be done by large five axle trucks. Calculations then give the following energy for trucking:

(1960 BTU/ton/mile) (16 mile) (2 way trip) = 62,720 BTU/ton

The second value of concern is the haul of the aggregate for this company. This value is assumed to be zero because the pits for this company are located at the plant site. Thus, the only energy required to produce aggregate is that used to crush the material.

A third value of concern is the haul of the mix from the plant to the job site. For Asphalt Paving, this haul is assumed to be done one half of the time by three axle trucks and one half of the time by larger five axle trucks. As calculated with Western Paving, this requires an average of 2880 BTU/ton/mile. For Asphalt Paving, this value will be multiplied by an estimated 5.5 miles to find the energy required to haul the mix:

$$(2880\ \text{BTU/ton/mile})\ (5.5\ \text{mile})\ (2\ \text{way trip}) = \frac{31{,}680\ \text{BTU}}{\text{ton}}$$

Table 6 may now be used to find the energy required by Asphalt Paving Company to produce the material for this job. At the bottom of the table the entire energy required for the job may be found. The quantities used are from the preliminary analysis covered at the beginning of this report.

Similar to the two examples above, Peter Kiewit and Sons (PKS) has three major deviations from the general analysis. Like Asphalt Paving, PKS uses AC-10 which has been piped to Denver. The haul for PKS has been estimated to be 23 miles using five axle trucks. Calculations for this energy requirement show:

Table 6
Asphalt Paving - Alternate #5

Item	HBP @ 5.8% AC		PMBB @ 5% AC	
Produce AC	1,000,000 BTU/ton		1,000,000 BTU/ton	
Pipe AC	62,545 BTU/ton		62,545 BTU/ton	
Haul AC (16 mi)	62,720 BTU/ton		62,720 BTU/ton	
	1,125,265 BTU/ton		1,125,265 BTU/ton	
Crushed Gravel	40,000 BTU/ton		40,000 BTU/ton	
Haul 0.0 mi	- 0 -		- 0 -	
	40,000 BTU/ton		40,000 BTU/ton	
Mix Composition (1 ton)				
% AC	65,265 BTU		56,263 BTU	
% Aggregate	37,680 BTU		38,000 BTU	
	102,945 BTU	Subtotal	94,263 BTU	Subtotal
Plant Operations (1 ton)				
Dry Aggregate	131,600 BTU		133,000 BTU	
Heat Aggregate	101,614 BTU		102,695 BTU	
Other	19,800 BTU		19,800 BTU	
	253,014 BTU	Subtotal	255,495 BTU	Subtotal
Haul and Place (1 ton)				
Haul 5.5 mi @ 2880	31,680 BTU		31,680 BTU	
Place	8,340 BTU		8,340 BTU	
	40,020 BTU	Subtotal	40,020 BTU	Subtotal
TOTAL PER TON MIX	395,979 BTU		389,778 BTU	

Job Requirements:

HBP: 2" overlay and widening $\left(\frac{395{,}979 \text{ BTU}}{\text{ton}}\right)$ (7,743 + 31,544 ton) = 15.556827×10^9 BTU

PMBB: Widening $\left(\frac{389{,}778 \text{ BTU}}{\text{ton}}\right)$ (31,544 ton) = 12.295157×10^9 BTU

AC for crack fills: current & future $\left(\frac{1{,}125{,}265 \text{ BTU}}{\text{ton}}\right)$ (27 + 13.5 ton) = 45,573,233 BTU

Future overlays $\left(\frac{395{,}979 \text{ BTU}}{\text{ton}}\right)$ (67,173 ton) = 26.599097×10^9 BTU

Table 7
PKS - Alternate #5

Item	HBP @ 5.8% AC		PMBB @ 5.0 % AC	
Produce AC	1,000,000 BTU/ton		1,000,000 BTU/ton	
Pipe AC	62,545 BTU/ton		62,545 BTU/ton	
Haul AC (23 mi)	90,160 BTU/ton		90,160 BTU/ton	
	1,152,705 BTU/ton		1,152,705 BTU/ton	
Crushed Gravel	40,000 BTU/ton		40,000 BTU/ton	
Haul	5,760 BTU/ton		5,760 BTU/ton	
	45,760 BTU/ton		45,760 BTU/ton	
Mix Composition (1 ton)				
% AC	66,857 BTU		57,635 BTU	
% Aggregate	43,106 BTU		43,472 BTU	
	109,963 BTU	Subtotal	101,107 BTU	Subtotal
Plant Operations (1 ton)				
Dry Aggregate	131,600 BTU		133,000 BTU	
Heat Aggregate	101,614 BTU		102,695 BTU	
Other	19,800 BTU		19,800 BTU	
	253,014 BTU	Subtotal	255,495 BTU	Subtotal
Haul and Place (1 ton)				
Haul 18 mi @ 2880	103,680 BTU		103,680 BTU	
Place	8,340 BTU		8,340 BTU	
	112,020 BTU	Subtotal	112,020 BTU	Subtotal
TOTAL PER TON MIX	474,997 BTU		468,622 BTU	

Job Requirements:

HBP: 2" overlay and widening $\left(\frac{474{,}997 \text{ BTU}}{\text{ton}}\right)(7{,}743 + 31{,}544 \text{ ton}) = 18.661207 \times 10^9$ BTU

PMBB: widening $\left(\frac{468{,}622 \text{ BTU}}{\text{ton}}\right)(31{,}544 \text{ ton}) = 14.782212 \times 10^9$ BTU

AC for crack fills: current & future $\left(\frac{1{,}152{,}705 \text{ BTU}}{\text{ton}}\right)(27 + 13.5 \text{ ton}) = 46{,}684{,}553$ BTU

Future overlays $\left(\frac{474{,}997 \text{ BTU}}{\text{ton}}\right)(67{,}173 \text{ ton}) = 31.906973 \times 10^9$ BTU

(1960 BTU/ton/mile) (23 mile) (2 way) = 90,160 BTU/ton

The haul for aggregate of PKS is unique as compared to others because one of their pits is at the plant site and the other is two miles from the plant. Of the aggregate that is hauled, one half is assumed to be done by small trucks and the other half by larger trucks. As was established before, the combination of trucks requires 2,880 BTU/ton/mile. Calculations now yield the following energy requirement for the aggregate haul.

(2880 BTU/ton/mile) (2 mile) (2 way) (1/2 of agg.) = 5,760 BTU/ton

As with the others, the hauling of the mix by PKS is unique. This distance is assumed to be covered with the two types of trucks which again require 2880 BTU/ton/mile. Table 7 may now be followed to see the energy required by PKS.

Table 8 may now be followed to observe the differences in energy requirements. The values on this table may be found on all other tables. Table 9 shows the differences between the concrete alternate and the several asphalt analyses. Here a positive number will indicate that the concrete alternate requires more energy. A negative number would show that the concrete alternate requires less energy. The calculation of equivalent gallons of gasoline is based on 125,000 BTU/gallon of gas. The positive and negative numbers in this column apply as they do in Table 9.

Conclusions

The major purpose of this report has been to investigate the energy required to complete a highway project. Upon completion of this report it can be concluded that less energy would be consumed if asphalt were used as the basic roadway material. This conclusion is based upon the results shown on Table 8 with the understanding that these values are based on several previously stated assumptions.

A study reveals that the energy requirements for the production of AC-10, the major component of asphalt mix, is variable. Therefore, it can also be debated that the energy requirements for asphalt mix, itself, is variable. This factor will always remain such a variable when calculating the energy required to produce and use AC-10 in asphalt mix.

Looking at the concrete alternative shows that the major energy cost is in the production of cement. All data indicates that the energy required to produce cement is descending. For this reason the value as calculated for this report may and hopefully

Table 8

Item	(1) Concrete Energy	
Present Grinding	1.345344×10^9	
Lean Base	15.749564×10^9	
Concrete Pavement	44.926943×10^9	Initial Subtotal: 62.021851×10^9 BTU
Future Grinding	3.353937×10^9	
Future Overlay	5.0657008×10^9	Future Subtotal: 8.4196378×10^9 BTU
TOTAL	70.441489×10^9 BTU	

Item	(2) General Haul AC	(3) General Pipe AC	(4) Western	(5) Asphalt Paving	(6) P K S
PMBB	14.579101×10^9	13.094987×10^9	14.416239×10^9	12.295157×10^9	14.782212×10^9
HBP	18.713105×10^9	16.568978×10^9	18.492509×10^9	15.556827×10^9	18.661207×10^9
CSS-1h	80,897,816	80,897,816	80,897,816	80,897,816	80,897,816
Crack fill	28,053,000	15,349,838	28,053,000	15,191,078	15,561,511
Subtotal	33.401156×10^9	29.760213×10^9	33.017669×10^9	27.948073×10^9	33.539878×10^9
Future Overlays	31.995709×10^9	28.329675×10^9	31.618533×10^9	26.599097×10^9	31.906973×10^9
Future CSS-1h	153,439,759	153,439,759	153,439,759	153,439,759	153,439,759
Future Crack Fill	56,106,000	30,699,675	56,106,000	30,382,155	31,123,022
Subtotal	32.205255×10^9	28.513814×10^9	31.828079×10^9	26.782919×10^9	32.091536×10^9
TOTALS (BTU)	65.606411×10^9	58.274027×10^9	64.845748×10^9	54.730992×10^9	65.631414×10^9

Table 9

Energy Comparisons

Analysis #1 - Analysis # n			BTU Difference	Equivalent Gallons of Gas
#1	-	#2	+ 4.835078×10^9 BTU	+ 38,680 gal.
#1	-	#3	+ 12.167462×10^9 BTU	+ 97,340 gal.
#1	-	#4	+ 5.595741×10^9 BTU	+ 44,766 gal.
#1	-	#5	+ 15.710497×10^9 BTU	+ 125,684 gal.
#1	-	#6	+ 4.810075×10^9 BTU	+ 38,481 gal.

will change to a lower value. Any small change will make no difference in the conclusions drawn by this report. However, a large change may make a difference in the current conclusions.

Other assumptions in this report may be found, debated, and changed. As discussed above some parts of this report will always remain variable factors. Other parts will change because of industrial changes in production. Yet, the parts of this report based on assumptions are as valid and true as current evidence indicates. For this same reason any portion of this report used for other purposes should first be verified as the most current information.

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66-3 Interim Report on the Clifton-Highline Canal Experimental Project I 70-1(14)33 #1
66-4 Final Report on Statistical Research Project - Quality Control Study on Asphalt Pavement
66-5 Final Report on the Automatic "Icy Road" Sign Study
66-6 Interim Report on Crawford-South Experimental Project S 0125(9) #1
66-7 Final Report on the Strasburg E & W Pavement Study I 70-4(30)
66-8 ASCE Report on High Altitude Multiple Vehicle Emission Tests
66-9 Final Report on Photo and Engineering Geology Along Interstate Route 70 from Dotsero to Rifle, Colorado
66-10 Interim Report on the Reflective Traffic Bead Study #1
66-11 Rock Slope Stability in the Precambrian Metamorphic Rocks of the Front Range, Colorado

67-1 Interim Report on Experimental Base Project at Ordway, Colorado #2
67-2 Second Interim Report on Crawford-South Experimental Project S 0125(9)
67-3 Interim Report on Clifton-Highline Canal Experimental Project I 70-1(14)33 #2
67-4 Reflective Traffic Bead Study #2
67-5 Density-Temperature-Roller Data from Asphalt Paving Projects in Colorado
67-6 Skid Resistance in Colorado
67-7 Swelling Soils Study at Cedar Point, Colorado
67-8 Lime Shaft and Lime Till Stabilization of Subgrades on Colorado Highways
67-9 Embankment Construction Without Moisture-Density Control
67-10 Study of Preformed Open Cell Neoprene Joint Sealer
67-11 Dielectric Measurements of Asphalt Content
67-12 Revision of Colorado CHLOE Profilometer
67-13 Performance of Box Beam Guard Rail Having Vertical Post Mounted in Sand
67-14 Scaling on Concrete Bridge Decks

68-1 Rock Rippability Study
68-2 Equilibrium Moisture and Density Study of Subgrades in Colorado
68-3 Grooving of Concrete Pavement Surfaces in Colorado to Prevent Hydroplaning
68-4 A Statistical Study of Rock Slopes in Jointed Gneiss with Reference to Highway Rock Slope Design
68-5 Reflective Traffic Bead Study -Interim #3
68-6 Use of a Microwave Oven for Rapid Drying of Aggregate Samples
68-7 Means for Measuring Surface Smoothness
68-8 Culvert Performance at Test Sites in Colorado
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69-2 The Whitewater Experimental Project - First Interim Report
69-3 Evaluation of Dielectric Measurement Apparatus for Determining Pavement Density
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69-7 Follow Up Report, Colorado's Reflective Bead Study
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71-2 Effect of Vibration on Durability of Concrete
71-3 Lighted Deer Crossing Signs and Vehicular Speed

72-1 Reflection Cracking in Bituminous Overlays - Interim Report
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72-3 Skid Testing in Colorado
72-4 Development of Dwarf Ground Cover for Erosion Control in Colorado
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72-6 Styrofoam Highway Insulation on Colorado Mountain Passes
72-7 Colorado Tunnel Ventilation Study - Interim Report
72-8 Effectiveness of Absorptive Form Liner for Horizontal Surfaces
72-9 Partially Beaded Centerline Markings
72-10 Field Study of Erosion Control Agents in Colorado
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73-2 The Ordway Colorado Experimental Base Project
73-3 Noise Levels Associated with Plant Mix Seals
73-4 Accelerated Concrete Strength Study
73-5 Colorado Tunnel Ventilation Study
73-6 Clifton-Highline Canal Experimental Report
73-7 Seibert Experimental Project

74-1 Implementation Package for Swelling Soils in Colorado
74-2 Embankments With and Without Moisture Density Control

75-1 Erosion Control and Revegetation on Vail Pass
75-2 The Effects of Vibration on Durability of Concrete Pavement
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76-3 Absorptive Form Liner and Burlap and Cement and Sand to Assist Bridge Deck Cure
76-4 Low Profile Markers for Wet/Night Visibility
76-5 Erosion Control and Revegetation on Vail Pass
76-6 Reflection Cracking in Bituminous Overlays
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