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Estimating The Consumptive Use Costs of Shale Natural Gas Extraction on Pennsylvania Roadways

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Abstract

The development of natural gas resources in the Marcellus Shale formation has progressed rapidly in the last several years, particularly in the Commonwealth of Pennsylvania. These activities require many heavy truck trips for equipment and materials, which can damage state and local roads that were not designed for high volumes of heavy truck traffic. For state transportation agencies, one measure of costs of shale gas development is the potential degradation of roadways resulting from shale gas development. This technical note provides a first-order estimate of roadway consumptive use costs of additional heavy truck traffic on Pennsylvania state-maintained roadways from Marcellus Shale natural gas development in 2011, estimated at about $13,000-$23,000 per well for all state roadway types, or $5,000-$10,000 per well if state roads with the lowest traffic volumes are excluded. This initial estimate of costs is based on data on the distribution of well activity and roadway type in Pennsylvania, estimates for the number of heavy truck trips to construct and operate a single well, the corresponding equivalent single-axle loadings, and estimates of roadway life and reconstruction costs by roadway maintenance class in Pennsylvania.

Subject Headings: Energy, transportation engineering, maintenance costs, trucks, infrastructure

Introduction

The combined use of horizontal drilling and hydraulic fracturing in shale deposits has contributed to expanded natural gas resource estimates and lower natural gas prices in the United States (EIA, 2012). Natural gas extraction in the Marcellus Shale formation has developed rapidly in the last several years, particularly in the Commonwealth of Pennsylvania. This activity has been met with enthusiasm for potential economic benefits and concern regarding some potentially adverse environmental and community impacts of the development (Kargbo, Wilhelm and Campbell, 2010; Osborn et al., 2011). The distribution of these benefits and costs vary across stakeholders, geographic regions, taxing authorities and state agencies. For state transportation agencies, one measure of costs of shale gas development is the potential degradation of roadways resulting from shale gas development. In this technical note, we provide an initial, first-order estimate of the costs of additional heavy truck traffic associated with shale gas development on Pennsylvania state-maintained roadways.

Shale gas extraction requires many heavy truck trips for equipment and materials, which can damage state and local roads that do not normally experience high volumes of heavy truck traffic. Shale development firms, through agreements with the State and local municipalities, often reconstruct visibly damaged roads. This study focuses on the costs of roadway degradation on other state-maintained roads with higher traffic volumes, where such reconstruction agreements are not in place. These estimates should help inform stakeholders and long-term decisionmaking in managing the costs associated with shale gas development and transportation infrastructure systems.

Damage to roads is affected by many factors, including truck weight and type, traffic patterns, construction material, drainage, and environmental conditions (Federal Highway Administration, 2000). A common approach for understanding the effects of weight loads on roadway pavement is to express all loads as equivalent single axle loads (ESAL), which represents a single axle load of 18,000 pounds (Pennsylvania Department of Transportation, 2010). The American Association of State Highway and Transportation Officials (AASHTO) has developed standard equations for estimating ESALS based on number of axles, load weight, and pavement characteristics. A generally accepted approximation for the calculation of ESALs is the generalized fourth power law, which states that the damage caused by a particular load is roughly related to the load per axle by a power of four (AASHTO, 1993). Though previously challenged by scholars, it remains the most common approach and has proven to be fairly robust from a policy perspective (Johnsson, 2004). Examples for uses of this approximation to estimate road damage include Sathaye et al. (2010) and Belcheff and Associates (2010).

For different roadway types, vehicle weights, and axle combinations, the load equivalency factor (LEF) is the roadway damage caused by a single pass of each vehicle relative to the damage per single pass of an ESAL. The damage increases exponentially with vehicle weight. For example, on flexible pavement, a LEF for a roadway pass of a 3,000-pound single axle is 0.0011, the LEF for an 18,000-pound single axle is 1.0, and the LEF for a 30,000 pound single axle is 8.28 (Federal Highway Administration, 2011). This means that 18,000 pound and 30,000 pound single axle passes do about 900 times and 7,500 times more damage than a 3,000 pound single axle pass, respectively.

Roadways are designed and constructed to different specifications depending on the projected use, passenger traffic, and truck traffic. Roads such as interstate highways are designed to withstand heavier loads than local roadways. The “design life” of specific roadway types can be estimated in total number of ESALs; after this total number of ESALs has occurred on this roadway, it will likely require reconstruction. Hence, the useful life of a roadway is directly related to the frequency and weight of truck traffic using the roadway, and roadways consistently experiencing greater annual truck traffic will generally require reconstruction sooner than similar roadways with less truck traffic. Several models have been proposed to estimate design life, taking into account factors such as the thickness of the various layers of the pavement structure, its drainage characteristics, as well as the predicted loading patterns of vehicles using the road. Such estimations are also sensitive to (but do not always account for) the road maintenance schedule as well as environmental factors. Examples of advanced

modeling approaches beyond the original AASTHO equation (1993) are Madanat, Prozzi and Han (2002) Hong and Prozzi (2006), and recent assessments showing that models that account for heterogeneity lead to improved predictive capabilities (Chu and Durango-Cohen, 2008).

Several studies have attempted to assess the expected roadway damages from the development of oil and gas extraction activities, or other growing industries, in various areas of the country. From an earlier period of energy development, Mason (1983) estimated the pavement life reduction on low-volume roadways due to oil well activities. Recently, studies have been conducted at a local scale to assist cities, counties and states to estimate expected damages to roads from energy development activities. For example, a study for the City of Keller, Texas, conducted by Belcheff and Associates (2010), estimated the expected damage to roads per gas well for four different cases that represent alternate ways of conducting activities necessary for the transportation of hydraulic fracturing water and the removal of production water, which affect the total number of truck trips. The authors of this study estimated the total number of heavy truck vehicle trips associated with constructing and operating a single well. They then estimated the total ESALs available on each of the eight types of city roads and estimated the cost of roadway reconstruction per lane-mile of each of these roads. These findings enabled them to derive a fee per lane-mile ranging from $53 to almost $20,000 to offset the expected damages, depending on the transportation methods and type of roads used (Belcheff and Associates, ,2010).

A study for Rio Blanco County in Colorado by RPI Consulting (2008) assessed the damage to existing roads as well as attempted to project future traffic growth and improvement needs. The authors also included costs for buy-in for past projects designed to accommodate future traffic, as well as road and bridge incremental facility and fleet expansion needs, based on an assumption of maintaining the current level of service. This study proposed a fee per ESAL, which would be translated into a fee per well based on the expected ESALs needed over the lifetime of the well. Taking into account future needs, and using other less conservative assumptions such as a longer well lifetime of 40-years, resulted in relatively high cost estimates of $18,762 (in 2010 dollars) per well (RPI Consulting, 2008).

A study on the effects of the meat production industry in Kansas on damage to roads by Bai et al. (2009) took similar approaches to Keller's study but provided a more nuanced assessment. This study isolated the truck's direct damages from damage caused by environmental factors and the maximum life of a road was defined in terms of a tolerable decline in Present Serviceability Rating (PSR). The loss in PSR from environmental factors was computed using the time-related deterioration function for a typical design performance period. Subtracting the environmental factors' effects lowers the estimates for the damages inflicted on roads.

Finally, the Texas Transportation Institute examined the impacts of energy development on Texas infrastructure (Quiroga et al., 2012). The researchers used traffic and pavement condition data, coupled with inspection and field-collected data, to conduct a remaining pavement life analysis. They estimated that a typical rural Texas new road that experienced the truck traffic associated with the development of one hundred horizontal gas wells would have sixty percent of its design life remaining after the first year. The researchers also highlighted the considerable impact that annual maintenance and refracking every five years could have on roadway life.

All of these studies have, in principal, taken a similar approach to the one used in this analysis. First, the expected loss of road life caused by the truck trips needed to construct and operate a well or to otherwise provide service to the industry in question is estimated. Second, the remaining roadway life and reconstruction costs of the relevant roads are estimated. By matching the two estimates, it is possible to estimate the consumptive roadway use costs associated with the specific industry. The abovementioned studies also took into account case-specific factors, and in some cases took more sophisticated approaches that resulted in both higher and lower estimates of damage. Some studies provided fairly detailed analyses of damage estimations for specific cases, depending on particular types of wells, trucks, and roads. Roadway types, reconstruction and maintenance costs, schedules, and disposal distances all vary across states experiencing growth in unconventional oil and gas operations. Stakeholders in Pennsylvania need an initial estimate of potential roadway impacts of expanding shale gas operations, to inform near-term policies and analyses. This technical

note provides these estimates and makes a contribution to the literature by presenting a method and data to estimate impacts on Pennsylvania state-maintained roadways, based on a county-level weighting of shale gas activity and roadway classification type.

Methods

To assess potential roadway damage resulting from Marcellus Shale development in Pennsylvania in 2011, the total number of heavy truck trips required to construct and operate a single well and the expected corresponding loss of road life were first estimated. Second, estimates of roadway life and reconstruction costs in Pennsylvania were obtained. Third, truck travel and repair costs were combined to estimate consumptive roadway use costs associated with the shale gas extraction industry.

The number of heavy truck trips associated with each Marcellus shale gas well depends on whether the water used for hydraulic fracturing arrives by truck or pipeline, whether the produced water is disposed of by truck or pipeline, how many wells are located on each well pad, the amount of equipment, materials and water needed for each site, and other factors. For our analysis, we assume the number of heavy truck trips used for the construction and operation of a single well in Pennsylvania would be similar to the number estimated by the New York State Department of Environmental Conservation's Environmental Impact Statement (2011). We also assume that each truck travels a distance of 20 miles each way to and from the well site. The specific assumptions for number of truck trips associated with different stages of the well development process appear in Table 1. The number and type of trucks, and distance traveled, are variables that can be used for sensitivity analyses, to determine how changes in these assumptions affect the results.

Table 1 [Tables are included at the end of this document]

It is assumed that half of the heavy truck trips are 4-axle single unit trucks (FHWA classification 7) and half are 6-axle single trailers (FHWA classification 10). According to the Pennsylvania Department of Transportation (PennDOT) Pavement Policy Manual (2010) the estimated ESALs for flexible pavement attributed to these trucks are 4.5 and 0.75, respectively. Based on the previously assumed number of trips, this means that total road damage per well is in the range of 1641 – 3014 ESALs per one-way mile of travel distance (denoted d_{well} in equation 2).

The analysis of the type of roads used for shale gas activity in PA is based on the 2010 PennDOT Highway Statistics Report (2011) which includes a list of linear miles of road per county, classified by 5 maintenance classes of roads - A to E. Each of these functional maintenance classes represents different types of roadways, from Interstates (Class A) to Local Roads (Class E). The greater amounts of earthwork, materials, and labor required for higher functional classes generally result in higher construction costs per lane-mile (Giessen et al., 2009). Each Pennsylvania County has both different proportions of roadway miles by the different functional classes, as well as varying levels of Marcellus shale gas development. To approximate the share of heavy truck vehicle miles traveled for shale gas development on each type of roadway functional class in Pennsylvania, for each county that had horizontal natural gas wells in 2011, the distribution of roadway functional classes in that county were weighted by the number of shale gas wells in that county relative to the number of shale gas wells in Pennsylvania. Equation 1 gives an example of this estimate for the weighted share of shale gas operations truck traffic on Type A roadways attributed to a single county i, given by $f_{Type\ A\ County\ i}$. Summing across all counties for Type A roadways, yields the percentage of shale gas truck traffic on all Type A roads statewide, or $f_{Type\ A}$, estimated at about 2 percent. This enables a first-order estimate on the types of roadways used by heavy truck traffic associated with shale gas development across the state, and weights the results toward roadway types observed in counties with a higher proportion of shale gas wells. Data on horizontal wells within

Pennsylvania was taken from the Pennsylvania Department of Environmental Protection (2011). This weighted estimation results in a distribution of shale gas heavy truck VMT among roadway types A, B, C, D and E of 2 percent, 2 percent, 22 percent, 46 percent and 28 percent, respectively (see Table 2).

$$f_{Type\ A\ Roads_{County_i}} = \frac{Horizontal\ Wells\ in\ County_i}{\sum_{i=1}^{nAll\ Counties} Horizontal\ Wells} \times \frac{Type\ A\ Roadway\ Classification\ Linear\ Miles\ in\ County_i}{\sum_{i=1}^{County_i} All\ Roadway\ Linear\ Miles} \qquad \textbf{Eq. 1}$$

Pennsylvania data on pavement ESAL design life, denoted as $E_{Roadway\ Type}$, for the four types of roads (National Highway System (NHS) Interstate, NHS Non-interstate, Non-NHS > 2000 Average Daily Traffic (ADT), NHS < 2000 ADT), as well as reconstruction costs per lane mile for each roadway type were obtained through personal communications from PennDOT (Fogle, 2012) and shown in Table 2. When comparing these four types of roads and the five-letter PennDOT maintenance classification, it was assumed that Type A roads are similar to Interstate, B and C roads are NHS roadways, D is non-NHS > 2000 Average Daily Traffic (ADT) and E is similar to non-NHS < 2000ADT.

Table 2 [Tables are included at the end of this document]

As shown in Equation 2 in an example for Type A roads, the expected consumptive use of a well's operations on each road type, is a function of the range of ESALs each well is responsible for, the roadway's design life, and the amount of shale gas truck traffic on that roadway type. Consumptive use is calculated by dividing the expected ESALs (d_{well} in Eq. 2) from shale gas operations per well by the total design pavement ESALs ($E_{Type\ A}$ in Eq. 2) of each road type and multiplying by the fraction of shale gas truck traffic on each road type statewide, ($f_{Type\ A}$ in Eq. 2). Damage costs per road type are then found by multiplying this consumptive use by the lane-mile reconstruction costs of each road type. Summing across roadway types, yields a total well damage per mile of travel distance across all roadways types of about $300 for the low truck trip scenario and $600 for the high truck trip scenario, as shown in Table 3. These results are then multiplied by the average miles driven to the well (both ways). Assuming an average of 20 miles travel distance one way, the range of consumptive road use costs per well between about $13,000 and $23,000, depending on the number of heavy truck trips assumed to be associated with shale gas development.

$$\boldsymbol{Consumptive\ Use\ of\ Statewide\ Type\ A\ Roads} = \frac{d_{well}}{E_{Type\ A}} \times f_{Type\ A} \qquad \textbf{Eq. 2}$$

Table 3 [Tables are included at the end of this document]

However, as noted above, many smaller state posted roadways close to well sites are bonded, repaired, and restored by trucking operators associated with Marcellus shale development. If it is assumed that all consumptive damage for the smaller Type E roadways occurs on posted roads and is fully paid for by Marcellus shale operators, it is then possible to bound the estimate by excluding the Type E roadways from per-well costs. This reduces total damages per well to between $5,400 and $10,000. These bonded roadways are typically not charged for consumptive use; only visual damages to the roadway require repairs under the excess maintenance agreements. Therefore, this complete exclusion is a conservative assumption that all such roads are visibly damaged and fully repaired.

These results are linearly dependent on truck trips. If actual truck trips were reduced by 50 percent, then the per-well fee would be also reduced by 50%, to $6,300-$11,600 or $2,700-$5,000, excluding Type E roads. Similarly, if the average one-way trip length would be reduced by 50% to 10 miles, then the per-well fee would also be reduced by 50 percent. Conversely, if refracking and substantial maintenance were needed every few years for Pennsylvania wells, consumptive use costs would be higher due to an increase in required truck trips. These results are also sensitive to the types of trucks used. If the proportion of heavy truck trips between 4-axle single unit trucks and 6-axle single trailers changes to be 60-40 instead of 50-50, then fees would increase by about 14%, to $14,400-$26,500 or $6,200-$11,400, including and excluding Type E roads, respectively. A proportion of 70-30 would increase fees by 29% compared to the 50-50 case. The results are also dependent on the type of roads used by the trucks. If the usage of larger roads (Maintenance classes A, B and C) is increased by a sum total of 10 percentage points to be 5%, 5% and 26% of the total usage, then the fee drops by 9% to be roughly $11,500-$21,200.

Discussion

First-order costs of additional heavy truck traffic on Pennsylvania state-maintained roadways from Marcellus Shale natural gas development in 2011 were estimated at about $13,000- $23,000 per well for all state roadway types, or $5,000-$10,000 per well if state roads with the lowest traffic volumes are excluded. Roadway damages in Pennsylvania, and subsequent costs to PennDOT, are expected given the increase in road traffic associated with this industry. The accumulated experience in government and the literature make estimating these damages relatively straightforward, once full information is obtained regarding truck trips, roadway types, and roadway reconstruction and maintenance costs. In this sense, road damage differs from other costs such as air pollution (Matthews et al., 2001; Litovitz et al., 2013), where the actors bearing the direct costs are spread across populations rather than a single government agency.

As with other adverse effects caused by economic activity, there are three mechanisms typically used to mitigate damages. The first is by recovering the costs of the damage through a fee or tax, in excess of existing fees if necessary. This would both enable the government to finance the necessary repairs and at the same time provide incentives to the companies to minimize activities that damage the roads. In the context of road damage, a fee could be levied separately on each truck trip depending on its characteristics, or on each well given expected total damage to the roadway. The second method to reduce damage is through regulations or incentives compelling companies to engage in less damaging activities. In the context of road damage, this could for example include limitations on truck size and weight or requirements to maximize the use of pipelines for transferring water, rather than hauling water by truck. Some of these regulations could be tailored specifically to the type of roads in question (Muench et al., 2007). Requiring heavier trucks to have more axles to distribute the load has the potential to reduce roadway damage, but Salama et al. found contrasting effects from additional axles. For their analysis on flexible pavements, single and tandem axles caused more cracking while tridem or more axles caused more rutting (Salama et al., 2006). A third approach would be to adjust the infrastructure system in a way that could absorb the expected damages at lower costs. In our context, plans for future pavements structures and construction quality, as well as road maintenance policies, could be adjusted to support heavier traffic volumes. A recent example for this approach is in Texas' oil-rich Eagle Ford shale play, where officials have indicated their intention to upgrade some heavily-used roads (Gerlach, 2013).

A comprehensive policy design would combine elements of these three approaches. In particular, it would redesign an infrastructure management policy that takes into account the effects of new regulations or fees on traffic patterns (see, for example, Fekpe (1997)). Additionally, policy makers should take into account other externalities related to road transport such as congestion, greenhouse gas or air pollutant emissions (Lidicker et al., 2013).

These first-order estimates of roadway consumptive use damages due to shale gas development are intended to highlight the potential size of these costs in Pennsylvania for a rapidly growing industry. A detailed engineering assessment of Pennsylvania roadways would need to be undertaken to provide more precise estimates of costs associated with consumptive road use so that appropriate policy actions can be developed. Such estimates would require more precise information on the variables used to estimate these costs such as the types and weights of trucks employed, the number and distance of trips, the timing and magnitude of roadway maintenance and reconstruction costs, and the full characteristics of each lane-mile the existing and planned roadways. A more comprehensive estimate would account for the environmental and design risk factors affecting pavement conditions (Hastak and Baim, 2001), the motor fuels taxes generated by shale gas development, and an understanding of future road needs. Moreover, we limited our analysis to damage to state-maintained roadways from heavy trucks; we did not include consumptive damage from shale gas development to local roadways.

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Tables

Table 1: Assumed heavy truck trips used for the construction and operation of a single well in Pennsylvania

	High Range	**Low Range**
Well Pad Activity	**Number of Heavy Truck Trips for Early Well Pad Development**	**Number of Heavy Truck Trips for Peak Well Pad Development**
Drill pad construction	45	45
Rig mobilization	95	95
Drilling fluids	45	45
Non-rig drilling equipment	45	45
Drilling (rig crew, etc.)	50	50
Completion chemicals	20	20
Completion equipment	5	5
Hydraulic fracturing equipment (trucks and tanks)	175	175
Hydraulic fracturing water hauling	500	60
Hydraulic fracturing sand	23	23
Produced water disposal	100	17
Final pad prep	45	45
Miscellaneous	-	-
Total One-Way, Loaded Heavy Truck Trips Per Well	**1,148**	**625**

Source: Data from New York State Department of Environmental Conservation (2011).

Table 2: Characteristics of Roads Assumed to Be Used for Construction and Operation of Shale Gas Wells in Pennsylvania

PennDOT Road Maintenance Class	A	B	C	D	E
Assumed Description	Interstate	NHS	NHS	Non-NHS >2000 ADT	Non-NHS <2000 ADT
Design Pavement Life in ESALs	65,000,000	25,000,000	25,000,000	21,000,000	6,000,000
Lane Mile Reconstruction Costs ($2012)	$3,175,182	$2,684,367	$2,684,367	$2,571,398	$2,333,664
Average Distribution of Shale Gas Activity VMT	2%	2%	22%	46%	28%

Table 3: Estimated Consumptive Road Use and Costs per Lane Mile Driven by Trucks Used for Construction and Operation of Shale Gas Wells in Pennsylvania

	Road Class	A	B	C	D	E	Total
Low Truck Trip Range	Consumptive roadway use per well	0.0001%	0.0001%	0.0015%	0.0036%	0.0077%	
	Damage Costs per lane mile for each well	$2	$3	$40	$92	$180	**$315**
High Truck Trip Range	Consumptive roadway use per well	0.0001%	0.0002%	0.0027%	0.0066%	0.0142%	
	Damage Costs per lane mile for each well	$3	$5	$72	$168	$331	**$580**