Estimating Diesel Fuel Consumption and Carbon Dioxide Emissions from Forest Road Construction

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Abstract: *Forest access road construction is a necessary component of many on-the-ground forest vegetation treatment projects. However, the fuel energy requirements and associated carbon dioxide emissions from forest road construction are unknown. We present a method for estimating diesel fuel consumed and related carbon dioxide emissions from constructing forest roads using published results from a study designed to measure road construction costs together with machine productivity and fuel consumption rates. Our resulting estimate of diesel fuel required per mile of road constructed on slopes up to 50% using a cut-fill construction method is 590 gallons, with 13,400 pounds of carbon dioxide emitted per mile of road built. Using a full bench road construction method on slopes greater than 50% where volume of material handled and moved is very sensitive to hill slope and soil type, we estimated between 3,265 and 8,000 gallons of diesel fuel are required per mile of road emitting between 74,400 to 182,700 pounds of carbon dioxide.*

Keywords: forest roads, carbon, carbon accounting, forest management, road construction, forest products, diesel emissions

Introduction

In 2007 the Chief of the US Forest Service outlined three ways in which forests, including national forest system lands, can be used to address climate change. The first is to manage forests in ways that make them more resistant to fires, insects, and disease resulting in more resilient forest stands. Second, the

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Forest Service should reduce its own carbon footprint, which includes generating more heat from woody biomass, a renewable source of energy that offsets the use of non-renewable fossil fuels. And third is to use the nation's forests to reduce the buildup of greenhouse gases, with support for carbon markets that ultimately convert forests into a carbon sink (Kimball 2007). All three of these proposals share a common theme, as stated by the Chief: "…protecting the existing carbon sink through forest conservation and increasing carbon sequestration through reforesting degraded land, improving forest health, and supporting sustainable forest management" (Kimball 2007). Accomplishing almost any aspect of this agenda will require some form of on-the-ground wood fiber removal.

While carbon storage in forest products is viewed as a means to defer disturbance-related emissions (Skog and Nicholson, 2000), the forest operations enabling this deferral almost always involve the release of fossil carbon, including harvesting and hauling products, and constructing the forest roads, either temporary or permanent, over which raw products are initially hauled. Healey and others (this volume) used historical harvest records and some assumptions about product carbon dynamics to calculate the magnitude and timing of carbon sequestration related to harvesting in Ravalli County, Montana. Healey and others also digitized a county-wide visual assessment of new roads apparent in sequential Landsat satellite imagery. These new-road maps, used together with spatially co-registered slope data, will in the future provide an application for the forest road construction emission factors discussed here. While forest operations release fossil carbon, little attention has been devoted to measuring carbon emissions associated with the various aspects of forest operations and forest products procurement.

The literature discussing carbon accounting methods and guidelines for harvested wood product flows between carbon pools is well established (Birdsey 2006; IPCC 2003, 2006). The Consortium for Research on Renewable Industrial Materials modeled fossil fuel consumption for stump-to-truck harvesting of wood products in the US Northwest and Southeast (CORRIM 2006) and Markewitz (2006) provides a detailed methodology for tracking fossil fuel consumption during silvicultural activities. However, the literature directly discussing the fossil fuel requirements and related emissions to construct the forest roads over which forest operations equipment travel is extremely sparse. A small portion of the forest road construction literature is financially-based, but contains little or no information about the fuel consumption underlying road construction costs (Balcom 1988; Layton and others 1992; Erickson and others 1992; USFS 2007).

Because forest access road construction is a necessary and critical component of many forest vegetation treatment projects, the range of fuel energy requirements and associated emissions from road construction are needed for an accurate carbon accounting of forest vegetation treatments. Here we present a methodology for estimating diesel fuel consumption and corresponding carbon dioxide emissions associated with building forest roads, and discuss its benefits and limitations.

Methods and Results

There are two common ways to construct a forest road in mountainous terrain – the cut-fill method and the full bench method. The cut-fill method is used on gentle to moderate hill slopes ranging from approximately 0% – 50% and the full bench method is employed for steeper slopes. Using the cut-fill method, the builder would *cut* into hillside approximately half of the total road width, and then use the material removed by that cut as *fill* to construct the remaining half of the road on the downhill slope (Figure 1). When the full bench method is employed, the builder cuts into the hillside the entire width of the road, essentially creating a *bench* in the hill serving as the base of the road (Figure 2). Historically bulldozers have been the primary equipment used to construct forest roads. However, according to Forest Service Northern Region engineers most forest road building contractors switched to using hydraulic excavators in the mid to late 1980's (pers. comm. Rich Raines 3 October 2008; pers. comm. Marcia Hughey 15 October 2008). Excavators were found to be much more versatile and efficient for building forest roads, able to incorporate all aspects of road building into one single pass (Balcom 1988).

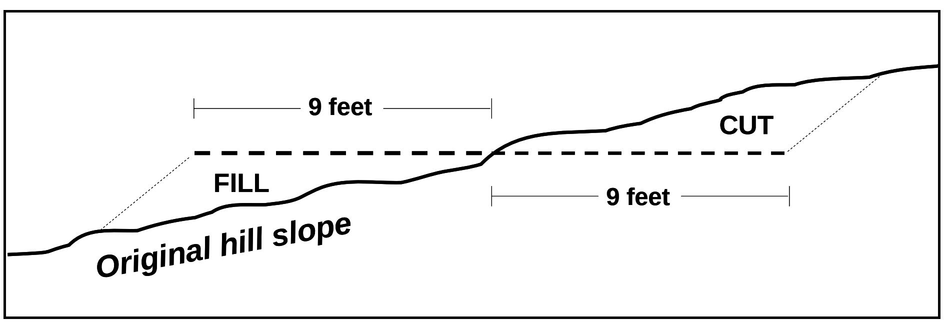

Figure 1: Cross sectional view of hill slope on which an eighteen feet wide road base would be constructed with the cut-fill method.

In this paper we have derived estimates of fuel consumption and resulting carbon dioxide emissions from building forest roads using information from Balcom (1988) and the Caterpillar Performance Handbook (CAT 1989, 2007). We estimate fuel consumption and emissions for each of the following major road building activities for both the cut-fill and full bench methods: 1) pioneering, 2) clearing and grubbing, and 3) sub-grade excavation. However, the following methodology is not limited to using the results from our selected sources. Rather, we have conceptualized a framework for estimating fuel consumption and emissions that is not limited to our selected sources.

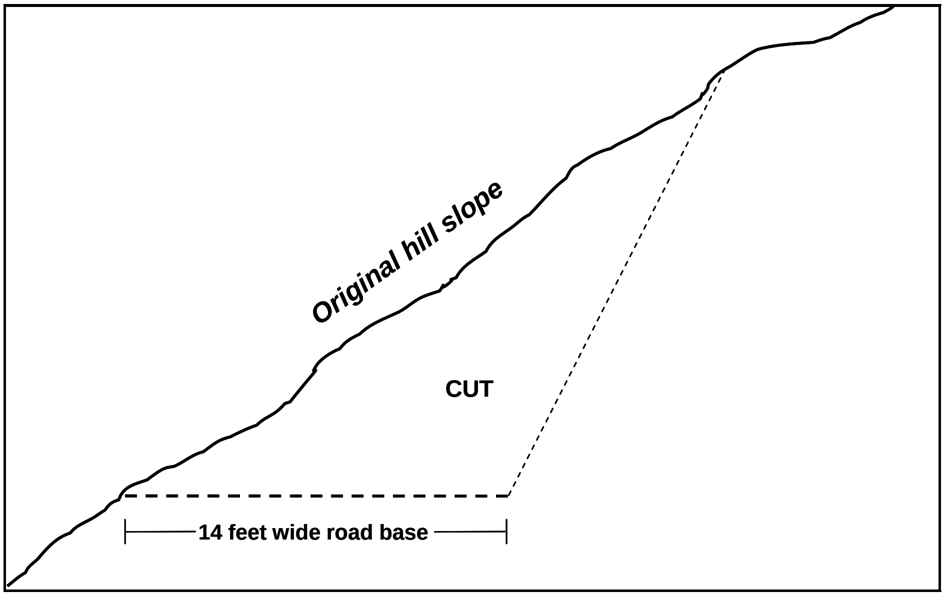

Figure 2: Cross sectional view of hill slope on which a fourteen feet wide road base would be constructed with the full bench method.

Cut-Fill Road Construction

Balcom (1988) conducted a time-motion study of forest road construction costs in Oregon using both crawler tractors and hydraulic excavators. This time-motion study provides results of feet per hour for building roads using the cut-fill method on hill slopes up to 50%. Although several types of machines were analyzed by Balcom, we isolated the results from the Caterpillar 235 hydraulic excavator and acquired that machine's fuel consumption rate of 8 gallons per hour from the 1989 Caterpillar Performance Handbook (CAT 1989) assuming 72% utilization, the midpoint in the utilization range listed for forestry operations. Average construction rates in linear feet per hour reported by Balcom were used to estimate pioneering, clearing and grubbing, and sub-grade excavation. Table 1 displays the average production per hour and fuel consumption per linear foot of road constructed for each of the three major road building activities listed above. Our estimates show that using a hydraulic excavator to construct forest roads with the cut-fill method on gentle slopes consumes approximately 0.11140 gallon of diesel per linear foot of road constructed, or approximately 590 gallons per mile.

We then combined the diesel fuel consumption estimate with emissions data for internal combustion diesel engines reported by the US Environmental Protection Agency (EPA 1995) and diesel energy content reported by the US Energy Information Administration (EIA 2008), which resulted in a carbon dioxide emission factor of 22.796 pounds per gallon of diesel. Combining this with molecular weights for carbon (12) and oxygen (16) yields the carbon dioxide and carbon equivalent results displayed in Table 2.

Table 1: Diesel fuel consumption per linear foot of forest road construction using the cut-fill method on slopes less than 50% for eighteen feet wide roads.

Road construction activity	Production (feet/hour)[a]	Diesel consumption (gallon/foot)	Diesel consumption (gallons/mile)
Pioneering	582	0.01375	73
Clearing and grubbing	129.5	0.06178	326
Sub-grade excavation with sidecasting	223	0.03587	189
Total of all activities		0.11140	588

[a] From Balcom (1988)

Approximately 2.5 pounds of carbon dioxide are emitted from diesel fuel burned per linear foot of forest road constructed on slopes less than 50%, or 13,400 pounds per mile. The carbon equivalent using the carbon-to-carbon dioxide ratio of 12/44 equals roughly 0.7 pound of carbon per linear foot of road construction, or 3,650 pounds of carbon per mile.

Table 2: Carbon dioxide emissions per linear foot of forest road construction using the cut-fill method on slopes less than 50% for eighteen feet wide roads.

Road construction activity	Carbon dioxide emissions (pounds/foot)	Carbon dioxide emissions (pounds/mile)	Carbon equivalent (pound/foot)	Carbon equivalent (pounds/mile)
Pioneering	0.31345	1,655	0.08548	451
Clearing and grubbing	1.40834	7,436	0.38409	2,028
Sub-grade excavation	0.81769	4,317	0.22301	1,177
Total of all activities	2.53947	13,408	0.69258	3,657

Full Bench Road Construction

Contrary to gentle slopes for which the cut-fill method would be appropriate, the amount of material that needs to be handled and moved to construct a full bench road in steep terrain is very sensitive to percent hill slope and soil type. Because of this, measuring the amount of cubic material handled and moved is critically important. To estimate the amount of cubic material for any given hill slope and cut slope, we multiply the cross sectional area that would be cut into the hill by the linear distance of road constructed (Douglas 1999). The cross sectional area of the hill cut out to build the road (bold area in Figure 3) is calculated with the following equation (see Appendix A):

$$Area = \frac{1}{200} \cdot w^2 \cdot \frac{c \cdot s}{c - s} \qquad \text{[Equation 1]}$$

In this equation, $Area$ is the cross sectional area in square feet, w denotes the width of the road base in feet, and s and c denote the percent hill slope and percent cut slope, respectively, where $0 < s < c$. Note that for a slope of, for example, 35%, $s = 35$; more notably $s \neq .35$ (the same condition also holds for c).

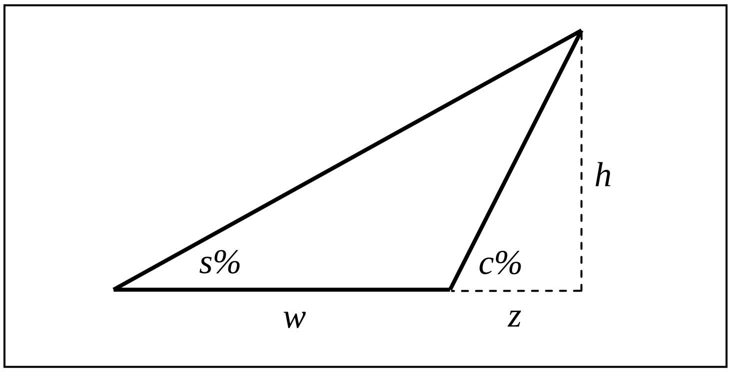

Figure 3: Triangle used to estimate cut material to build forest roads.

Next, to calculate total cubic feet volume of material handled and moved, we multiply the results from Equation 1 by the linear road distance measured in feet (d) and a material swell factor (sf)[6], which accounts for the percent increase in material volume due to air voids introduced into the material when disturbed:

$$TotalVolume = d * sf * Area \qquad \text{[Equation 2]}$$

Appendix B presents an approach for calculating total volume of material to be handled and moved for constructing roads having varying percent hill slopes.

To estimate fuel consumption and emissions for handling and moving the material calculated with the above equations, we used average production rates of cubic material moved per hour with a hydraulic excavator and two dump trucks from Balcom (1988). We assumed the same fuel consumption and utilization rate as above for the excavator. To estimate fuel consumption for endhauling the cut material $(TotalVolume)$, we used the average dump truck production rates reported by Balcom and assumed the use of two Caterpillar D25D articulated dump trucks requiring 4.7 gallons of diesel per hour each (CAT 1989). Additionally, according to a US Forest Service transportation planner, spreading the endhauled material at a waste site is also a necessary component of full bench road construction (pers. comm. Fred Bower, 13 January 2009). For this we assumed a Caterpillar D7 track type dozer is used 4 hours daily (pers. comm. Bob Greil, road construction contractor, 29 January 2009) requiring 8 gallons of diesel per hour (CAT 1989). We further assumed a material swell factor of 1.3.

The resulting fuel consumption and emissions estimates per cubic foot of handled material from road construction on slopes greater than 50% are displayed

[6] If material swell is 30% then the swell factor is $sf = 1+.30 = 1.3$.

in Table 3. The estimates are based upon the same diesel fuel emissions and energy content as with the cut-fill method. The estimates show approximately 0.007 gallon of diesel fuel is required per cubic foot handled and moved to construct a forest road using the full bench method. Carbon dioxide emissions are about 0.17 pounds per cubic foot and the carbon equivalent is roughly 0.05 pound per cubic foot.

Table 3: Diesel fuel consumption and carbon dioxide emissions per cubic foot of handled material with full bench method on slopes greater than 50%.

Road construction activity	Production (cubic feet/hour)	Diesel consumption (gallon/cubic foot)	Carbon dioxide emissions (pound/cubic foot)	Carbon equivalent (pound/cubic foot)
Pioneering, Clearing and grubbing, Sub-grade excavating (excavator)	2926.8[a]	0.00273	0.06223	0.01697
Endhauling (2 dump trucks)	2948.4[a]	0.00319	0.07272	0.01983
Waste site spreading (dozer)	5896.8[b]	0.00136	0.03100	0.00846
Total of all activities		0.00728	0.16595	0.04526

[a]From Balcom (1988)
[b]Assumes dozer operation is half the time as the other equipment (pers. comm. Bob Greil, road construction contractor 29 January 2009)

Tables 4 and 5 display diesel fuel consumption and carbon dioxide emissions by incremental hill slopes. The values are derived from total cubic feet of material to handle and move from Equations 1 and 2 and the estimate of diesel consumed per cubic foot from Table 3. We also assumed a fourteen foot wide road and 200% cut slope (pers. comm. Bob Greil, road construction contractor, 29 January 2009). Our estimates of total diesel fuel consumption for building forest roads on hill slopes greater than 50% range from approximately .62 – 1.5 gallons per linear road foot, and roughly 3,260 – 8,000 gallons per mile. Carbon dioxide emissions range from approximately 74,400 pounds per mile at 50% hill slope to 182,700 pounds per mile at an extreme hill slope of 90%. The carbon equivalent ranges from 20,300 – 49,800 pounds per mile.

Table 4: Diesel fuel consumption estimates by percent hill slope greater than or equal to 50% assuming a cut slope of 200% and fourteen feet wide roads.

Road construction method	Hill slope (percent)	Material to move per linear road foot		Diesel fuel consumption per linear road foot (gallons)				Gallons per mile
		(cubic yards)	(cubic feet)	Excavator	Dump trucks	Dozer	Total	
Full-bench	50	3.15	84.93	0.23187	0.27094	0.11551	0.61831	3,265
	55	3.58	96.65	0.26385	0.30831	0.13144	0.70360	3,715
	60	4.04	109.20	0.29812	0.34835	0.14851	0.79498	4,197
	65	4.54	122.68	0.33492	0.39135	0.16685	0.89312	4,716
	70	5.08	137.20	0.37456	0.43767	0.18659	0.99882	5,274
	75	5.66	152.88	0.41736	0.48769	0.20792	1.11297	5,876
	80	6.29	169.87	0.46374	0.54187	0.23102	1.23663	6,529
	85	6.98	188.33	0.51414	0.60077	0.25613	1.37105	7,239
	90	7.72	208.47	0.56913	0.66503	0.28352	1.51768	8,013

Table 5: Diesel fuel consumption, carbon dioxide emissions and carbon equivalent estimates by percent hill slope greater than or equal to 50% assuming a cut slope of 200% and fourteen feet wide roads.

Road construction method	Hill slope (percent)	Total diesel fuel consumption (gallons/foot)	Total diesel fuel consumption (gallons/mile)	Total carbon dioxide emissions (pounds/foot)	Total carbon dioxide emissions (pounds/mile)	Total carbon equivalent (pounds/foot)	Total carbon equivalent (pounds/mile)
Full-bench	50	0.61831	3,265	14.10	74,422	3.84	20,297
	55	0.70360	3,715	16.04	84,687	4.37	23,097
	60	0.79498	4,197	18.12	95,686	4.94	26,096
	65	0.89312	4,716	20.36	107,499	5.55	29,318
	70	0.99882	5,274	22.77	120,220	6.21	32,787
	75	1.11297	5,876	25.37	133,960	6.92	36,535
	80	1.23663	6,529	28.19	148,844	7.69	40,594
	85	1.37105	7,239	31.25	165,023	8.52	45,006
	90	1.51768	8,013	34.60	182,673	9.44	49,820

Discussion

It is common practice for road engineers to use published machine productivity equations to estimate costs or other related information. Here we have combined mathematical estimates with published production information to estimate fuel consumption and carbon dioxide emissions from building forest access roads. However, the results presented above rely on published studies designed to estimate forest road construction costs. While such studies are based upon field collected data, and general machine production rates were presented, machine fuel consumption during road construction was not investigated. Here we have estimated fuel consumption and emissions from forest road construction by combining computed average production estimates with estimates of machine-specific fuel consumption rates.

We recognize that our estimates have limitations. First, as Erickson (1992) described, forest road construction costs are difficult to estimate due to site-specific variations; therefore it is logical that fuel consumption would also be difficult to estimate due to similar variations. Second, applying the limited information provided by Balcom should be with caution, as conditions such as soil type can significantly impact the necessary cut slope and overall production. Third, there is no way to account for operator experience and production, or control for job-specific variations, such as culvert installment, turnout construction, seeding and stabilization, rolling dip construction, etc. We also cannot reasonably account for machine positioning and re-positioning, idling or other down time exclusive of the basic utilization rate used in our estimation process. Here we assumed that the amount of cut material equals the fill needed to build the road base with the cut-fill method, requiring no relocation of fill material. However, actual hill slope angles are not linear as displayed in Figure 3 and thus can require moving either more or less material for any given hill slope percent.

Additionally, in this analysis we have not included estimates of fuel consumption or emissions for road reconstruction, grading and maintenance, prism obliteration, employee commute to and from the job site, equipment mobilization via a lowboy tractor trailer, or delivery of supplies. We have limited our estimates to the basic elements of road construction, and suggest much more effort be devoted to this and other aspects of forest management as they relate to carbon accounting.

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Appendix A

To verify the area in Equation 1, we first note that the hill slope s in percent equals 100 multiplied by rise over run: $s = 100\frac{h}{w+z}$ (see Figure 3). Similarly, $c = 100\frac{h}{z}$. The area of the triangle is $\frac{1}{2}wh = \frac{1}{2}w^2\frac{h}{w}$. Also,

$$\frac{h}{w} = \frac{h^2}{h[(w+z)-z]} = \frac{h^2}{h(w+z)-hz} = \frac{\frac{h^2}{z(w+z)}}{\frac{h(w+z)-hz}{z(w+z)}} = \frac{\frac{h}{z}\cdot\frac{h}{w+z}}{\frac{h}{z}-\frac{h}{w+z}}.$$

Using that $\frac{h}{z} = \frac{c}{100}$ and $\frac{h}{w+z} = \frac{s}{100}$, we obtain $\frac{h}{w} = \frac{1}{100}\cdot\frac{c\cdot s}{c-s}$. Consequently, the area of the triangle is $\frac{1}{2}wh = \frac{1}{2}w^2\frac{h}{w} = \frac{1}{200}w^2\frac{c\cdot s}{c-s}$.

Appendix B

When building a forest road, the hill slope is usually not constant over any significant distance. To use the data from Tables 1, 2, 4 and 5 to estimate fuel consumption and emissions in this more general setting, proceed as follows. Estimate the total length of forest road to be built in d miles (or feet). Then determine the total length of the road pieces that will be built on gentle to moderate hill slopes < 50% and denote this length by d_{mod}. Next, determine the total lengths of the road segments that will be built on hill slopes of approximately 55%, 60%, 65%, etc. Denote these lengths by $d_{55\%}$, $d_{60\%}$, $d_{65\%}$, etc. Therefore

$$d = d_{\text{mod}} + d_{55\%} + d_{60\%} + d_{65\%} + \cdots + d_{90\%}.$$

Next denote the estimate for fuel consumption or carbon emissions from forest road construction on gentle to moderate slopes from Table 1 or 2 (per foot or mile) by E_{mod}. Similarly, for a given hill slope of $s\%$ on which the full bench construction method would be used, denote the corresponding estimate for fuel consumption or emissions from Table 4 or 5 by $E_{s\%}$. The total estimate TE for fuel consumption or carbon dioxide emissions for building the entire forest road is then given by

$$TE = d_{\text{mod}} * E_{\text{mod}} + d_{55\%} * E_{55\%} + d_{60\%} * E_{60\%} + d_{65\%} * E_{65\%} + \cdots + d_{90\%} * E_{90\%}.$$