University Transportation Research Center - Region 2

Final Report

Analysis of Environmental and Infrastructure Impacts of Transportation Activities Associated with High Volume Horizontal Hydraulic Fracturing Operations in the Marcellus Shale Formation Using the Geospatial Intermodal Freight Transport (GIFT) Model

Performing Organization: Rochester Institute of Technology

January 2015

Sponsor:
University Transportation Research Center - Region 2

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

Research

The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

Education and Workforce Development

The modern professional must combine the technical skills of engineering and planning with knowledge of economics, environmental science, management, finance, and law as well as negotiation skills, psychology and sociology. And, she/he must be computer literate, wired to the web, and knowledgeable about advances in information technology. UTRC's education and training efforts provide a multidisciplinary program of course work and experiential learning to train students and provide advanced training or retraining of practitioners to plan and manage regional transportation systems. UTRC must meet the need to educate the undergraduate and graduate student with a foundation of transportation fundamentals that allows for solving complex problems in a world much more dynamic than even a decade ago. Simultaneously, the demand for continuing education is growing – either because of professional license requirements or because the workplace demands it – and provides the opportunity to combine State of Practice education with tailored ways of delivering content.

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UTRC's Technology Transfer Program goes beyond what might be considered "traditional" technology transfer activities. Its main objectives are (1) to increase the awareness and level of information concerning transportation issues facing Region 2; (2) to improve the knowledge base and approach to problem solving of the region's transportation workforce, from those operating the systems to those at the most senior level of managing the system; and by doing so, to improve the overall professional capability of the transportation workforce; (3) to stimulate discussion and debate concerning the integration of new technologies into our culture, our work and our transportation systems; (4) to provide the more traditional but extremely important job of disseminating research and project reports, studies, analysis and use of tools to the education, research and practicing community both nationally and internationally; and (5) to provide unbiased information and testimony to decision-makers concerning regional transportation issues consistent with the UTRC theme.

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16. Abstract

The natural gas extraction method, High-Volume Horizontal Hydraulic Fracturing (HVHF), has a significant transportation component that impacts transport infrastructure and rural communities in both positive and negative ways. Estimates provided by the US Energy Information Administration put natural gas reserves of the entire Marcellus Shale formation, our area of interest, at 410.3 trillion cubic feet. The New York State Department of Environmental Conservation estimates each Marcellus Shale well will require 625-1148 one-way truck trips for equipment, materials, and waste movement. There are currently upwards of 20,000 wells or approved permits in the study area. While economically benefiting rural areas, where the majority of the wells would be located, there are environmental and social tradeoffs to developing these resources, many of which are associated with transportation activities. Water resources needed to operate a well are typically delivered to the site by truck, as local water resources are often inadequate to provide the 1-8 million gallons needed to operate a HVHF well. Five to three hundred percent of the fluids used in HVHF operations are recovered as waste fluids and must be treated or disposed of, typically by transporting the waste materials to treatment or disposal facilities by truck, often over considerable distances. Sand, used as a proppant, is delivered to the well site, often from out of state, and this sand is transported multi-modally (a combination of truck, rail, and ship). Industry estimates of sand use range from 2.5–7 million pounds per well, with an average use of 5 million pounds per well. The researchers analyzed the environmental impacts of transporting sand and water to and waste from well sites in 2011, providing a series of assessments of truck traffic on area roads by road segment, and assessing potential pollution impacts on communities by calculating emission loads, energy usage, and operating costs using the Geospatial Intermodal Freight Transport (GIFT) model within ArcGIS Network Analyst. By using the wells, resource supply areas, and waste disposal facilities as a series of origin and destination (OD) pairings, probable transportation routes were generated and combined with estimated vehicle counts, based on the volume of materials transported and well locations. For roadways, the maps generated for this project illustrate spatially the impacts of estimated truck traffic on specific road segments linked to natural gas extraction, highlighting areas of higher pollution emissions and infrastructure wear and tear. Our results also help to put in context the impacts on-site waste recycling may have on pollution emissions and indirectly on road infrastructure. The case studies developed during this project point to the need for better data collection and distribution efforts in areas currently extracting gas and those considering whether or not to allow high volume horizontal hydraulic fracturing. Our results will enable policy analysts and environmental planners to better understand the impacts (pro and con) associated with the movement of materials in the HVHF industry.

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UTRC Region 2 Out of the Box Grant Project

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Executive Summary

The natural gas extraction method, High-Volume Horizontal Hydraulic Fracturing (HVHF) (Figure 1), has a significant transportation component that impacts transport infrastructure and rural communities in both positive and negative ways. Estimates provided by the US Energy Information Administration put natural gas reserves of the entire Marcellus Shale formation, our area of interest, at 410.3 trillion cubic feet. The New York State Department of Environmental Conservation estimates each Marcellus Shale well will require 625-1148 one-way truck trips for equipment, materials, and waste movement. There are currently upwards of 20,000 wells or approved permits in the study area. While economically benefiting rural areas, where the majority of the wells would be located, there are environmental and social tradeoffs to developing these resources, many of which are associated with transportation activities.

Water resources needed to operate a well are typically delivered to the site by truck, as local water resources are often inadequate to provide the 0.5-8 million gallons needed to operate a HVHF well. Five to three hundred percent of the fluids used in HVHF operations are recovered as waste fluids and must be treated or disposed of, typically by transporting the waste materials to treatment or disposal facilities by truck, often over considerable distances. Sand, used as a proppant, is delivered to the well site, often from out of state, and this sand is transported multi-modally (a combination of truck, rail, and ship). Industry estimates of sand use range from 2.5–7 million pounds per well, with an average of 5 million.

The researchers analyzed the environmental impacts of transporting sand and water to and waste from Pennsylvania well sites in 2011, providing a series of assessments of truck traffic on area roads by road segment, and assessing potential pollution impacts on communities by calculating emission loads, energy usage, and operating costs using the Geospatial Intermodal Freight Transport (GIFT) model. By using the wells, resource supply areas, and waste disposal facilities as a series of origin and destination (OD) pairings, probable transportation routes were generated and combined with estimated one-way trip counts, based on the volume of materials transported and well locations. Several load weights were simulated, and the annual emissions, vehicle miles traveled, travel hours, and estimated one-way truck trips are provided below.

2011 LOADS	TRUCKS (oneway)	MILES (oneway)	HOURS (oneway)	VOC (Mg)	SO_x (Mg)	PM_{10} (Mg)	NO_x (Mg)	ENERGY (MBTU)	CO_2 (Mg)	CO (Mg)
22 TONS	1,903,869	31,092,412	796,594	13.90	0.37	6.81	267.80	671,596	54,101	72
16 TONS	2,618,937	42,595,034	1,092,673	19.04	0.51	9.33	366.87	920,053	74,115	98
10 TONS	4,184,132	67,580,151	1,736,914	30.21	0.81	14.80	582.07	1,459,731	117,589	156

For roadways, the maps generated for this project illustrate spatially the impacts of estimated truck traffic on specific road segments linked to natural gas extraction, highlighting areas of higher pollution emissions and infrastructure wear and tear. By altering parameters within the GIFT model, we can explore the impacts of different fuel mixtures and emission control devices on pollution generated by truck traffic. Our results also help to put in context the impacts on-site waste recycling may have on pollution emissions and indirectly on road infrastructure. The case studies developed during this project point to the need for better data collection and data distribution efforts in states currently extracting gas and those considering whether or not to allow high volume horizontal hydraulic fracturing. Our results will enable policy analysts and environmental planners to better understand and evaluate the impacts (pro and con) associated with the movement of materials in the HVHF industry.

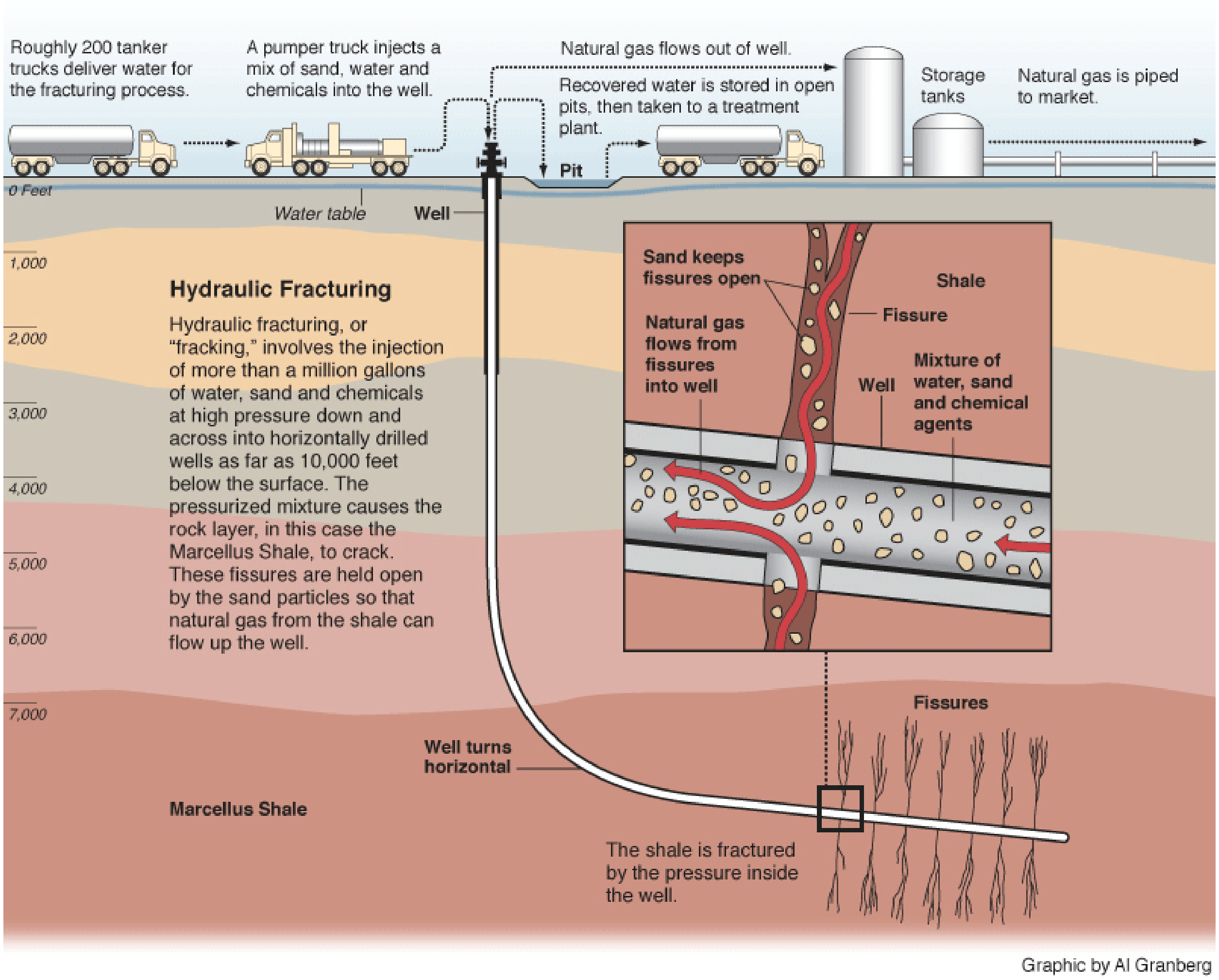

Figure 1. Overview of horizontal hydraulic fracturing process, with several transport components highlighted. https://www.propublica.org/special/hydraulic-fracturing-national (Accessed 01-18-2015)

Introduction and Overview

Transportation is critical to this nation's energy usage, delivering fuel and raw materials to refineries and energy facilities from mines and wells over a variety of transportation modes and networks. While coal has been a primary energy resource in the past, concerns over extraction impacts and emissions affecting human health and global climate have slowed its development. Recent technological advances in the extraction of natural gas, however, have greatly expanded the known and available reserves of this fuel, considered to be a cleaner fossil energy source. Natural gas has been discussed as a bridging fuel to help the US transition to more sustainable energy sources, such as second generation biofuels, solar, wind, and hydrogen (Myhrvold and Caldeira, 2012).

The natural gas extraction methodology that employs horizontal drilling and hydraulic fracturing techniques (referred to here as high volume hydraulic fracturing or HVHF) has a significant transportation component that impacts transport infrastructure and rural communities in both positive and negative ways (Figure 1). Estimates provided by the US Energy Information Administration (EIA) put natural gas reserves of the entire Marcellus Shale formation (Figure 2) at 410.3 trillion cubic feet (55% of the US reserves), although not all of that will be recoverable (EIA, 2011). Through land leases, employment opportunities, and economic development stemming from the natural gas industry, this vast resource represents a real economic boon for struggling rural areas, where the majority of the wells would be located. There are, however, environmental and social tradeoffs to developing these resources associated with transportation activities.

Developing and operating a HVHF natural gas well is resource and infrastructure intensive, primarily because of the rural locations of the prime drilling sites. In the Marcellus Shale region, the bulk of the water resources needed to operate a well are delivered to the site by truck, as local water resources are often inadequate to provide the 1-8 million gallons needed to drill a single well (NELT, 2011; Biello, 2012; NYC DEP, 2012). Assuming 2500-5500 gallons per tanker truck (10-22 ton loads), a single well using 5 million gallons of water would require between 909 and 2000 one-way deliveries per fracturing event. Based on geospatial data downloaded from Frac Tracker (www.fractracker.org), there are over 20,000 active or permitted wells distributed throughout the Marcellus Shale (Figure 3). If each required service by truck, this would result in between 18-40 million one-way deliveries of water alone, from variable distances, to variable locations. Common issues raised in the debate over HVHF activities related to transport are congestion due to high truck traffic in rural communities, spills and accidents, pollution emissions, and the wear and tear of truck traffic on rural roads and bridges not necessarily designed for the volume or weight of the truck traffic they are now or would be experiencing.

Estimates of recovered wastewater fluids used in HVHF range from 5-300%, but there is considerable uncertainty and variability in recovered volumes (US EPA, 2011; NETL, 2011; Cooley and Donnelly, 2012; Clark et. al, 2012). Because of contaminants, these fluids must be disposed of or treated, usually by transporting the waste materials to treatment or disposal facilities by truck, often over considerable distances. As displayed in Figure 2, regionally there were over 100 facilities that accepted HVHF wastes from Pennsylvania wells, based on 2010 PA Department of Environmental Protection records downloaded from Frac Tracker (www.fractracker.org). A growing number of municipalities, however, are banning HVHF wastes at their treatment facilities due to treatment limitations and public opposition, so well operators may need to send their wastes far out of state if they opt not to treat on-site. Cost effective on-site treatment methods and recycling processes are still under development, but a growing volume of waste fluid is being recycled on-site (Lutz, et.al, 2013). Some portion of these waste materials, however, will ultimately need to be transported off site for treatment or disposal.

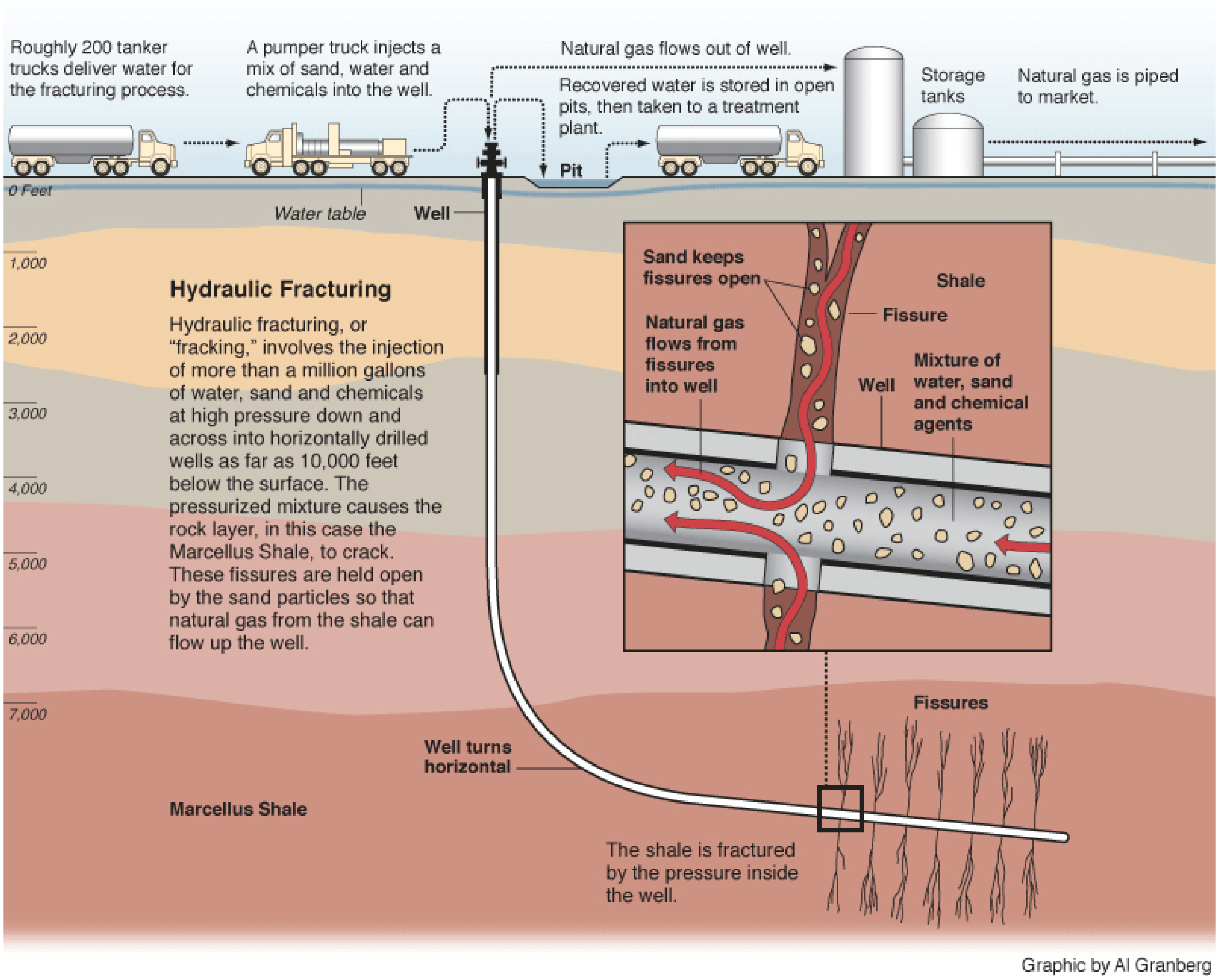

Figure 1. Overview of horizontal hydraulic fracturing process, with several transport components highlighted. https://www.propublica.org/special/hydraulic-fracturing-national (Accessed 01-18-2015)

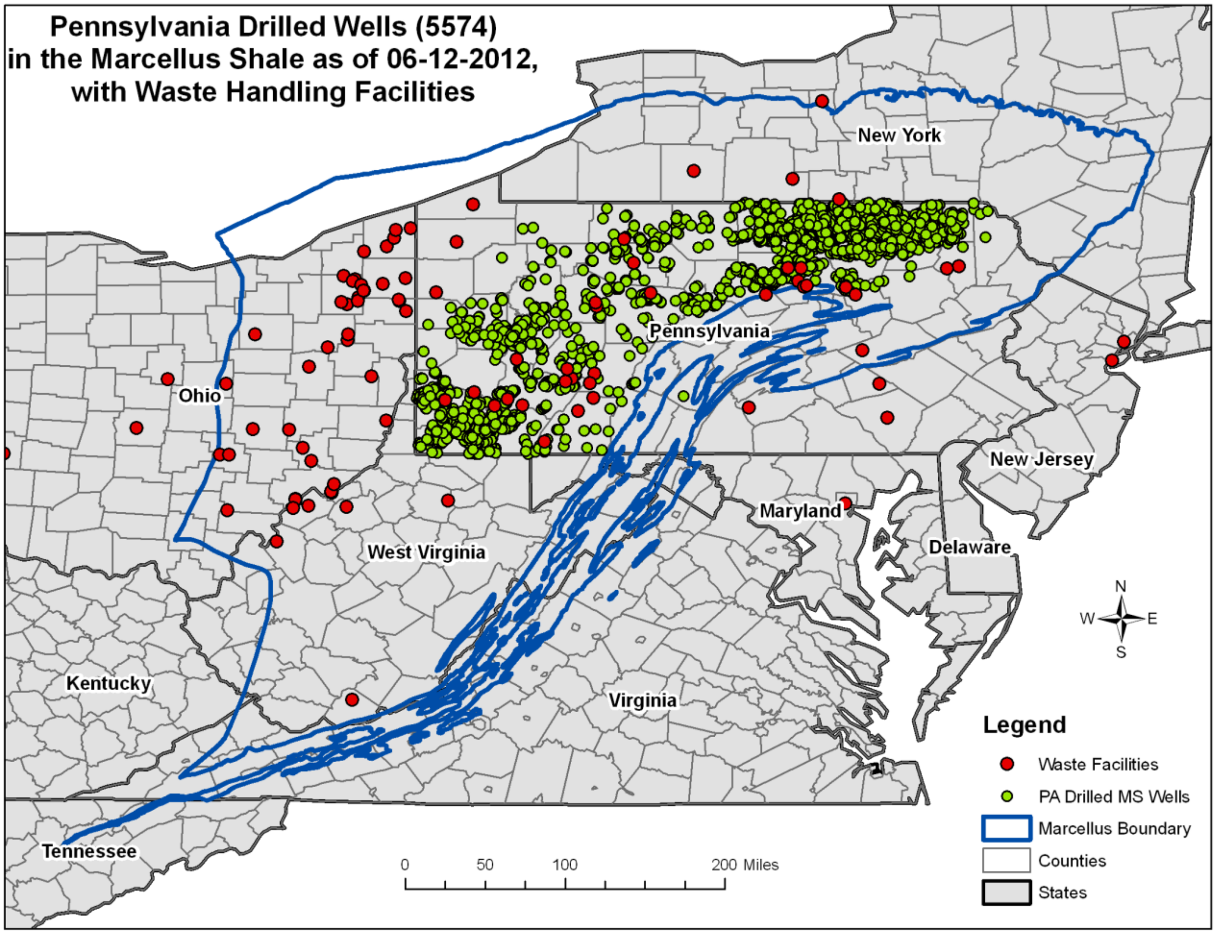

Figure 2 – Marcellus Shale Boundary from the US Geological Survey (http://certmapper.cr.usgs.gov/data/noga00/prov67/spatial/shape/au670464g.zip), with drilled wells in Pennsylvania as of June 12, 2012 and waste handling facilities, downloaded from www.fractracker.org.

Sand, used as a proppant in the injection process to help keep fractures open, is a critical component that must be delivered to the well site. According to the US Geological Survey, in 2012, eight states (TX, IL, WI, MN, AR, MO, MI, and OK) produce over 73% of domestic sand and gravel (over 45 million tons), and 57% of all sand used was for HVHF activities (USGS, 2013). Industry estimates of sand use range from 1,250-3,500 tons per well, with an average use of 2,500 tons per well, per fracturing event. If a large truck can deliver 22 tons of sand, a single well could need up to 113 truckloads. If trucks were restricted to a 10-ton load, that number would jump to 250 deliveries per well.

Between 2009 and 2013, PA DEP records indicate that 27,283 permits were issued for both conventional (vertical) and unconventional (horizontal) wells, and that 12,830 conventional and unconventional wells were drilled (http://www.portal.state.pa.us/portal/server.pt/community/oil_and_gas_reports/20297). By June, 2012, there were upwards of 20,000 wells or approved permits in the four primary states of the Marcellus Shale region (Figure 3), based on well records and drilling permit applications downloaded from Frac Tracker (www.fractrackr.org). While rail and/or ship can transport HVHF sands as bulk cargo, final deliver to the well sites will continue to be dominated by truck transport. Because of limited road networks in rural areas, truck traffic will be concentrated on certain segments, leading to increased congestion, higher road repair costs, and possible bridgework.

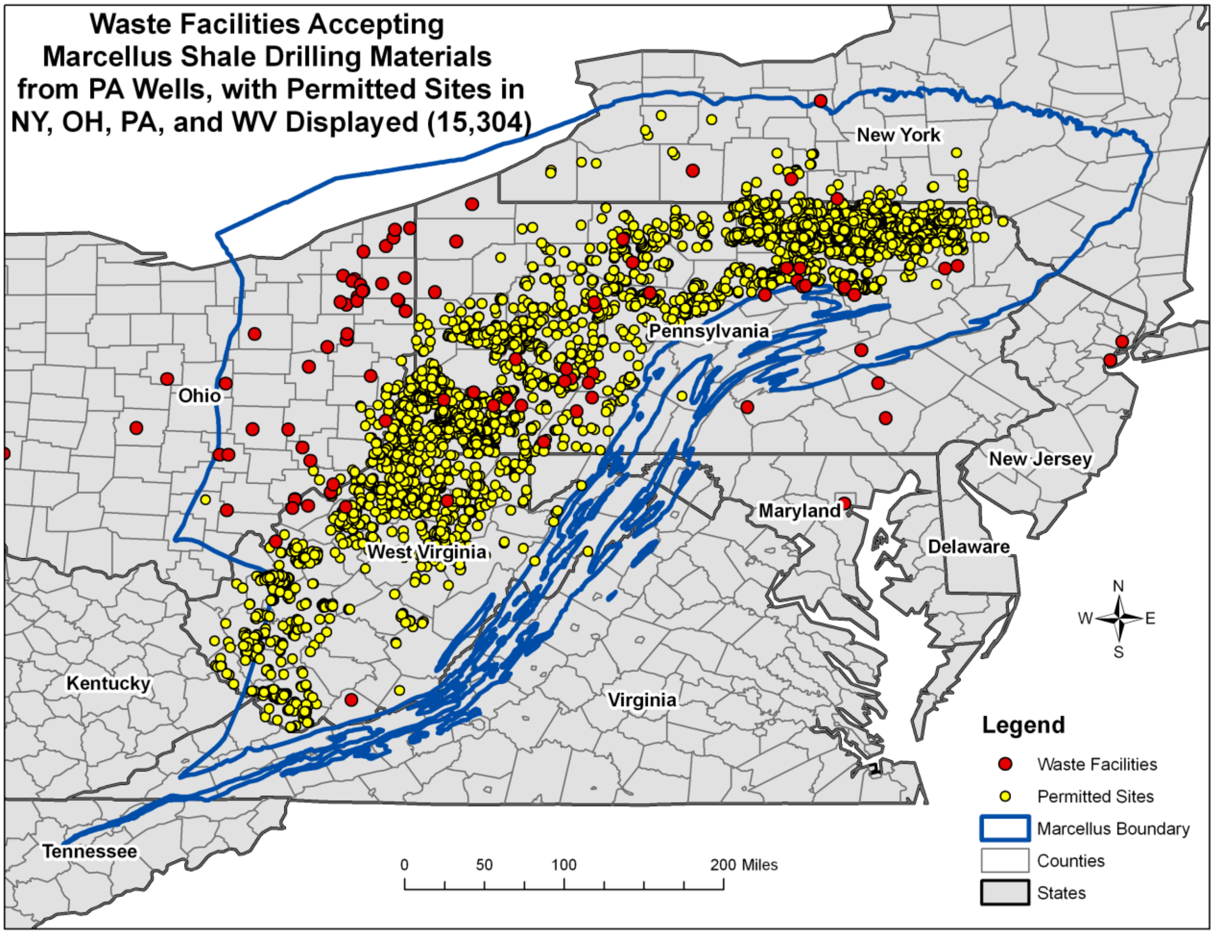

Figure 3 – Approved Marcellus Shale permits in NY, PA, and WV, based on records downloaded June 18, 2012 from www.fractracker.org.

Transporting these raw materials and wastes results in considerable environmental impacts due to vehicle emissions. These include CO_2, volatile organic compounds (VOCs), NO_x, SO_x, and particulate matter (PM_{10} and $PM_{2.5}$). CO_2 emissions contribute to climate change, while emissions like NO_x and PM_{10} are linked to human health impacts, so rural communities may face greater exposure to these pollutants due to the high volume of truck traffic in certain areas. Increased truck traffic may also alter rural society by straining transportation infrastructure beyond intended capacities. This in turn may lead to increased road and bridge repairs, accidents, and spills, which may impact the local environment and water resources. Yet economic development, if done sustainably, will benefit the communities greatly over a long period of time. Central to the debates surrounding hydraulic fracturing is balancing economic development, livable communities, and environmental protection in the Marcellus Shale area and in other areas where HVHF activities are taking place. Analyzing transportation impacts, pro and con, will contribute to these discussions.

RESEARCH APPROACH

The transportation analysis was conducted using ArcGIS and the Network Analyst extension, a geographic information system software created by ESRI, and the Geospatial Intermodal Freight Transport (GIFT) model. GIFT is an ArcGIS extension that integrates into Network Analyst, allowing the user to input economic, emission, fuel, load, and engine characteristics for trucks, railroad engines, and ships to calculate pollution emissions and transport costs (Winebrake, et al, 2008, Comer, et al., 2010). Figure 4 provides a screenshot of the cost factor and emission calculators. User defined Truck, Rail, and Ship parameters are input (and saved) by the user, or pulled from pre-determined vehicles stored in a growing transportation library.

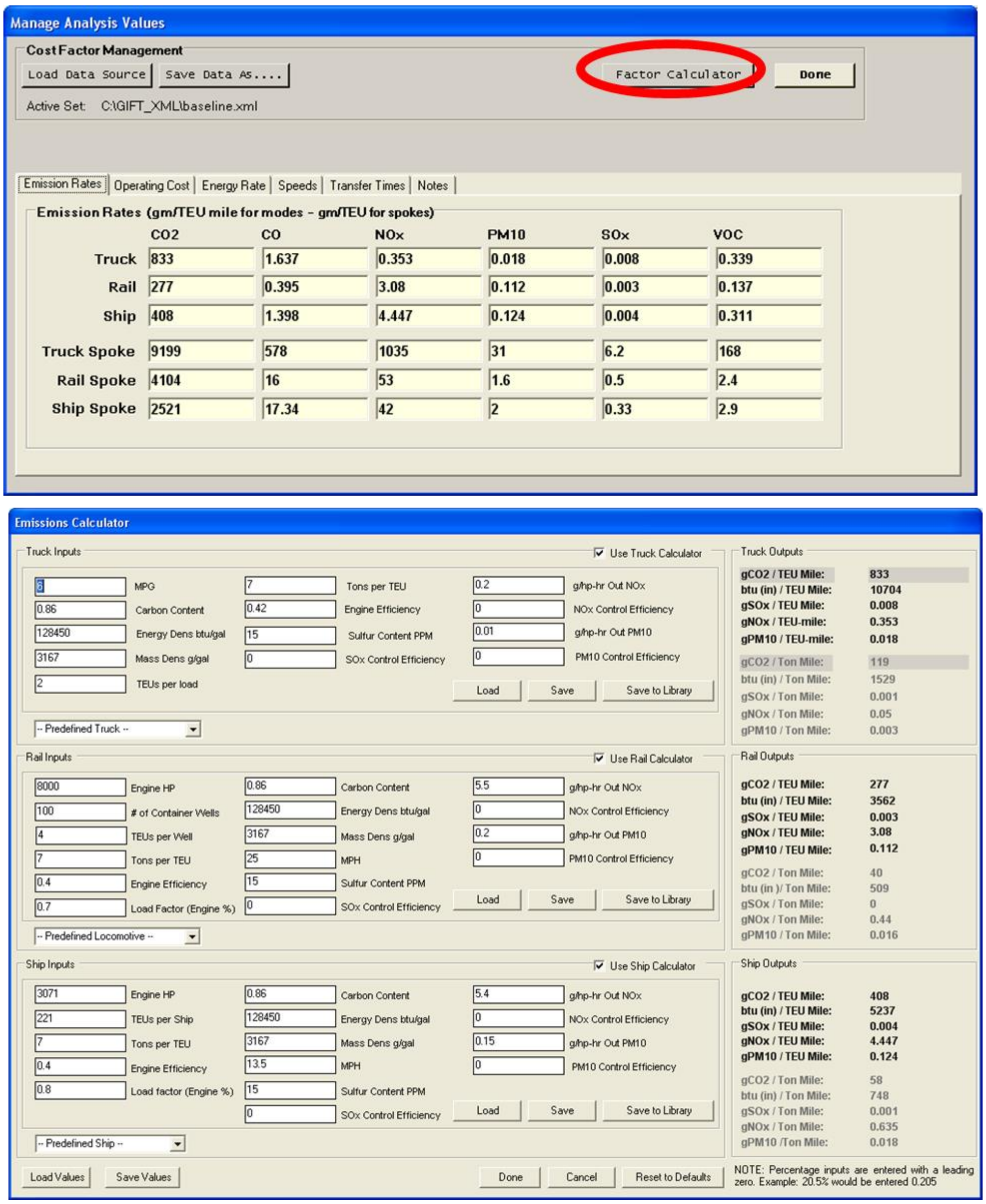

Figure 4. The GIFT Model input windows with example inputs.

Using a single mode network, such as TIGER road data (US Census, 2010), or an integrated intermodal transportation network based off of the National Transportation Atlas Database (NTAD, 2013), single mode or multimodal simulations can be generated. Origins and Destinations are imported from locations of features such as wells, waste facilities, and material depots. Barriers, such as bridge or road restrictions, can be added to adjust routes from an optimal solve based strictly on time and/or distance.

The transportation network database used in this project was created in ArcGIS from TIGER line files for state road networks in PA, NY, OH, and WV. General speed limits were assigned by road class, and transport hours for each segment were calculated by dividing segment distance (miles) by segment speed (MPH). We initially planned to use the National Transportation Atlas Database (NTAD) as our road network, but discovered that too many small rural roads were omitted from NTAD, resulting in many "unlocated" wells and facilities in our analysis. Using TIGER line files allows for the generation of a more realistic route through rural areas, and all wells were located on the network. The trade-off, however, is the resulting network database size and the impact on model performance (each model run takes several hours to complete). Figure 5 illustrates the difference between these two road networks, with 2011 Pennsylvania wells shipping waste to the Allied Waste Systems Facility in Niagara County, NY. Without including the smaller rural roads from the TIGER files, most wells were either not located on the NTAD network, or required search tolerances in excess of 10 kilometers.

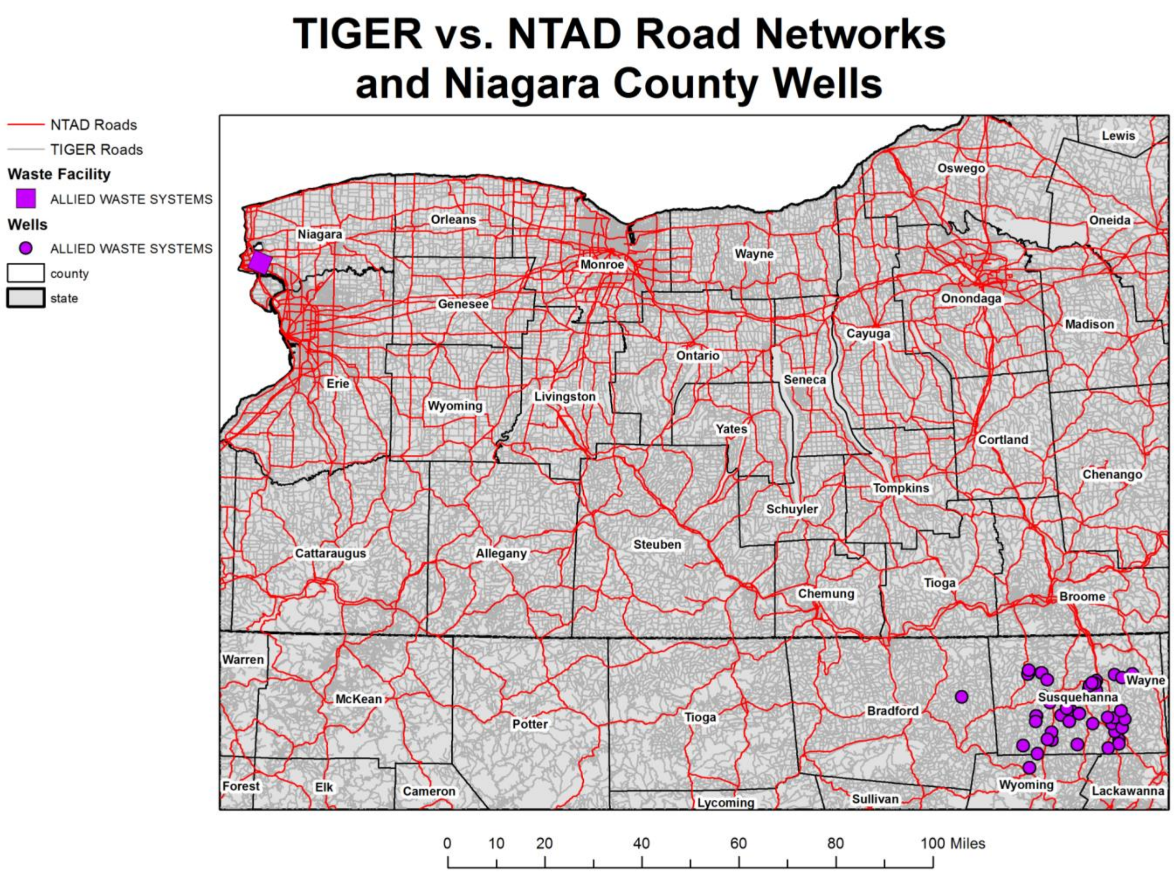

Figure 5. NTAD vs. TIGER road networks.

CASE STUDIES

Because of the rapid growth of natural gas development in Pennsylvania from 2004-present, we decided to focus on the year 2011 for our analyses. Earlier reporting years were subject to certain data quality issues (see Lutz, et al, 2013 for an overview) that were largely corrected by 2011. When we started the project, the 2011 data were complete for the full year. 2011 also represents the largest well development year in the region, and wells drilled prior to 2011 would be producing waste as well as natural gas. Our long-term plan is to build upon this base year, now that our analysis steps are developed, with 2012 and 2013 data in the coming months, and revisiting the 2004-2010 data in the summer of 2014, to track the changes over time in transport usage and impacts. The following sections document three case studies. First is a study of the transportation impact of moving HVHF waste away from the drilling sites. The second is a study of the transportation impact of moving water to the drilling sites. The third is a study of moving sand to the drilling site. We then combine these results into a 2011 analysis of materials and waste transport. These combined results are then compared to emission offsets by on-site waste treatment (reported 2011 on-site totals) and estimated emission reductions if trucks are outfitted with advanced pollution control devices or shift to natural gas as a fuel source.

Waste Case Study

Our simulations of Waste, Sand, and Water transport rely on creating a series of Origin and Destination (OD) point pairs and solving routes between each unique pair. For the HVHF **waste analysis**, the Pennsylvania Department of Environmental Protection (PA DEP) provides coordinates for well locations and treatment disposal facilities in spreadsheet format every six months, starting with the 2010 data - (https://www.paoilandgasreporting.state.pa.us/publicreports/Modules/DataExports/DataExports.aspx).

Each record includes information on a well, the type and amount of waste moved, and the destination facility, as well as the location coordinates of the well and the waste facility. We added a unique ID value to each record in order to import the locations of the wells and the facilities as ordered pairs (wells were origins, facilities were destinations, and both points are linked to the unique record ID, used as the route NAME and as a key field to join attributes from external databases). Using the reported amounts and types of waste shipped, we generated estimates of the number of trucks needed to move the materials. The Roundup function in Microsoft Excel was used to convert **tons of waste** into trucks, dividing recorded tons by 22, 16, and 10 to simulate 22, 16, and 10 ton loads (a large tractor trailer, a large dump truck, and a smaller dump truck that would not exceed most bridge and road limits). For **barrels of waste**, barrels were multiplied by 42 to convert to gallons, then divided by the volume of the simulated pump truck (5500, 4000, and 2500 gallons to form equivalents to the 22, 16, and 10 ton trucks). The range of truck counts provides us with a “bookend” analysis of probable loads and road/bridge friendly loads. Well and Facility positions were imported into ArcGIS as event tables (from the same file, to ensure a common unique ID) and then converted to shapefiles.

ArcGIS Network Analyst provides several options for generating routes, and we experimented with two – **New Closest Facility** and **New Route**. For the Waste Analysis, we initially opted for **New Closest Facility**, loading in the location of a specific waste facility and the wells that shipped to that facility as the FACILITIES and INCIDENTS, respectively. For New York, with only five receiving facilities in 2011, this was a reasonable approach (five sets of model runs). But for a state like OH, with 61 receiving facilities listed in 2011, this approach became impractical. So to solve for large numbers of wells going to a series of specific facilities, we used the unique ID for each record with the **New Route** module.

New Route allows the user to load stops by XY location and assign each stop a name. The names of the two stops are combined in ArcGIS to produce a route name. We first loaded the Wells, using the unique ID as the stop name. We then loaded the facilities, with the unique ID as the stop name. This creates a series of ordered pairs, linked by a common unique record ID, which became the unique route name. To minimize computer memory issues, we opted to solve batch routes in six month blocks (Period 1 covering records from January through June, and Period 2, covering records from July through December, as provided by PADEP) and then merge the results into an annual file. This is especially critical for the edges analyses, which generated large files.

Using the GIFT Model with Network Analyst, distance attributes and total emissions from a user defined vehicle are generated for each route. For the 2011 baseline analyses, truck emission rates were set as follows, using input values from the 2008 average in-use heavy duty diesel vehicles from the US EPA (2008) (http://www.epa.gov/otaq/consumer/420f08027.pdf) and diesel fuel parameters were derived from the GREET Model 1.8b, including low-sulfur diesel fuel (11 ppm sulfur) and six mpg (ENERGY is btu/mile, all others are g/mile):

VOC	SO_x	PM_{10}	NO_x	ENERGY	CO_2	CO
0.447	0.012	0.219	8.613	21600	1740	2.311

Once routes and edges are generated, the estimated truck counts contained in the external well point database are joined using the route name, and the truck estimates are copied over. For edge tables, the route layer OBJECTID attribute is the same as the edge layer ROUTE_ID attribute, and the route truck counts can be joined using these attributes.

To generate total pollution estimates by route, the number of trucks is multiplied by the route emissions for a specific pollutant (Table 1). These route totals are for one-way trips from the wells to the receiving facilities for all trucks associated with an ordered pair. Routes frequently overlap certain road segments, and these cumulative impacts at the segment level have higher truck counts, resulting in higher emissions along those segments. To generate estimates of combined truck counts and emission from overlapping segments, the Network Analyst tool **Traversal Result** was used to generate edges for each route, and overlapping edges were combined to show localized, cumulative impacts.

Edges are linked to specific segments of the underlying ArcGIS network database by the network attribute **SourceOID**. Overlapping edges from the route can be combined using SourceOID in the DISSOLVE command, summing truck counts assigned to each edge segment and taking the mean value for each pollutant for each edge segment. This provides an annual estimate of the total number of trucks traveling a given segment related to the HVHF industry, and the pollution emitted by a single truck along a given segment (distance dependent). Multiplying the truck count by the emission values provides an estimate of the annual pollution generated by the simulated truck traffic for a given segment. These combined truck counts and pollution estimates in the edge (segment) layer show network hot spots and can be used as input for pollution dispersion models like AERMOD (USEPA, 2013). Maps showing generated waste routes and truck counts by road segment are provided in Figures 6-12. Truck counts, representing one-way trips, serve as an indication of pollution emissions (higher counts lead to higher total emissions per mile).

The high truck counts along the Interstates and State Highways linking PA and OH reflect the large amount of waste shipped to OH injection wells in 2011 from wells throughout the Marcellus Shale play

(Figure 7). The model routes trucks onto these major roads based on assigned speed limits and distance, so the Interstates and higher speed highways draw trucks to them quickly, as expected. I-86 in New York also draws some OH bound truck traffic, although the number of trucks is relatively small compared to PA roads (less than 1000 trucks). Trucks delivering PA well wastes to facilities within PA, however, use a variety of road types (Figure 8). Within PA, portions of I-79 and PA-21 around Pittsburg experience high truck traffic counts as routes merge towards specific treatment plants. Around Williamsport, treatment plants off of I-180 and Highway 15 draw high numbers of trucks, and there are segments on more minor, rural roads that also have high truck counts, such as the facility near Blossburg, PA. The model sends some trucks up through NY, drawn by I-86, but the generated counts are less than 500.

Figure 9 illustrates model results for NY roads used with PA to NY OD pairs. Pennsylvania wells sending waste to NY tend to be located nearby the NY border in the NE portion of the study area and tend to use landfill facilities for drill cuttings. But a few wells in the SW portion of the study area shipped liquid waste up to the Niagara facility, rather than OH injection wells. Based on model truck counts, in 2011 NY received an estimated 9% of the waste transported from PA wells, OH received 30% of the waste, and PA facilities received 61% of the waste (Figures 7-9). Figures 10-12 show the spatial patterns of the estimated truck counts of the combined waste results for 22, 16, and 10 ton loads.

Table 1. Estimated truck counts by variable loads and associated emission totals for the delivery of **waste materials** from PA wells to treatment/disposal facilities in NY, OH, and PA in 2011. Miles and hours represent total vehicle miles and hours for one way trips from the wells to the facilities.

LOAD	TRUCKS (oneway)	MILES (oneway)	HOURS (oneway)	VOC (Mg)	SO_x (Mg)	PM_{10} (Mg)	NO_x (Mg)	ENERGY (MBTU)	CO_2 (Mg)	CO (Mg)
22 TONS	109,119	11,998,047	234,293	5.36	0.14	2.63	103.34	259,158	20,877	28
16 TONS	148,094	16,247,516	317,246	7.26	0.19	3.56	139.94	350,946	28,271	38
10 TONS	232,882	25,491,329	497,859	11.39	0.31	5.58	219.56	550,613	44,355	59

Truck Routes Generated from PA Wells Reporting Waste Sent to Treatment/Disposal Facilities in NY, OH, and PA in 2011

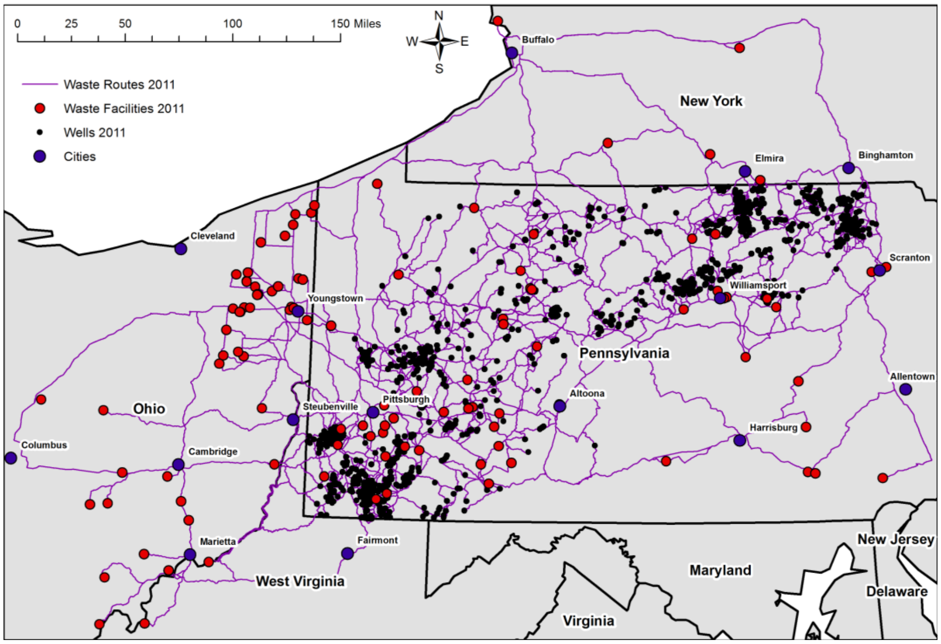

Figure 6. Combined routes of waste deliveries from PA wells in 2011 to treatment/disposal/recycling facilities in NY, OH, and PA, as reported to the PA Department of Environmental Protection.

Estimated Truck Counts (16-ton Loads) for WasteTransport from PA Wells to OH Disposal Facilities in 2011

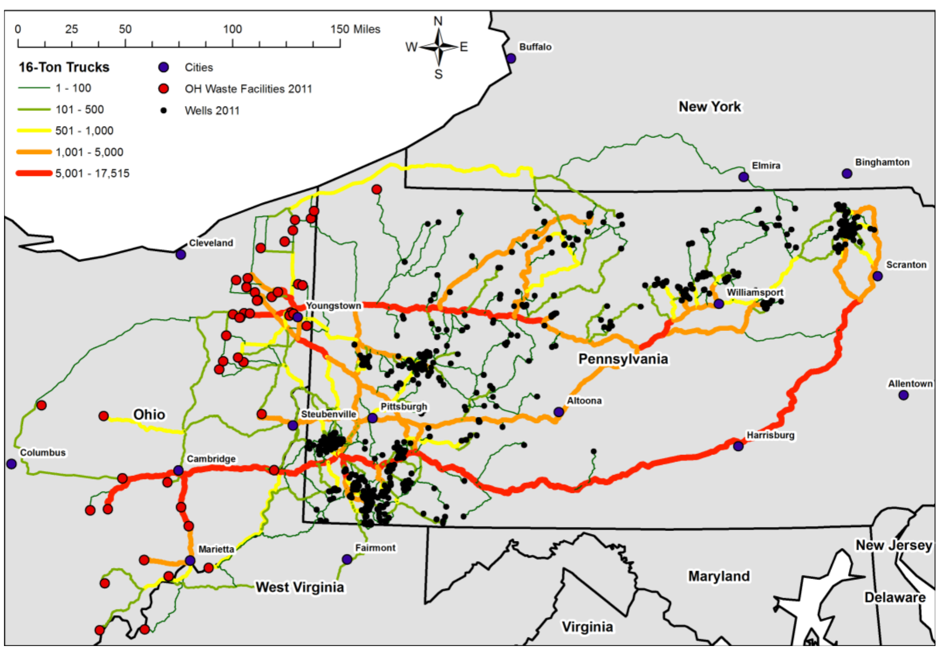

Figure 7. Routes and truck counts by edge for simulated 16-ton loads of waste delivered to OH facilities from PA wells in 2011.

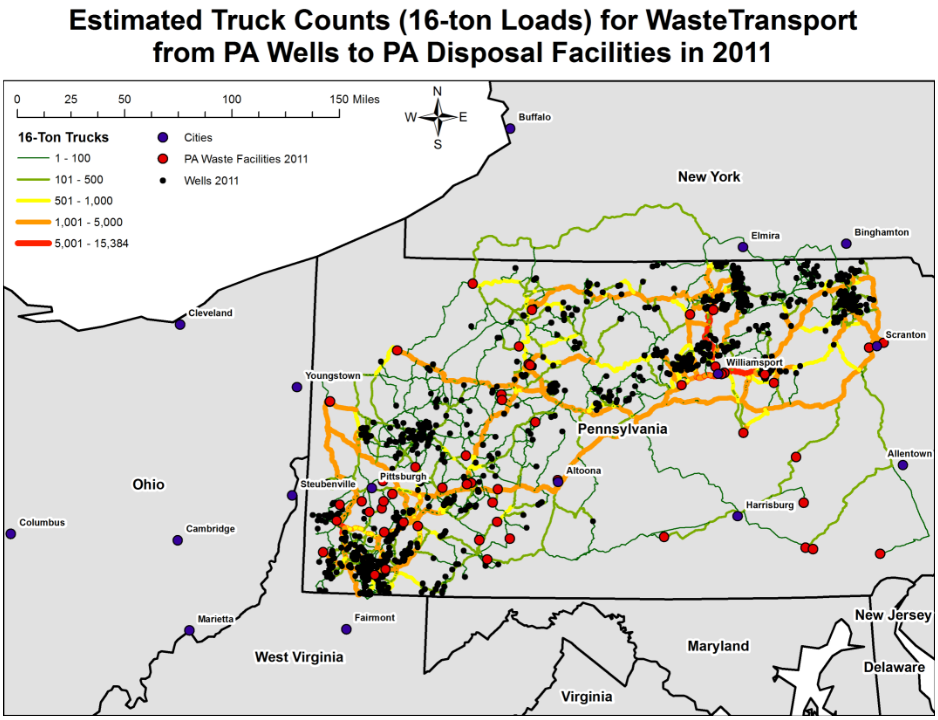

Figure 8. Routes and truck counts by edge for simulated 16-ton loads of waste delivered to PA facilities from PA wells in 2011.

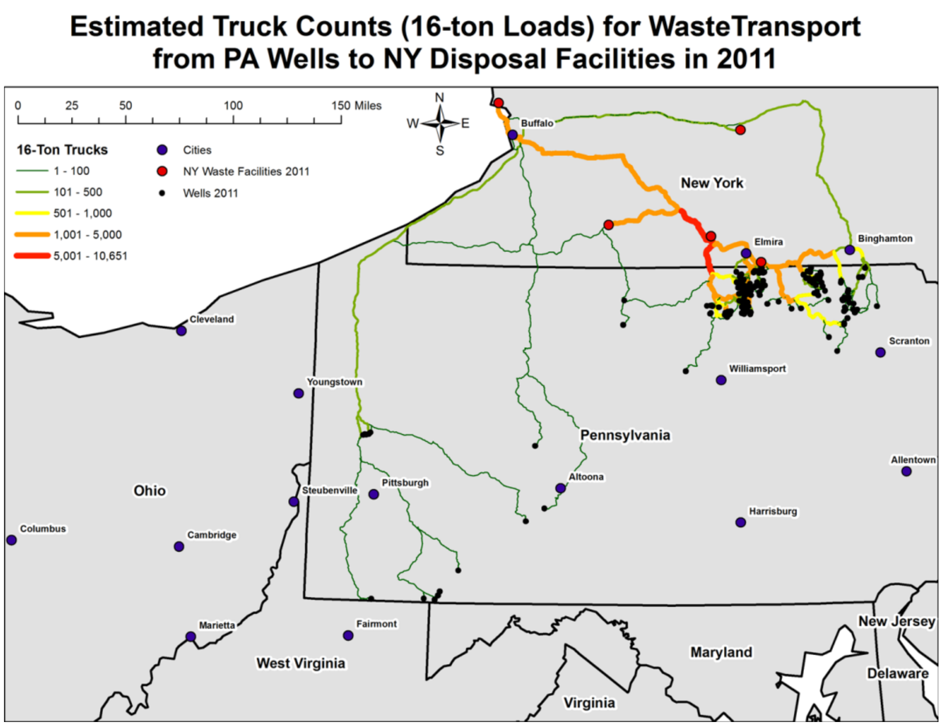

Figure 9. Routes and truck counts by edge for simulated 16-ton loads of waste delivered to NY facilities from PA wells in 2011.

Estimated Truck Counts (22-Ton Loads) by Road Segment for Pennsylvania Well Waste Shipped to NY, OH, and PA Facilities, 2011

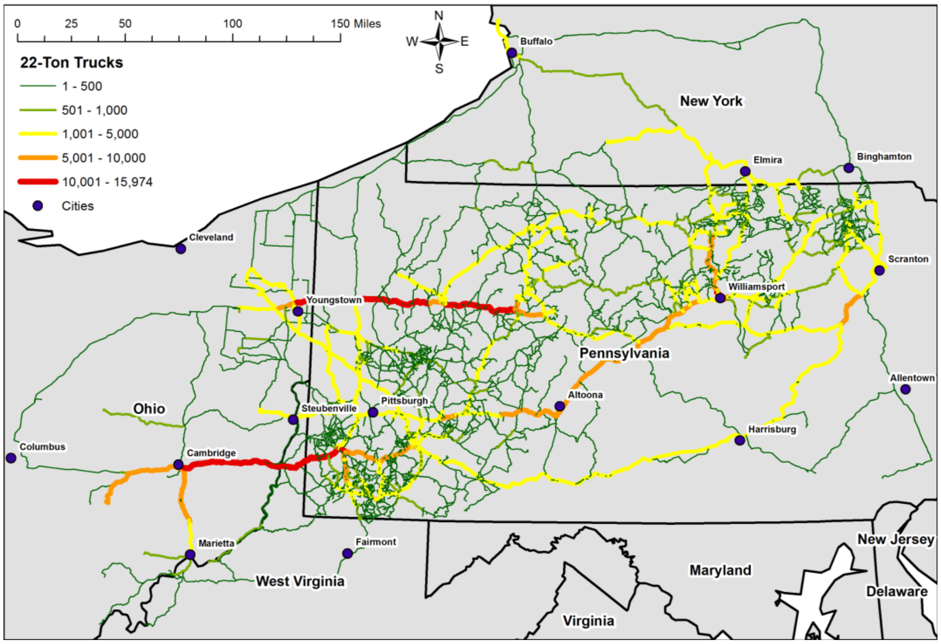

Figure 10. Estimated truck counts assuming 22-ton waste loads. This size mimics loads approaching Federal Highway weight limits without requiring special permits.

Estimated Truck Counts (16-Ton Loads) by Road Segment for Pennsylvania Well Waste Shipped to NY, OH, and PA Facilities, 2011

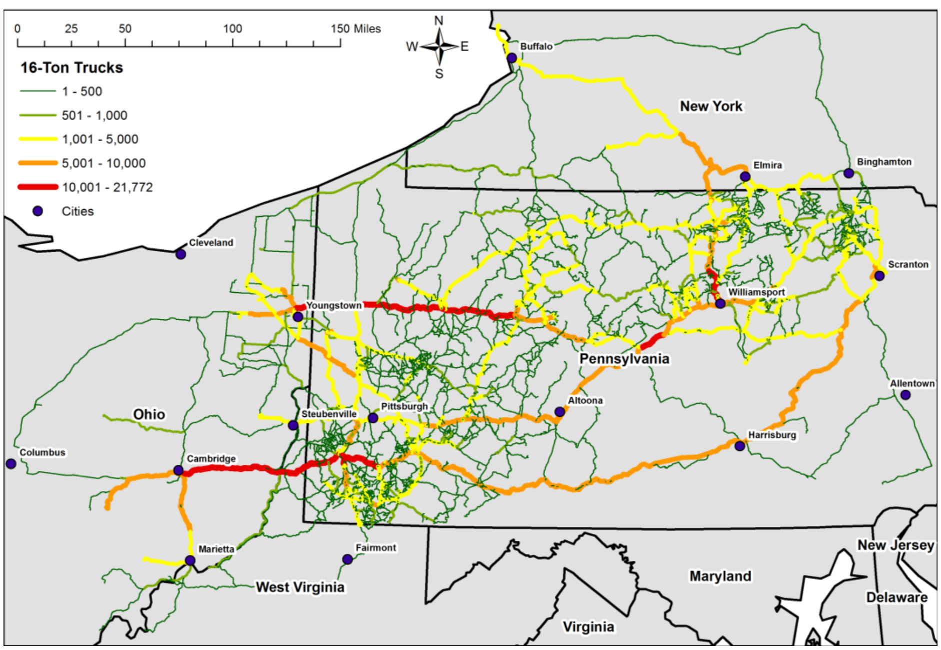

Figure 11. Estimated truck counts assuming 16-ton waste loads. This size mimics loads carried by large dump trucks or 4000 gallon tanker trucks. It also represents an average load between the 22-ton and 10-ton simulations.

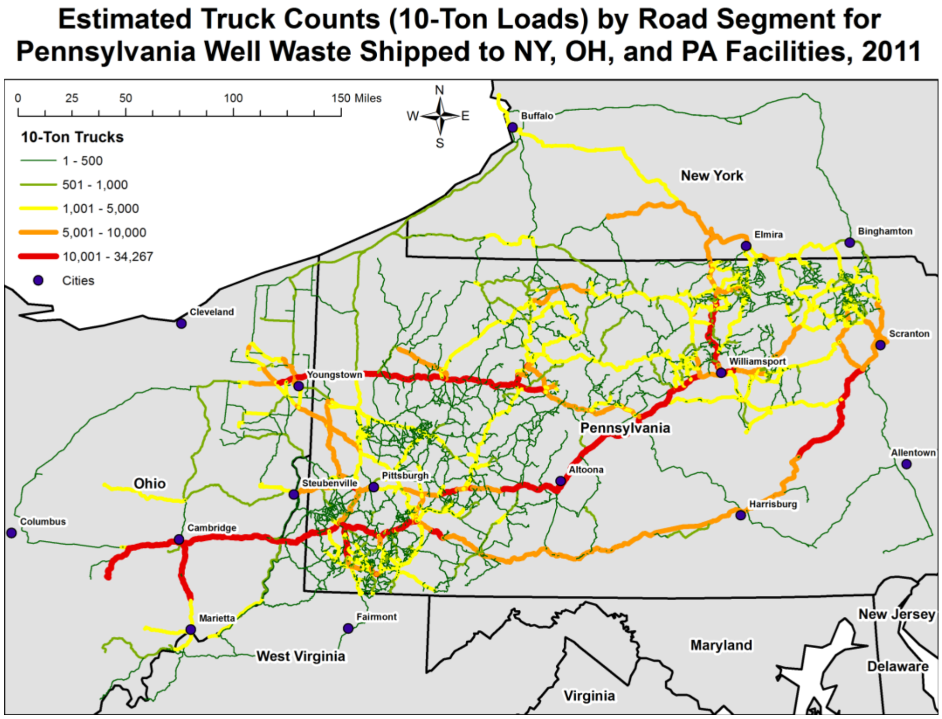

Figure 12. Estimated truck counts assuming 10-ton waste loads. This size mimics loads designed to meet most bridge load restrictions in rural areas.

Water Case Study

The OD pair information for water used at a PA well in 2011 does not exist in the same detailed digital format as the waste data (PADEP, personal communication, 2014). Locations of water sources are available, but not the locations of the specific wells using the water. Water Management Plan (WMP) data for the Marcellus Shale area, collected by PA DEP and made available for download from the Pennsylvania Spatial Data Access (PASDA) clearinghouse (ftp://www.pasda.psu.edu/pub/pasda/dep/), list the XY locations of the water withdrawal sources and which drilling companies use that source, but there is no readily available information on which specific wells are serviced by a specific water source, or how much water was used by a given well from a given source. Some wells may also pull water from nearby sources using flexible pipe, but this information is not publically available by well, so our analysis assumes all water delivery is by truck.

For the water delivery analysis, spud well data for 2011 were used for well location and company ownership and matched to water sources and company ownership. According to a water resources paper from ALL Consulting (Arthur, et al, 2010), delivery costs of water can "quickly and dramatically exceed" the actual cost of purchasing the water, so companies look for water sources as close to the well sites as possible. The 2011 spud well data from PADEP also indicates if a well was active in 2011, so 1750 wells were used as the destinations for water deliveries, assuming that they were drilled and went into production in 2011. Hydraulic fracturing requires an average of 5 million gallons per well (Arthur, et al, 2010), so each target well was assumed to need 5 million gallons. Following the logic of the truck types used in the waste analysis, we estimated truck trips needed for water delivery for several load limits. 5500, 4000, and 2500 gallon tankers mimic 22, 16, and 10 ton loads, so each well was assigned 909, 1250, and 2000 trucks for the "bookend" analysis.

The location of each water source was loaded into ArcGIS, along with the ownership information, as XY event tables and then converted into shapefiles. This process was repeated for the spud well data. Because we were uncertain which source(s) serviced which well(s), we opted to run a series of company specific **New Closest Facility** analyses, loading wells as **Incidents** and water sources as **Facilities**, selected by drilling company. Typically, company water sources were located near clusters of company wells. Solving routes from incidents to facilities ensured that each well routed to a nearby water source, although typically a cluster of wells all routed to a single, closest source, leaving other, nearby sources unmatched. Inverting the analysis generated routes from each water source, but typically to a single well (the closest one). We ultimately opted to keep the routes linking each well for this analysis, in order to capture truck traffic along the small roads servicing the wells. We are currently exploring combining a Network Analyst **New Service Area** analysis, set for a one hour drive time cut off, with the **New Closest Facility** analysis. Using this approach, we may be able to assign each well to a probable water source (a best estimate OD pair), based on drive time proximity, allowing us to utilize more of the water sources controlled by a particular company.

Assuming 5 million gallons of water for each well, each route was assigned 909, 1250, and 2000 trucks, in order to generate truck counts for the edge analysis. Results of the water analysis are provided in Table 2 and Figures 13-16. While many seemingly unconnected water sources may be providing water to the 2011 spud wells (Fig. 13), pre-2011 wells may also require water if they are re-fractured. Without well specific information on water usage and delivery, however, we are unable to generate more exact OD pairs for the route analysis, and the results show our best estimates of traffic around the well sites, if not the water sources.

Results show short, one-way routes between wells and water sources, but the estimated pollution generated by the water trucks is higher than the amounts estimated by the waste analysis due to the sheer number of trucks needed to deliver an estimated 8.75 billion gallons of water. The average estimated drive time is less than 16 minutes (range 0-3.2 hours) and the average estimated trip is 8 miles (range 0-127 miles). But 1.6-3.5 million trips were needed, based on model assumptions. The roads around and north of Williamsport, PA show the highest use, but many of the miles generated by this case study are on smaller roads. Many of these smaller roads also lack traffic count estimates, so this analysis provides an estimate of truck traffic impacts on smaller roads.

Table 2. Estimated truck counts by variable loads and associated emission totals for the **delivery of water** from company assigned water sources to company drilled PA spud wells in 2011. Miles and hours represent total vehicle miles and hours for one way trips from the closest company assigned water source to the wells.

LOAD	**TRUCKS (oneway)**	**MILES (oneway)**	**HOURS (oneway)**	**VOC (Mg)**	**SO_x (Mg)**	**PM_{10} (Mg)**	**NO_x (Mg)**	**ENERGY (MBTU)**	**CO_2 (Mg)**	**CO (Mg)**
22 TONS	1,597,113	12,765,571	408,852	5.71	0.15	2.80	109.95	275,736	22,212	30
16 TONS	2,196,250	17,554,415	562,228	7.85	0.21	3.84	151.20	379,175	30,545	41
10 TONS	3,514,000	28,087,064	899,564	12.55	0.34	6.15	241.91	606,681	48,871	65

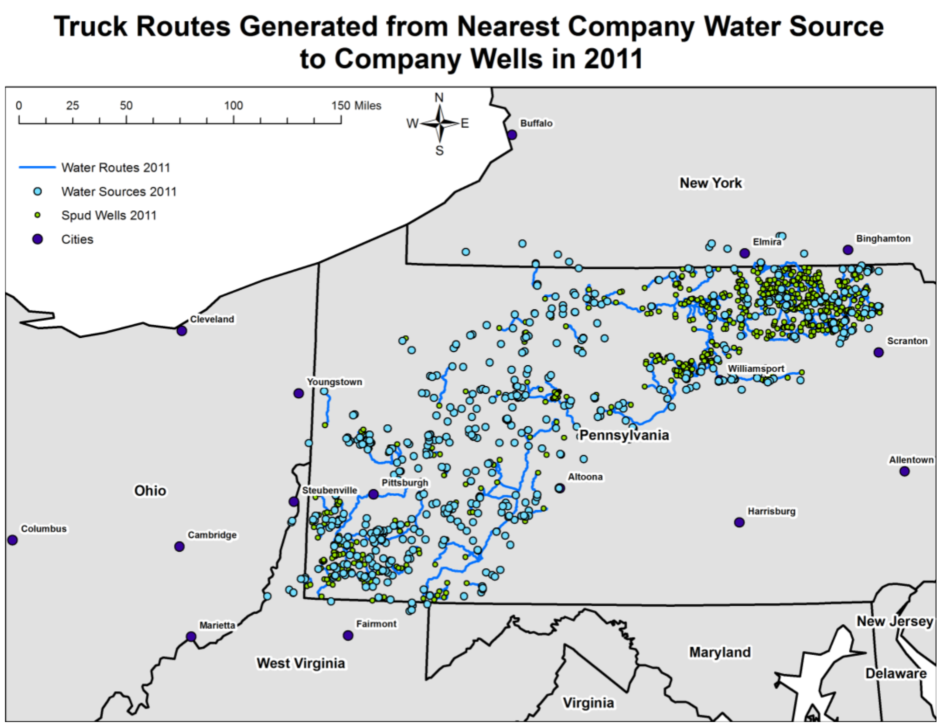

Figure 13. Combined routes of water deliveries from company assigned water sources to company specific spud wells in 2011, as documented by the PA Department of Environmental Protection.

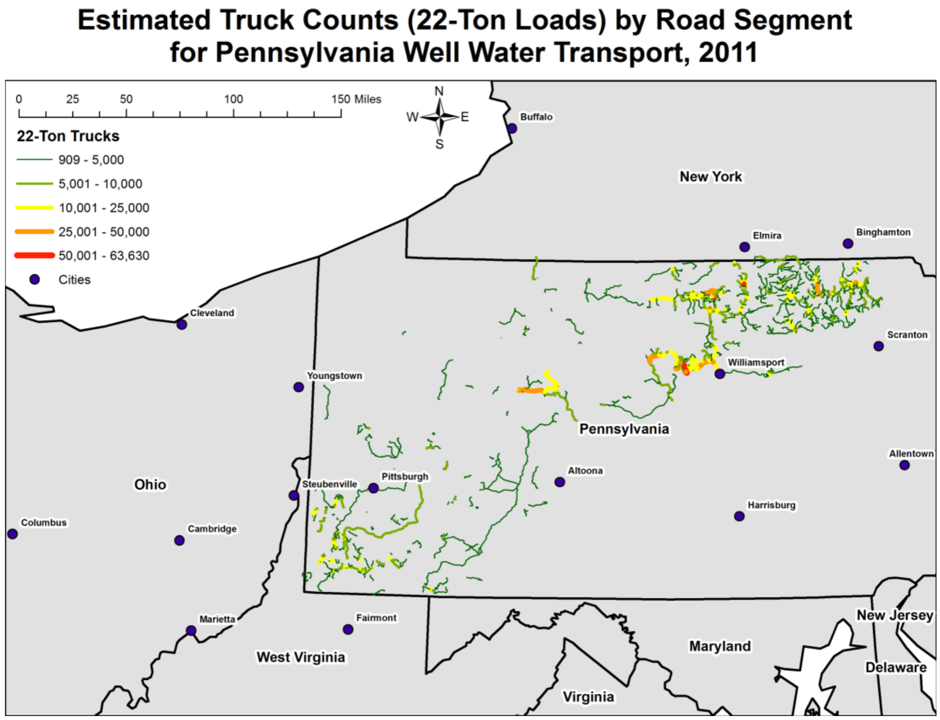

Figure 14. Estimated truck counts assuming 22-ton water loads.

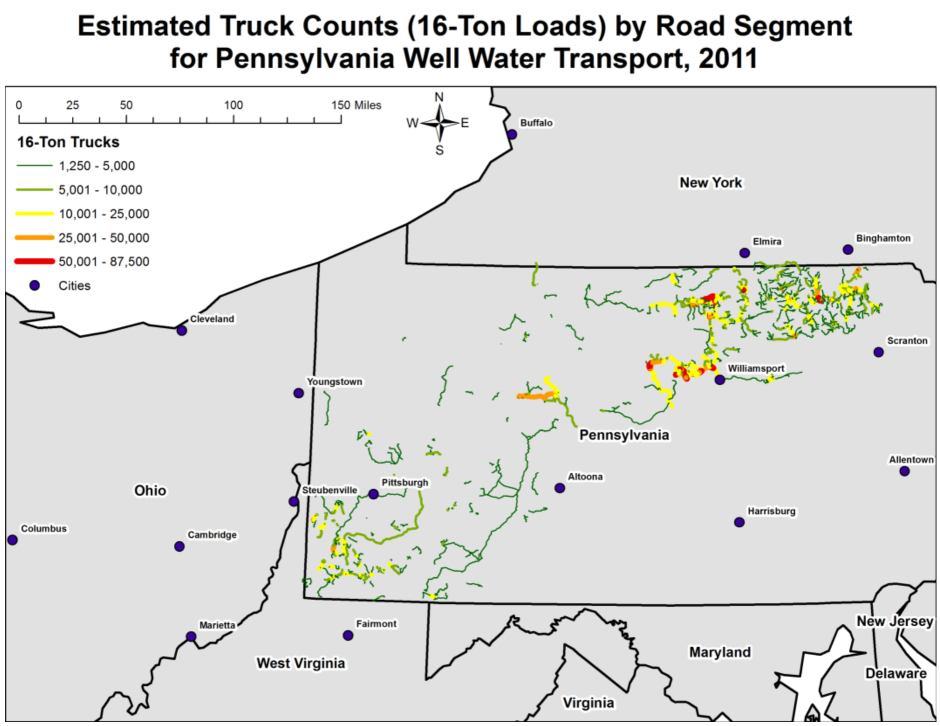

Figure 15. Estimated truck counts assuming 16-ton water loads.

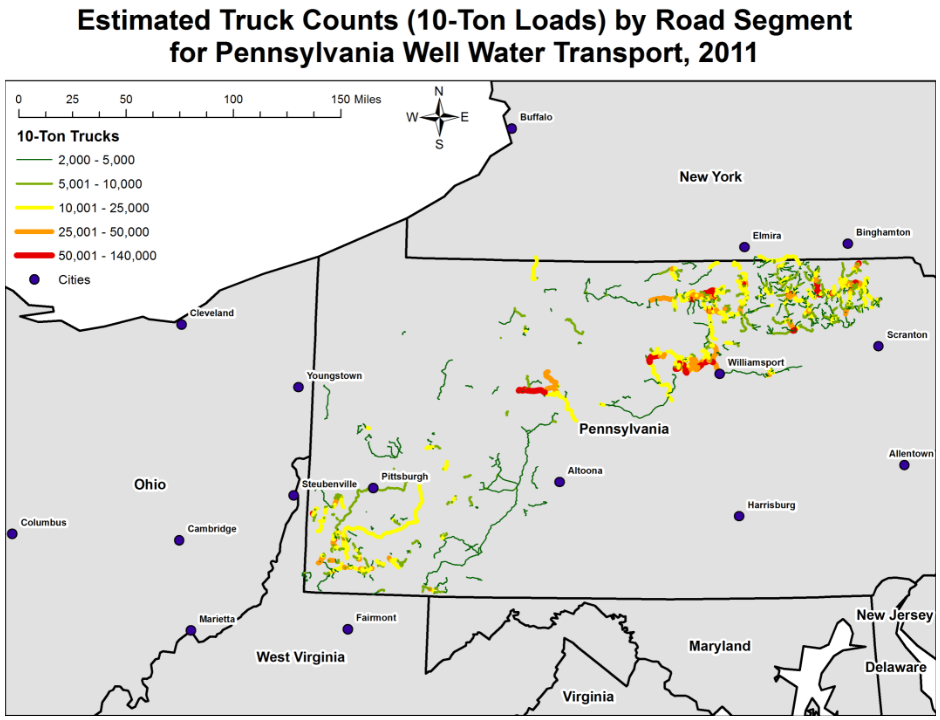

Figure 16. Estimated truck counts assuming 10-ton water loads.

Sand Case Study

Similar to the water case study, proppant information is not digitally available by well from PA DEP. To generate this case study, we identified material warehouses/depots and transloading facilities for major and minor railways serving the region and the types of materials handled at these facilities. Additional facilities were found through literature and internet searches. We then used address matching in Google Earth to determine the XY coordinates of facilities we believe support the natural gas drilling industry. Google Earth also provided a way of checking for sand transfers at these facilities, as transferring sand from railcars to trucks often results in some spillage, as indicated by piles of white sand near the tracks. As the Marcellus Shale region expands drilling, railroads are increasingly investing in infrastructure upgrades and several new depots have been established, or are in the process of being established, to handle 100+ car unit trains of materials, like sand. An example is the expanded TRANSFLO CSX frac sand terminal in Fairmont, WV, in partnership with US Silica (Progressive Railroading, 2013).

Once the sand transfer locations were imported into ArcGIS, we again used New Closest Facility to generate routes from the 2011 spud wells to the sand sources. Results are presented in Table 3 and Figures 17-20. Several sources remain unconnected in our analysis, due to their distance from the well fields. Because we were unable to determine the amounts of sand delivered to each rail transfer facility, the amounts delivered to each well, and which wells actually were served by a given facility, these route results should be treated as preliminary. The truck counts for road segments closest to the wells are considered accurate, as the network analysis forces routes to move from the wells to the sand sources (to ensure every well has an associated route), limiting the network segment choices at each well. But once away from the well, the model algorithm forces routes to the closest sand facility, so estimated truck counts near certain sand facilities, such as the depot outside of Elmira NY, may be high. As better data are collected on sand volumes and truck and rail origins and destinations, these will be refined.

The analysis indicates that NY facilities are some of the busiest sand depots, based on their proximity to the PA wells. While our estimates may be high, NY facilities are supplying sand and materials to PA wells, as evidenced by videos showing sand trucks being loaded at a rail yard in Binghamton, NY (Sand Trucks for Fracking at Rail Yard in Binghamton, NY - www.youtube.com/watch?v=gqjS2amBeNQ). Several facilities are expanding, such as the Horseheads, NY facility, even though HVHF is not allowed in NY (as of Feb, 21, 2014). If data indicating loads received at the rail facilities and amounts shipped to specific wells become available, we can generate more specific route estimates, similar to the waste analyses. Should NY allow HVHF, we would expect increased traffic around these NY facilities and we would recommend that more detailed OD records be kept by NYSDEC and made publically available.

Table 3. Estimated truck counts by variable loads and associated emission totals for the delivery of sand from regional rail transfer facilities to PA spud wells in 2011. Miles and hours represent total vehicle miles and hours for one way trips from the wells to the closest sand facility.

LOAD	TRUCKS (oneway)	MILES (oneway)	HOURS (oneway)	VOC (Mg)	SO_x (Mg)	PM_{10} (Mg)	NO_x (Mg)	ENERGY (MBTU)	CO_2 (Mg)	CO (Mg)
22 TONS	197,637	6,328,794	153,450	2.83	0.08	1.39	54.51	136,702	11,012	15
16 TONS	274,593	8,793,104	213,200	3.93	0.11	1.93	75.74	189,931	15,300	20
10 TONS	437,250	14,001,757	339,490	6.26	0.17	3.07	120.60	302,438	24,363	32

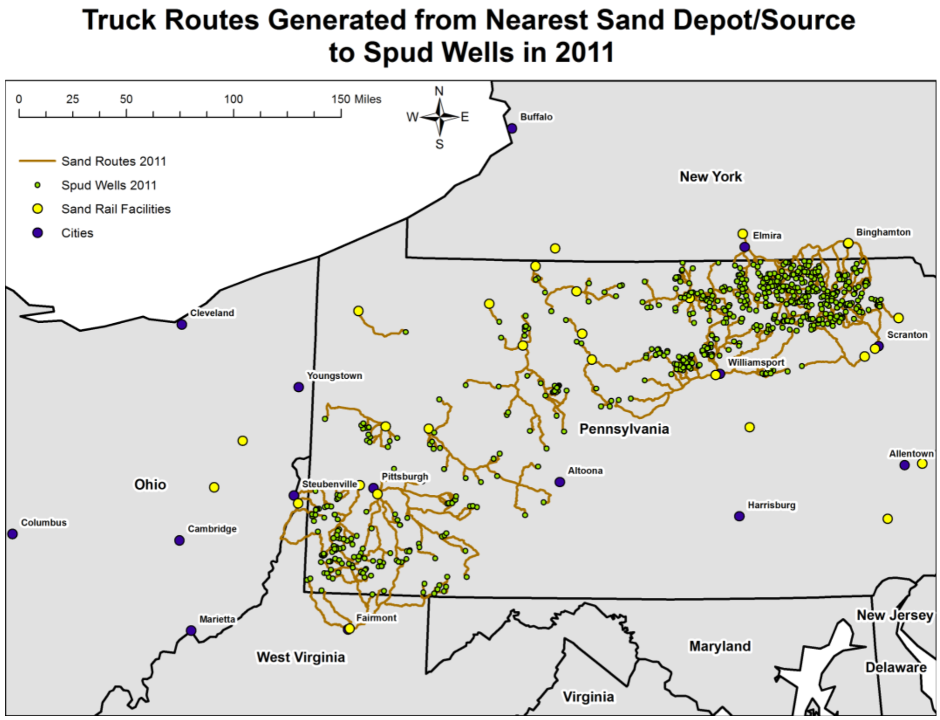

Figure 17. Sand routes generated from PA spud wells to closest sand facilities in 2011.

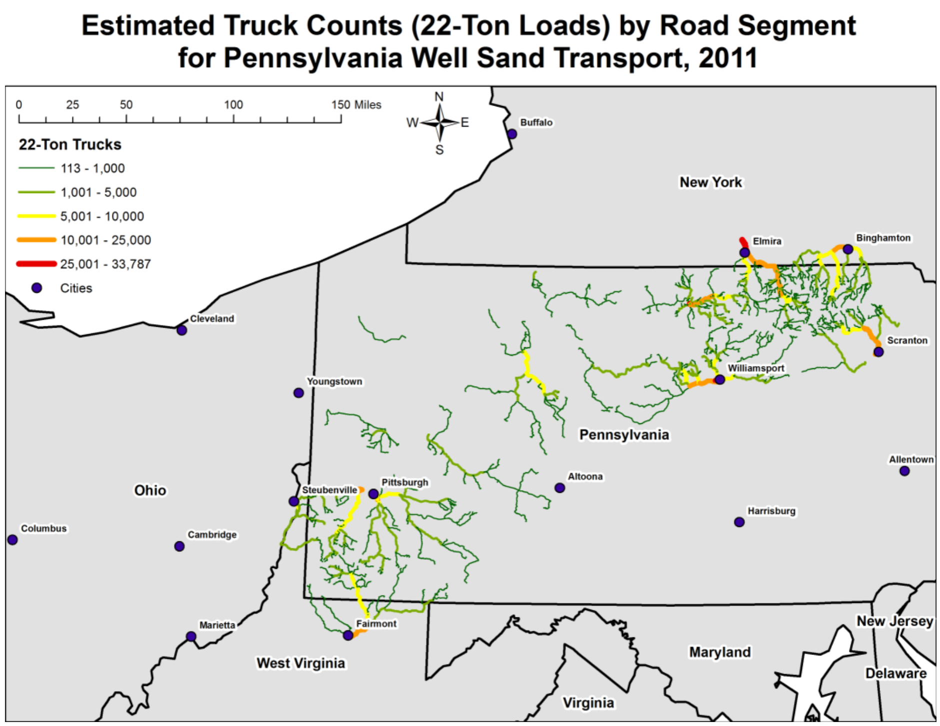

Figure 18. Estimated truck counts assuming 22-ton sand loads.

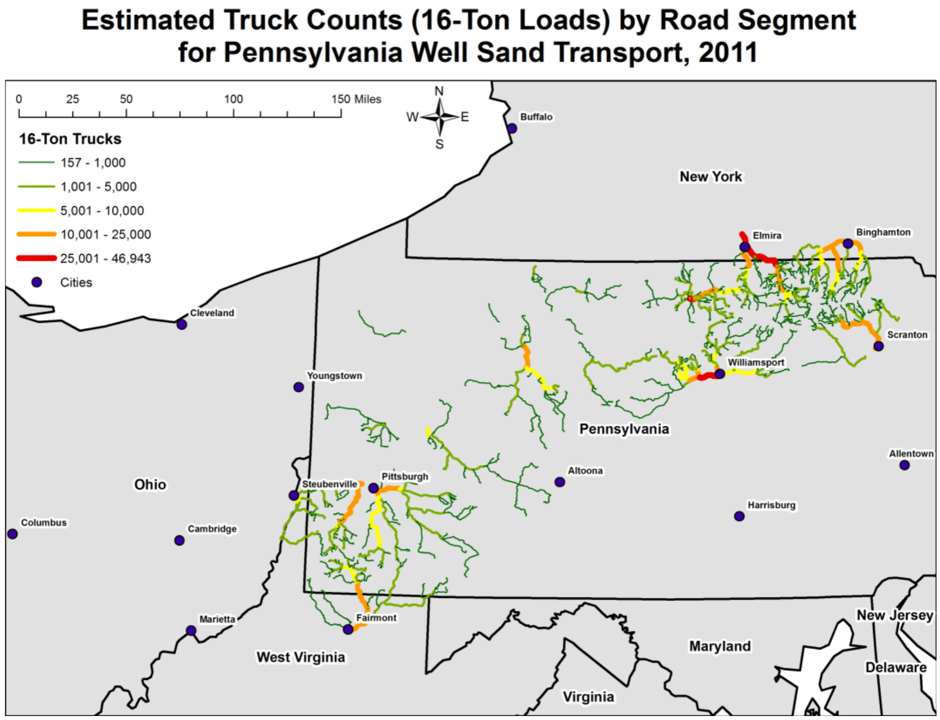

Figure 19. Estimated truck counts assuming 16-ton sand loads.

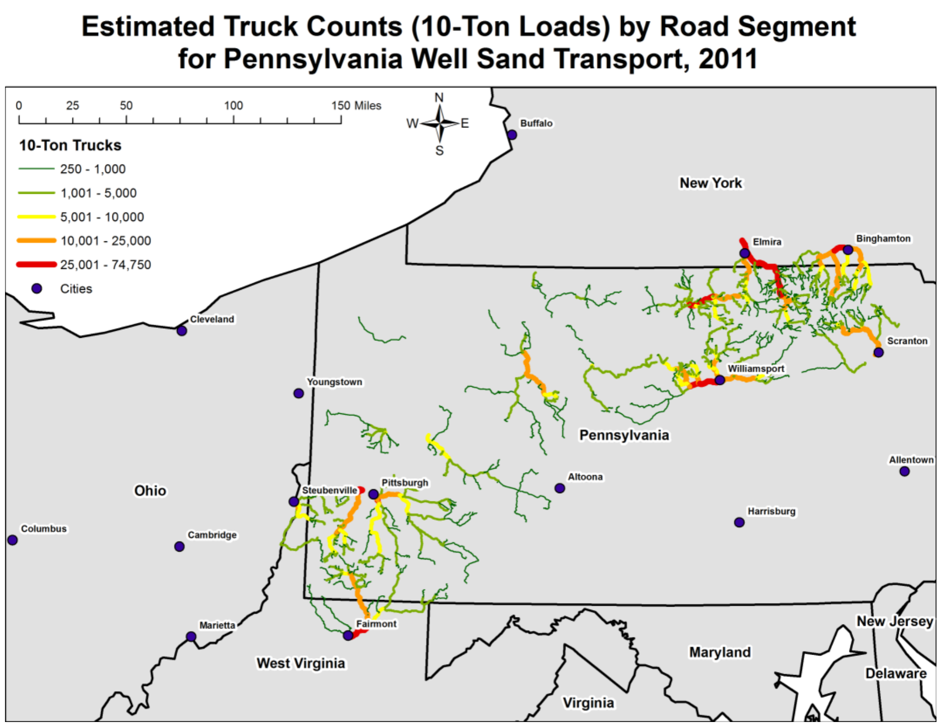

Figure 20. Estimated truck counts assuming 10-ton sand loads.

Combining the Results (Waste, Water, Sand)

To estimate combined truck traffic and emissions from sand, water, and waste transportation activities, the route totals were summed from the attribute tables of the component route analyses (Table 4). Edge layers from the component analyses were combined into a single edge layer using the DISSOLVE command in ArcGIS, with SourceOID as the dissolve attribute (in order to link back to the road network). Edges and truck counts were summed, while emission and travel attributes per edge were averaged, in order to determine emissions generated traversing a given segment. Multiplying truck counts by the segment emissions generates total emissions for a segment, based on the truck traffic estimates, and the totals were summed to generate the totals provided in Table 4. To show this information on a map, the segment totals were normalized by the length in miles, since edges were different lengths, to display the emission totals on a per mile basis. These maps highlight areas where high truck numbers related to the natural gas activities may be producing excessive pollution. Future analyses related to human health assessments and infrastructure impacts will focus on these high traffic areas as seed sites for modelling purposes. Examples of truck counts and emission patterns are provided in Figures 21-30.

Results indicate that the area around Williamsport, PA and the well fields in the northeast portion of the Marcellus Shale are producing the highest truck counts and associated emissions from the natural gas extraction activities. While our models indicate that most of this impact occurs in PA, NY roads are also experiencing high traffic counts and emissions, primarily from waste and sand transport. Should NY allow HVHF to begin, it is likely that similar truck counts and patterns would develop across the border, mirroring the results in PA.

The Pennsylvania Department of Transportation (PennDOT) provides annual GIS data of PA roads with estimates of daily average truck counts starting in 2008 (accessed through statewide and FTP datasets at www.pasda.psu.edu). Multiplying truck counts by 365 to generate an annual truck count for each road, these data can be compared to the results of the project estimates to help identify roads where truck traffic is predominately due to gas well development. This is not a perfect check, however, as PennDOT does not use TIGER line files for its road network, so some road segments do not match up exactly and some roads are missing from one or the other databases. But these two estimates of truck counts do provide a visual assessment. Figures 31 shows the annual PennDOT truck count estimates for 2011 and highlights the importance of the Interstates and major state highways. Because our model results only show one-way trips, we doubled our truck counts to simulate round trips and scaled the model display to mirror the total truck traffic legend (Figure 32). Figure 32 highlights areas where predicted truck counts associated with HVHF activities make up a large proportion of the annual truck traffic. Thicker yellow, orange, and red lines (model results) overlaid by thin blue lines (PennDOT estimates) indicate segments with high estimated HVHF traffic proportions. We are currently working on ways to extract the information from the two datasets to generate and map proportion estimates, but the visual assessment indicates that the northeast portion of the Marcellus Shale is the primary area of concern for road wear and bridge impacts due to HVHF related loads and truck volume, and possible health impacts due to additional HVHF truck traffic.

Table 4. Estimated truck counts by variable loads and associated emission totals for the delivery of sand and water and the removal of waste materials to and from PA wells in 2011. Miles and hours represent total vehicle miles and hours for one way trips, trucks represent number of truck trips.

2011 LOADS	TRUCKS (oneway)	MILES (oneway)	HOURS (oneway)	VOC (Mg)	SO_x (Mg)	PM_{10} (Mg)	NO_x (Mg)	ENERGY (MBTU)	CO_2 (Mg)	CO (Mg)
22 TONS	1,903,869	31,092,412	796,594	13.90	0.37	6.81	267.80	671,596	54,101	72
16 TONS	2,618,937	42,595,034	1,092,673	19.04	0.51	9.33	366.87	920,053	74,115	98
10 TONS	4,184,132	67,580,151	1,736,914	30.21	0.81	14.80	582.07	1,459,731	117,589	156

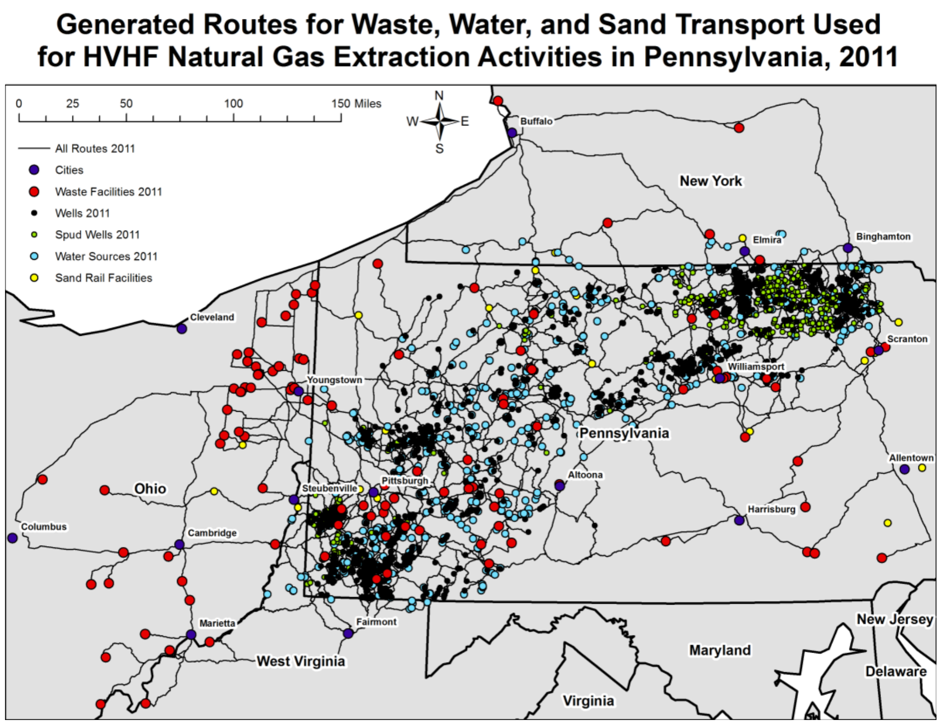

Figure 21. Combined routes for sand, water, and waste transport activities supporting PA wells in 2011. Black wells shipped waste to red treatmnet facilities in NY, OH, and PA. Green spud wells were used as destinations for water and sand deliveries from cyan water sources and yellow sand depots.

Estimated Truck Counts (22-Ton Loads) by Road Segment for Pennsylvania Well Materials and Waste Transport, 2011

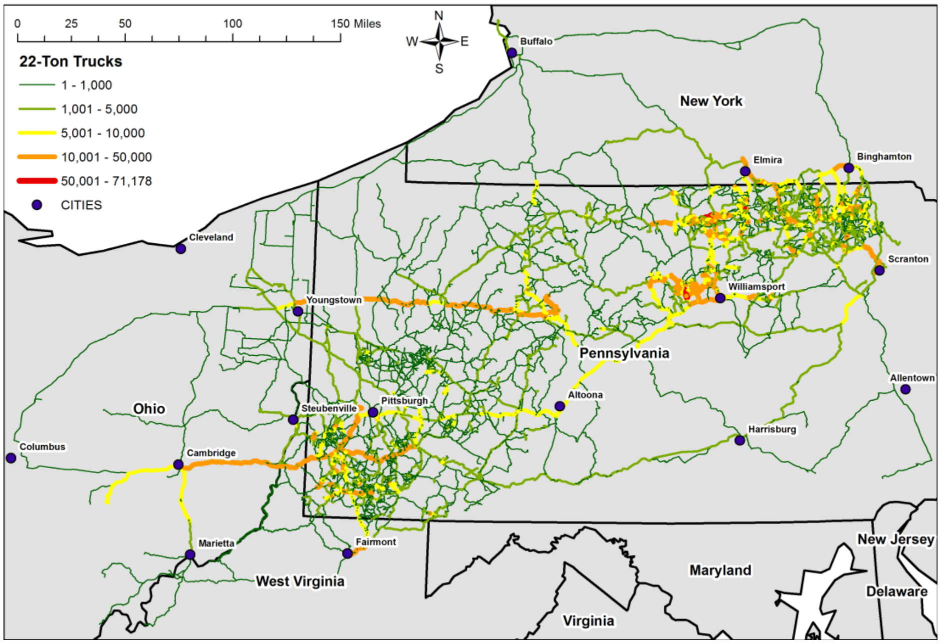

Figure 22. Estimated truck counts simulating 22-ton loads for sand, water, and waste in 2011.

Estimated Truck Counts (16-Ton Loads) by Road Segment for Pennsylvania Well Materials and Waste Transport, 2011

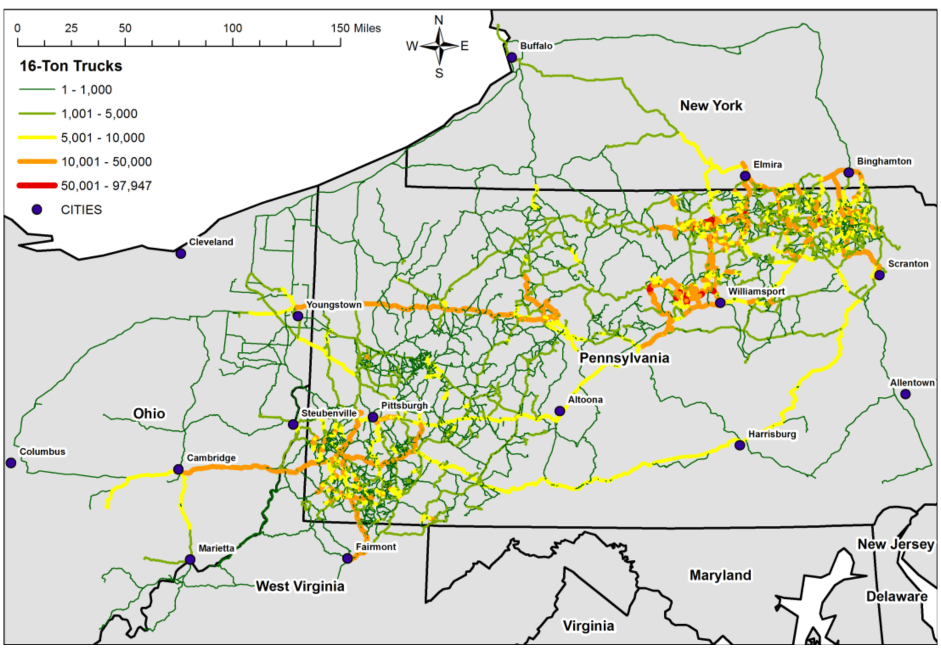

Figure 23. Estimated truck counts simulating 16-ton loads for sand, water, and waste in 2011.

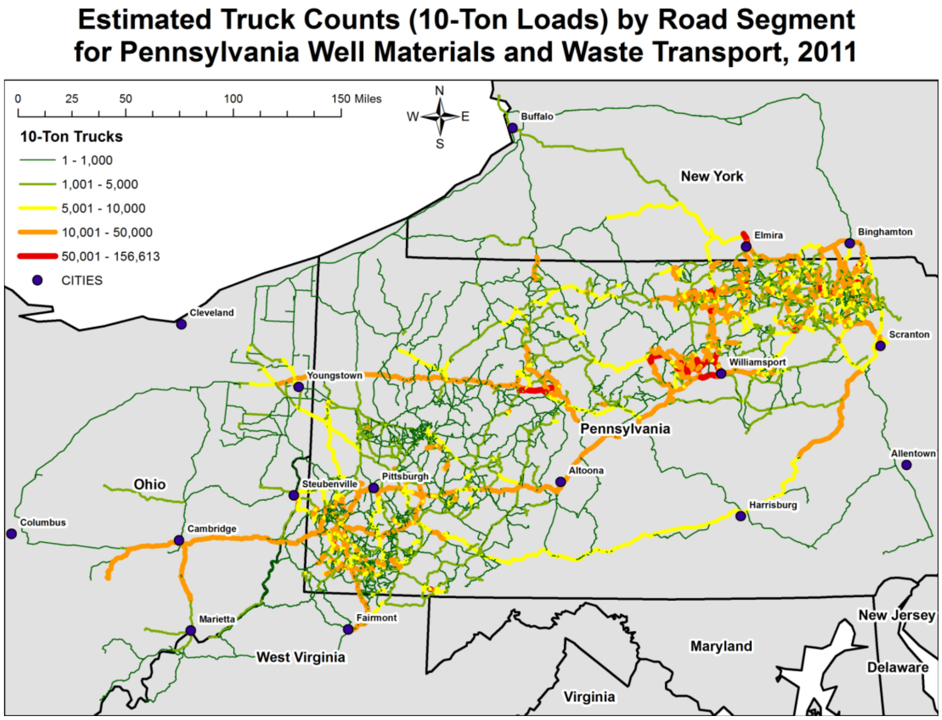

Figure 24. Estimated truck counts simulating 10-ton loads for sand, water, and waste in 2011.

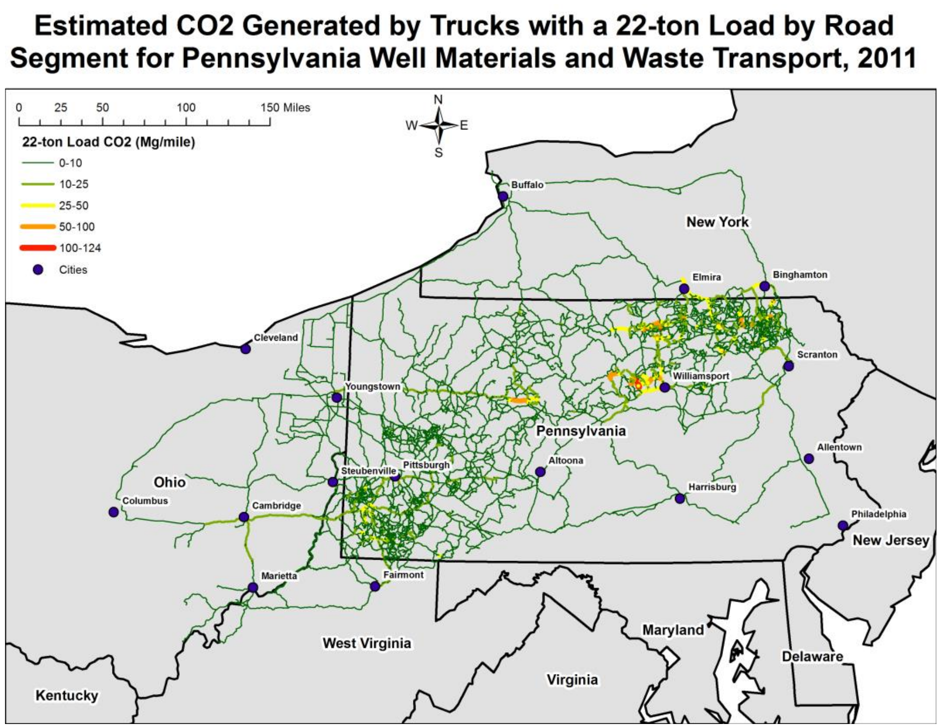

Figure 25. Estimated CO_2 emissions (Mg/mile) from 22-ton loads 2011.

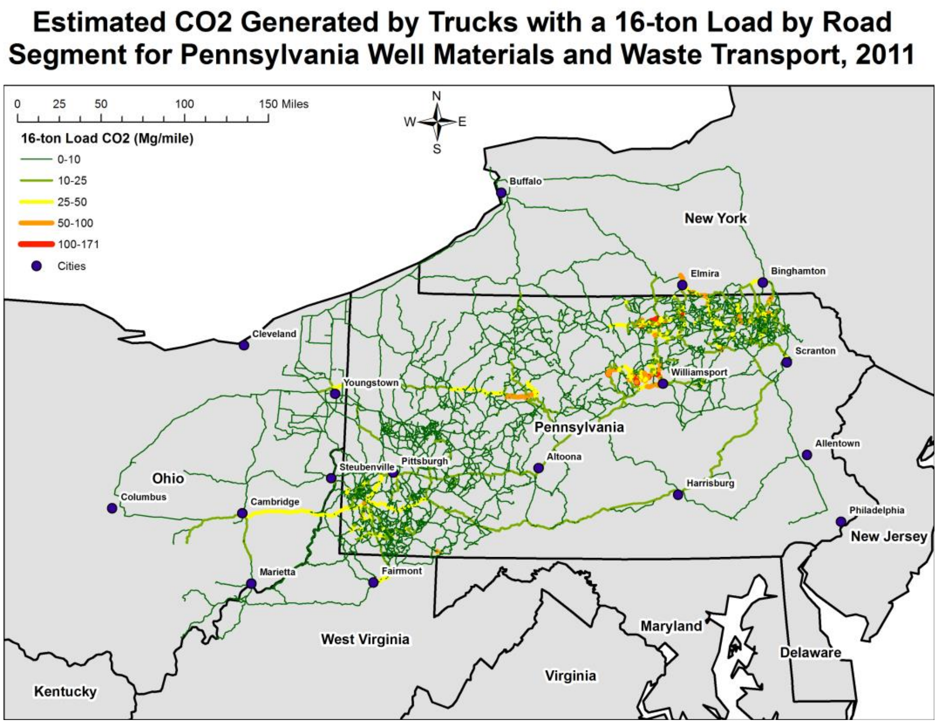

Figure 26. Estimated CO_2 emissions (Mg/mile) from 16-ton loads 2011.

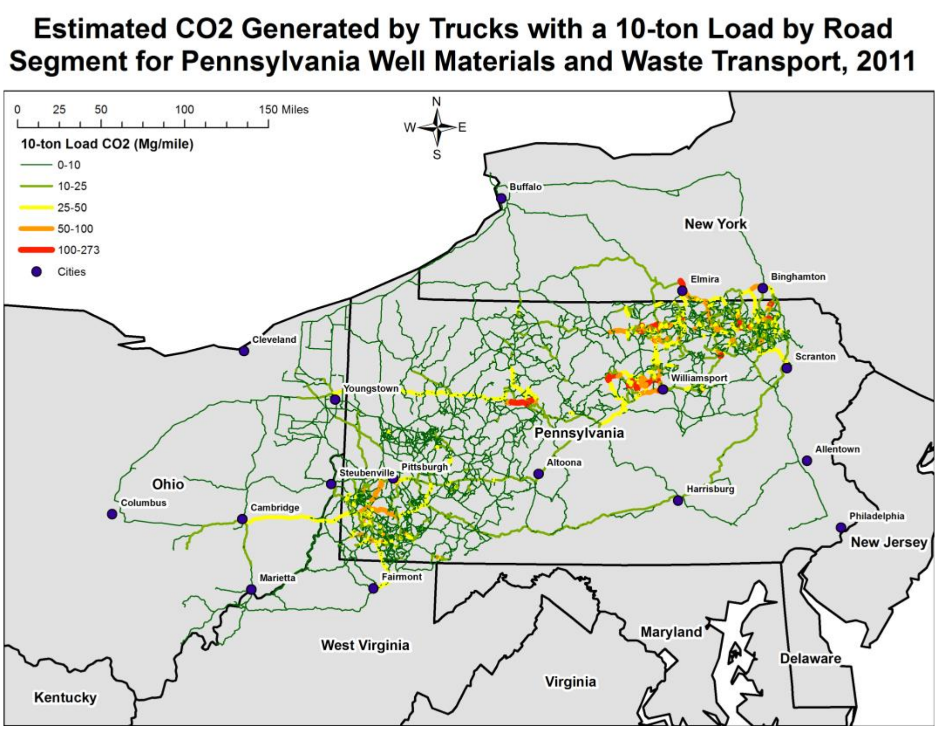

Figure 27. Estimated CO_2 emissions (Mg/mile) from 10-ton loads 2011.

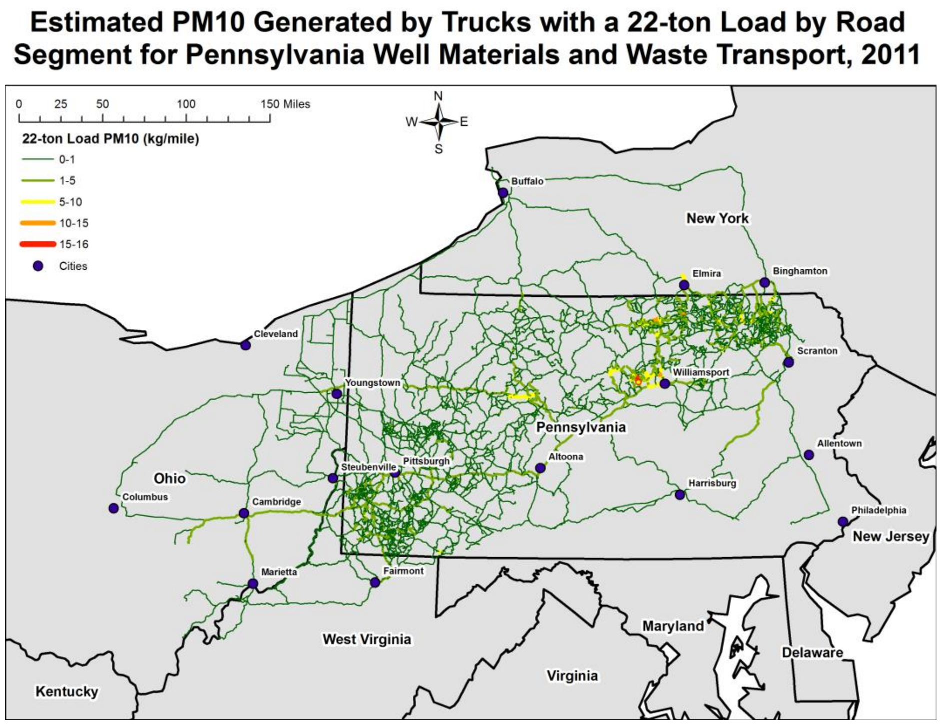

Figure 28. Estimated PM_{10} emissions (kg/mile) from 22-ton loads 2011.

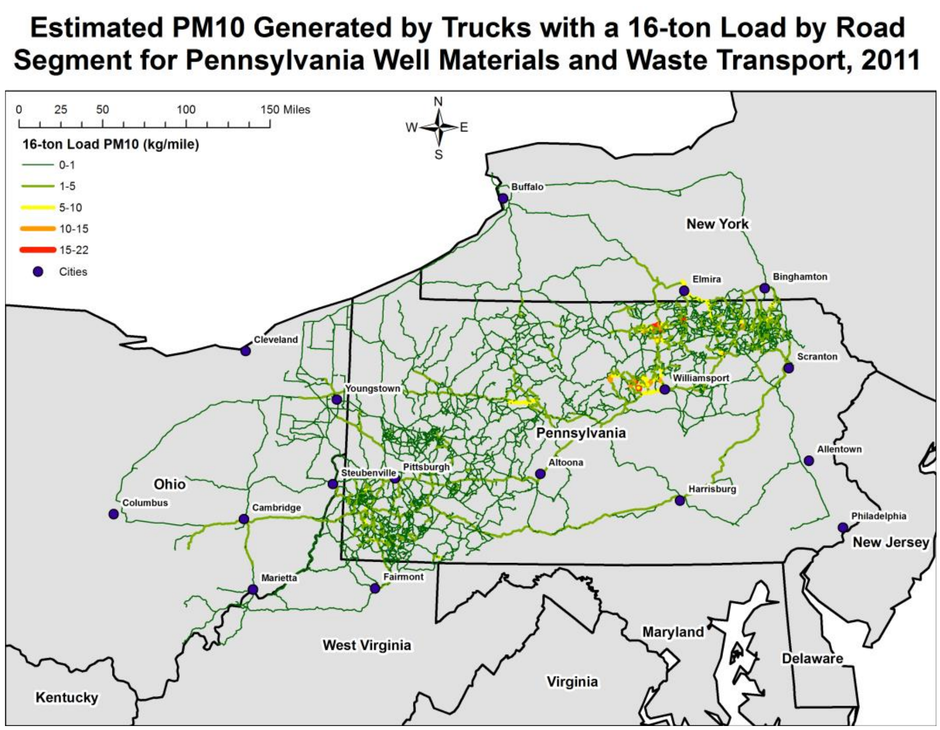

Figure 29. Estimated PM_{10} emissions (kg/mile) from 16-ton loads 2011.

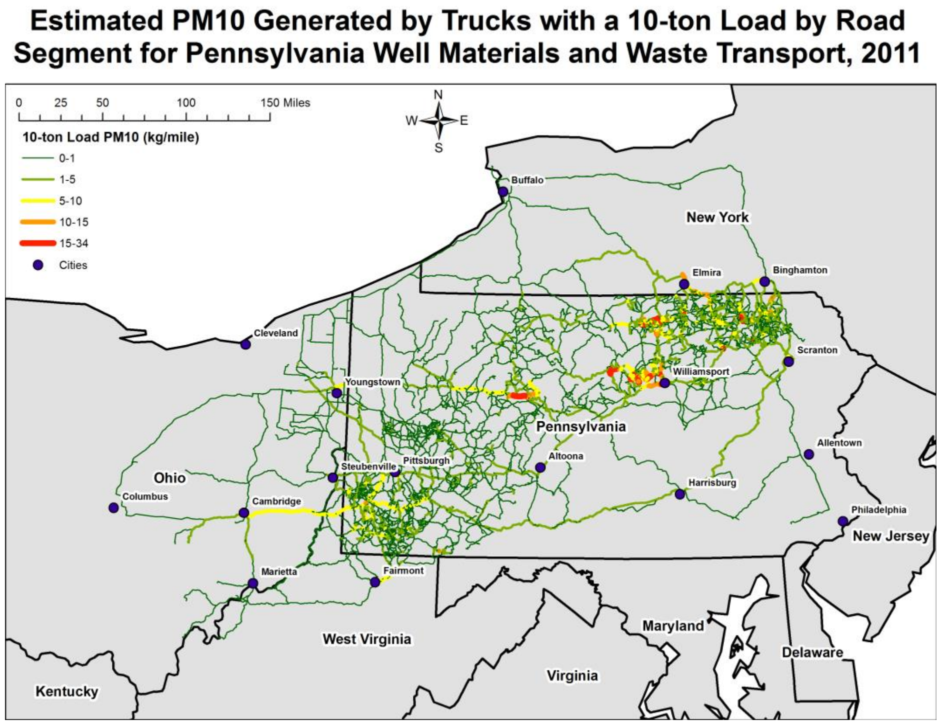

Figure 30. Estimated PM_{10} emissions (kg/mile) from 10-ton loads 2011.

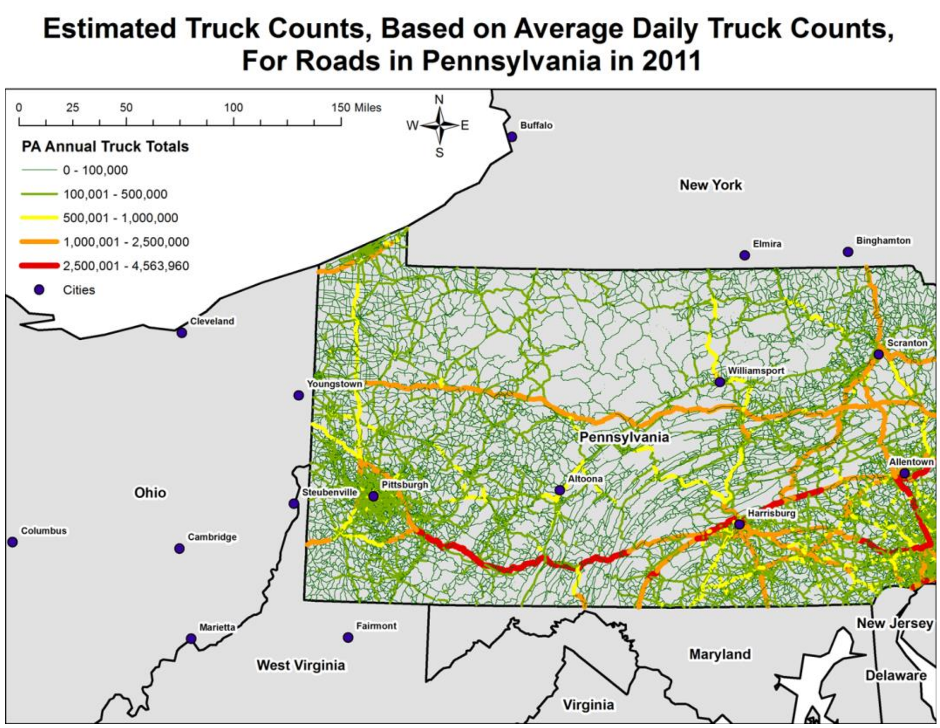

Figure 31. Annual truck estimates generated from average daily truck counts from 2011 PennDOT traffic count data.

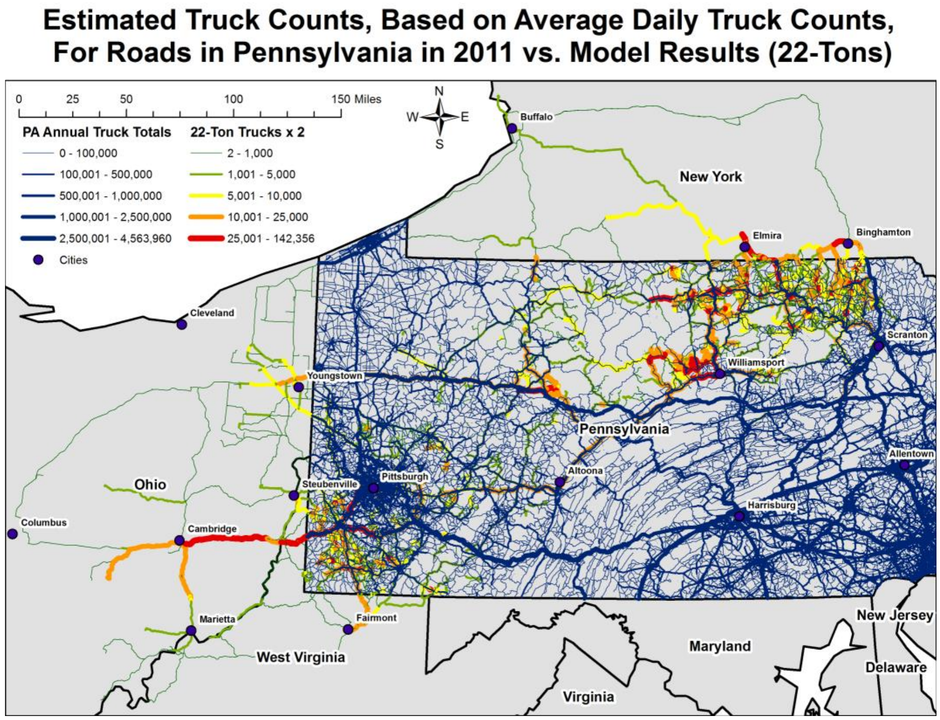

Figure 32. Annual truck estimates generated from average daily truck counts from 2011 PennDOT traffic count data, superimposed on model results with 22-ton loads doubled to approximate round trip traffic along a road segment due to HVHF activities.

Implications for New York Roads, On-site Treatment, Emission Controls, and Infrastructure

The impact of HVHF activities on NY roads and communities appears to have been relatively minor in 2011, limited primarily to roads in communities with landfills and material depots. In December 2014, Governor Andrew Cuomo banned HVHF actives in NY, but NY communities along the PA border will likely continue to support the development of PA well fields through water, sand, and equipment depots, as well as waste disposal. If NY allows high volume horizontal hydraulic fracturing in the future, regional roads would likely see significant increases in truck traffic and associated emissions in these areas and around well sites, with similar spatial patterns of higher emissions and truck counts where routes congregate. To accurately assess the impacts of these transportation activities, we strongly recommend that NYSDEC, in partnership with PA DEP, require companies to provide more complete records on material movements to and from well sites, as well as sources of raw materials and equipment shipped to warehouses and material depots.

The PA DEP waste database, with specific OD pair information (well and facility locations, amount of waste shipped, and the type of waste), offers an example of the type structure needed to confidently predict routes and identify high traffic areas. The drawback of the PA waste database is that the information is voluntarily provided by the companies, so it is likely incomplete, leading to underreporting. Based on reported waste transported or recycled on-site and assuming 2.5 million gallons of waste per well, we estimate only 19% of the waste potentially generated was reported in 2011. Since waste routes are the longest transport component, underreporting greatly impacts emissions and truck trip estimates. By requiring companies to provide detailed origin and destination information for all materials and waste movements, more accurate truck counts and emission totals could be generated, allowing for more accurate assessments. For our own research, knowing the types of trucks used by well or company, along with hours of operation, would be extremely useful, but such detailed data may be logistically cumbersome to collect.

The water case study indicates that PA gas wells in the northeast portion of the study area have water sources in NY (see Figure 13), but it is not certain which specific wells these service, or if the water is trucked into PA. According to Dr. Kevin Gilmore, an Assistant Professor at Bucknell University, some companies in the Susquehanna River Basin have begun transporting water from nearby streams using flexible pipelines laid along roadways (personal communication, October, 2014). Our analysis assumes all water is trucked in, since the water database from PA DEP does not indicate which wells use pipelines. Because of the distance to the PA wells, water from NY sources would likely be trucked. But future analyses should try to account for the impact of these temporary pipelines on emissions. The Susquehanna River Basin Commission has begun to collect some of water use information by well, but charges a data fee and the data are not statewide (Kevin Gilmore, personal communication).

Our analysis focused on waste, water, and sand analyses because these are major transportation components in natural gas drilling that had complete or partial OD pair data available. We emphasize that our results estimate emissions and truck counts for one way trips only, since we do not have information on the origins or destinations of the empty trucks. Faced with a similar issue, Gilmore, et.al (2014), assumed most of the empties returned to their origin, which added 30% to the emission impacts of that study. Therefore, we believe our emission estimates are conservative.

We are also at this time unable to estimate emissions for trucks delivering drilling and construction equipment, since that OD information is not readily available to the public. The movement of drilling and construction equipment can make up 30-33% of the truck traffic to a well. NYSDEC estimates in its

2011 Draft SGEIS that 625 - 1148 one-way heavy duty truck trips are needed per well, 100-623 of them for the modelled parameters of sand, water, and waste. This compares well with reported truck use in the Bakken Shale play in ND, where an average of 1150 loaded (2300 loaded and empty) trucks are used per well. Of that total, 775 are used for water, waste, and sand movement (Tolliver, 2014). Our emission estimates are therefore low on a per well basis, since we don't account for all trucks.

Our results do indicate considerable pollution emissions from the movement of water, sand, and waste materials (Tables 1-4), which in turn emphasize the environmental significance of on-site recycling of waste and/or the use of advanced pollution control technologies on trucks for air quality concerns (Tables 5 and 6). In 2011, PA wells treated on-site 11,484,926 barrels of wastewater, rather than shipping the waste off site for disposal or treatment. Not only does this reduce waste transport emissions, but it would significantly reduce the number of truck trips needed to deliver water to the wells, since the waste water could be re-used. Using the average distance and time for water deliveries and waste routes, we estimate the on-site recycling reduced truck use by 175,406 to 385,894 one-way truck trips, as well as the associated emissions (Table 5). These totals are nearly equal to the truck use and emissions generated by transporting wastes off site for treatment and disposal in 2011 (Table 1).

Table 5. Truck reductions and emissions conserved by the recycling of 11,484,926 barrels of HVHF wastewater in 2011.

LOADS	TRUCKS (oneway)	MILES (oneway)	HOURS (oneway)	VOC (Mg)	SO_x (Mg)	PM_{10} (Mg)	NO_x (Mg)	ENERGY (MBTU)	CO_2 (Mg)	CO (Mg)
22 TONS	175,406	10,344,278	210,761	4.62	0.12	2.27	89.10	223,436	17,999	24
16 TONS	241,186	14,194,247	289,205	6.34	0.17	3.11	122.26	306,596	24,698	33
10 TONS	385,894	22,662,240	461,879	10.13	0.27	4.96	195.19	489,504	39,432	52

We also modelled reduced truck emissions through control technologies and alternative fuels as part of Rachel Zoyhofski's Masters thesis research (Table 6). The US Environmental Protection Agency runs a program called the National Clean Diesel Campaign (NCDC - http://epa.gov/cleandiesel/), where they list typical emission reductions for various control technologies. We applied mid-range PM and maximum NO_X reduction values for Diesel Oxidation Catalysts (DOC – 30%), Diesel Particulate Filters (DPF – 90%), Selective Catalytic Reduction (SCR – 75%), and combinations of these strategies to our baseline results. Results indicate that DOC controls would prevent 2.0 to 4.4 Mg of PM_{10}, at a cost of \$600 - \$4000 per engine retrofit. DPF controls would prevent 6.1 to 13.1 Mg of PM_{10}, but at a cost of \$8,000 - \$50,000 per engine retrofit. SCR technologies would prevent 200.8 to 436.6 Mg of NO_x at a cost of \$10,000 - \$20,000 per retrofit. If the truck fleet were converted to heavy duty natural gas vehicles (NVG), PM_{10} and NO_x emissions from 2008 estimates may be reductions by 79% and 24%, respectively, based on data from the International Energy Agency (IEA, 2010). We do not yet have a vehicle replacement cost estimate.

We attempted to determine the impact of our model results on bridges and to generate routes with bridge weight restrictions enforced as route barriers, but the available bridge point data (National Bridge Inventory, available in the NTAD 2013 database) have too many points with unknown limits. Additionally, PennDOT is in the process of updating weight limits for many Pennsylvania bridges. An updated list is available (PennDOT, 2013), but the bridge coordinates are not published. According to the Pennsylvania Spatial Data Access (PASDA) clearinghouse, (Maurie Kelly, personal communication, 02-17-2014), Penn DOT currently restricts this sensitive information for security reasons, so we will need to conduct an address matching analysis to try and locate updated bridges in this list.

Table 6. Emissions for PM_{10} and NO_x based on Diesel Oxidation Catalysts (DOC), Diesel Particulate Filters (DPF), Selective Catalytic Reduction (SCR) technologies and using natural gas vehicles (NVGs) to move materials and waste in 2011. SCR technologies can be used in combinations with DOC and DPF systems and are reported together in this table, with SCR responsible for NO_x reductions and DOC and DPF responsible for PM_{10} reductions. 2008 values are from Table 1, which use 2008 average in-use emission rates for a mixed age fleet. Emission reductions using Model Year 2007 trucks emission rates, simulating a newer, compliant truck fleet, are provided as a target comparison (0.036 g/mile for PM10 and 0.725 g/mile for NOx).

2011 LOADS	TRUCKS (oneway)	MILES (oneway)	2008 PM_{10} (Mg)	SCR+DOC PM_{10} (Mg)	SCR+DPF PM_{10} (Mg)	NVG PM_{10} (Mg)	MY 2007 PM_{10} (Mg)	2008 NO_x (Mg)	SCR+DOC NO_x (Mg)	SCR+DPF NO_x (Mg)	NVG NO_x (Mg)	MY 2007 NO_x (Mg)
22 TONS	1,903,869	31,092,412	6.8	4.8	0.7	1.4	1.1	267.8	66.9	66.9	203.5	22.5
16 TONS	2,618,937	42,595,034	9.3	6.5	0.9	2.0	1.5	366.9	91.7	91.7	278.8	30.9
10 TONS	4,184,132	67,580,151	14.8	10.4	1.5	3.1	2.4	582.1	145.5	145.5	442.4	49.0

Throughout this project, we also attempted to integrate rail and ship transport of raw materials and waste, in order to simulate intermodal possibilities and potential pollution reductions. Unfortunately, the OD data needed to generate meaningful routes are not readily available for public use. We continue to build spatial databases of sand mines, transload facilities, warehousing operations, and ports used in materials and waste movement, based on press releases and company websites, but our model databases are currently incomplete.

Conclusions

This research suggests that in 2011, between 1.9 and 4.2 million truck trips, totaling 31 to 68 million vehicle miles, were used to transport sand and water to, and to remove waste from, high volume horizontally fractured natural gas wells in the Pennsylvania portion of the Marcellus Shale region. These trips generated considerable emissions from the burning of diesel fuel, and our emission model estimates range from 7 to 15 Mg of PM_{10}; 268 to 582 Mg of NO_x; and 54,100 to 117,600 Mg of CO_2, depending on the load simulated (10-22 tons). By using the wells, resource supply areas, and waste disposal facilities as a series of origin and destination (OD) pairings, probable transportation routes were generated and combined with estimated vehicle counts to produce a network segment impact analysis of material transport, predicting specific areas where truck counts and emissions were high. Our results indicate that the wells around Williamsport, PA and in the northeast portion of the study area generated the most traffic and the highest pollution loads by road segment in 2011. These areas will become the focus of future emission dispersion modeling efforts by the research team.

Our results also provide a baseline to compare against the benefits of recycling HVHF wastes on-site. In 2011, PA wells treated nearly 11.5 million barrels of wastewater on-site, resulting in a reduction of truck trips and emissions greater than those estimated for actual waste disposal. By altering parameters within the network emission model, we also explored emission reductions linked to advanced control technologies and converting diesel engines to natural gas. Combinations of Diesel Oxidation Catalysts (DOC), Diesel Particulate Filters (DPF), and Selective Catalytic Reduction (SCR) can significantly reduce PM_{10} and NO_x, but at costs ranging from $600-$20,000 per engine retrofit. Our emission estimates and spatial output can help policy analysts and environmental planners evaluate the cost benefit of these retrofits and to better understand the pollution impacts associated with the movement of materials in the HVHF industry, a potentially huge economic force in the region. Results of this research can help address interrelated health, infrastructure, and sustainable community issues, such as the tradeoffs between recycling materials and treating wastes on site, developing pipeline supply networks or central treatment and distribution centers, and continuing the movement of materials and wastes using existing transportation networks and transportation modes or looking to intermodal solutions.

Our project also highlights the need to collect and make publically available more complete records of materials and goods movement related to the HVHF industry. In particular, knowing where equipment, supplies, and wastes originate and their destination locations would help generate more robust model predictions, which in turn will make trade off analyses more complete. More complete information on the origin and destination of equipment, materials, and wastes would also allow for more robust intermodal analyses, evaluating/optimizing the environmental and economic impacts and tradeoffs of moving materials by truck, rail, and ship. The PADEP waste inventory provides a good template, but we also strongly recommend that these data be required of the companies involved in HVHF activities, not voluntary, and that these data be publically available.

The results of this research address several gaps in the current analysis of HVHF impact assessment by focusing on the impacts of transportation on emission and infrastructure. There are a number of studies looking at emissions from the production wells, particularly involving VOCs and methane, but research on impacts of emissions due to the transport of materials and wastes appears to be just beginning (Stokes and Horvath, 2006; Jiang, et.al, 2011, Cooley and Donnell, 2012; Myhrvold and Caldeira, 2012). Gilmore, et. al (2014) estimate greenhouse gas emissions for waste and water transport in the Susquehanna River Basin using ArcGIS Network Analysis and a hierarchy approach to route selection. Our research builds on these earlier works by showing spatially where the biggest impacts to transport infrastructure and rural communities are potentially located (in addition to providing emission estimates) through the network analyses and the identification of specific road segments.

A number of studies and articles have looked at issues of water usage and wastewater generated by the HVHF process (Soeder and Kappel, 2009; Biello, 2012; Cooley and Donnelly, 2012; Hammer and VanBriesen, 2012, Lutz, et. al, 2013; Gilmore et.al, 2014). This research builds on existing analyses that estimate the volume of wastes generated and the types of treatment and disposal options available, adding the impact of shipping wastes off-site for treatment and disposal, and the environmental and infrastructure impacts resulting in the movement of those wastes. We also estimate the pollution reduction due to on-site treatment of HVHF wastes based on reported volumes in 2011.

Health impact assessments of emissions and byproducts of HVHF materials are currently underway. In addition to the methane and VOC emissions, there is concern that waste fluids may contain naturally occurring radioactive materials (NORM) and other toxins that would theoretically make them hazardous materials. The sand used in the HVHF process is extremely fine, and there is a growing concern over the health impacts of dust (PM_{10} and $PM_{2.5}$) from the mining stage and the use at the well site (http://www.wvrecord.com/news/244293-afl-cio-alerts-worker-safety-bureaus-to-silica-exposure-at-fracking-sites). Spills of sand and waste fluids are also of concern to public health and the environment (Cooley and Donnelly, 2012; Hammer and VanBriesen, 2012). We continue to build network databases designed to address these issues, and are now using the result of this project as inputs to emission dispersion models, such as AERMOD, to help assess human health impacts of PM_{10} in areas of high predicted truck counts (Figure 33). This is the focus of Alyssa Mathews' Masters thesis and our 2014 UTRC funded project.

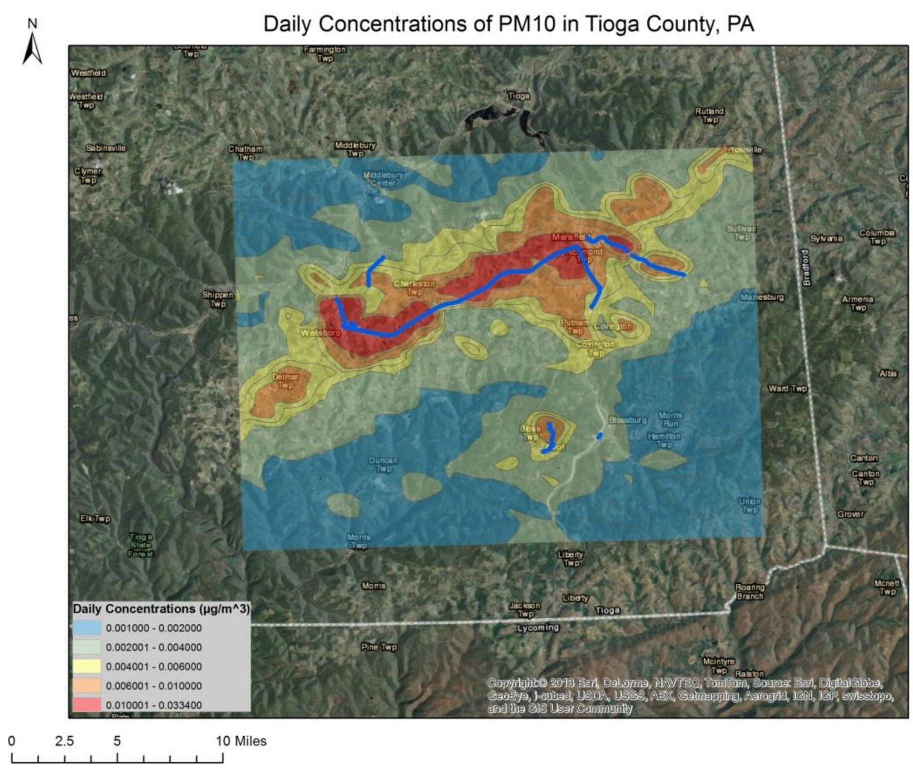

Figure 33. Draft output of an AERMOD emission dispersion simulation of PM_{10} along a high volume road segment in Tioga County, PA, identified through ArcGIS Network Analysis and GIFT Model simulations.

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