Transportation Activities Associated with High-Volume Hydraulic Fracturing Operations in the Marcellus Shale Formation

Analysis of Environmental and Infrastructure Impacts

Karl Korfmacher, J. Scott Hawker, and James Winebrake

The natural gas extraction method of high-volume hydraulic fracturing (HVHF) has a significant truck transportation component, with estimates ranging from 625 to 1,148 heavy truck trips for equipment, materials, and waste movement for each well drilled in the Marcellus Shale. ArcGIS Network Analyst was used to analyze the environmental impacts of transporting sand and water to, and waste from, Pennsylvania wells from 2011 to 2013. The locations of wells, resource supply areas, and waste disposal facilities served as a series of origin and destination pairings for probable truck routes. Material and waste volumes per well were used to estimate the truck counts assigned to each route, leading to estimates of truck traffic by road segment. Emission loads and energy usage were calculated with the geospatial intermodal freight transport model. Simulation results of 22-ton loads estimated 4.4 million one-way truck trips totaling nearly 86.5 million vehicle miles and producing nearly 19 Mg of particulate matter and 745 Mg of nitrogen oxides, among other pollutants. Maps showing road segments with high truck counts identified areas of potential health and infrastructure impacts. On-site recycling of wastes offset an estimated 842,678 truck trips and associated emissions. Case studies developed during this project pointed to the need for better data collection and data distribution efforts in states extracting gas and those considering whether to allow HVHF operations. The results will help policy analysts and environmental planners to understand and evaluate the environmental, health, and economic impacts (pro and con) associated with the movement of HVHF equipment and materials.

Transportation is critical to the 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. However, recent advances in natural gas extraction techniques, referred to here as high-volume hydraulic fracturing (HVHF), have greatly expanded the known and available reserves of this fuel, considered by some to be a cleaner fossil energy source. Some researchers have designated natural gas as a bridging fuel to help the United States transition to more sustainable energy sources, such as second-generation biofuels, solar, wind, and hydrogen (*1*); but others are critical of this designation (*2*).

Horizontal drilling that uses HVHF techniques has a significant transportation component that impacts transport infrastructure and rural communities in positive and negative ways. Estimates put the natural gas reserves of the entire Marcellus Shale Formation (Figure 1) at 29.5 trillion to 410 trillion ft^3, although not all of those reserves are recoverable (*3, 4*). 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. However, there are environmental and social trade-offs to developing these resources associated with transportation activities.

Developing and operating an HVHF natural gas well is resource and infrastructure intensive, primarily because of the rural locations of the prime drilling sites. The New York State Department of Environmental Conservation estimated that each well developed in the Marcellus Shale will require 625 to 1,148 one-way heavy truck trips for multiple categories of equipment, materials, and waste movement, with 100 to 623 trips needed for sand, water, and waste (*5*). The upper New York State Department of Environmental Conservation estimates compare well with reported heavy truck estimates in the Bakken Shale play in North Dakota, where an average of 1,150 loaded one-way (2,300 loaded and empty) trucks are used per well. Of that Bakken total estimate, 775 trips are used for water, waste, and sand movement, categories common to both lists (*6*).

Common issues raised in the debate over HVHF operations related to transportation are congestion caused by 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 designed for the volume or weight of the truck traffic they are now, or would be, experiencing (*5, 7–9*). This research focused on waste, water, and sand transport, because these are major transportation components in natural gas drilling that had publically available

---

K. Korfmacher, Environmental Science Program, Gosnell School of Life Sciences, College of Science, 85 Lomb Memorial Drive; J. S. Hawker, Department of Software Engineering, Golisano College of Computer and Information Sciences, 134 Lomb Memorial Drive; and J. Winebrake, College of Liberal Arts, 92 Lomb Memorial Drive, Rochester Institute of Technology, Rochester, NY 14623. Corresponding author: K. Korfmacher, kfkscl@rit.edu.

Transportation Research Record: Journal of the Transportation Research Board, No. 2503, Transportation Research Board, Washington, D.C., 2015, pp. 70–80.
DOI: 10.3141/2503-08

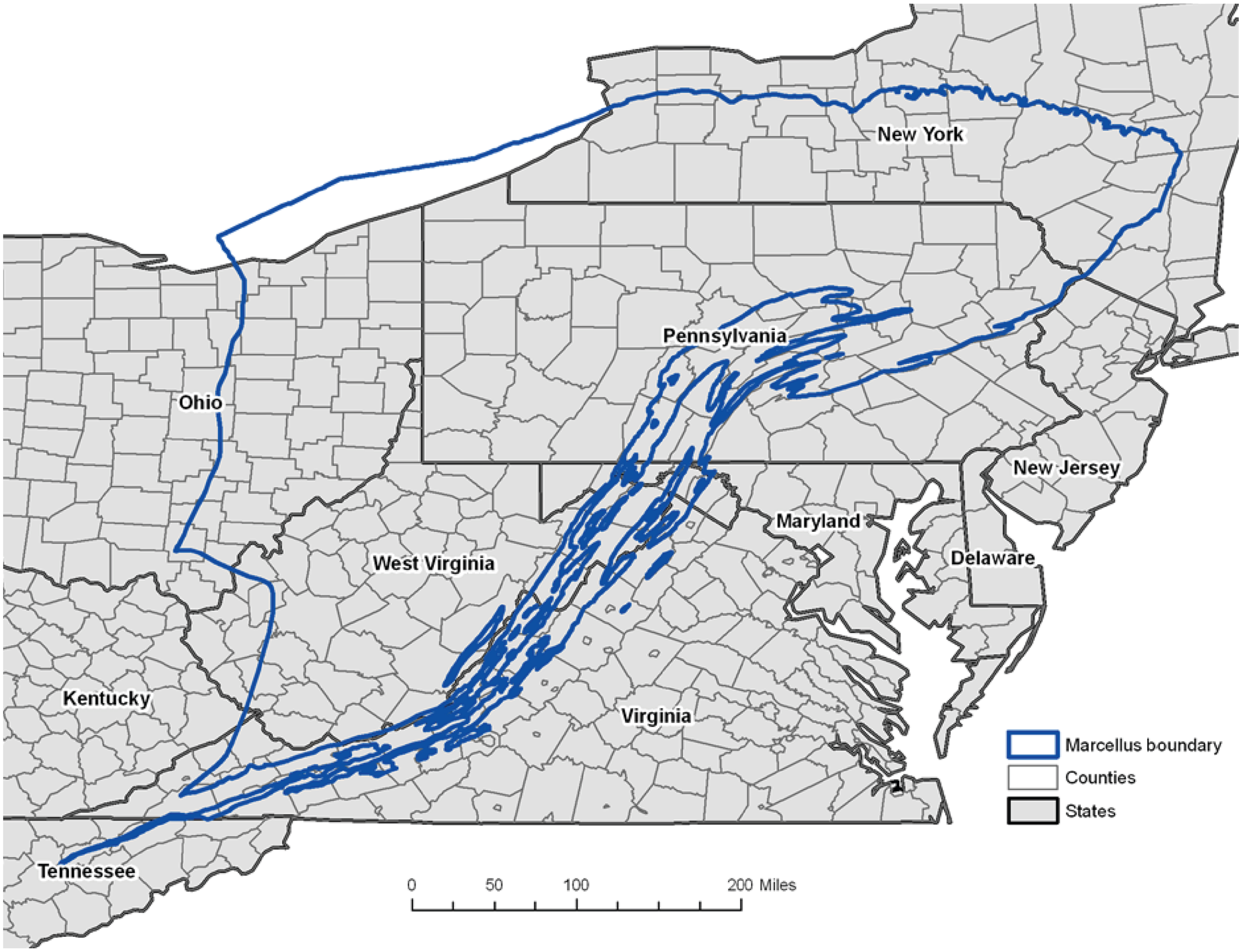


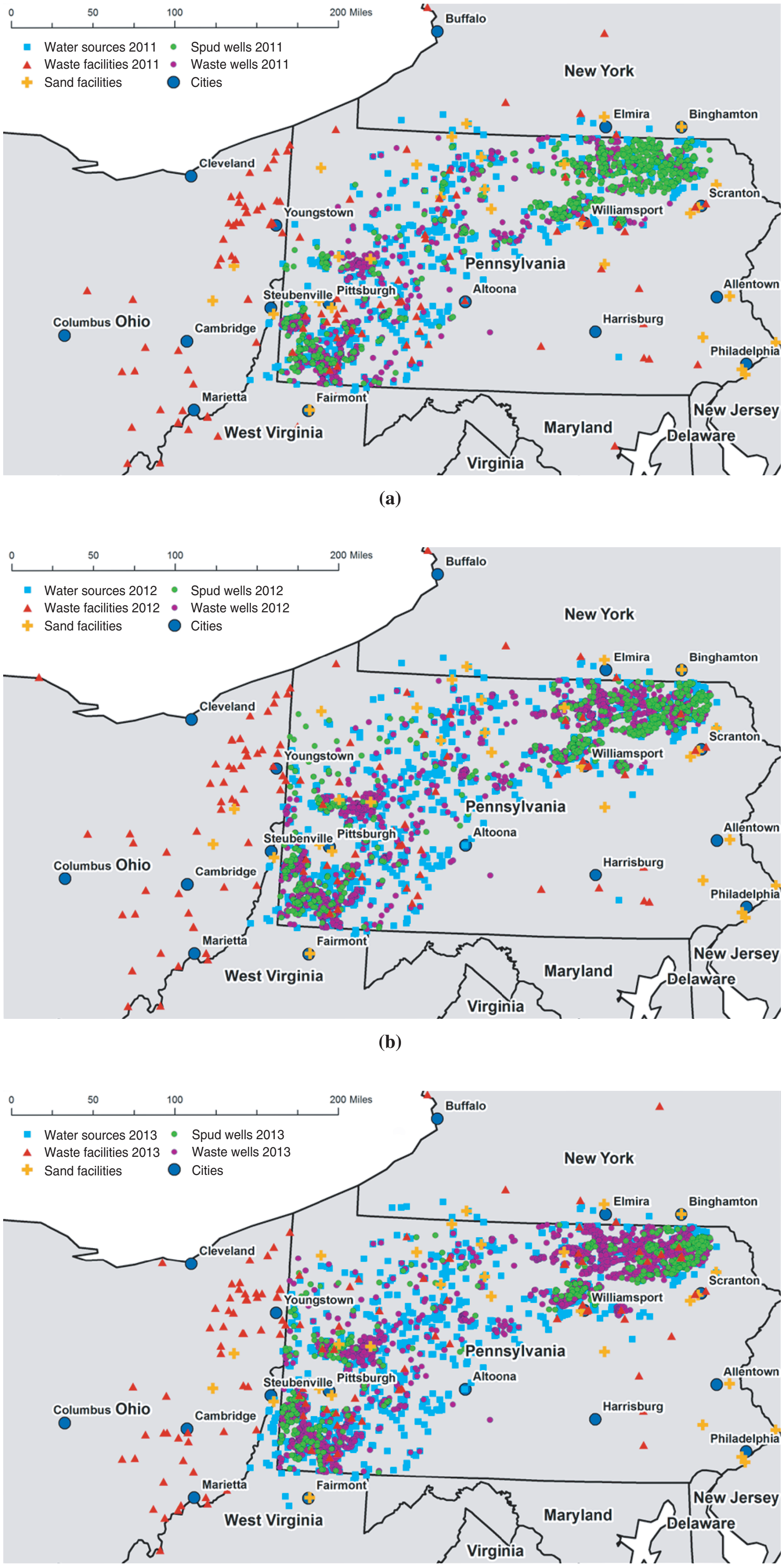
FIGURE 1 Marcellus Shale boundary from U.S. Geological Survey.

complete or partial origin–destination (O-D) pair data. The project estimated emissions and truck counts for one-way trips only, since publicly available information on the origins or destinations of empty trucks is not available. Estimates of emissions for trucks delivering drilling and construction equipment were also excluded from the analysis, because of the lack of publicly available O-D data.

In the Marcellus Shale region, the bulk of the water resources needed to operate a well are delivered to the site by truck, as onsite water resources are often inadequate to provide the 500,000 to 8 million gal needed to drill a single well (*5, 7–14*). Assuming 2,500 to 5,500 gal per tanker truck (10 to 22 ton loads) (*9, 11, 12*), a single well that uses 5 million gal of water (*10*) would require somewhere between 900 and 2,000 one-way deliveries per fracturing event. From 2011 to 2013, Pennsylvania Department of Environmental Protection (PADEP) Department of Oil and Gas digital records indicate that 9,171 permits were issued for unconventional, horizontal wells, with 4,299 wells drilled during that period (*15*). Assuming an average of 5 million gal per well, servicing each drilled well by truck alone converts to between 3.9 million and 8.6 million one-way deliveries of water, from variable distances, to variable locations.

Estimates of recovered wastewater fluids used in HVHF range from 5% to 300%, but there is considerable uncertainty and variability in recovered volumes (*8, 10, 14, 16, 17*). Because of contaminants, these fluids must be disposed of or treated, often by transporting the waste materials to treatment or disposal facilities by truck over considerable distances. As displayed in Figure 2, regionally more than 100 facilities accepted HVHF wastes from Pennsylvania wells from 2011 to 2013, based on PADEP records containing voluntarily reported waste amounts (*15*). However, in 2011, PADEP asked operators to stop sending wastes to 15 publically owned treatment works and centralized waste treatment facilities still accepting wastes under a grandfather clause (*18*), so well operators may need to send their wastes further or out of state if they opt not to treat wastewater on-site. Cost-effective on-site treatment methods and recycling processes are being developed, and a growing volume of waste fluid is being treated and recycled on-site (*19*). Some portion of these waste materials, however, will ultimately need to be transported off-site for treatment or disposal.

Sand, used as a proppant in the injection process to keep fractures open, is a critical component that must be delivered to the well site, typically by a rail and truck combination. According to the U.S. Geological Survey, in 2013, eight states (Wisconsin, Illinois, Texas, Minnesota, Oklahoma, Arkansas, Michigan, and Iowa) produced more than 74% of domestic sand and gravel, and 62% of all sand



(a)

(b)

(c)

FIGURE 2 Locations of producing and spud wells, waste facilities, water sources, and sand depots in (*a*) 2011, (*b*) 2012, and (*c*) 2013.

used was for HVHF activities (more than 32.5 million metric tons) (*20*). Industry estimates of sand use range from 1,250 to 3,500 tons per well, with an average use of 2,500 tons per well per fracturing event (*7, 12*). An average railcar holds 100 tons of sand, requiring four to five trucks to deliver to the well site (*7, 12*). Assuming a 22-ton load, a single well could need more than 100 truckloads of proppant sand. Restricting trucks to a 10-ton load jumps that number to 250 deliveries per well per fracturing event.

Transporting these raw materials and wastes could result in considerable environmental impacts caused by vehicle emissions. Emissions include carbon dioxide (CO_2), volatile organic compounds (VOCs), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM_{10}). CO_2 and NO_x emissions contribute to climate change, while emissions like VOCs, NO_x, SO_x, and PM_{10} are linked to human health impacts. Communities that find themselves part of major thoroughfares for HVHF-related materials and waste transportation may face greater exposure to these pollutants (*8, 21*). Increased truck traffic may also alter rural communities in particular 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 hydraulic fracturing debate is balancing economic development, livable communities, and environmental protection in areas with HVHF activities. Analyzing transportation impacts, pro and con, will contribute to these discussions.

This research addresses several gaps in the current analysis of the assessment of HVHF impacts by focusing on the effects of transportation on emissions and infrastructure. Several studies have looked at emissions from the production wells, particularly involving VOCs and methane (*1, 17, 22, 23*), but research on the impacts of emissions caused by the transport of materials and wastes is an identified need (*24, 25*). Several studies and articles have looked at issues of water usage and wastewater generated by the HVHF process (*9, 17, 19, 26, 27*). Gilmore et al. (*9*) conducted a six-month analysis (July to December 2011) of waste and water movements from Marcellus Shale wells in the Susquehanna River Basin. That study used a similar approach as in this research, but focused primarily on greenhouse gas emissions. This research expanded on that work, covering all of Pennsylvania for a three-year period and identifying specific road segments and areas where the traffic and associated environmental and health impacts would be greatest. Estimated pollution offsets from on-site treatment of HVHF wastes reducing truck trips, based on reported amounts from 2011 to 2013, are also provided.

RESEARCH APPROACH AND METHODS

The transportation analysis was conducted with ESRI's ArcGIS 10.0 and the Network Analyst extension, and the geospatial intermodal freight transport (GIFT) model. GIFT is an ArcGIS extension, developed by the Rochester Institute of Technology and the University of Delaware, 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 (*28, 29*). Truck, rail, and ship parameters are input by the user or pulled from predetermined vehicles stored in a growing transportation library.

The transportation network database used in this project was created from TIGER line files for state road networks in Pennsylvania, New York, Ohio, and West Virginia (*30*). General speed limits were assigned by road class and drive time (h) for each road segment was calculated by dividing segment distance (mi) by segment speed (mph). The project initially used the National Transportation Atlas Database (*31*) as the road network, but discovered that too many small rural roads were omitted, resulting in many unlocated wells and facilities (the O-D pairs) unless a search tolerance of more than 6 mi was used. TIGER line files allowed for the generation of more realistic routes through rural areas, and all wells were located on the network. The trade-off, however, was the network database size and model performance (model runs took several hours to complete, even with O-D pairs limited to 4,000 pairs per simulation).

WASTE, WATER, AND SAND CASE STUDIES

The research used Network Analyst for three case studies. The first is an assessment of the transportation impact of moving HVHF waste away from the drilling sites. The second is an assessment of the transportation impact of moving water to the drilling sites. The third is an assessment of moving sand to the drilling sites. Each case study required different sets of O-D pairs and generated separate transportation statistics. The results were combined into an overall analysis of materials and waste transport by year. These combined results are then compared with estimated emission and transport offsets created by on-site waste treatment, as reported from 2011 to 2013.

While HVHF activities in the Marcellus Shale region have been increasing since 2005, the study focused on materials transport from 2011 to 2013. Earlier reporting years were subject to certain data quality issues [see Lutz et al. (*19*) for an overview] that were largely corrected by 2011. And 2011 represents the largest well development year in the region; wells drilled prior to 2011 produced waste and natural gas.

Waste Case Study

For the waste analysis, PADEP has compiled information voluntarily submitted by companies for well and treatment and disposal facilities, in spreadsheet format, every six months since 2010 (*15*). Each record includes information on a well, the type and amount of waste moved, the destination facility, and the location coordinates of the well and the waste facility. A unique ID value was added to each record to import the locations of the wells and the facilities as ordered pairs (wells were origins, facilities were destinations, with the unique record ID used as the route name, doubling as a key field to join attributes from external databases). The reported amounts and types of waste shipped were used to generate 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 loads, dividing reported tons of waste 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, respectively, that would not exceed most bridge and road weight limits). For barrels of waste, reported barrel counts were multiplied by 42 to convert to gallons, then divided by the volume of the simulated pump truck (5,500, 4,000, and 2,500 gal to form equivalents to the 22-, 16-, and 10-ton loads). This 6-ton incremental load range provided a bookend analysis of probable loads and road- and bridge-friendly loads. Simulated load weights were derived from a variety of sources (*7, 10–12*). Well and facility positions were imported into ArcGIS as event tables (from the same file, with the same unique ID as the point name) and then converted to shapefiles.

ArcGIS Network Analyst provides several options for generating routes, and this project experimented with two: New Closest Facility and New Route. To solve for the large numbers of trucks going to specific facilities in different states, the New Route module was ultimately used in the waste analysis. 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. Well locations were loaded first as origins, with the unique ID as the stop name. Waste facility locations were loaded second as destinations, with the same unique ID as the stop name. This process created a series of ordered pairs, linked by a common unique record ID, which became the unique route name. To minimize computer memory issues, routes were solved for no more than 4,000 O-D pairs in six-month blocks: Period 1 (January through June) and Period 2 (July through December), as provided by PADEP.

The GIFT Model and Emissions Calculator was used with Network Analyst to generate distance attributes and total emissions from a user-defined vehicle for each route. For the analysis from 2011 to 2013 analyses, truck emission rates were set as listed below, to simulate a fleet of mixed-age 2008 average in-use heavy-duty diesel vehicles (*32*) and a new fleet of trucks adhering to stricter U.S. Environmental Protection Agency NO_x and PM_{10} emissions standards for model year (MY) 2007 trucks and beyond. This setup provided high and low estimates for key emissions, as the average age and emissions characteristics of the actual truck fleet for 2011 to 2013 are unknown. Both simulations assumed the use of low-sulfur diesel fuel (11 ppm), 6 mpg, and diesel fuel parameters as described in the GREET Model 1.8b (*33*):

- CO_2 = 1,740 g/mi,
- Carbon monoxide = 2.311 g/mi,
- NO_x = 8.613 g/mi (0.725 g/mi for 2007 MY trucks),
- PM_{10} = 0.219 g/mi (0.036 g/mi for 2007 MY trucks),
- SO_x = 0.012 g/mi,
- VOC = 0.447 g/mi, and
- Energy = 216,000 btu/mi.

After the routes were generated, the route name (the assigned unique ID) was used to estimate truck counts in the well point database and the truck estimates were copied over. To generate total pollution and travel statistics by route, the number of trucks used on a given route was multiplied by the route emissions for a specific pollutant. The route totals were for one-way trips from the wells to the receiving facilities for all trucks associated with a given ordered pair.

Routes frequently overlap certain road segments and these cumulative impacts at the segment level have higher cumulative truck counts, resulting in higher emissions along those segments. To generate estimates of combined truck counts and emissions from overlapping route segments, the Network Analyst tool Add Traversal Results was used to generate edges for each route (routes are made up of connected segments or edges). In edge tables, the attribute ROUTE_ID is the same as the route attribute OBJECTID, so the route truck counts can be joined and copied over to the edges table with these key field attributes.

Overlapping edges from the route can be combined with SourceOID, the attribute that links edges to specific segments of the underlying ArcGIS network database. SourceOID in the DISSOLVE command was used to combine overlapping edges into a single edge feature, and truck counts assigned to each overlapping edge segment were summed and the mean value for each pollutant was generated. This provided 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 mean emissions values provides an estimate of the annual pollution generated by the simulated truck traffic for a given edge or segment. These combined truck counts and pollution estimates in the edge layer were used to identify network hot spots and can be used as input for pollution dispersion models like AERMOD (*34*).

Water Case Study

The O-D pair information for water used at a Pennsylvania well from 2011 to 2013 does not exist in the same detailed digital format as the waste data. Locations of water sources are available, but not the identification or the locations of the specific wells that use the water from a specific water source. Water management plan data for the Marcellus Shale area, collected by PADEP and made available for download from the Pennsylvania Spatial Data Access clearinghouse (*35*), list the XY locations of the water withdrawal sources and the drilling companies that use each source, but there is no readily available public information detailing which specific wells are serviced by a specific water source, or how much water was used by a given well from a given source.

For the 2011 to 2013 water delivery analyses, spud well data were used for well locations and company ownership, and then matched to water source locations by company ownership. According to a water resources paper from ALL Consulting (*10*), delivery costs of water can quickly and dramatically exceed the actual cost of purchasing the water, so companies typically look for water sources as close to the well sites as possible. The spud well data set from PADEP also indicates if a well was active, so only active wells were used as the destinations for water deliveries, assuming that they were drilled and went into production in 2011. Horizontal hydraulic fracturing in the Marcellus Shale requires an estimated average of 5 million gal per well (*10*), so each target well was assumed to need 5 million gal. Following the logic of the truck types used in the waste analysis (*7, 10–12*), estimated truck counts needed for water delivery for several load limits are 909 5,500-gal tanker trucks, 1,250 4,000-gal tanker trucks, and 2,000 2,500-gal tanker trucks.

The location and ownership of each water source was loaded into ArcGIS as XY event tables and then converted into shapefiles. This process was repeated for the spud well data. Because of the uncertainties of specific water sources and volumes for each well, a series of company-specific New Closest Facility analyses were run, 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 a cluster of wells were usually all routed to a single, closest water source, leaving other, nearby sources unmatched. Inverting the analysis generated routes from each water source, but typically to a single well (the closest one). The routes linking each well to a water source were ultimately used in the analysis, to capture truck traffic along the small roads servicing the wells.

Sand Case Study

Similar to the water case study, proppant information is not publically available by well from PADEP. To conduct this case study, routes and edges for sand deliveries were generated with the New Closest Facility option of Network Analyst, similar to the water case study. Material warehouses and depots and transloading facilities for major and minor railways serving the region and the types of materials handled at these facilities were identified through literature and Internet searches. XY locations for sand facilities were found through address-matching in Google Earth and subsequently loaded as Facilities. Google Earth also provided a way to check for evidence of sand transfers at these facilities, as transferring sand from railcars to trucks often results in spillage, indicated by piles of white sand near the tracks. Spud wells again served as Incidents. This analysis assumed each well would use 2,500 tons of sand (*7, 12*), resulting in 114 to 250 one-way truck trips per well (22-ton to 10-ton loads).

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 90+ car unit-trains of materials, like sand. An example is the expanded TRANSFLO CSX frac sand terminal in Fairmont, West Virginia, in partnership with U.S. Silica. The sand database is therefore an evolving database and the sand results should be treated as best estimates.

RESULTS AND DISCUSSION

Results

Table 1 presents the summarized route information from 2011 to 2013. Referring to the 22-ton results, nearly 4.4 million truck trips were estimated over the three-year period, traveling more than 86 million mi. But while the number of truck trips decreased each year, the estimated miles traveled in 2013 were nearly equal to those in 2011. Analyzing the case study results shows that although the average distance traveled to deliver sand and water decreased over the three-year period (31.4, 30.8, and 30.3 mi for sand and 8.9, 7.4, and 6.0 mi for water), average waste delivery route mileage greatly increased in 2013 (110, 104, and 170 mi in 2011, 2012, and 2013, respectively). The increase in waste miles in 2013 offset the benefits of 392,967 fewer predicted truck trips, resulting in 2013 pollution totals nearly equal to 2011 totals. This finding suggests that in Pennsylvania in 2011, banning many unsuitable waste facilities from accepting liquid wastes had a large impact on waste route distances and generated pollution.

Discussion

Longer waste routes may in turn be helping to boost on-site treatment and recycling of HVHF wastes. Treating wastewater on-site not only reduces waste transport, but would also reduce water deliveries. Table 2 summarizes projected transportation statistics and emission loads offset by on-site recycling and treatment. Truck counts are based on reported volumes of waste treated or recycled on-site. Annual miles are calculated by multiplying truck counts by the average waste route distances. Multiplying miles by the emission factors provides emission loads. These numbers represent one-way truck trips saved and emission loads avoided. The volume of reported on-site waste treatment increased dramatically in 2012 and 2013 (20,667,697 and 21,696,302 barrels, respectively), nearly double the volume of 2011 (11,484,925 barrels). The significance of this shift is apparent if the values in Tables 1 and 2 are added. Without on-site recycling, the 2012 and 2013 pollution totals each exceed the 2011 pollution totals, despite lower truck counts.

Figure 3 shows the combined route and road segment truck count analyses for 2011, 2012, and 2013. The high truck counts along the interstates and state highways linking Pennsylvania and Ohio reflect

TABLE 1 Summarized Route Information

Year	Trucks (one way)	Miles (one way)	Hours (one way)	Energy (MBTU)	CO (Mg)	CO_2 (Mg)	NO_x (Mg)	NO_x (Mg)	PM_{10} (Mg)	PM_{10} (Mg)	SO_x (Mg)	VOC (Mg)
22 ton												
2011	1,698,309	30,205,955	743,656	652,449	70	52,558	260	22	6.6	1.1	0.4	13.5
2012	1,360,696	26,086,795	603,783	563,475	60	45,391	225	19	5.7	0.9	0.3	11.7
2013	1,305,342	30,181,121	649,648	651,912	70	52,515	260	22	6.6	1.1	0.4	13.5
Total	4,364,347	86,473,872	1,997,087	1,867,836	200	150,465	745	63	18.9	3.1	1.0	38.7
16 ton												
2011	2,333,823	41,297,632	1,017,975	892,029	95	71,858	356	30	9.0	1.5	0.5	18.5
2012	1,868,351	35,450,289	822,600	765,726	82	61,684	305	26	7.8	1.3	0.4	15.8
2013	1,792,420	41,017,377	884,726	885,975	95	71,370	353	30	9.0	1.5	0.5	18.3
Total	5,994,594	117,765,298	2,725,302	2,543,730	272	204,912	1,014	85	25.8	4.2	1.4	52.6
10 ton												
2011	3,728,132	65,511,397	1,617,571	1,415,046	151	113,990	564	47	14.3	2.4	0.8	29.3
2012	2,981,697	55,843,364	1,299,828	1,206,217	129	97,167	481	40	12.2	2.0	0.7	25.0
2013	2,859,589	64,486,156	1,394,986	1,392,901	149	112,206	555	47	14.1	2.3	0.8	28.8
Total	9,569,418	185,840,917	4,312,385	4,014,164	429	323,363	1,601	135	40.7	6.7	2.2	83.1

NOTE: Values are estimated truck counts by variable loads and associated emissions totals for delivery of sand and water and removal of waste materials to and from Pennsylvania wells in 2011, 2012, and 2013. Results simulate an older, mixed-age fleet of trucks based on U.S. EPA 2008 average in-use emission rates except for gray columns, which reflect 2007 MY trucks meeting more stringent NO_x and PM_{10} emissions standards.

TABLE 2 Projected Transportation Statistics and Emission Loads Offset by On-Site Recycling and Treatment

Year	Trucks (one way)	Miles (one way)	Hours (one way)	Energy (MBTU)	CO (Mg)	CO_2 (Mg)	NO_x (Mg)	NO_x (Mg)	PM_{10} (Mg)	PM_{10} (Mg)	SO_x (Mg)	VOC (Mg)
22 ton												
2011	89,808	9,878,880	225,418	213,384	23	17,189	85	7	2.2	0.4	0.1	4.7
2012	161,648	16,811,392	329,762	363,126	39	29,252	145	12	3.7	0.6	0.2	8.0
2013	169,883	28,880,110	507,950	623,810	67	50,251	249	21	6.3	1.0	0.3	13.8
Total	421,339	55,570,382	1,063,130	1,200,320	128	96,692	479	40	12	2	1	27
16 ton												
2011	122,717	13,498,870	308,020	291,576	31	23,488	116	10	3.0	0.5	0.2	6.4
2012	220,882	22,971,728	450,599	496,189	53	39,971	198	17	5.0	0.8	0.3	11.0
2013	232,017	39,442,890	693,731	851,966	91	68,631	340	29	8.6	1.4	0.5	18.8
Total	575,616	75,913,488	1,452,350	1,639,731	175	132,089	654	55	17	3	1	36
10 ton												
2011	195,009	21,450,990	489,473	463,341	50	37,325	185	16	4.7	0.8	0.3	10.2
2012	351,112	36,515,648	716,268	788,738	84	63,537	315	26	8.0	1.3	0.4	17.4
2013	368,701	62,679,170	1,102,416	1,353,870	145	109,062	540	45	13.7	2.3	0.8	29.9
Total	914,822	120,645,808	2,308,157	2,605,949	279	209,924	1,039	87	26	4	1	58

NOTE: Values are truck trips (one way), travel statistics, and truck emissions avoided by on-site recycling of wastewater at Pennsylvania wells in 2011–2013. Truck numbers estimate the number of trucks needed to haul to a disposal facility the reported volume of waste recycled or reused, based on load. Miles and hours represent total estimated vehicle mile and hour offsets for one-way trips, based on average waste route distances and drive times in 2011, 2012, and 2013. Emissions were calculated by multiplying 2008 average in-use emission rates for an older, mixed-age fleet of trucks except for gray columns, which reflect 2007 MY trucks meeting the more stringent NO_x and PM_{10} emissions standards.

the large amount of waste shipped to Ohio injection wells from wells throughout the Marcellus Shale region. 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.

In Pennsylvania, portions of I-79 and PA-21 around Pittsburgh experience high truck traffic counts as routes merge before fanning out again toward specific treatment and disposal facilities. Around the clusters of wells in the southwest and northeast portions of the study area, high truck counts were found on segments of major and minor roads as waste, water, and sand deliveries funnel though towns like Washington (in the southwest) and Williamsport (in the northeast). These short bottlenecks shift annually with well distributions, frequently associated with shifting water and sand delivery routes (many trucks over short distances). But towns with fixed features, such as landfills, approved waste treatment facilities, and primary material depots, will likely continue to experience heavy truck traffic. These high-volume segments will become the focus of emissions dispersion modeling in the next phase of this research.

The Pennsylvania Department of Transportation (DOT) provides annual geographic information system data on Pennsylvania roads, including estimates of daily average truck counts starting in 2008 (*35*). Multiplying truck counts by 365 to generate an annual truck count for each road, these data can be compared with the results of this work to help identify roads where truck traffic is predominately caused by gas well development. The Pennsylvania DOT does not use TIGER line files for its road network, so the two road data sets do not match perfectly (the positions of some road segments are offset and some roads are missing from one or the other database). But these two estimates of truck counts do provide for a visual assessment. Figure 4 shows the annual Pennsylvania DOT truck count estimates for 2011, 2012, and 2013 and highlights the volume of truck traffic along interstates and major state highways. Because the model results only show one-way trips, the truck counts were doubled to simulate round-trips and then thematically scaled to mirror the total truck traffic legend for the Pennsylvania DOT data.

Figure 4 highlights areas where predicted truck counts associated with HVHF activities make up a large proportion of the annual truck traffic. Areas of visible color appear when thicker colored lines (model results) are not completely masked by thinner blue lines (Pennsylvania DOT estimates), indicating segments with higher estimated HVHF traffic proportions. This visual analysis indicates that the northeast portion of the Marcellus Shale in Pennsylvania is the primary area of concern for truck traffic, probable road wear, and bridge impacts caused by loads and truck volume related to HVHF, and possible health impacts because of the additional HVHF truck traffic. Areas in the southeast portion of the study area also show high truck counts related to HVHF, but the roads in that area appear to have higher truck volumes already and may be better suited for higher truck counts.

Implications for New York State Roads

On December 15, 2015, Governor Andrew Cuomo banned hydraulic fracturing in New York State, but New York counties along the border with Pennsylvania continue to support drilling operations. The Binghamton, New York, railway serves as a major sand depot for Pennsylvania wells in the northeast portion of the Marcellus Shale region. A major materials distribution center (Horseheads Sand and Transloading Terminal) opened on September 26, 2012, in Horseheads, New York. PADEP records document solid drilling waste sent to landfills in Chemung, Alleghany, and Steuben counties, and liquid wastes shipped to the industrial treatment plant in Niagara Falls. PADEP records also indicate that several companies have water sources in New York, although it is unclear if they have

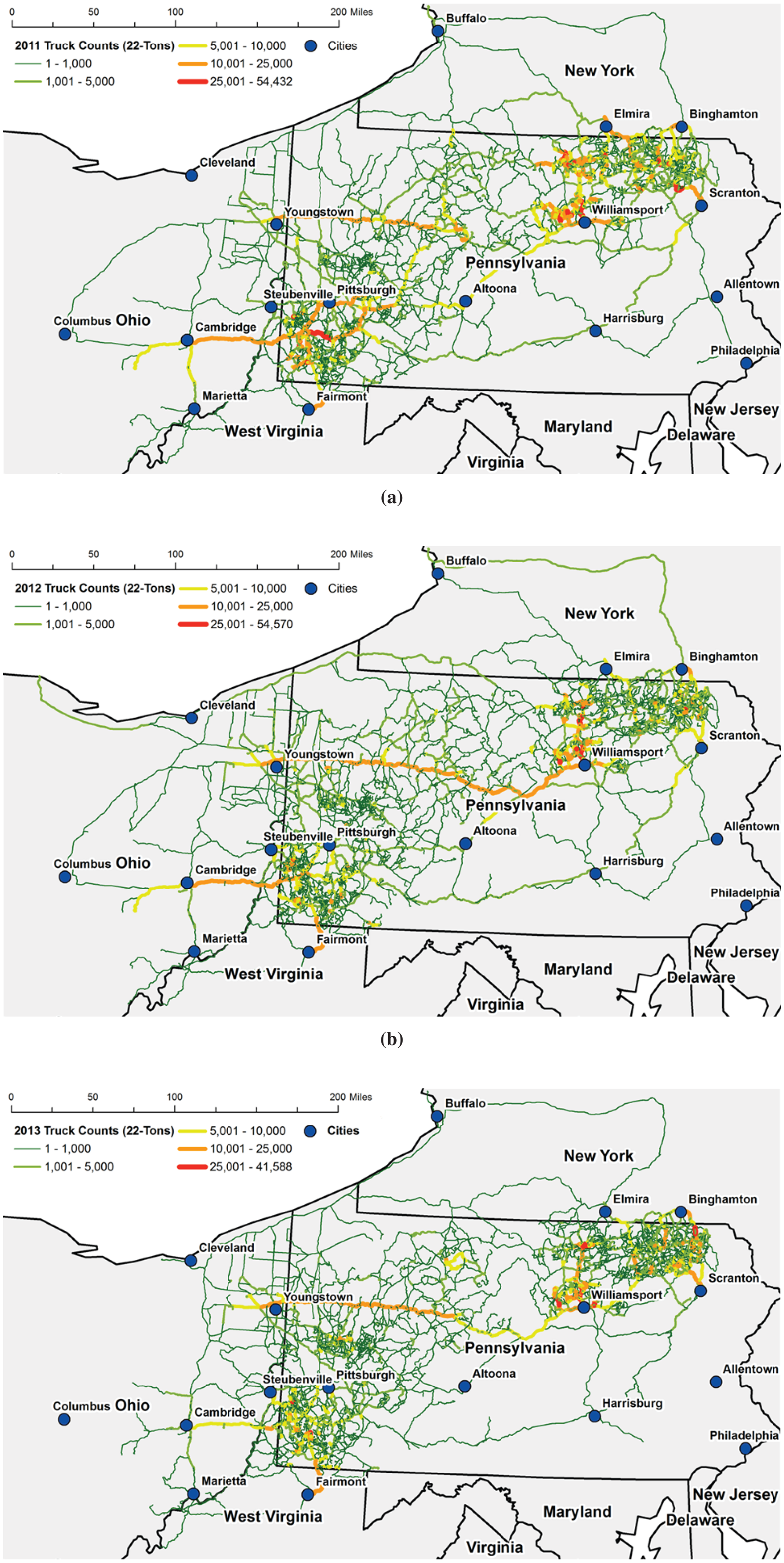


FIGURE 3 Routes and calculated truck counts (22-ton loads) by road segments for waste, water, and sand transport for unconventional horizontal Pennsylvania wells in (*a*) 2011, (*b*) 2012, and (*c*) 2013.

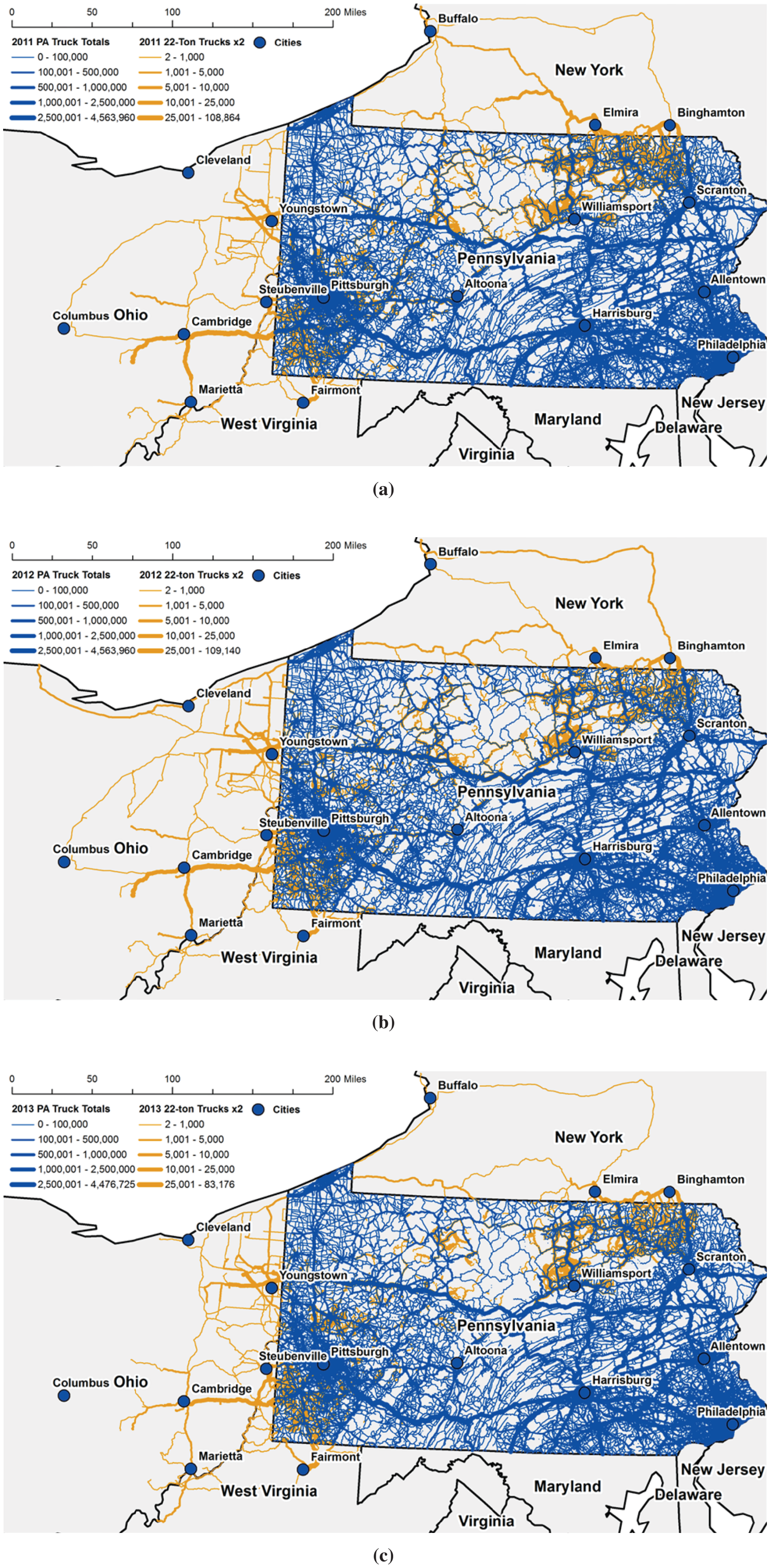


FIGURE 4 Estimated total annual truck counts (the Pennsylvania DOT traffic count data) superimposed on annual 22-ton truck HVHF transport estimates (doubled) for (*a*) 2011, (*b*) 2012, and (*c*) 2013.

been utilized. So while the transportation impacts on New York roads appear to be relatively minor to date, allowing horizontal HVHF operations in New York at some later date would likely lead to spatial transportation patterns similar to those in Pennsylvania, with higher emissions and truck counts where routes congregate.

CONCLUSIONS

This research estimated that between 2011 and 2013, 4.4 million to 9.6 million one-way truck trips, totaling 86.5 million to 185.8 million vehicle miles (22- or 10-ton loads) were used to transport sand and water to, and to remove waste from, HVHF natural gas wells in the Pennsylvania portion of the Marcellus Shale region. The bookend emissions model estimates for the three-year period range from 18.9 to 40.7 Mg PM_{10} for older trucks, and 3.1 to 6.6 Mg PM_{10} for newer trucks, depending on the load simulated. For NO_x, the bookend analysis estimated 745 to 1,601 Mg emitted by older trucks, and 63 to 135 Mg for MY 2007 trucks, depending on the load simulated. These findings show the importance of pollution control devices and are a key part of this project's ongoing emissions dispersion modeling.

The analysis used wells, resource supply areas, and waste disposal facilities as a series of O-D pairings to generate probable transportation routes. The routes were 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. The results indicate that the wells around Williamsport, Pennsylvania, and in the northeast portion of the study area generated the most traffic and highest pollution loads by road segment. The results also provide a baseline to compare against the benefits of recycling HVHF wastes on-site. Between 2011 and 2013, Pennsylvania wells treated nearly 54 million barrels of wastewater on-site, resulting in substantial pollution offsets from an estimated 421,339 to 914,822 diverted truck trips.

This project also highlighted the need to require the collection and public dissemination of more complete records of the materials and goods movement related to the HVHF industry. In particular, knowing the origins of equipment, resources, and wastes and their destination locations would help generate more robust model predictions, which in turn would make environmental, health, and economic trade-off analyses more complete. More transparent information on equipment, materials, and waste transport would also allow for more robust intermodal analyses, for evaluation and optimization of the environmental and economic impacts and trade-offs of moving materials by truck, rail, and ship. Recommended required information from energy and transport companies would include equipment, raw materials, and waste information from trucks, rails, ships, and pipelines. Information on actual vehicles used in the transport of equipment, materials, and wastes would also be extremely useful in creating more accurate models.

The PADEP waste inventory, with specific O-D pair information (well and facility locations, amount of waste shipped, and type of waste), provides a good template, but the voluntary waste data are almost certainly underreported, impacting emissions calculations. From 2011 to 2013, nearly 1.2 billion gal of waste were shipped off-site, but that is only 11% of the estimated 10.7 billion gal of wastewater potentially generated by the 4,299 wells drilled during that period, assuming 50% flowback (*5, 6, 10*). Reported on-site treatment and recycling accounts for another 22% (2.3 billion gal), leaving 67% (7.2 billion gal) unaccounted for.

The results from this project can help policy analysts and environmental planners evaluate the pollution impacts associated with the movement of materials in the HVHF industry, a potentially huge economic force in the region. The results of this research can also help address interrelated health, infrastructure, and sustainable community issues, such as the trade-offs between recycling materials and treating wastes on-site, development of pipeline supply networks, or development of central treatment and distribution centers (expanded intermodal possibilities with rail and ship to minimize pollution and road impacts).

ACKNOWLEDGMENTS

The authors acknowledge contributions by graduate students of the Rochester Institute of Technology who were involved in this research—Erika Mesh, Alyssa Mathews, and Rachel Zoyhofski—and the University Transportation Research Center, Region 2, for funding this project.

REFERENCES

1. Myhrvold, N. P., and K. Caldeira. Greenhouse Gases, Climate Change and the Transition from Coal to Low-Carbon Electricity. In *Environmental Research Letters,* Vol. 7, 2012. iopscience.iop.org/1748-9326/7/1/014019. Accessed March 3, 2015.
2. Howarth, R. W. A Bridge to Nowhere: Methane Emissions and the Greenhouse Gas Footprint of Natural Gas. *Energy Science and Engineering,* Vol. 2, No. 2, 2014, pp. 47–60.
3. Energy Information Administration, U.S. Department of Energy. *Review of Emerging Resources: U.S. Shale and Gas and Shale Oil Plays.* 2011. www.eia.gov/analysis/studies/usshalegas/pdf/usshaleplays.pdf. Accessed March 7, 2015.
4. Lee, D. S., J. Herman, D. Elsworth, H. T. Kim, and H. S. Lee. A Critical Evaluation of Unconventional Gas Recovery from the Marcellus Shale, Northeastern United States. *Korean Society of Civil Engineering Journal of Civil Engineering,* Vol. 15, No. 4, 2011, pp. 679–687.
5. *Revised Draft Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program: Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs.* New York State Department of Environmental Conservation, Albany, N.Y., 2011. www.dec.ny.gov/data/dmn/rdsgeisfull0911.pdf. Accessed March 7, 2015.
6. Tolliver, D. Freight System Effects of the Bakken Shale Boom. Presented at 93rd Annual Meeting of the Transportation Research Board, Washington, D.C., 2014.
7. Gannett Fleming GFX. *Marcellus Shale Freight Transportation Study—Final Report.* Navarro and Wright Consulting Engineers, Inc.; Northern Tier Regional Planning and Development Commission, Towanda, Pa., 2011. www.northerntier.org/upload/NTRPDC%20Marcellus%20Shale%20Freight%20Transp.%20Study.pdf. Accessed March 7, 2015.
8. Clark, C., A. Burnham, C. Harto, and R. Horner. The Technology and Policy of Hydraulic Fracturing and Potential Environmental Impacts of Shale Gas Development. *Environmental Practice,* Vol. 14, 2012, pp. 249–261.
9. Gilmore, K. R., R. L. Hupp, and J. Glathar. Transport of Hydraulic Fracturing Water and Waste in the Susquehanna River Basin, Pennsylvania. *Journal of Environmental Engineering,* Vol. 140, No. 5, 2014. ascelibrary.org/doi/abs/10.1061/(ASCE)EE.1943-7870.0000810. Accessed March 7, 2015.
10. Arthur, J., M. Uretsky, and P. Wilson. *Water Resources and Use for Hydraulic Fracturing in the Marcellus Shale Region.* ALL Consulting, Tulsa, Okla., 2010. www.all-llc.com/publicdownloads/WaterResourcePaperALLConsulting.pdf. Accessed March 7, 2015.
11. Stockdill, P. Managing Bakken Wastewater. *Bismarck Tribune,* Bismarck, N.Dak., July 31, 2014. http://bismarcktribune.com/bakken/breakout/managing-bakken-wastewater/article_41f4c1e8-18d5-11e4-98a0-0019bb2963f4.html. Accessed March 7, 2015.

12. Hart, V., T. Adams, and A. Schwartz. *Transportation Impact of Frac Sand Mining in the MAFC Region: Chippewa County Case Study* (*Draft*). White Paper Series 2013. National Center for Freight and Infrastructure Research and Education, University of Wisconsin–Madison, 2013. http://midamericafreight.org/wp-content/uploads/FracSandWhitePaperDRAFT.pdf. Accessed March 7, 2015.
13. *Natural Gas Drilling in Marcellus Shale: Natural Gas Drilling Overview.* New York City Department of Environmental Protection, N.Y., 2012. http://www.nyc.gov/html/dep/html/news/natural_gas_drilling_overview.shtml. Accessed March 7, 2015.
14. Mitchell, A. L., M. Small, and E. A. Casman. Surface Water Withdrawals for Marcellus Shale Gas Development: Performance of Alternative Regulatory Approaches in the Upper Ohio River Basin. *Environmental Science and Technology,* Vol. 47, 2013, pp. 12669–12678.
15. Office of Oil and Gas Management. *PA DEP Oil and Gas Reporting Website.* Pennsylvania Department of Environmental Protection, Harrisburg, Pa., 2014. https://www.paoilandgasreporting.state.pa.us/publicreports/Modules/Welcome/Welcome.aspx. Accessed March 7, 2015.
16. Office of Research and Development. *Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources.* EPA/600/R-11/122. U.S. Environmental Protection Agency, 2011. water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/upload/hf_study_plan_110211_final_508.pdf. Accessed March 7, 2015.
17. Cooley, H., and K. Donnelly. Hydraulic Fracturing and Water Resources: Separating the Frack from the Fiction. Pacific Institute, Oakland, Calif., 2012. www.pacinst.org/reports/fracking/. Accessed March 7, 2015.
18. DEP Calls on Natural Gas Drillers to Stop Giving Treatment Facilities Wastewater. *Commonwealth News Bureau,* Pennsylvania Department of Environmental Protection, Harrisburg, Pa. April 19, 2011. www.portal.state.pa.us/portal/server.pt/community/newsroom/14287%3Fid%3D17071%26typeid%3D1. Accessed March 7, 2015.
19. Lutz, B., A. Lewis, and M. Doyle. Generation, Transport, and Disposal of Wastewater Associated with Marcellus Shale Gas Development. *Water Resources Research,* Vol. 49, 2013, pp. 1–10.
20. Dolley, T. P. *US Geological Survey Mineral Commodity Summaries 2014.* U.S. Geological Survey, 2014, pp. 138–139. minerals.er.usgs.gov/minerals/pubs/commodity/silica/mcs-2014-sandi.pdf. Accessed March 7, 2015.
21. Litovitz, A., A. Cutright, S. Abramzon, N. Burger, and C. Samaras. Estimation of Regional Air-Quality Damages from Marcellus Shale Natural Gas Extraction in Pennsylvania. *Environmental Research Letters,* Vol. 8, 2013. iopscience.iop.org/1748-9326/8/1/014017/. Accessed March 7, 2015.
22. Stokes, J., and A. Horvath. Life Cycle Energy Assessment of Alternative Water Supply Systems. *International Journal of Life Cycle Assessment,* Vol. 11, No. 5, 2006, pp. 335–343.
23. Jiang, M., W. M. Griffin, C. Hendrickson, P. Jaramillo, J. VanBriesen, and A. Venkatesh. Life Cycle Greenhouse Gas Emissions of Marcellus Shale Gas. *Environmental Research Letters,* Vol. 6, No. 3, 2011. iopscience.iop.org/1748-9326/6/3/034014/. Accessed March 7, 2015.
24. Penning, T. M., P. N. Breysse, K. Gray, M. Howarth, and B. Yan. Environmental Health Research Recommendations from Inter-Environmental Health Sciences Core Center Working Group on Unconventional Natural Gas Drilling Operations. *Environmental Health Perspectives,* July 2014. dx.doi.org/10.1289/ehp.1408207. Accessed March 7, 2015.
25. *Compendium of Scientific, Medical, and Media Findings Demonstrating Risks and Harms of Fracking* (*Unconventional Gas and Oil Extraction*), 2nd ed. Concerned Health Professionals of New York, 2014. http://concernedhealthny.org/wp-content/uploads/2014/07/CHPNY-Fracking-Compendium.pdf. Accessed March 7, 2015.
26. Soeder, D. J., and W. M. Kappel. *Water Resources and Natural Gas Production from the Marcellus Shale: U.S. Geological Survey Fact Sheet 2009–3032.* U.S. Geological Survey, Washington, D.C., 2009. pubs.usgs.gov/fs/2009/3032/. Accessed March 7, 2015.
27. Hammer, R., and J. VanBriesen. *In Fracking's Wake: New Rules are Needed to Protect Our Health and Environment from Contaminated Wastewater.* NRDC Document D:12-05-A. Natural Resources Defense Council, 2012. www.nrdc.org/energy/files/Fracking-Wastewater-FullReport.pdf. Accessed March 7, 2015.
28. Winebrake, J., J. Corbett, A. Falzarano, J. S. Hawker, K. Korfmacher, S. Ketha, and S. Zilora. Assessing Energy, Environmental, and Economic Tradeoffs in Intermodal Freight Transportation. *Air and Waste Management Association,* Vol. 58, No. 8, 2008, pp. 1004–1013.
29. Comer, B., J. Corbett, J. S. Hawker, K. Korfmacher, E. Lee, C. Prokop, and J. Winebrake. Marine Vessels as a Substitute for Heavy-Duty Trucks in Great Lakes Freight Transportation. *Air and Waste Management Association,* Vol. 60, No. 7, 2010, pp. 884–890.
30. *Tiger Products.* U.S. Census Bureau, 2010. www.census.gov/geo/maps-data/data/tiger.html. Accessed March 7, 2015.
31. Bureau of Transportation Statistics, U.S. Department of Transportation. *National Transportation Atlas Database 2012.* 2012. www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_atlas_database/2014/index.html. Accessed March 7, 2015.
32. Office of Transportation and Air Quality, U.S. Environmental Protection Agency. *Average In-Use Emissions from Heavy-Duty Trucks.* EPA420-FR-08-027. 2008. http://www.epa.gov/otaq/consumer/420f08027.pdf. Accessed March 7, 2015.
33. Argonne National Laboratory. *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation* (*GREET*) *Model release 1.8b.* Transportation Technology Research and Development Center, U.S. Department of Energy, Chicago, Ill., 2008.
34. Office of Air Quality Planning and Standards and Office of Air and Radiation. *AERMOD Modeling System.* U.S. Environmental Protection Agency, Research Triangle Park, N.C., 2013. http://www.epa.gov/ttn/scram/dispersion_prefrec.htm#aermod. Accessed March 7, 2015.
35. Penn State Institutes of Energy and the Environment. *Pennsylvania Spatial Data Access* (*PASDA*)*: The Pennsylvania Geospatial Data Clearinghouse.* Pennsylvania State University. ftp://www.pasda.psu.edu/pub/pasda. Accessed March 7, 2015.

The Standing Committee on Transportation and Air Quality peer-reviewed this paper.