Results of a Case Study on Quantifying Fuel Use and Emissions for a Bridge Replacement Project

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ABSTRACT

As the nation moves toward more sustainable energy and environmental standards, it is important to examine all sources of fuel consumption and pollution, including heavy-duty diesel (HDD) construction equipment. In order to quantify these sources at the project level, they must be identified with their respective activities. A case study was performed on an Oklahoma Department of Transportation (ODOT) bridge replacement project in order to establish a baseline of real-world activity, equipment, fuel use, and emissions data. This data was collected on a daily basis via jobsite visits and included specific information such as the equipment's model year, engine horsepower, and hours worked. These data were used to estimate fuel use and emissions based on calculations from the EPA's NONROAD model. Using these estimates, traditional project management techniques were expanded to evaluate the energy and environmental impacts of the project, in addition to the economic impacts. Histograms and cumulative frequency diagrams (s-curves) were created to summarize fuel use and emissions on a daily and project total basis. These results were combined with the preliminary and final ODOT pay items and quantities to define new fuel use and emission factors based on quantity of work completed, dollars of work completed, and specific activities. Recommendations include using the new fuel use and emission factors to identify activities with high energy and environmental impacts as well as evaluating various mitigation strategies.

INTRODUCTION

In order to build new, demolish old, or refurbish existing infrastructure, heavy duty diesel (HDD) equipment must be used. This equipment requires fossil fuel for energy and emits air pollutants that are harmful to the environment and human health. HDD equipment is a substantial contributor to this growing problem. New ways to quantify and characterize this pollution problem must be found in order to reduce and mitigate it.

Diesel exhaust (DE) poses risks for humans and the environment (EPA 2003). For example, tiny particles found in DE, known as particulate matter (PM), may cause lung damage as well as aggravate existing respiratory diseases. DE also contains nitrogen oxides (NO_x) and hydrocarbons (HC) which are precursors to ozone. Carbon monoxide (CO) is another air pollutant found in DE that adversely affects human health and may even cause death in high concentrations, although unlikely in ambient conditions. Approximately 99% of the carbon in diesel fuel is emitted in the form of carbon dioxide (CO_2), a greenhouse gas that contributes to global warming and climate change. PM, NO_x, CO, and ozone are regulated by the United States Environmental Protection Agency (EPA) through the National Ambient Air Quality Standards (NAAQS) (EPA 2012). EPA also enacted engine tier standards for nonroad diesel equipment (including HDD equipment used in construction) that establishes limits for the emission rates of NO_x, HC, CO, and PM based on horsepower rating and model year. Although these regulations have been helpful, more needs to be done at the operational level to further reduce DE and mitigate the resulting environmental and health problems.

The economic, energy, and environmental impacts of HDD equipment used for the construction, maintenance, and rehabilitation of the infrastructure are inextricably related. This equipment consumes mass quantities of energy in the form of diesel fuel, at a significant cost to the project, and in turn produces harmful byproducts in the form of environmental air pollution. Real world data is needed to truly understand these relationships. New metrics are needed to assess the energy and environmental footprint of infrastructure projects, along with their economic impact. This paper presents a methodology and results of a case study performed on an Oklahoma Department of Transportation (ODOT) bridge replacement project. The results show the relationships between the economic, energy, and environmental impacts of the project in the form of project cost, fuel use, and CO_2 emissions, respectively. New estimating factors were developed that will prove useful in forecasting the energy and environmental footprints of future projects. Future work will present these relationships for NO_x, HC, CO, and PM.

METHODOLOGY

In order to characterize the economic, energy, and environmental impacts of a construction project, a real-world baseline of project costs, fuel use, and CO_2 emissions was needed. An ODOT bridge replacement project was chosen to establish this baseline. The bridge was located in Payne County on state highway SH-51 west of Stillwater, OK over Harrington Creek. The total cost of the project was $1,267,238. The costs of the roadway and bridge activities were $1,199,940 and included earthwork; construction of a reinforced concrete box (RCB) culvert to replace the existing bridge; detour construction and removal; demolition of the existing bridge; asphalt paving over the RCB culvert; and erosion control. These activities required the use of HDD equipment and thus contributed to the economic, energy, and environmental impacts of the project. Other activities, such as mailbox installation and pavement striping, composed the remaining project costs but were not included in this particular analysis because they did not require HDD equipment.

The economic impact of the above mentioned activities were calculated using actual ODOT payment records and schedules. There were a total of 10 activities that represented each stage of the project. These activities included Excavation/Box Preparation, RCB Construction, Shoo-Fly Earthwork, Shoo-Fly Asphalt, Remove Bridge, Mainline Earthwork, Stabilize Subgrade, Asphalt, Remove Shoo-Fly, and Erosion Control. The contract for the project stipulated 120 calendar days for completion but only 95 calendar days were used. Excluding adverse weather days and project downtime (which were not counted against the contractors schedule), the contractor used a total of 58 calendar days to complete the project, approximately one-half of the allotted time.

In order to measure the project's energy and environmental impacts, an activity log and equipment inventory were taken daily via job site visits. For each item of HDD equipment that was on the job site for a particular day, the type, manufacturer, and model was recorded. Since the project was subdivided into many different activities, the equipment and its time of use were recorded for each activity. In addition, a brief summary of the day's activities, job information, and completed tasks was recorded. Pictures were taken throughout the project for a visual reference of what was accomplished. Once per week, the research team met with the ODOT project inspector for a project progress report.

Equipment model year, engine horsepower rating, and hours of use were needed to calculate diesel fuel use and CO_2 emission rates and, ultimately, total project fuel use and emissions. The model year and engine horsepower rating for each item of equipment were obtained from contractor's records. The hours of use for the equipment, however, proved particularly problematic to acquire. Initially, the equipment operators were asked to record the equipment's hour meter reading at the end of each work day for each item of equipment that was used. These readings would have been used to calculate the equipment daily hours of use by subtracting the previous day's hour meter reading from the current day's reading. This attempt proved fruitless for many reasons. In some instances, the operators were generally nonresponsive and did not collect the readings. Furthermore, the equipment owners were reticent to let non-project personnel on their equipment to gather the readings. In other cases, the equipment may not have had an hour meter or it may have malfunctioned and not recorded hours of use. To remedy this problem, the research team consulted with the ODOT project inspector and developed reasonable estimates of daily hours of use for each item of equipment. Based on these estimates, hours of use for each item of equipment ranged between 4-8 hours per day.

In order to develop the fuel use and emissions inventory for this project's HDD fleet, fuel use factors were needed for each item of equipment. These factors are estimates of the amount of fuel consumed by a particular item of equipment on a horsepower-hour basis. The factors used for this inventory were based on calculations and the methodology employed by the EPA NONROAD model (EPA 2005). For fuel use, NONROAD uses brake specific fuel consumption (BSFC) reported in pounds per horsepower-hour (lb/hp-hr). The factors used by NONROAD are based on engine dynamometer test data and adjusted accordingly to account for in-use operation that differs from the typical test conditions and is based on the following equation.

$$EF_{adj\ (BSFC)} = EF_{ss} \ x\ TAF \qquad (1)$$

where:
EF_{adj} = final fuel use factor used in NONROAD (lb/hp-hr)
EF_{ss} = zero-hour, steady-state fuel use factor (lb/hp-hr)
TAF = transient adjustment factor (unitless)

The individual fuel use values for each item of equipment were computed according to the methodology presented in *Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling* (EPA 2010) and the following equation:

$$BSFC = Pop \times Power \times LF \times A \times EF_{adj\ (BSFC)} \quad (2)$$

where:
BSFC = total fuel consumption for the specified equipment (lb)
Pop = equipment population
Power = engine rated horsepower (hp)
LF = engine load factor (fraction of available power)
A = equipment activity (hr)
$EF_{adj\ (BSFC)}$ = BSFC factor (lb/hp-hr)

The total project fuel use values were calculated for each item of equipment by setting *Pop = 1*. The engine rated horsepower (*Power*) for each item of equipment was obtained from the contractor's database, thus the individual and overall fuel use values are specific to this particular project. The engine rated horsepower is the maximum level of power that an engine is designed to produce at its rated engine speed. Nonroad equipment seldom operates at its rated power for extended periods and frequently operates at a variety of speeds and loads. NONROAD uses a load factor (*LF*) to indicate the average proportion of rated power used to account for the effects of operation at idle and partial load conditions. Equipment activity values were based on estimates from the ODOT project inspector.

CO_2 emissions are highly correlated to fuel use; therefore, a simple emission factor was applied to the fuel use estimates in order to estimate CO_2 emissions. According to the United States Energy Information Administration (EIA 2013), approximately 22.3 pounds of CO_2 are emitted per gallon of diesel fuel consumed. The total fuel use and CO_2 emissions were tabulated for each item of equipment and the entire fleet on a daily basis, activity basis, and overall project basis.

RESULTS

The contractor's bid price for the bridge and approach job was $1,193,759. A change order was submitted to over-excavate the proposed RCB site and fill it in with rip rap and small rock to stabilize the unanticipated unstable soil type. This change added $73,480 to the project total. Other quantity over- and under-runs, in addition to the change order changed the final contract amount to $1,267,238. Of this contract value, HDD equipment contributed to $1,199,939 of the total activity cost (95%); therefore, this amount was considered the overall economic impact of HDD equipment on the project and was used in the subsequent calculations for the energy and environmental impacts. Table 1 shows the fuel-consuming and pollutant-emitting activities and pay items associated with the HDD equipment.

Table 1. Total Project Cost Breakdown

Activity	Pay Item	Quantity	Unit Price	Total Item Price	Total Activity Cost
Excavation & Box Prep	Clearing and Grubbing	LSUM	$3,300	$3,300	$32,844
	Removal of Existing Pipe	90 LF	$5	$405	
	Unclassified Excavation	3,993 CY	$6	$21,962	
	Structural Excav. Unclass.	239 CY	$30	$7,178	
RCB Construction	Class AA Concrete	833 CY	$280	$233,240	$413,856
	Type 1 Plain Riprap	1,037 TON	$52	$54,098	
	TBSC Type D	402 TON	$48	$19,382	
	Reinforcing Steel	148,800 LB	$1	$107,136	
Shoo-Fly Earthwork	Unclassified Borrow	12,903 CY	$9	$116,128	$126,349
	Inlet (SMD Type 2)	2 EA	$1,750	$3,500	
	Add'l Depth in Inlet	2 VF	$350	$700	
	18" CGSP	42 LF	$23	$966	
	24" CGSP	80 LF	$29	$2,320	
	Standard Bedding Material	42 CY	$47	$1,992	
	Trench Excavation	165 CY	$5	$743	
Shoo-Fly Asphalt	Fly Ash	70 TON	$62	$4,314	$124,140
	TBSC Type E	96 TON	$32	$3,072	
	Tack Coat	369 GAL	$3	$962	
	Superpave Type S3 (64-22)	1,045 TON	$75	$78,374	
	Superpave Type S4 (64-22)	425 TON	$88	$37,418	
Remove Bridge	Removal of Guardrail	328 LF	$3	$820	$15,320
	Removal of Bridge Items	LSUM	$7,000	$7,000	
	Removal of Existing Bridge	LSUM	$7,500	$7,500	
Mainline Earthwork	Unclassified Borrow	6,452 CY	$9	$58,064	$118,570
	Inlet GPI Type 2	2 EA	$2,350	$4,700	
	Add'l Depth in Inlet	1.5 VF	$400	$600	
	36" RC Pipe Class III	542 LF	$51	$27,642	
	36" CGSP	67 LF	$39	$2,613	
	42" CGSP	69 LF	$43	$2,967	
	Type D4 CET	4 EA	$790	$3,160	
	Standard Bedding Material	246 CY	$47	$11,551	
	Trench Excavation	671 CY	$5	$3,021	
	Removal of Ditch Liner	945 LF	$5	$4,253	
Stabilize Subgrade	Stabilized Subgrade	2,701 SY	$2	$5,401	$5,401

Activity	Pay Item	Quantity	Unit Price	Total Item Price	Total Activity Cost
Asphalt	Agg Base Type A	9 CY	$78	$722	$292,924
	Fly Ash	32 TON	$62	$1,958	
	TBSC Type E	470 TON	$32	$15,036	
	Tack Coat	1,107 GAL	$3	$2,888	
	Bituminous Binder	104 GAL	$8	$866	
	Superpave Type S3 (70-28)	991 TON	$80	$79,270	
	Superpave Type S3 (64-22)	1,292 TON	$75	$96,899	
	Superpave Type S4 (70-28)	766 TON	$88	$67,400	
	Cold Milling Pavement	5,044 SY	$4	$20,934	
	Removal of Asphalt	556 SY	$4	$2,281	
	Sawing Pavement	1,698 LF	$3	$4,670	
Remove Shoo-Fly	Removal of Asphalt	2,884 SY	$4	$11,826	$11,826
Erosion Control	Solid Slab Sodding	28,000 SY	$2	$47,600	$58,708
	Class C Concrete	44 CY	$250	$11,108	
				TOTAL PROJECT COST	**$1,199,939**

The activities with the greatest economic impact were RCB Construction and Asphalt. These two activities constituted approximately 70% of the HDD economic impact. The majority of Activity 2 was completed during the first half of the project and most of Activity 8 was completed during the second half of the project.

Figure 1 shows the total cost accumulation of the HDD economic impact over the duration of the project. These costs follow an “s-curve” that is typically found in graphs of construction project costs versus time. Figure 1 also shows the accumulation of fuel use (energy impact) over the duration of the project. Note that this curve does not follow the common “s-curve” but it is a smoother curved line, indicating that fuel use is somewhat consistent throughout the project, although it accumulates at a slightly lower rate during the second half of the project. Overall, it can be said that approximately 20,000 gallons of fuel were consumed to produce approximately $1,200,000 of project value – an economic-energy rate (ratio of project value to fuel consumed) of $60 per gallon. Although this rate varies at different points on the curve, it typically ranges from $45-60 per gallon.

Although not shown directly on the graph, Figure 1 may also be used to estimate the environmental impact over the project duration. Recall that approximately 22.3 pounds of CO_2 are emitted per gallon of diesel fuel used (EIA 2013); thus, the values on the fuel use curve in Figure 1 may be multiplied by 22.3 lbs/gallon to estimate CO_2 emissions. Overall, the project accumulated approximately 446,000 pounds (223 tons) of CO_2 emissions. The economic-environmental rate (ratio of project value to CO_2 emitted) for the project would be approximately $5400 per ton.

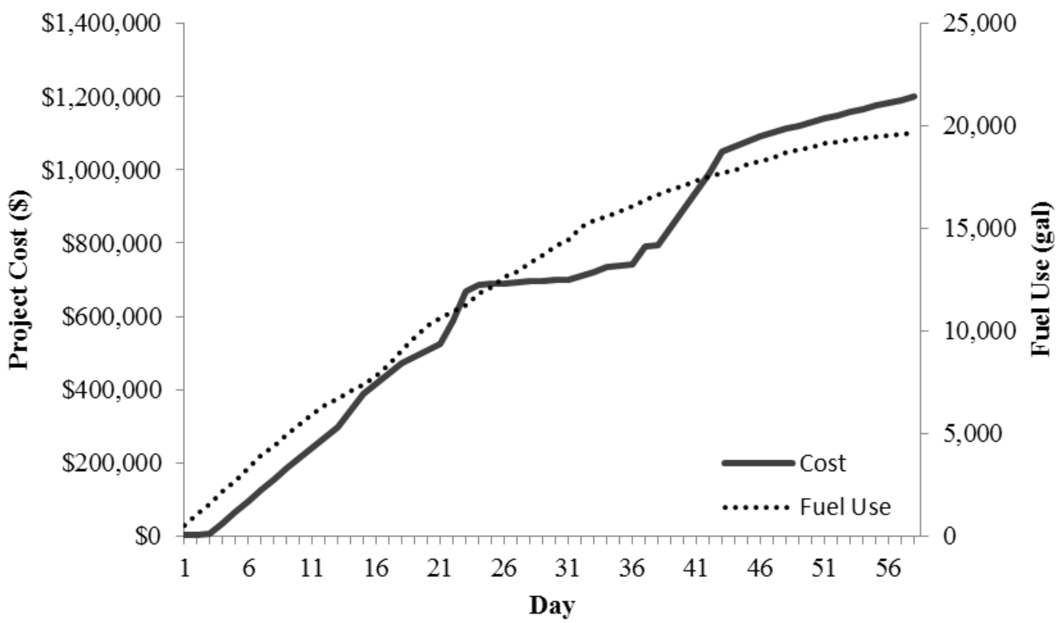

Figure 1. Economic and Energy Impact of Project

Based on the observations of Figure 1, a closer examination of the individual activities is warranted. Figure 2 presents the cost and fuel use for each activity. Recall that the CO_2 emissions may be estimated based on the fuel consumption. Some activities, such as RCB Construction and Stabilize Subgrade, appear to have a high correlation between activity cost and fuel use. Some activities, such as Excavation/Box Prep and Remove Bridge, have a low activity cost yet a high fuel use. Other activities, such as Shoo-fly Asphalt and Asphalt, have a high activity cost yet low fuel use. These observations indicate that economic-energy rates and economic-environmental rates are needed for each activity for more accurate estimating. Table 2 presents the economic-energy rates for fuel use and the economic-environmental rates for CO_2 emissions that were calculated for this project.

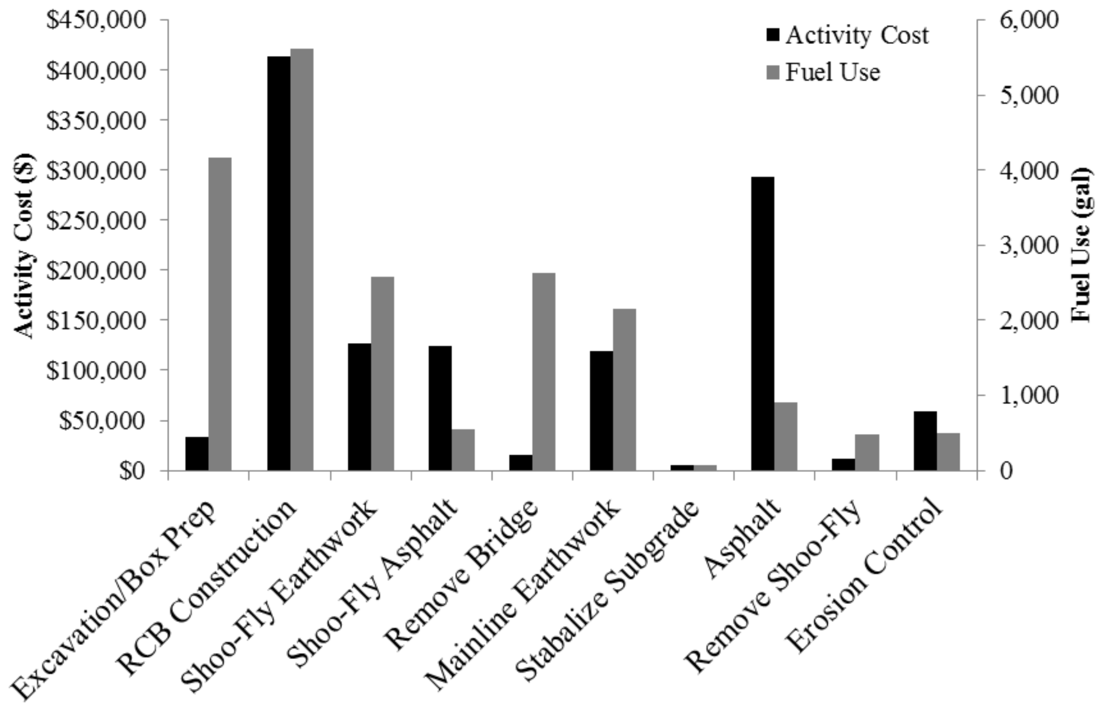

Figure 2. Activity Cost and Fuel Use

One of the primary goals of this case study was to develop new energy and environmental (EE) factors to estimate and quantify fuel use and emissions from HDD equipment. The total project cost factor developed can be used to estimate total CO_2 pollution and fuel use for a typical small bridge and approach job. The other activity factors were created by dividing the amount of pollutant an activity emitted by the quantity associated with each activity. These factors may be applied to any type of project which requires these types of activities. Table 2 presents the new fuel use and CO2 emission factors developed in this case study. For example, one gallon of fuel will produce 3.5 cubic yards of earthwork on a project basis and 310 cubic yards of earthwork will be produced for each ton of CO_2 emitted for that activity. These results demonstrate the use of familiar project management techniques in a wider range of application, including fuel use and emissions estimates.

Table 2. Emission and Fuel Use Factors for Case Study Project

Estimate Item	Fuel Use Factor	CO_2 Factor
Total Project Cost	*$60/gal*	*$5400/ton*
Earthwork	3.5 cy/gal	310 cy/ton
RCB Construction	0.03 lf/gal	2.5 lf/ton
Detour Paving	3.1 lf/gal	280 lf/ton
Mainline Paving	2.1 lf/gal	190 lf/ton
Sodding	56 sy/gal	5000 sy/ton
Detour Removal	3.5 lf/gal	320 lf/ton
Bridge Removal	0.05 lf/gal	4.7 lf/ton

CONCLUSIONS

Contractors and professionals in the construction industry are very familiar with the economic impact of their projects. They estimate price and schedule based on known quantities, historical data, and industry standards. Economic impacts can also be monitored and tracked to determine whether or not the project is on schedule and within budget. Quantifying and characterizing the energy and environmental impacts of a project has recently become an increasing concern. This paper demonstrates a methodology for identifying and quantifying these impacts via a case study of a real-world project. The paper also developed new metrics that reflect the relationship between the economic and energy components of a project, as well the economic and environmental aspects. With further refinement, these metrics may prove useful in estimating the overall economic, energy, and environmental footprints of infrastructure projects.

The case study of ODOT's bridge replacement project has provided valuable insight to the future of construction estimating. Not only can the construction industry estimate a project's cost and schedule to balance the economic impact, the energy and environmental impacts (in the form of fuel use and emissions) can be estimated in order to minimize their impact on society. Even though the economics of a project will likely continue to drive the bottom line and schedule, it is becoming more important to also consider sustainability issues during the planning and construction phases of a project.

RECOMMENDATIONS

The data and new estimating factors developed for this case study represent only one project. It is recommended that the methodology presented here be expanded to include similar projects in order to refine the data and create more robust estimating metrics. Furthermore, other types of projects should be studied to expand the breadth of this approach. Likewise, future studies should incorporate other pollutants, including those regulated by EPA, to promote a more holistic approach to environmental sustainability of infrastructure projects.

To fully analyze the impact of a project, the energy and environmental aspects must be taken into account along with the economic impact. Activities or days with high anticipated fuel use and emissions should be closely examined in order to identify mitigation strategies. For example, the effect that HC and NO_x have on the formation of ozone worsens as the outside air temperature increases. Therefore, if hot weather is forecasted and a construction activity with high predicted emissions is scheduled for the same time period, but has activity float in the schedule, that activity may be moved to a cooler period when it would lessen the effects of ozone formation. Thus, it may soon be possible to include "ozone days" in the schedule, similar to adverse weather days that are already considered.

Perhaps the most important recommendation arising from this case study is to improve data collection through the use of telematics. A telematics device can be installed on an item of equipment and be used to track information such as the hours, engine load, fuel use, and location – all which is currently difficult to do. This data is updated in real-time and tracked by the fleet manager. This data will be valuable in providing accurate, real-world estimates of fuel use and emissions (Moore 2012).

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