Feasibility Study for Liquefied Natural Gas Utilization for Commercial Vehicles on the Pennsylvania Turnpike

FINAL REPORT

October 31, 2012
February 22, 2013, Revision #1

Prepared by the Penn State Facilities Engineering Institute
and The Thomas D. Larson Pennsylvania
Transportation Institute

PENNSYLVANIA TURNPIKE COMMISSION

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16. Abstract

Recent advances in horizontal drilling and fracturing technology in gas shale formations have increased natural gas supply such that its price has decoupled from petroleum and is likely to remain significantly lower for the foreseeable future. In the meantime, gasoline and diesel fuel prices in the United States have peaked above $4 per gallon several times, creating renewed interest in natural gas as an economical, alternative fuel. Liquid natural gas (LNG) has become particularly attractive for commercial long-haul trucks due to its price and ability to provide a safe traveling distance of approximately 600 miles between stops for refueling if the truck is equipped with dual fuel tanks. Owners of commercial trucking fleets are beginning to recognize the competitive advantages that LNG fuel may bring to their business but remain cautious about new truck purchases or engine conversions. This cautious approach to LNG fuel is a result of the increased price for equipment (as compared to the conventional, diesel-fueled truck) and lack of infrastructure for LNG fueling stations. The Pennsylvania Turnpike Commission recognized the potential for natural gas as an alternative fuel and released a white paper in February 2012 titled *Feasibility of Utilizing Natural Gas Vehicles Traveling/Maintaining the Pennsylvania Turnpike*, from which recommendations to conduct a feasibility study on the topic were made. The recommendations from the white paper were further refined for the purposes of this study to focus on the use of LNG as an alternative fuel for the commercial trucking industry along the Turnpike highway system. This study provides detailed information on these issues, including a mathematical model that shows the optimal locations, specific site considerations, and costs for construction of fueling stations at the site of existing and surplus service plazas; technical and economic information on LNG engines; and numerous other issues such as safety and benchmarking with other states.

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FEASIBILITY STUDY FOR LIQUEFIED NATURAL GAS UTILIZATION FOR COMMERCIAL VEHICLES ON THE PENNSYLVANIA TURNPIKE

FINAL REPORT

Prepared for the Pennsylvania Turnpike Commission
Contract No. 4400002634

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List of Acronyms

AADTT	Annual Average Daily Truck Traffic
AADPTT	Annual Average Daily Percentage of Truck Traffic
AFDC	Alternative Fuels Data Center
AFV	Alternative fuel vehicle
AFIG	Alternative Fuels Incentive Grant Program
AGNA	America's Natural Gas Alliance
API	American Petroleum Institute
ATT	Annual truck traffic
BOG	Boil off gas from an LNG tank
CI	Compression ignition
CMAQ	Congestion Management and Air Quality
CNG	Compressed Natural Gas
DGE	Diesel Gallon Equivalent unit of fuel energy
DME	Dimethyl ether
EB	East bound
EPA	Environmental Protection Agency
GGE	Gasoline Gallon Equivalent unit of fuel energy
H/C	Hydrogen/carbon ratio
HOV	Refers to a High Occupancy Vehicle lane
HPDI	High Pressure Direct Injection
IRR	Internal Rate of Return
LCNG	Combined liquid and compressed natural gas dispensing technology
LINGO	software for linear, non-linear, and integer programming
LNG	Liquid (or Liquefied) Natural Gas
MAP-21	Moving Ahead for Progress in the 21st Century
MATLAB	Mathworks Inc. software
MP	Mile Post on the Pennsylvania Turnpike
NB	North bound
NGV	Natural gas vehicle
NPV	Net Present Value
O/D	Origin/Destination traffic data
p	Number of LNG stations in model
P3	Public Private Partnerships
PASDA	Pennsylvania Spatial Data Access
PA DEP	Pennsylvania Department of Environmental Protection
PCTC	Pennsylvania Clean Transportation Corridor
PennDOT	Pennsylvania Department of Transportation
PFI	Port Fuel Injection in spark ignited engines
PPE	Personal Protective Equipment for safety
PPTP	Public/Private Transportation Partnership
psi	pounds per square inch
PTC	Pennsylvania Turnpike Commission
R	Safe traveling distance without refueling
ROI	Return on Investment
SAFETEA-LU	Safe, Accountable, Flexible, and Efficient Transportation Act, a Legacy for Users
SB	South bound traffic
scfd	Standard cubic feet per day of methane
SI	Spark ignited engine
VJ	Vacuum Jacketed
WB	West bound

Executive Summary

Recent advances in horizontal drilling and fracturing technology in gas shale formations have increased natural gas supply such that its price has decoupled from petroleum and is likely to remain significantly lower for the foreseeable future. In the meantime, gasoline and diesel fuel prices in the United States have peaked above $4 per gallon several times, creating renewed interest in natural gas as an economical, alternative fuel for long-haul commercial trucks. Liquefied natural gas (LNG) has become particularly attractive for commercial long-haul trucks due to its price and the ability to provide a safe traveling distance of up to 600 miles between stops for refueling. Owners of commercial trucking fleets are beginning to recognize the competitive advantages that LNG fuel may bring to their business but remain cautious with new truck purchases or engine conversions. This cautious approach to LNG fuel is a result of the increased price for equipment (as compared to the conventional, diesel-fueled truck) and lack of infrastructure for LNG fueling stations. This study provides detailed information on these issues including a mathematical model that shows the optimal locations, specific site considerations, and costs for construction of fueling stations at the site of existing and surplus service plazas; technical and economic information on LNG engines; and numerous other issues such as safety and benchmarking with other states.

The Commission recognized the increased spotlight on alternative fuels for vehicles and released a white paper in February 2012 titled *Feasibility of Utilizing Natural Gas for Vehicles Traveling/Maintaining the Pennsylvania Turnpike*, from which recommendations to conduct a feasibility study on the topic were made. The recommendations from the white paper were further refined for the purposes of this study to focus on the use of LNG as an alternative fuel for the commercial trucking industry along the Turnpike highway system. Penn State Facilities Engineering Institute (PSFEI) and a team of associated faculty were selected to carry out this feasibility study.

Based on the research of this study, we find that LNG for long-haul commercial trucks on the Turnpike is feasible. Given that the market is still emerging and some of the technology applications are being refined, a decision by the Commission to move forward with the installation of LNG fueling stations on the Turnpike should be executed with proper planning and detailed knowledge of business and technology issues.

Mathematical modeling of truck traffic and travel shows that the top sites for LNG fueling stations along the Turnpike are Allentown, Sidling Hill, Oakmont/Plum, and King of Prussia. The Peter J. Camiel, New Stanton, and Midway service plazas emerge on a second tier. Chapter 2 and Appendix B of this report provide extensive details on the optimum locations for many different scenarios.

The mathematical model is a valuable portion of this study since it is specifically based on the performance and logistics of a vehicle fueled by LNG. However, the nature of LNG as a fuel changes the dynamics of executing station development relative to demand from customers in an emerging market. LNG is a cryogenic fuel that will gradually degrade and is a perishable product in storage if not consumed in a timely manner. For this reason, we recommend that the Commission place special emphasis on the acquisition of an anchor customer(s) that will agree to use a minimum amount of fuel at a specific fueling location(s). With an initial commitment from trucking companies, a mobile fueling station could be sited and operational in a relatively short period of time while engineering and construction of permanent stations proceed. The Commission should be aware that the fuel demand and travel logistics of the anchor customer(s) could play a major role in the quantity and location of the new LNG fueling stations and these locations may not coincide with the optimal locations that were determined by the mathematical model.

The initial period of time in which customers are being served by a mobile fueling station could also be used by the Commission to evaluate the success of the relationships and the initial commitment from the trucking companies. This time could also be used to market the new economic, environmentally advantageous fuel option of LNG provided on the Turnpike system.

The Commission should be aware that the use of LNG fuel involves unique safety requirements and risks but can be safely managed with proper training, processes, and procedures. Turnpike and service plaza employees and truck drivers should receive some form of LNG training either in the form of classroom training or through an informational video.

Finally, we recommend that strong consideration be given to constructing fueling stations that incorporate LNG (cold and saturated), boil-off gas (BOG) collection, and Compressed Natural Gas (CNG) into design and implementation. Combined LNG and CNG (LCNG) station technology may add significant capital cost to initial construction but it has several advantages. It offers the widest possible options of natural gas based fuels to consumers for commercial trucks as well as cars and light trucks. Furthermore, this will reduce environmental impact through collection of vented BOG, possible avoidance of future modifications if BOG gas becomes regulated and creates positive public relations for taking a proactive approach by reducing emissions and offering both CNG and LNG.

Introduction: Application of LNG Technology

Since the Pennsylvania Turnpike first opened in 1940, the proportion of goods moved by commercial trucks has steadily increased in volume relative to rail. During this entire period, commercial truck fuel has been almost entirely petroleum based in the form of gasoline or diesel. While U.S. domestic oil production peaked in the early 1970s, a volatile foreign oil supply coupled with increasing worldwide demand has resulted in fluctuating and steadily increasing petroleum fuel prices for commercial trucks. As a result, a variety of alternative fuels and advanced propulsion technologies have been explored for heavy trucks, including battery electric, hybrid electric, bio-diesel, ethanol, propane, dimethyl ether (DME), LNG, CNG, and both liquefied and gaseous hydrogen. Up to this point in time, emerging technologies for alternative fuels have not been entirely competitive with petroleum fuels in cost, performance, and range.

LNG as a Viable Alternative Fuel for Commercial Trucking

Recent advances in horizontal drilling and hydraulic fracturing technology have been applied to U.S. shale gas formations and resulted in a surge of natural gas supply, such that its price has decoupled from petroleum and is likely to remain significantly lower for the foreseeable future. Figure I.1 shows average monthly retail prices for various fuels in the United States from 2000 to 2011 in gasoline-gallon equivalents (GGE). [1] A GGE represents a quantity of fuel with the same amount of energy contained in a gallon of gasoline. Similarly, a diesel-gallon equivalent (DGE) of fuel represents the same amount of energy found in a gallon of diesel fuel. This new drilling technology has been especially effective at recovering trapped natural gas reserves, but it may also yield increased petroleum production in the future. In the meantime, gasoline and diesel fuel prices in the United States have peaked above $4 per gallon several times, creating renewed interest in CNG and LNG as alternative fuels. Appendix C contains an economic analysis for LNG truck payback.

The market for LNG transportation fuel is emerging and relatively immature, therefore the retail price of LNG is not shown on this figure of historical retail prices. At the present time, the retail price of LNG fuel in the northeastern United States ranges from $2.75 to $3.00 per DGE. LNG industry sources have stated that the retail price of LNG fuel has crept slightly upward over the past year but should remain steady in 2013.

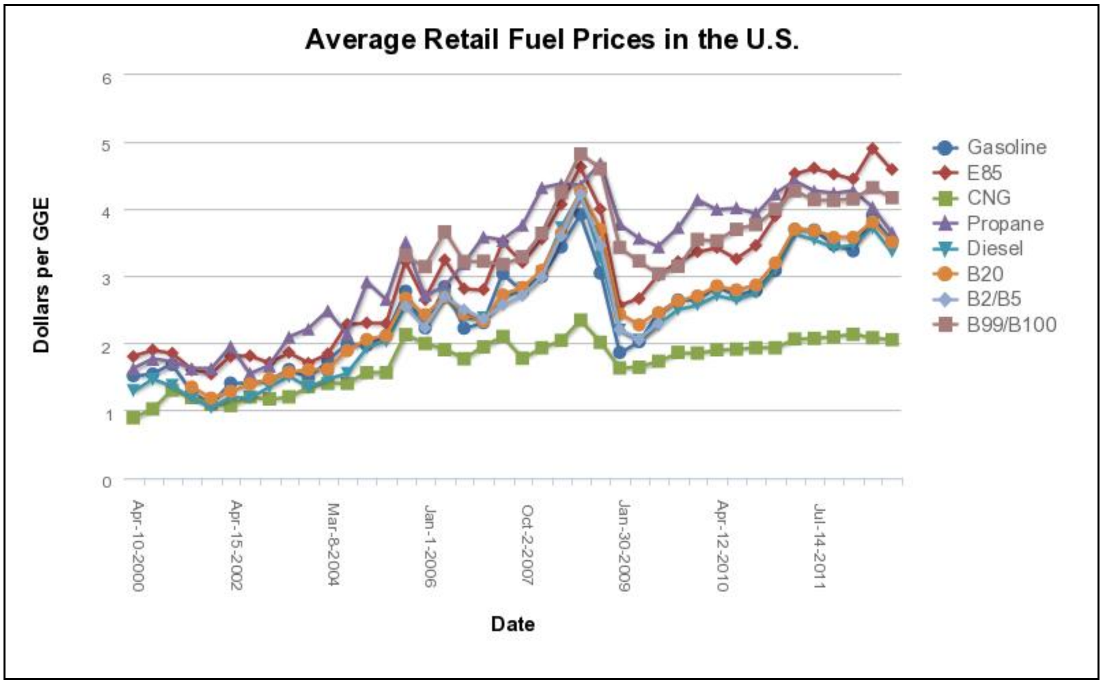

Figure I.1. Average monthly retail fuel prices in the United States from 2000 to 2011 [1]

LNG Engines and Trucks

According to the Natural Gas Vehicle Coalition, there are currently 150,000 natural gas vehicles (NGVs) on the road in the United States and more than five million NGVs worldwide. In fact, the transportation sector accounts for 3% of all natural gas used in the United States. Figure I.2 shows the U.S. Federal Highway Administration (FHWA) vehicle classification scheme.[2] Classes 1-5 represent light vehicles, including motorcycles, cars, and light trucks. Class 1-5 natural gas vehicles on the road today are primarily dedicated CNG or bi-fuel CNG/gasoline spark-ignited engines. There are also a small but growing number of converted pickup trucks with dual-fuel diesel/CNG systems. This CNG light vehicle market is growing quickly and may come to represent a significant portion of the driving public using the Turnpike system. Both CNG and LNG engines have been developed for heavy trucks in classes 6-10. CNG spark-ignited engines and refueling systems have already been deployed in significant numbers for heavy trucks in fleet maintained and fueled applications such as transit buses and garbage collection trucks. In contrast, LNG has become particularly attractive for long-haul or regional commercial trucks because it can be stored onboard a truck in dual insulated tanks at densities comparable to diesel fuel to provide ranges approaching 600 miles, which are required for profitable long-haul trucking.

LNG that is at the boiling point temperature of about -260°F is referred to as saturated LNG and is required for spark-ignited LNG engines. LNG will continue to boil off vapors and/or build pressure while stored in a tank without refrigeration, boiling off more rapidly as the volume drops and completely within about two weeks. BOG is not an issue for over-the-road LNG trucks because they consume a full tank of fuel every day or two. LNG that is colder and not as close to boiling off thermodynamically is referred to as “cold” LNG. It is the preferred fuel for high pressure direct injection (HPDI) engines because it is denser than saturated LNG and provides greater range per fill, although HPDI engines can run on saturated LNG if necessary. Over the last few years, truck engine manufacturers have begun offering several LNG engines in the 12–15-liter range that are compatible with over-the-road trucks. These LNG trucks are being sold at a premium ranging from $50,000 to $150,000 over diesel trucks. The number of LNG trucks on the road remains relatively small, however, and the lack of a nationwide fueling infrastructure has restrained trucking companies from investing in the technology.

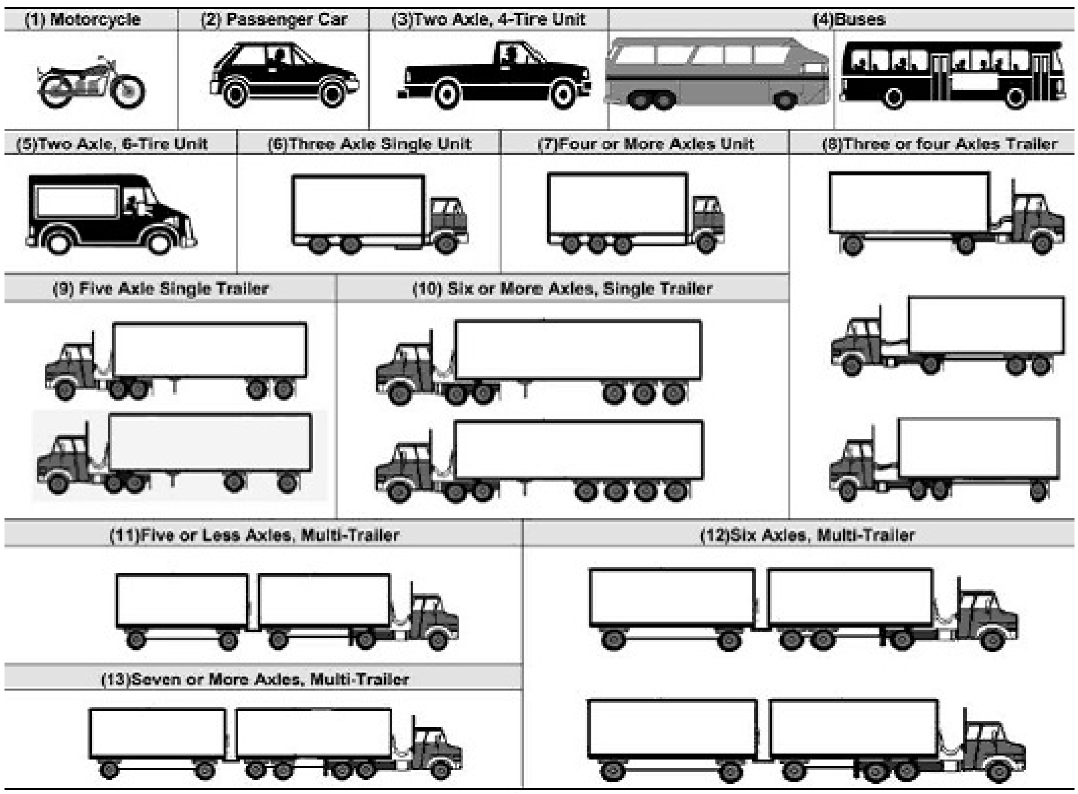

Figure I.2. FHWA vehicle classification scheme [2]

LNG Supply and Fueling Infrastructure

LNG is processed natural gas consisting of mostly methane that has been liquefied by the process of compression, cooling, expansion, and condensation. LNG production and a large-scale storage capacity already exist within the United States. In the Northeast region, much of the liquefaction capacity was initially built to serve as peaking facilities for the natural gas pipeline system. The peaking facilities generally have relatively small production capacity and relatively large storage capacity. For example, UGI Utilities Inc.’s liquefaction plant near Reading, Pennsylvania, has 1.25 billion gallons of storage. LNG can be purchased from natural gas peaking facilities, although the contracting environment for price and delivery is currently complicated by the competing priorities and economics of the natural gas peaking market. According to our industry sources, LNG can be economically transported up to about 500 miles in 10,000-gallon, double-walled tanker trucks. Cold LNG is transferred from the tanker truck into 15,000–20,000-gallon insulated storage tanks at the LNG fueling station. LNG fueling stations have the technology to dispense on demand either saturated LNG for spark-ignited engines or cold LNG for HPDI engines, depending on the requirement of the truck being fueled. In 2012, significant private investment and new business partnerships have begun to build out an LNG fueling infrastructure for commercial trucks that covers the U.S. interstate highway system. In its 2011 annual report, Clean Energy, the largest provider of natural gas fuel for transportation in North America, stated that it is building America's Natural Gas Highway, a network of approximately 150 LNG truck fueling stations connecting major trucking corridors across the country, including three stations in Pennsylvania.[3] Figure I.3 shows the locations of the existing and planned LNG stations along the Interstate Highway System and in major metropolitan areas. The three stations in Pennsylvania are currently being built in Carlisle, Mill Hall, and Smithton at Flying J trucking stations, and are scheduled to be completed by the end of 2012.

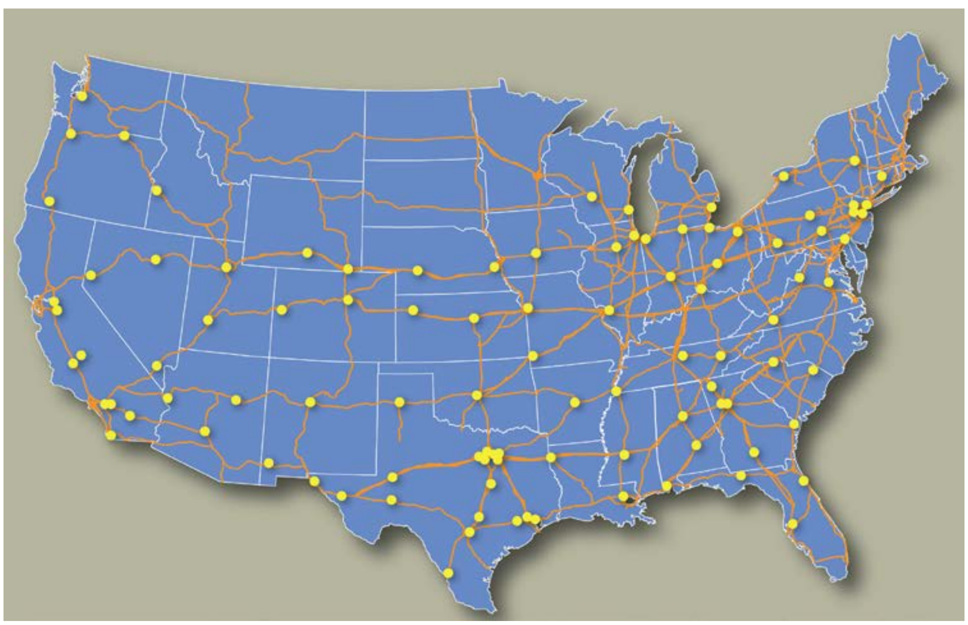

Figure I.3. America's Natural Gas Highway planned by Clean Energy [3]

Assessing the potential impact of LNG on the Pennsylvania Turnpike system

In February 2012, the PTC Facilities and Energy Management Operations (FEMO) and Maintenance Departments issued a White Paper (Appendix A) on the feasibility of using CNG and LNG for vehicles either traveling over or maintaining the Pennsylvania Turnpike. PSFEI was selected to carry out this Phase I study to assess the feasibility of an LNG fueling infrastructure for commercial trucks on the Pennsylvania Turnpike system. The Phase I tasks are intended to assess the feasibility of LNG fueling of commercial vehicles at active and surplus Turnpike service plazas. Table I.1 lists how the 14 tasks, carried out by PSFEI and associated Penn State faculty from other departments, are incorporated into the seven chapters of this report. A follow-on feasibility study may be conducted to consider LNG fueling infrastructure, vehicles, and maintenance facilities for the Turnpike maintenance fleet.

Table I.1. Study task list

Task	Task Description	Report Chapter
1	Identify optimum locations for LNG fueling stations along the Turnpike through development and use of a mathematical model.	2
2	Examine fueling station infrastructure considerations including costs, site location considerations, and applicable standards and codes	3
3	Examine operating and maintenance considerations of LNG fueling locations via market survey and site visits to existing facilities.	3
4	Identify standard types of contract methods used to procure LNG and recommend a path forward.	3
5	Analyze/identify funding mechanisms available (federal/state) for infrastructure development (i.e. grants).	6
6	Survey LNG-fueled vehicle/truck percent market penetration. Estimate LNG fleet growth versus time and the likelihood to utilize Turnpike LNG fueling facilities, if constructed.	2
7	Analyze the environmental impact of vehicle exhaust emissions associated with the increased use of LNG vehicles on the Turnpike.	7
8	Analyze training/safety requirements for the public, fueling station employees, and Turnpike employees relative to the use of LNG. This includes examination of LNG fueling infrastructure and vehicle standards and codes.	5
9	Assess the risks of transporting, storing and dispensing of LNG fuel.	4
10	Analyze and report on incentive programs in place by other states' toll road operators, manufacturers, or natural gas companies to attract use of natural gas as a transportation fuel source.	6
11	Identify the number of trucks utilizing the Turnpike and the average daily truck traffic count within a 50-mile radius of the Turnpike on all major routes and interstate highways within Pennsylvania.	2
12	Identify the key supply chain routes of both major and mid-size trucking companies.	2
13	Analyze/recommend required security upgrades.	4
14	Analyze of existing/potential public-private partnerships (i.e. other states', pending legislation, etc.) for NG use/conversions.	6

References

[1] U.S. Department of Energy (2012). Average Retail Fuel Prices in the U.S., Alternative Fuels Data Center: http://www.afdc.energy.gov/data/#tab/all/data_set/10326.

[2] Federal Highway Administration (FHWA), U.S. Department of Transportation (2012). FHWA Vehicle Classification Scheme: http://www.fhwa.dot.gov/policy/ohpi/vehclass.htm.

[3] Clean Energy (2011). We are Building America's Natural Gas Highway. 2011 Summary Annual Report and Form 10-K. Seal Beach, CA 90740.

Chapter 1: Overview

This chapter provides a concise summary of the conclusions and recommendations reached by the research team during this extensive study for the Commission regarding the feasibility of implementing an LNG fueling infrastructure at the Turnpike service plazas for commercial trucks. Topics are summarized in the order in which they appear, followed by overall recommendations of the study.

1.1 Optimal Fueling Station Locations

In Chapter 2 of this study, the Commission is presented with a mathematical model that was developed to optimize the location of LNG fueling stations along the Turnpike system. The potential location of LNG fueling stations was focused on the sites of 17 existing service plazas and 2 of the surplus service plazas for a total of 19 available sites. Key parameters of this model include the safe traveling distance (R) for an LNG truck to travel without refueling and the number of LNG stations to be located (p). The model maximizes the (annual) commercial truck traffic for classes 6-10 which trips can be covered by a predetermined number of LNG stations and is based on the Commission’s 2011 Origin-Destination Report. [1] As shown in Table 1.1, if the Commission decided to construct 4 LNG fueling stations based on a safe traveling distance of R=300 miles for an LNG fueled truck, the optimal locations based on truck traffic would be Oakmont-Plum (MP 49.33E), Sideling Hill (MP 172.27EW), King of Prussia (MP 328.40W), and Allentown (MP 55.90NS). These four service plazas have the ability to cover a total of 5,972,866 truck trips per year, which is about 39.57% of all truck trips along the Turnpike and 51.7% of all truck trips that could be covered if LNG fueling stations were located in all 19 available sites.

Table 1.1. Optimal LNG fueling station locations for a safe traveling distance of R=300 miles

No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Overall Coverage (%)	Service Plazas
1	2,066,994	17.89	13.7	Allentown
2	3,580,184	30.99	23.72	Sideling Hill, Allentown
3	4,930,604	42.68	32.67	Sideling Hill, King of Prussia, Allentown
4	5,972,866	51.7	39.57	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
5	6,996,119	60.56	46.35	Oakmont-Plum, Sideling Hill, Highspire, Peter J. Camiel, Allentown
6	7,942,264	68.75	52.62	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, Allentown
7	8,876,487	76.84	58.81	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, North Neshaminy, Allentown
8	9,623,615	83.31	63.76	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown

Numerous additional scenarios very analyzed to determine the impact of various parameters on the outcomes. Perhaps the most significant variable is whether or not a truck is equipped with a single fuel tank, giving the truck a safe travel distance of 300 miles, or if it is equipped with two tanks, effectively doubling the distance to 600 miles. Therefore, the model was re-run for a percentage of LNG trucks on the roadway with a single tank that ranges from 0 to 100%, in 20% intervals. For each case, the number of LNG stations increases from 1 to 15, one station at a time. Detailed results for these scenarios are provided in Appendix B. Here, the results are summarized in Table 1.2. Figures 1.1 and 1.2 provide maps with the optimal station locations for four stations and traveling distances of 300 and 600 miles, respectively. The locations of the three Clean Energy LNG stations in Pennsylvania are also shown in the maps.

Although this study examines multiple scenarios to optimally locate fueling stations, there may be other overriding factors that ultimately determine the location of fueling stations, such as preferences of large trucking firms using LNG and site suitability.

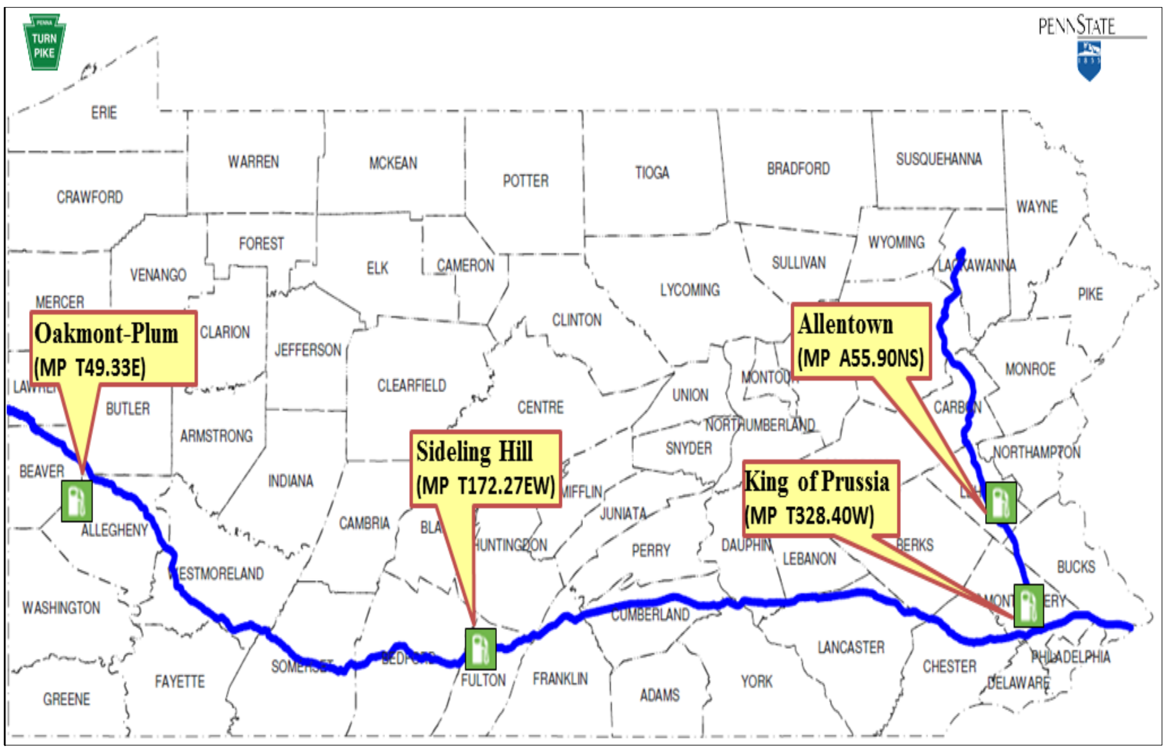

Figure 1.1. Four optimal LNG fueling station locations for a safe traveling distance of 300 miles

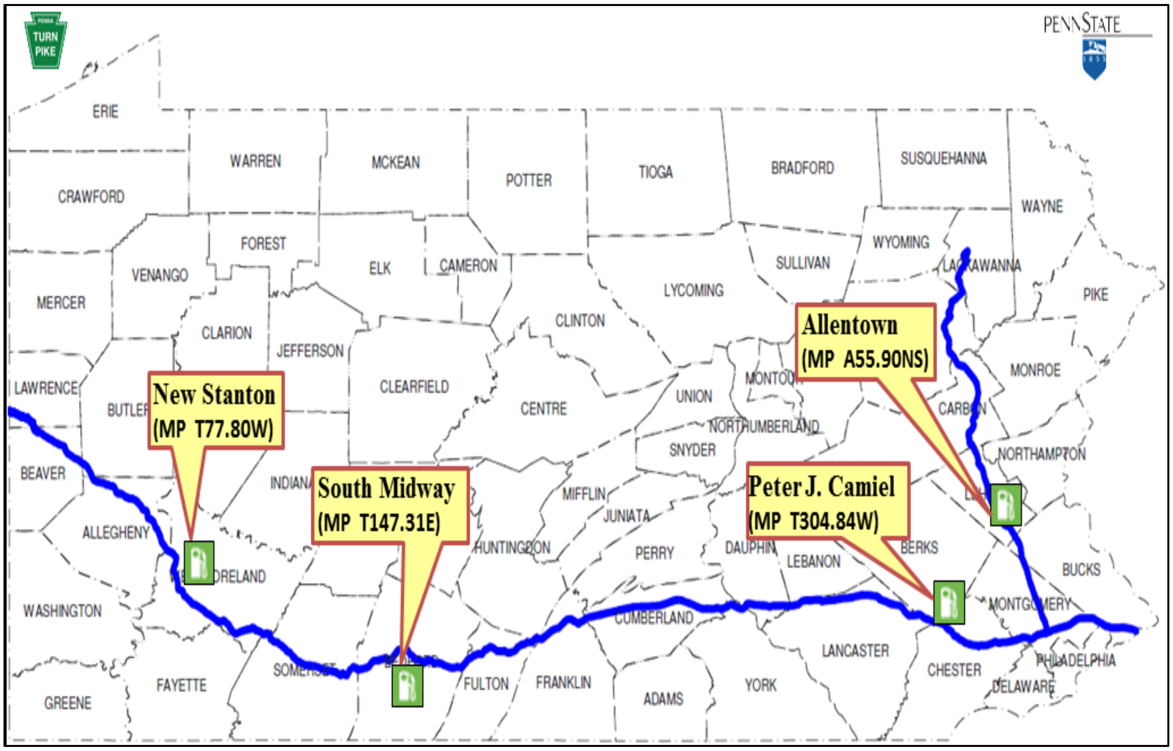

Figure 1.2. Four optimal LNG fueling station locations for a safe traveling distance of R=600 miles

Table 1.2. Effective coverage for combinations of trucks with safe traveling distances of R=300 and 600 miles

Safe Distance (% for R = 300, % for R = 600)	No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Service Plazas
(100, 0)	2	3,580,184	30.99	Sideling Hill, Allentown
	4	5,972,866	51.70	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
	6	7,942,264	68.75	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, Allentown
	8	9,623,615	83.31	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
(80, 20)	2	3,755,579	32.51	Sideling Hill, Allentown
	4	6,265,851	54.24	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
	6	8,064,552	69.81	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, Allentown
	8	9,645,505	83.50	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
(60, 40)	2	3,930,975	34.03	Sideling Hill, Allentown
	4	6,558,836	56.78	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
	6	8,230,724	71.25	Oakmont-Plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown
	8	9,667,395	83.69	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
(40, 60)	2	4,106,370	35.55	Sideling Hill, Allentown
	4	6,851,820	59.31	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
	6	8,569,234	74.18	Oakmont-Plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown
	8	9,765,323	84.53	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, Allentown
(20, 80)	2	4,281,766	37.07	Sideling Hill, Allentown
	4	7,153,329	61.92	Oakmont-Plum, Sideling Hill, Peter J. Camiel, Allentown
	6	8,959,900	77.56	Zelienople, New Stanton, Sideling Hill, Peter J. Camiel, King of Prussia, Allentown
	8	10,037,105	86.89	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Peter J. Camiel, King of Prussia ,Allentown, Hickory Run
(0, 100)	2	4,457,161	38.58	Sideling Hill, Allentown
	4	7,566,645	65.50	New Stanton, South Midway, Peter J. Camiel, Allentown
	6	9,433,047	81.66	Zelienople, New Stanton, Cumberland Valley, Peter J. Camiel, King of Prussia, Allentown
	8	10,490,740	90.81	Zelienople, Oakmont-Plum, New Stanton, Cumberland Valley, Peter J. Camiel, King of Prussia, Allentown, Hickory Run

1.2 Characteristics, Considerations, and Costs of LNG Stations

In Chapter 3 of this study, the Commission is introduced to the components of an LNG fueling station and presented with special site considerations and costs to construct an LNG fueling station. An LNG fueling station has several features that are distinctive from the diesel and gasoline fueling stations that are currently found at the Commission's service plazas. A thorough understanding of these features is a vital component in the decision to install LNG fueling stations.

As shown in Figure 3.1, an LNG fueling station is comprised of many components that are not customary to the vehicle fuel industry. The storage tanks and equipment required for this type of fuel are typically contained above-ground in a containment area which, when coupled with the fuel island canopy, form the outline of a 3,200-square-foot area.
The results of the mathematical model present the Commission with the optimal service plaza locations based on several factors related to vehicle performance and logistics but consideration must also be given to the physical challenges that may occur at each site. The sites of the existing service plazas, whether recently developed or not, do not have space allocated for an LNG fueling station and will present some challenges for construction regardless of their ranking in the model.

Chapter 3 takes a conceptual look at the proposed installation of an LNG fueling station at the site of several service plazas that routinely appeared among optimal locations. The conceptual plans for the sites utilize aerial photography and a scaled version of an LNG fueling station to offer the Commission some perspective on the impact this construction will have on the existing site and the estimated cost to construct. Whenever possible, the project team provided several options for the proposed location of a new LNG fueling station. The most prominent sites, based on the traffic optimization modeling, are as follows:

Allentown Service Plaza (MP A55.90)

Option 1 – New LNG fuel station at west (rear) end

- *Estimated Cost to Construct - $3.8 million w/o property acquisition*

Option 2 – New LNG fuel stations at north and south ends

- *Estimated Cost to Construct - $3.6 million*

Sideling Hill Service Plaza (MP T172.27)

Option 1 – New LNG fuel station at north (rear) end

- *Estimated Cost to Construct - $3.95 million*

Option 2 – New LNG fuel station at north (rear) end with separated fuel islands

- *Estimated Cost to Construct - $3.45 million*

Option 3 – New LNG fuel stations at east and west ends

- *Estimated Cost to Construct - $3.4 million*

Oakmont-Plum Service Plaza (MP T49.33)

Option 1 – LNG fuel station at SE corner

- *Estimated Cost to Construct - $1.8 million*

Option 2 – LNG fuel station at rear

- *Estimated Cost to Construct - $2.6 million w/o property acquisition*

King of Prussia Service Plaza (MP T328.40)

- *Estimated Cost to Construct - $1.9 million*

New Stanton Service Plaza (MP T77.80)

Option 1 – LNG fuel station at west end

- *Estimated Cost to Construct – $2.5 million*

Option 2 – LNG fuel station at east end of truck service electrification parking area

- Estimated Cost to Construct - *$2.3 million*

Option 3 – LNG fuel station at north end of truck service electrification parking area

- *Estimated Cost to Construct - $3.4 million*

South & North Midway Service Plazas (MP T112.33 & 112.37)

South Midway Service Plaza (MP T147.31) – *Currently under reconstruction*

- *Estimated Cost to Construct - $1.8 million*

North Midway Service Plaza (MP T147.32)

- *Estimated Cost to Construct - $1.8 million*

Peter J. Camiel Service Plaza (MP T304.84)

- *Estimated Cost to Construct - $1.8 million*

Note: An additional $750,000 should be added to each option above when considering an LCNG station with BOG collection.

Based on our assessment of these locations, it became quite clear that the most challenging requirement to accommodate a new LNG fueling station at an existing service plaza is the availability of adequate space for the station and the proposed path of travel for semi-trailer trucks, rather than the infrastructure required to operate the fueling station. Although the physical challenges of the existing service plaza sites cannot be eliminated, there are several options for the Commission to consider that could improve the installation of LNG fueling stations along the Turnpike. These options are briefly described in the following sections and include:

- The model LNG fueling station
- An independent fueling station
- A mobile fueling station

The concept of a model LNG fueling station incorporates the ability to dispense LNG (cold and saturated), CNG, and diesel fuels as shown in Figure 3.15 in Chapter 3. An LCNG station will most likely require an additional construction cost of $750,000 as compared to the conventional LNG fueling station, but this option offers several advantages. It meets the complete fuel needs of the natural gas customer and eliminates one of the common site disadvantages regarding truck access between the existing diesel fuel dispensers and the new LNG fueling station.

The independent fueling station is one that would utilize an undeveloped or surplus property for the construction of a fueling station independent of existing service plazas. However, two important site considerations in the cost of development are the need for acceleration and deceleration ramps and the availability of utilities. If adequate access ramps are not part of a site being considered, they would have to be built. The access to utilities is essential since a facility of this type will require a 480-volt, three-phase electric service as well as cable data lines for remote monitoring of the alarm, fire, and fuel management control systems. For these reasons, a previously developed surplus site may have advantages over an undeveloped site.

The combination of supplying a “perishable” fuel such as LNG with a speculative market of trucking companies that are on the verge of purchasing LNG engines has created demand for an innovative product known as the LNG mobile fueling station. Several companies in the drilling and construction industry utilize an LNG mobile fueling station due to the transient nature of their business but, in this case, the Commission could make wise use of this technology for initial deployment of the LNG fueling stations until an anchor customer or defined customer base is determined.

The mobile fueling station has a much smaller footprint and requires less infrastructure than a permanent fueling station but is still able to offer many of the same services. This option is presented in more detail in Chapter 3. Industry resources informed us that the cost to purchase a mobile fueling station is approximately $400,000 to $500,000, but leasing options may be available.

Several business models are available to execute the installation of LNG fueling stations. The business model used to construct a fueling station traditionally involves a capital expenditure and an “If we build it, they will come” approach with regard to the location. This approach is still valid for fueling stations that offer gasoline and diesel fuels to consumers, but the model must change when LNG fuel is added to the equation. The “perishable” nature of the LNG fuel in the storage tank requires fueling station owners to use the fuel in a timely manner in order to avoid a monetary loss in their fuel investment. For this reason, the business model in use by several leading alternative fuel vendors is to locate an anchor customer that will agree to use a pre-determined amount of LNG fuel over a given period of time.

Regardless of the business model selected, the research team finds it most important to establish an anchor customer for the success of this program. The preferred anchor customer would be a large- or medium-sized trucking fleet with a defined path of travel that includes the Turnpike. Although this search may sound easy to accomplish, the customer base is currently small and may need incentives to switch from the conventional diesel-fueled engines. This incentive could naturally appear in the form of higher diesel prices, but it could also appear in the form of a commitment from the Commission to build LNG fueling stations and offer incentives to purchase alternative fuels while traveling on the Turnpike.

1.3 General Safety, Operation and Maintenance, and Training for LNG Stations

In Chapters 4 and 5 of this study, the Commission is presented with safety considerations and risks involved with the installation of LNG fueling stations at the service plazas.
Like any fuel, safe handling procedures and proper safety precautions must be followed when working with LNG. Many years of experience using natural gas vehicles have proven that natural gas can be used safely as a fuel for vehicles. However, using LNG, or any other alternative fuel, involves different safety issues than most fuel providers and consumers are accustomed to following. LNG is a cryogenic fuel stored at temperatures down to -260°F and at pressures up to 230 psi and when vaporized is not explosive in an uncontained environment. The primary concerns to address are explosion, combustion, and spills. Although a large amount of energy is stored in LNG, it is generally not released rapidly enough to cause the overpressures associated with an explosion. LNG vapors (methane) mixed with air are combustible but not explosive in an unconfined environment.

LNG spills or leaks will quickly vaporize since LNG has a boiling point of -260°F. Should a tank ever fail and a leak result, fire is possible, but only if there is the right concentration of LNG vapor in the air and a source of ignition. Small leaks in enclosed spaces present a fire and explosion hazard because of the potential for methane to build up in the necessary 5–15% concentration to ignite. LNG vapors also have a higher ignition point than either gasoline or diesel (1000°F, 500°F, and 495°F, respectively).

LNG fires should be extinguished using dry chemicals only (Purple–K). Water fog or high-expansion foam can be used to suppress or contain fires. Water should not be sprayed directly into an LNG pool, since it will increase the rate of LNG vaporization. Other hazards of freeze burn and asphyxiation are outlined in more detail in Chapter 5.

Every Turnpike employee, from janitors to executives, should receive some form of *basic* LNG training. This basic training would be designed as an overview of the major physical properties and safety information about LNG and fueling stations. This training effort could take the form of either classroom training or an informational video.

It is important to ensure that drivers who stop to refuel at Turnpike LNG facilities have been properly trained. LNG fueling is relatively simple but contains more steps than typical gas or diesel fueling. Although many new LNG refueling stations claim to be easy to use with "minimal or no training," it still makes sense to ensure that drivers are aware of the safety precautions and fueling procedures for those specific stations. This can be accomplished through instructional videos or certification. Drivers could be required to view a brief tutorial video each time before fueling. Some LNG pumps incorporate this video into the pump itself. Alternatively, drivers could be required to view a longer video tutorial and a "certification" program could be implemented. After watching the video and passing the "quiz," that driver would be certified to refuel at all Turnpike LNG stations in the future without further training. The certification could be handled with a simple pin number system. Personal Protective Equipment (PPE) in the form of gloves and a face shield may also be required for LNG fueling. Because of the specialized storage and distribution equipment for LNG, each station will need to have staff trained in the basic operation and maintenance of the equipment. Many existing fueling facilities simply contract out the LNG portion of their station to an outside company. Local emergency responders near each station will need to be educated in how to respond to any potential emergencies concerning the LNG fuel because LNG has different properties from traditional gas and diesel fuels. This process will vary significantly depending on the locality of each station. Several trainings exist to educate emergency responders to the unique circumstances that may be encountered relating to LNG.

In summary, the LNG industry has exhibited an excellent safety record and taken many steps to ensure the safe use, transport, and dispensing of this fuel. The LNG fueling station includes many safety components as denoted in Figure 4.1 to ensure the safety of all personnel—employees and consumers. The Commission should be aware of the risks associated with LNG fuel but should not hesitate to install LNG fueling stations along the Turnpike due to safety considerations.

1.4 Funding Sources

Chapter 6 of this report explores sources that the Commission could use to fund planning, design, or operational elements for the proposed use of LNG as an alternative fuel on the Turnpike system. There are many options for obtaining outside funding for the conversion of existing and the purchase of new natural gas powered vehicles along with the construction of natural gas fueling facilities. However, the best approach may be to pursue multiple options in the hope of securing as much funding as possible to implement the planned program in stages. The primary opportunities identified in our research are summarized below.

The Federal Clean Cities Program provides resources to increase the use of natural gas powered vehicles and fund the construction of alternative fuel infrastructure. If the Commission decides to build stations with PTC funding, the Commission should approach both the Philadelphia-based (http://phillycleancities.org/) and Pittsburgh-based (http://www.pgh-cleancities.org/wordpress/) programs to explore the possibility of obtaining grants for fueling station construction. Clean Cities Pittsburgh has already funded many projects similar in character and scope (http://www.pgh-cleancities.org/wordpress/?page_id=462) to the direction of the Commission. Further, many of the organizations already funded could be potential "collaborators" for the Commission as users, vendors, or public-private partnerships (P3) (e.g., EQT, Giant-Eagle, Waste Management).

The Congestion Mitigation and Air Quality Improvement Program (CMAQ) can pay for costs related to the purchase of natural gas vehicles and alternative fuel refueling projects. These projects have to provide 20% local or regional co-funding, which the Commission could provide directly or with the assistance of partners. Funding can also be used for public-private partnerships. The Commission should approach PennDOT regarding the applicability of these funds for use in conjunction with local metropolitan planning organizations that abut the Turnpike with significant ozone or carbon monoxide issues.
The Commission should consider seeking funding through the Diesel Emission Reduction Program to replace or convert the PTC vehicle fleet to natural gas fuel use. As the program covers 75% of the cost of an existing retrofit or 50% of the cost to purchase a new truck and also provides funds for the construction of fueling infrastructure to be used in conjunction with "new" vehicles, this program could offer significant resources for a planned program.

There are programs within Pennsylvania that can provide some element of the costs to put in place natural gas refueling infrastructure and costs for vehicle conversion. The Commission should attempt to secure some of the resources available from Alternative Fuels Incentive Grant (AFIG) for the purchase cost of alternatively-fueled or converted vehicles that are part of its fleet and constructing of refueling stations. There should also be some attempt to use the Natural Gas Vehicle Grant Program to procure funds for natural gas vehicles. However, in the context of building natural gas fueling stations along the Turnpike, state funding may prove to be highly restricted and highly competitive if the Commission focuses on the aforementioned competitive programs. It may make the most sense, and be the best use of Commission staff time, to consider submitting an unsolicited proposal to the Department of Environmental Protection (DEP). The DEP formally advertises its willingness to consider unsolicited proposals (http://files.dep.state.pa.us/Energy/Enintech%20Temp/lib/enintech/Unsolicted_proposal_public.pdf), and this may be an effective means of obtaining support for natural gas infrastructure and bypassing the per-project funding limits that are part of programs such as AFIG, which has a maximum limit of approximately $400,000 per project.

Given the recent passage of Pennsylvania Act 88 of 2012 there appears to be a spirit of encouragement for state-related agencies to pursue P3 opportunities. Although the Act prohibits the Commission from engaging in any P3 relationships with respect to granting oversight and control over the Turnpike Mainline to another entity, it is recommended that the Commission open a dialog with any potential users, vendors, or contractors regarding the establishment of any type of P3 project related to this work.

1.5 Environmental Considerations

Chapter 7 of this report covers the potential environmental considerations of the operating LNG refueling stations. One of the promises of the natural gas vehicle is that operation of vehicles on natural gas leads to a net reduction in tailpipe greenhouse gas emissions (CO_2 equivalent emissions). However, studies show that there are opposing considerations to take into account when considering environmental effects. The Marcellus Shale Coalition report entitled “NGV Roadmap for Pennsylvania Jobs, Energy Security and Clean Air,” proposes the development of the Pennsylvania Clean Transportation Corridor. The report includes a “developed” case in which 17 stations would be installed around the Commonwealth and would lead to an estimated 21,000 metric ton reduction of greenhouse gas emissions. However, some other combustion studies show that inferior thermal efficiencies of the CNG vehicle negates the CO_2 emissions benefits one would expect by burning a high-hydrogen fuel like methane. The methane (CH_4) emissions can be nearly 100 times higher for CNG, and the US Environmental Protection Agency (EPA) believes that methane has 20 times higher global warming effect than CO_2. The methane emissions from the CNG vehicle lead to CO_2 equivalent emissions of 2,090 g/mi., compared to the 1,785 g/mi. of CO_2 emitted by the diesel vehicle. One must note that the particulate matter emissions from the CNG vehicle are negligible and the NO_x emissions are one-third lower for the CNG vehicle. Since the EPA regulates non-methane hydrocarbon emissions, vehicle CH_4 emissions are not directly regulated and therefore are not directly controlled at the present time. Thus, the promise of lower greenhouse emissions may be optimistic, depending on how well the vehicle system is designed to control methane emissions.

The key to improved environmental performance of the vehicle tailpipe emissions is applying the appropriate technologies. Research cited in the body of this report demonstrates, through a detailed life-cycle analysis comparison between diesel fuel and LNG, that LNG trucks equipped with high-compression, direct injection engine systems could result in a reduction of CO_2 equivalent greenhouse gas emissions of 10%, accounting for fuel production, processing, transport, dispensing, utilization, and exhaust emissions.

Both LNG-fueled vehicles and the operation of LNG fueling stations on the Turnpike will have an environmental effect with regard to methane emissions. Besides the vehicle exhaust emissions, it is also important to consider the BOG that results when the temperature of LNG at approximately -260ºF rises and some liquid will change phase to gas. As more liquid evaporates to gas, pressure builds in the tank. When tank pressures increases sufficiently, the tank will vent to the atmosphere in order bring the pressure down. BOG can be released at several places in the chain of transport and use. The points of potential BOG release include: bulk fuel transport trucking, transfer from the bulk fuel truck to the tank at the fueling station, the tanks at the fueling station, dispensing piping at the station to the commercial vehicles, and the fuel tank on the LNG vehicles. Currently, most of the industry simply vents the BOG to the atmosphere. While BOG is not currently regulated, the industry should consider that as a possibility in the future. In order to mitigate the loss of BOG by proposed Turnpike facilities, we recommend strong consideration be given to collection of BOG at fueling stations. Such systems should collect any gas from the transfer of fuel from bulk truck to tank and from tank to commercial vehicle and allow commercial vehicles to vent into the system as they bleed pressure prior to refueling. BOG could be fed to CNG storage that could be incorporated into the fueling stations. The addition of collection systems will add to the capital cost of the fueling station but will have several advantages, including the ability to offer CNG for cars and light trucks, improved environmental performance of the entire operation, possible avoidance of future modifications if BOG becomes regulated, and positive public relations for taking a proactive approach by reducing emissions and offering both CNG and LNG.

1.6 Recommendations

Based on the research of this study, we find that LNG for long-haul commercial vehicles on the Turnpike is feasible. Given the fact that the market is still emerging and some of the technology applications are being refined, a decision by the Commission to move forward with the installation of LNG fueling stations on the Turnpike should be executed with proper planning and detailed knowledge of business and technology issues.

Mathematical modeling of truck traffic and travel shows that the top sites for LNG stations along the Turnpike are Allentown, Sidling Hill, Oakmont/Plum, and King of Prussia. The Peter J. Camiel, New Stanton, and Midway service plazas emerge on a second tier. Chapter 2 and Appendix B of this report provide extensive details on the optimum locations for many different scenarios.

The mathematical model is invaluable because it is based on vehicle performance and logistics. However, the nature of LNG as a fuel changes the dynamics of executing station development relative to demand from customers in an emerging market. LNG is a cryogenic fuel that will gradually degrade and become a perishable product in the main storage tank if not consumed in a timely manner. For this reason, we recommend that the Commission place special emphasis on the acquisition of an anchor customer(s) that will agree to use a minimum amount of fuel at a specific fueling location(s). With an initial commitment from trucking companies, a mobile fueling station could be sited and operational in a relatively short period of time while engineering and construction of permanent stations proceed. The Commission should be aware that the fuel demand and travel logistics of the anchor customer(s) could play a major role in the quantity and location of the new LNG fueling stations, but these locations may not coincide with the optimal locations that were selected based on current truck traffic volumes.

The initial period of time in which customers are being served by a mobile fueling station could also be used by the Commission to evaluate the success of the relationships and the initial commitment from the trucking companies as well as market the new economic, environmentally advantageous fuel option of LNG provided on the Turnpike system.

Use of LNG fuel involves unique safety requirements and risks that the Commission should be aware of but can be safely managed with proper training, processes, and procedures. Turnpike and service plaza employees and truck drivers should receive some form of LNG training either in the form of classroom training or through an informational video.

Finally, we recommend that strong consideration be given to constructing fueling stations that incorporate LNG (cold and saturated), BOG collection, and CNG into design and implementation. While this may add significant capital cost to initial construction, it has several advantages. It offers the widest possible option of natural gas based fuels to consumers for commercial trucks as well as cars and light trucks. Furthermore, this will reduce environmental impact through collection of vented BOG, possible avoidance of future modifications if BOG becomes regulated and positive public relations for taking a proactive approach by reducing emissions and offering both CNG and LNG.

References

[1] Pennsylvania Turnpike Commission, Origin-Destination Report (2011).

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Chapter 2: Logistics Considerations in the Development of an LNG Fueling Infrastructure along the Pennsylvania Turnpike

This chapter presents the results of the three logistics tasks 1, 11, and 12 and market penetration task 6 of the study task list in Table I.1. The first task is concerned with the development of a mathematical model to determine the optimal locations for LNG stations along the Turnpike. The second task provides an analysis of truck volumes and densities along the Turnpike, interstate and U.S. routes, and local state-owned routes in Pennsylvania. The third task analyzes the main supply chain routes for large and mid-size truck transportation companies in Pennsylvania. The last portion of the Chapter focuses on task 6, which considers the pathways by which the market for LNG-fueled vehicles will develop.

2.1 Identification of Optimal Locations for LNG Dispensing Facilities System-wide for Commercial Use

Several studies have emphasized that the development of a refueling infrastructure is one of the most challenging obstacles toward the transition to alternative fuels in the U.S. road transportation system and other transportation networks all over the world. [1, 2, 3] In this section the authors propose the necessary methodology to set up the refueling infrastructure in the Pennsylvania Turnpike mainline (I-70, I-76, and I-276) and Northeast Extension (I-476). Basically, if the Commission decides to build a given number of LNG fueling stations, our model can find their optimal locations and the percentage of trucks (classes 6-10) for which trips will be covered by these stations. In its current implementation, the model considers 19 potential locations, including the 17 existing service plazas and 2 surplus service plazas.

This section first provides a literature review of the current models used previously to identify the best locations for alternative fueling stations. Then, the authors present a simplified Pennsylvania Turnpike network for the PA Turnpike mainline and the NE PA extension that can significantly reduce the problem size. We also present the origin/destination (O/D) truck flow matrix for classes 6-10 and the matrix of travel distances for the simplified network. These matrices contain the necessary data to construct the mathematical model. A brief discussion about the assumptions made in the development of the model is presented. Finally, optimal solutions for two scenarios are presented. The first scenario considers that the safe travel distance for an LNG truck is 300 miles; the second scenario considers a safe distance of 300 miles for a given percentage of trucks with a single tank and a safe distance of 600 miles for the remaining trucks with dual tanks. Details about the model's assumptions, the mathematical formulation, and additional computational results are provided in Appendix B.

Literature Review

The approaches published in the literature to locate refueling stations optimally in road transportation systems can be categorized into three classes. One class of methodologies employs variants of the *p*-median model, perhaps the most widely used model in the field of facility location. The purpose of the *p*-median model is to locate *p* new facilities, and to allocate each demand node to a single facility or a subset of facilities so as to minimize the total distance traveled by consumers to facilities. For locating alternative-fuel stations, the *p*-median model has the appeal of locating stations close to where customers live. The *p*-median model has been applied to alternative-fuel stations by Nicholas et al. [4], Greene et al. [5], and Lin et al. [3]

The second class of methods locates stations on high-traffic routes. Some researchers have employed the objective of maximizing the traffic flows on the roads passing by a station. [6, 7, 8] This approach recognizes that many drivers refuel on their way to somewhere else, and tries to maximize the passing traffic. The potential problem with traffic-count methods, however, is that they count the same trips by the same drivers more than once if the trip traverses multiple links, even though drivers might refuel only once. As a result, the traffic-count method could locate stations on several adjacent links of a high-volume freeway.

A third general approach to locating refueling stations maximizes passing flows without double counting. These models are classified as *path*-based or *flow*-demand models. The basic units of demand in these models are not points in space representing where people live (*p*-median models) nor network links (traffic-count models), but flows on paths across a network representing the routes people travel. The basic objective is to locate *p* facilities to maximize the number of trips intercepted. [9, 10, 11] A demand is considered captured or intercepted if there is a facility anywhere along the path. This approach has been applied to real-world networks at both the metropolitan scale and state scale in Florida [12] and Arizona [13] and has been selected here to model the problem of finding optimal locations for LNG dispensing facilities in the Pennsylvania Turnpike network.

Optimization Model

This subsection presents the development of an LNG station location model to optimally locate a given number of LNG refueling stations (p) on the PA Turnpike network so as to maximize the Annual Truck Traffic for truck classes 6-10 (ATT6-10) that can be covered. ATT6-10 is basically the total number of truck trips per year that can be refueled at the new LNG stations along the Turnpike. This model is based on an integer linear programming formulation where the set of potential refueling locations is limited to the 17 open service plazas located in the PA Turnpike mainline (I-70, I-76, and I-276) and NE PA (I-476) extension and 2 surplus service plazas. A list of these service plazas as well as their mileposts and orientations are provided in Table 2.1. Station orientations are characterized as eastbound (EB), westbound (WB), dual east/westbound (EB/WB), and dual north/southbound (NB/SB). Dual stations can refuel trucks on both sides of the Turnpike. The locations of these 19 service plazas are shown in Figure 2.1. Note that if none of these potential station locations falls between the entrance and exit points of a particular truck trip, then the trip cannot be covered. Therefore, the model can be simplified by aggregating subsequences of interchanges that do not have any service plaza on their travel paths. Each subsequence can be replaced by a single aggregated interchange, which location can be calculated as the weighted average of the original interchange locations, where the weights are the annual entrance/exit traffic counts at each interchange, available in the 2011 Entrance/Exit Traffic Counts Report. [25] For example, in the PA Turnpike map in Figure 2.1, there is a subsequence with four consecutive interchanges (T226, T236, T242 and T247) between two adjacent eastbound service plazas, Cumberland Valley (CLV) and Highspire (HSP). The four interchanges in the subsequence can be consolidated into a single aggregated interchange (No. 18). Table 2.2 provides the list of aggregated interchanges.

In this optimization model, the coefficients of the objective function are the elements of the aggregated origin/destination truck volume matrix for truck classes 6-10 (ATT6-10 coefficients) generated from the 2011 Origin-Destination Report. [26] A matrix of travel distances between aggregated interchanges has also been generated to formulate the model constraints. The constraints of the model turn out to mirror those of the maximum-covering location problem. Constraints can be categorized in four different types according to the travel distance between the entrance and exit points of a trip. For example, if a truck can travel a safe distance (R) of 300 miles and the truck is required to get on and off the Turnpike with a tank that is at least half full, and the length of the trip is between 300 and 450 miles, then the truck has to be able to refuel twice in each direction in order for the entire roundtrip to be considered covered. In each direction, given that the truck enters the Turnpike with its tank half full, the first refuel should be completed within 150 miles of the entrance point. The second refuel should be done within 300 miles of the first refuel as well as within150 miles of the exit point, so that the truck can leave with its tank at least half full. Appendix B section B.2 presents a detailed list of the assumptions made to develop the model, the resulting mathematical formulation, and some computational results.

Table 2.1. List of the 19 potential LNG fueling station locations (service plazas)

Number	Service Plaza	Milepost
2	Zelienople (closed)	T21.7 EB
4	Oakmont-Plum	T49.3 EB
6	New Stanton	T77.6 WB
8	South Somerset	T112.3 EB
9	North Somerset	T112.3 WB
11	South Midway	T147.3 EB
12	North Midway	T147.3 WB
14	Sideling Hill	T172.3 EB/WB
16	Blue Mountain	T202.5 WB
17	Cumberland Valley	T219.1 EB
19	Highspire	T249.7 EB
20	Lawn	T258.8 WB
22	Bowmansville	T289.9 EB
24	Peter J. Camiel	T304.8 WB
26	Valley Forge	T324.6 EB
28	King of Prussia	T328.4 WB
32	North Neshaminy (closed)	T351.9 WB
34	Allentown	A55.9 NB/SB
36	Hickory Run	A86.1 NB/SB

Number	Service Plaza	Milepost	Number	Service Plaza	Milepost
2	Zelienople (closed)	T21.7 EB	19	Highspire	T249.7 EB
4	Oakmont-Plum	T49.3 EB	20	Lawn	T258.8 WB
6	New Stanton	T77.6 WB	22	Bowmansville	T289.9 EB
8	South Somerset	T112.3 EB	24	Peter J. Camiel	T304.8 WB
9	North Somerset	T112.3 WB	26	Valley Forge	T324.6 EB
11	South Midway	T147.3 EB	28	King of Prussia	T328.4 WB
12	North Midway	T147.3 WB	32	North Neshaminy (closed)	T351.9 WB
14	Sideling Hill	T172.3 EB/WB	34	Allentown	A55.9 NB/SB
16	Blue Mountain	T202.5 WB	36	Hickory Run	A86.1 NB/SB
17	Cumberland Valley	T219.1 EB			

Figure 2.1. PA Turnpike mainline (I-70, I-76, and I-276) and NE PA extension (I-476)

Table 2.2. List of aggregated interchanges in the PA Turnpike mainline and Northeast Extension

Aggregated Interchange No.	Interchange Numbers	Interchange Names
1	T2, T10, T13	Gateway, New Castle, Beaver Valley
3	T28, T39, T48	Cranberry, Butler Valley, Allegheny Valley
5	T57, T67, T75	Pittsburgh, Irwin, New Stanton
7	T91, T110	Donegal, Somerset
10	T146	Bedford
13	T161	Breezewood
15	T180, T189, T201	Fort Littleton, Willow Hill, Blue Mountain
18	T226, T236, T242, T247	Carlisle, Gettysburg Pike, Harrisburg West, Harrisburg East
21	T266, T286	Lebanon – Lancaster, Reading
23	T298	Morgantown
25	T312	Downingtown
27	T326	Valley Forge
29	T333, A20, T339, T340 (WB only), T343, T351	Norristown, Mid-County, Fort Washington, Virginia Drive AEI, Willow Grove, Bensalem
30	T339, T340, T343, T351, A20, A31, A44	Fort Washington, Virginia Drive AEI, Willow Grove, Bensalem, Mid-County, Lansdale, Quakertown
31	T333, A20, A31, A44	Norristown, Mid-County, Lansdale, Quakertown
33	T352 (EB only), T358, T359	Street Road AEI, Delaware Valley, Delaware River Bridge
35	A56, A74	Lehigh Valley, Mahoning Valley
37	A95, A105, A112, A115, A122, A131	Pocono, Wilkes-Barre, Wyoming Valley Toll Plaza, Wyoming Valley, Keyser Avenue, Clarks Summit

Figure 2.2 shows the simplified PA Turnpike network. It is important to point out that aggregated interchanges 29, 30, and 31 correspond to the original intersection point between I-76, I-276 and I-476. The location of aggregated interchange 29 has been calculated as the weighted average of the locations of all interchanges between service plazas 28 (King of Prussia) and 32 (North Neshaminy) in I-76 and I-276: T333, A20, T339, T340, T343, and T351. The weights are the entrance/exit truck traffic counts in these interchanges. Similarly, the locations of aggregated interchanges 30 and 31 have been calculated with respect to the locations of the interchanges between service plazas 28 (King of Prussia) and 34 (Allentown) in I-76 and I-476, and between service plazas 32 (North Neshaminy) and 34 (Allentown) in I-276 and I-476, respectively. Note also that the truck volume in each edge of the triangle is independent from the truck volumes in the other two edges. Thus, since there is a unique path between any pair of aggregated interchanges, the simplified PA Turnpike network is actually a generalized tree.

Tables 2.3 and 2.4 provide the matrices of ATT6-10 values and travel distances for all pairs of aggregated interchanges, respectively, used in the mathematical model to determine the most desirable station locations. As shown in Table 2.3, 80,551 trucks (classes 6-10) traveled from Bedford (entrance 10) to Breezewood (exit 13) in 2011. The table also shows that a total of 15,092,924 trucks (classes 6-10) used the Turnpike in 2011. Note that if all 19 service plazas were open, including the 2 surplus plazas, 23.46% of the truck traffic could not be refueled on the Turnpike because none of the service plazas are located between their entrance and exit points (interchanges). Note also that 558,955 trucks (this is the last value in the column referred to as exit 18) get on and off the Turnpike using interchanges that belong to the original subsequence (T226, T236, T242, T247). As shown in Table 2.2, all of these interchanges have been aggregated into interchange 18, because no service plaza is located between any pair of interchanges in the subsequence. Moreover, there are some empty cells (-) in Tables 2.3 and 2.4, meaning aggregated interchanges 29, 30, and 31 are not accessible for entrance and exit from all other interchanges (see triangle defined by these interchanges in Figure 2.2). In particular, interchange 29 cannot be accessed from interchanges 30, 31, 35, and 37; interchange 30 cannot be accessed by any interchange between 1 and 31; and interchange 31 cannot be accessed from interchanges 29, 30, and 33. The ATT6-10 values in Table 2.3 are used as objective function coefficients of our model and the travel distances in Table 2.4 are used to set up the constraints of the model to detect the captured truck flows.

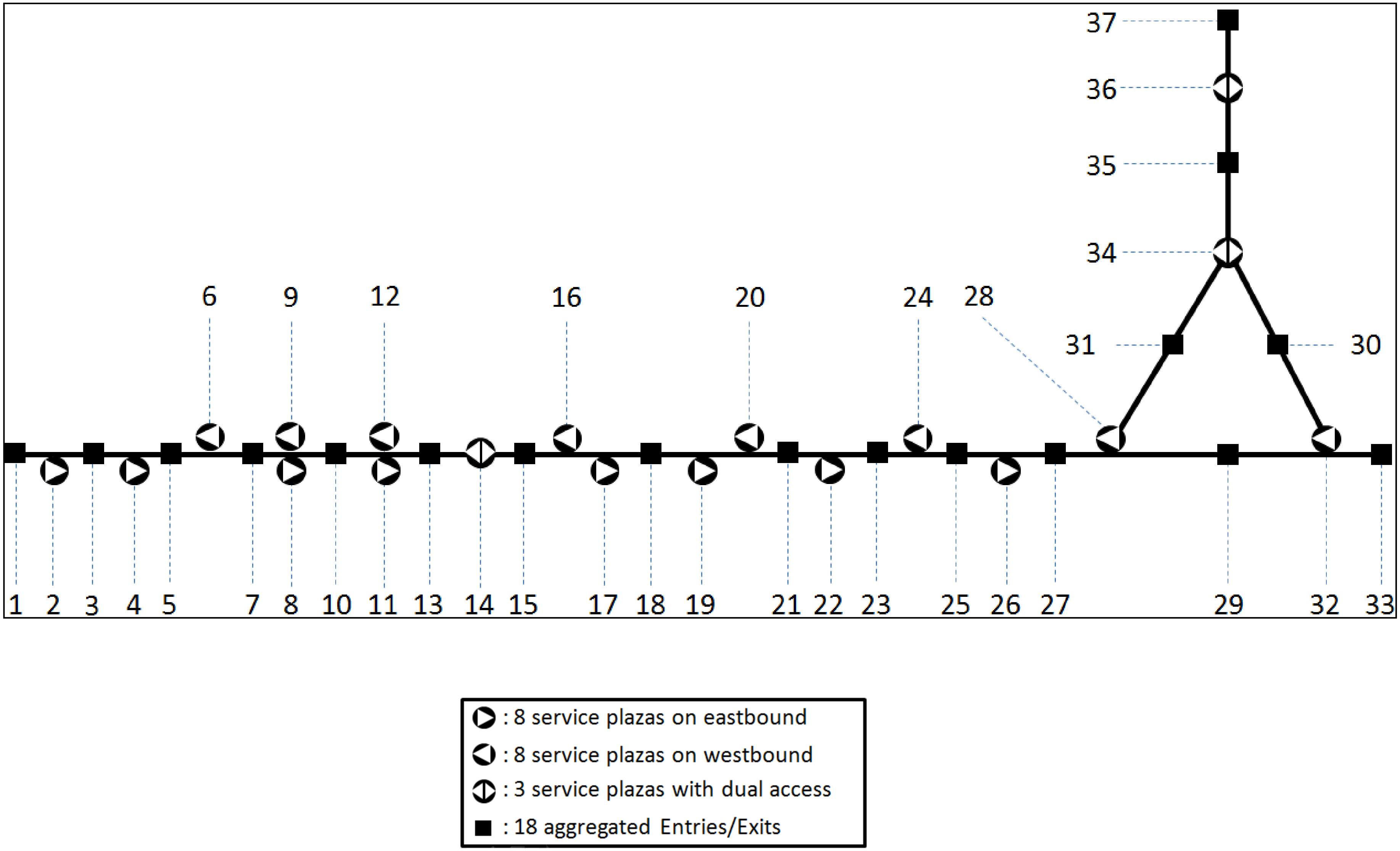

Figure 2.2. Simplified PA Turnpike network

Table 2.3. Origin/destination (annual) truck volume matrix for classes 6-10 (in trucks/year)

Entrance/ Exit	1	3	5	7	10	13	15	18	21	23	25	27	29	30	31	33	35	37
1	-	272,763	216,619	19,437	10,127	72,306	1,827	42,006	1,300	290	9,657	1,556	360	-	686	67	0	0
3	287,975	-	253,547	20,854	9,035	50,596	1,674	35,913	1,326	302	6,273	1,865	783	-	638	73	0	0
5	263,545	266,039	-	114,376	66,112	281,340	16,809	436,576	13,859	2,792	8,365	36,819	20,658	-	26,031	2,443	26	408
7	23,463	21,658	110,039	-	14,960	27,933	3,240	32,017	1,374	477	867	2,613	1,425	-	2,122	456	4	0
10	15,903	11,618	62,322	15,231	-	80,551	14,768	69,352	3,499	704	1,626	4,420	4,458	-	2,096	261	5	10
13	64,609	44,049	267,771	21,771	85,908	-	23,037	59,785	3,094	581	2,004	7,448	4,211	-	5,304	402	6	64
15	2,241	1,873	14,654	2,611	15,017	20,330	-	40,174	1,607	612	1,188	1,241	1,054	-	741	140	0	0
18	55,666	42,289	462,821	29,663	79,314	60,903	41,431	-	115,884	20,509	46,850	146,772	96,871	-	95,171	5,898	123	748
21	2,030	1,616	12,941	1,090	4,078	2,576	1,838	124,088	-	21,888	36,735	107,928	63,326	-	86,262	15,562	339	225
23	223	211	2,374	471	718	572	426	20,038	20,864	-	50,631	66,348	41,689	-	35,797	7,856	328	277
25	7,362	4,615	7,520	652	1,445	1,823	972	43,829	33,719	50,531	-	26,935	18,360	-	17,835	6,576	3,347	1,667
27	1,472	1,707	38,325	2,224	5,127	8,770	1,889	156,889	102,910	63,764	25,254	-	203,680	-	124,888	31,927	27,233	12,291
29	856	1,315	17,516	1,188	4,116	3,606	1,040	99,951	71,031	46,227	21,920	214,724	-	-	-	185,510	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	263,413	152,082	76,369
31	1,089	982	24,005	1,882	2,569	5,218	1,280	97,829	87,843	40,123	20,610	125,111	-	-	-	-	49,321	29,972
33	62	69	2,046	373	283	385	75	7,999	21,327	9,631	6,677	31,438	170,104	238,578	-	-	444,216	236,537
35	1	3	53	7	9	21	2	199	403	319	3,875	28,465	-	137,297	46,641	459,077	-	256,170
37	0	0	77	3	2	1	1	61	139	132	1,615	14,389	-	92,794	31,668	214,845	278,390	-

Uncovered Traffic Flow (TF)	0	166,411	363,309	18,629	0	0	23,112	558,955	17,736	0	0	0	1,626,087			433,823	68,214	264,643
Sum	**3,540,919**	**23.46%**																
Total TF	15,092,924																	

Table 2.4. Travel distance matrix (in miles)

Entrance/ Exit	1	3	5	7	10	13	15	18	21	23	25	27	29	30	31	33	35	37
1	0.00	30.01	61.18	95.90	137.17	153.17	182.11	227.43	272.90	290.00	303.60	318.29	336.84	-	343.89	345.94	365.83	396.56
3	0.00	0.00	31.17	65.90	107.16	123.16	152.10	197.42	242.89	259.99	273.59	288.28	306.84	-	313.88	315.93	335.82	366.55
5	0.00	0.00	0.00	34.73	75.99	91.99	120.94	166.25	211.72	228.82	242.42	257.11	275.67	-	282.71	284.76	304.66	335.39
7	0.00	0.00	0.00	0.00	41.27	57.27	86.21	131.52	176.99	194.10	207.70	222.39	240.94	-	247.98	250.03	269.93	300.66
10	0.00	0.00	0.00	0.00	0.00	16.00	44.94	90.26	135.73	152.83	166.43	181.12	199.67	-	206.72	208.77	228.66	259.39
13	0.00	0.00	0.00	0.00	0.00	0.00	28.94	74.26	119.73	136.83	150.43	165.12	183.67	-	190.72	192.77	212.66	243.39
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	45.31	90.79	107.89	121.49	136.18	154.73	-	161.78	163.83	183.72	214.45
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	45.47	62.57	76.17	90.86	109.42	-	116.46	118.51	138.41	169.14
21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.10	30.70	45.39	63.94	-	70.99	73.04	92.93	123.66
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.60	28.29	46.84	-	53.89	55.94	75.83	106.56
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.69	33.24	-	40.29	42.34	62.23	92.96
27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.55	-	25.60	27.65	47.54	78.27
29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	-	9.09	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	-	22.38	37.19	67.91
31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	-	0.00	0.00	21.95	52.68
33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	59.57	90.30
35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	30.73
37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00

Case 1:	Between 0 and 75 miles	42
Case 2:	Between 75 and 150 miles	30
Case 3:	Between 150 and 300 miles	48
Case 4:	Between 300 and 450 miles	15
	Sum:	135

Implementation of the Model

A MATLAB [14] code has been written to automatically generate the objective function and constraints for a given choice of safe travel distance and number of LNG stations. The code reads the matrices of ATT6-10 coefficients and travel distances for all pairs of aggregated interchanges shown in Tables 2.3 and 2.4. For the Turnpike problem, the mathematical model contains approximately 250 binary variables and 400 constraints.

A more general version of the MATLAB code has also been developed to automatically build an extended model to solve the case where some LNG trucks have a single fuel tank and the remaining trucks have two tanks. In this scenario, the safe distance for the trucks with two tanks is twice as long. For this version of the problem, the mathematical model uses twice as many variables and constraints compared to the basic model where all trucks have a single tank.

The MATLAB codes generate mathematical models in a format that is compatible with LINGO [15], which is an optimization modeling software for linear, non-linear, and integer programming. LINGO can solve the model for the Turnpike problem in a matter of seconds.

Computational Results

First, we consider a scenario with a safe distance for an LNG truck of R=300 miles. This is a conservative distance for a class 9 truck with a single gas tank of 119 gallons; such tanks can actually store an amount of 102 gallons of LNG (energy equivalent to 63 gallons of diesel) [22]. The number of LNG stations to be located varies from 1 to 15, in increments of 1. The reason we stop at 15 is because the entire volume of trucks can be covered with 15 stations. Table 2.5 provides a summary of the results. Note that, if p = 4 stations, the optimal station locations are Oakmont-Plum, Sideling Hill, King of Prussia and Allentown in Table 2.2. These stations can cover a total of 5,972,866 truck trips per year, which is about 51.7% of the trips that can be covered with 15 stations (11,552,005 trips). The overall coverage of 39.57% is calculated with respect to the total number of trucks using the Turnpike in one year (15,092,924 trucks). The effective coverage of trucks as a function of the number of LNG stations for R=300 miles is displayed in Figure 2.3. This is a concave function representing diminishing marginal return (coverage) for each additional station.

In most of the solutions provided in Table 2.5, the set of station locations (service plazas) selected for a given value of p includes the optimal station locations for smaller values of p. This result, however, cannot be generalized. For example, service plaza King of Prussia selected for p = 4 is not part of the solution for p = 5, where King of Prussia is replaced by two new service plazas, Highspire and Peter J. Camiel. Thus, if the goal for the Commission is to build a certain number of stations (for example, p = 8) in the long term with a short term goal to build a smaller number now, then the stations to be built now should be located in some of the eight service plazas selected for the case of p = 8. Appendix B Table B.1 shows a comparison of the results of the model when only the top eight station locations are considered as potential solutions and when all 19 station locations are considered. This second case is identical to the scenario discussed in the prior paragraph. Figure A.1 graphically displays the effective coverage of truck trips of the solutions with respect to the top 8 best station locations and the overall best solutions. Note that the solutions for p = 2, 3, 4 and 5 are different.

Table 2.5. Optimal LNG fueling station locations for a safe traveling distance of R=300 miles

No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Overall Coverage (%)	Service Plazas
1	2,066,994	17.89	13.7	Allentown
2	3,580,184	30.99	23.72	Sideling Hill, Allentown
3	4,930,604	42.68	32.67	Sideling Hill, King of Prussia, Allentown
4	5,972,866	51.7	39.57	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
5	6,996,119	60.56	46.35	Oakmont-Plum, Sideling Hill, Highspire, Peter J. Camiel, Allentown
6	7,942,264	68.75	52.62	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, Allentown
7	8,876,487	76.84	58.81	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, North Neshaminy, Allentown
8	9,623,615	83.31	63.76	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
9	10,184,353	88.16	67.48	Zelienople, Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
10	10,718,913	92.79	71.02	Zelienople, Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
11	11,249,221	97.38	74.53	Zelienople, Oakmont-Plum, New Stanton, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
12	11,407,846	98.75	75.58	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
13	11,460,035	99.2	75.93	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
14	11,509,253	99.63	76.26	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
15	11,552,005	100	76.54	Zelienople, Oakmont-Plum, New Stanton, South Somerset, North Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run

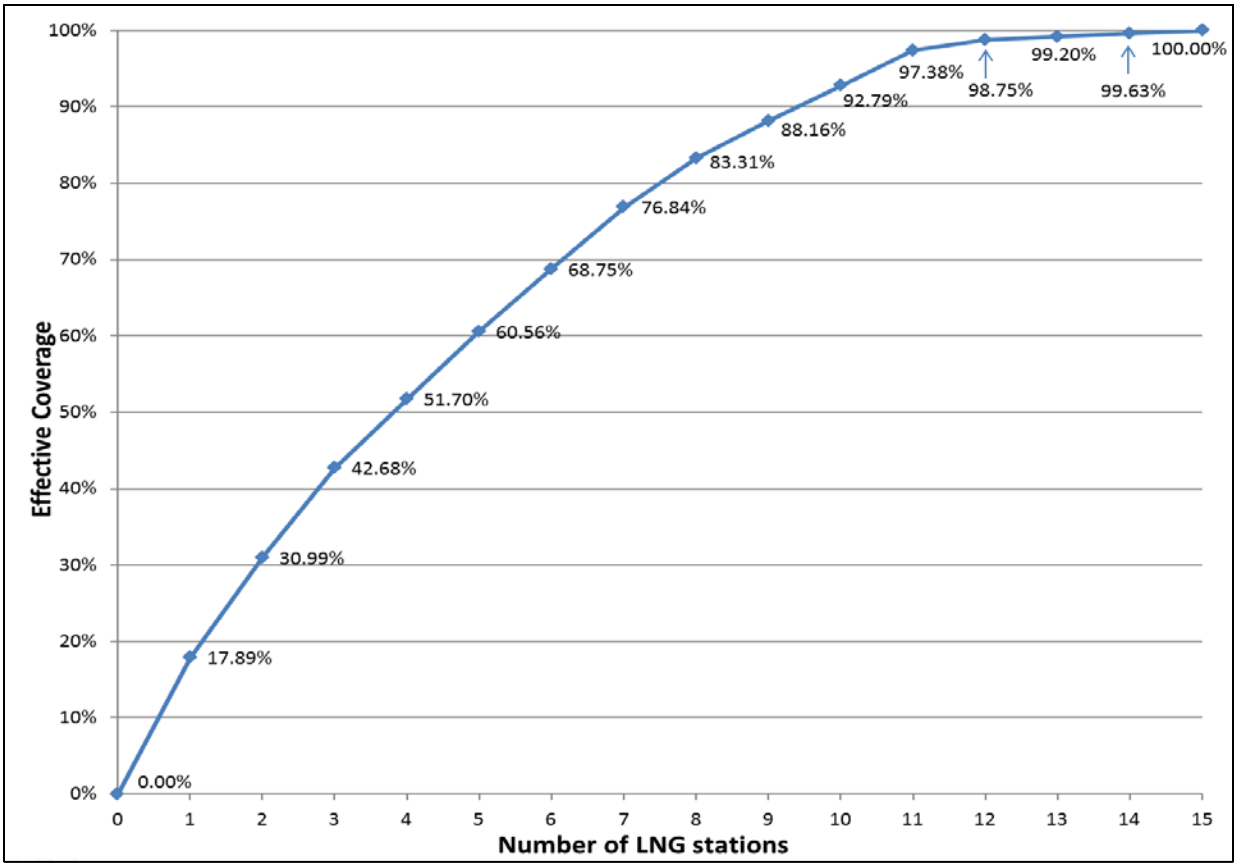

Figure 2.3. Effective ATT6-10 coverage for a safe traveling distance of R=300 miles

Now, we consider scenarios where some LNG trucks carry a single tank (R=300 miles) and the remaining LNG trucks have dual tanks (R=600 miles). The model is run for a percentage of LNG trucks with a single tank that ranges from 0 to 100%, in 20% intervals. For each case, the number of LNG stations increases from 1 to 15, one station at a time. Detailed results for these scenarios are provided in Appendix B. Here, the results are summarized in Table 2.6 and Figure 2.4. Figures 2.5 and 2.6 provide maps with the optimal station locations for p=4 stations, and R=300 and 600 miles, respectively. The locations of the three Clean Energy LNG stations in Pennsylvania are also shown in the maps.

Table 2.6. Effective coverage for combinations of trucks with safe traveling distances of R=300 and 600 miles

Safe Distance (% for R = 300, % for R = 600)	No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Service Plazas
(100, 0)	2	3,580,184	30.99	Sideling Hill, Allentown
	4	5,972,866	51.70	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
	6	7,942,264	68.75	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, Allentown
	8	9,623,615	83.31	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
(80, 20)	2	3,755,579	32.51	Sideling Hill, Allentown
	4	6,265,851	54.24	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
	6	8,064,552	69.81	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, Allentown
	8	9,645,505	83.50	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
(60, 40)	2	3,930,975	34.03	Sideling Hill, Allentown
	4	6,558,836	56.78	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
	6	8,230,724	71.25	Oakmont-Plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown
	8	9,667,395	83.69	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
(40, 60)	2	4,106,370	35.55	Sideling Hill, Allentown
	4	6,851,820	59.31	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
	6	8,569,234	74.18	Oakmont-Plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown
	8	9,765,323	84.53	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, Allentown
(20, 80)	2	4,281,766	37.07	Sideling Hill, Allentown
	4	7,153,329	61.92	Oakmont-Plum, Sideling Hill, Peter J. Camiel, Allentown
	6	8,959,900	77.56	Zelienople, New Stanton, Sideling Hill, Peter J. Camiel, King of Prussia, Allentown
	8	10,037,105	86.89	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Peter J. Camiel, King of Prussia, Allentown, Hickory Run
(0, 100)	2	4,457,161	38.58	Sideling Hill, Allentown
	4	7,566,645	65.50	New Stanton, South Midway, Peter J. Camiel, Allentown
	6	9,433,047	81.66	Zelienople, New Stanton, Cumberland Valley, Peter J. Camiel, King of Prussia, Allentown
	8	10,490,740	90.81	Zelienople, Oakmont-Plum, New Stanton, Cumberland Valley, Peter J. Camiel, King of Prussia, Allentown, Hickory Run

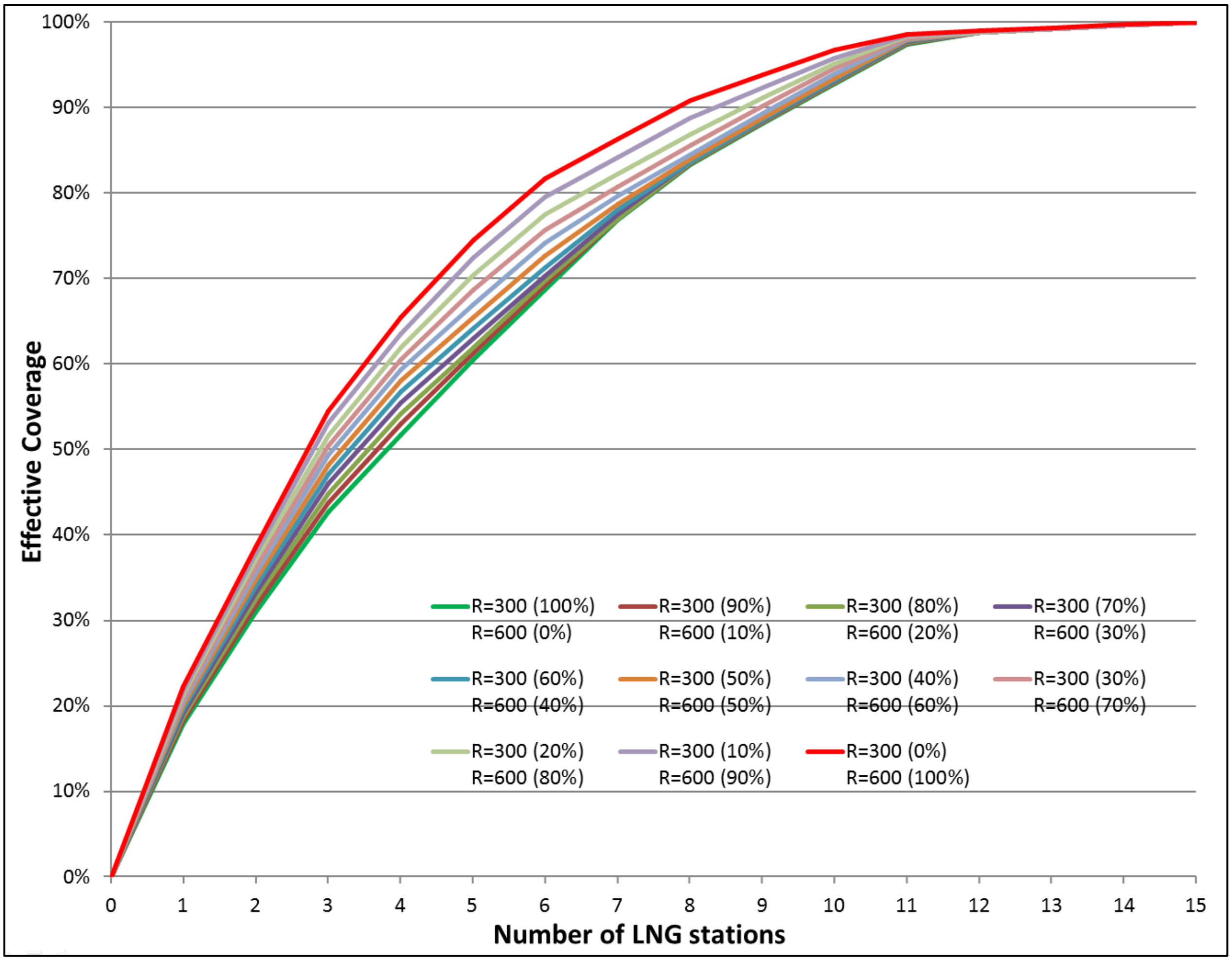

Figure 2.4. Effective coverage for different proportions of trucks with safe traveling distances of R=300 and R=600 miles

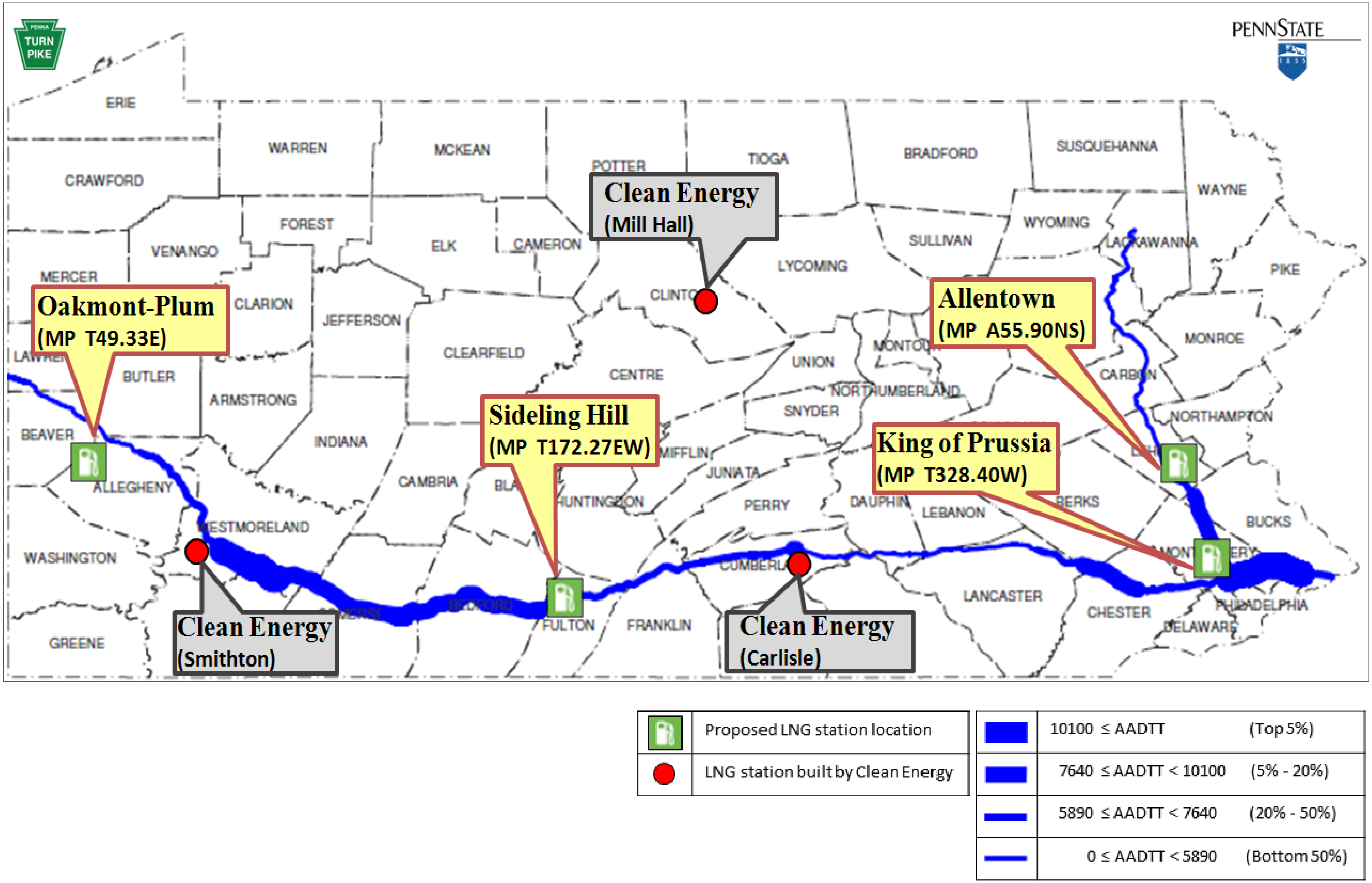

Figure 2.5. Four optimal LNG fueling station locations for a safe traveling distance of R = 300

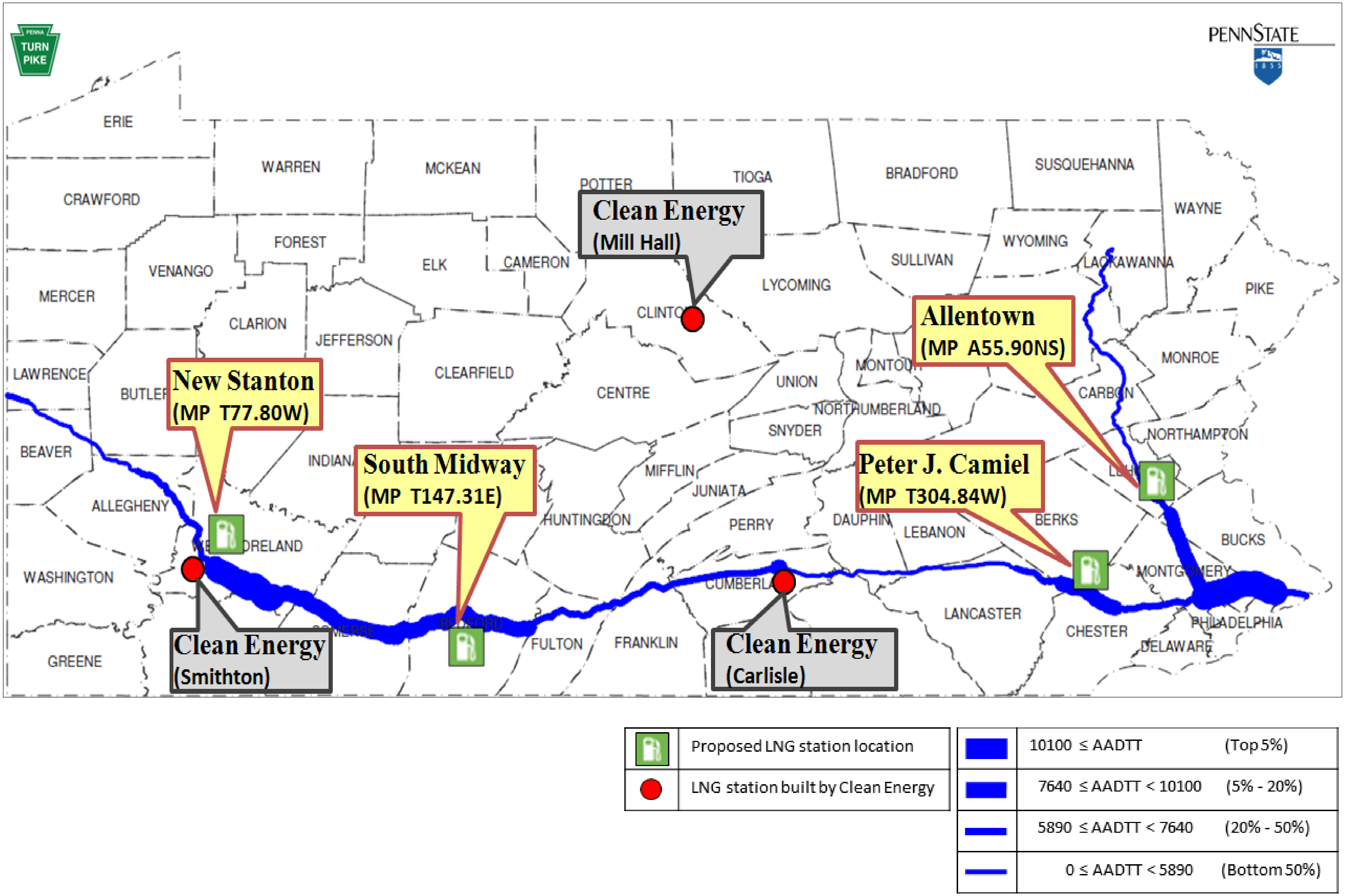

Figure 2.6. Four optimal LNG fueling station locations for a safe traveling distance of R = 600

2.2 Identification of the Number of Trucks Utilizing the Turnpike as well as the Average Daily Truck Traffic Count on all Major State Routes

In this section, we analyze the distribution of truck volume and truck density in the Turnpike, interstate highways, and U.S. routes in Pennsylvania. First, we have made a map to display the Annual Average Daily Truck Traffic (AADTT) in the Turnpike (I-70, I-76, I-276, I-376, and I-476), interstate highways, and U.S. routes. Next, a map has been constructed to represent the AADTT and the Annual Average of Daily Percentage of Truck Traffic (AADPTT) with respect to all traffic volume. This second map also focuses on all major state routes. Two additional maps have been produced for the PA Turnpike: one map focuses on AADTT information, and the other map provides AADTT and AADPTT results. The maps have been developed with AutoCAD Map 3D software [28]. Finally, a table describing the top 30 road segments with the highest AADTT values by county and road number is provided.

The mobility of goods in a state is dependent on the efficient use of the existing traffic infrastructure. The truck traffic analysis in this section is important to identify possible shifts in the distribution of truck traffic if an LNG refueling infrastructure is developed in the Turnpike. The potential increase in truck traffic in the Turnpike depends on the current truck volumes in major vicinity roads as well as the location of truck transportation companies and their customers. The location of truck transportation companies will be studied in detail in Section 2.3. Below, before presenting the results, we explain the process that has been used to gather truck traffic data and produce the maps.

Methodology

Pennsylvania Spatial Data Access (PASDA), the official public access geospatial information site, provides geographic information system data about Pennsylvania county boundaries, state roads, and Pennsylvania traffic counts, collected by PennDOT. [24] By using the AutoCAD Map 3D software, we were able to read and analyze the data, and produce the six maps described above. The PASDA database is composed of PA traffic information such as road names, traffic volumes, county names, and jurisdiction codes which are indictors to the road ownership. Based on the information provided, we first made a county boundary map with the name of each county and then processed the three pairs of truck volume and truck density maps.

In economics, it is a common rule of thumb to assume that roughly 80% of corporate profits come from 20% of customers. This rule is known as the 80-20 rule. In our context, we can assume that the Pennsylvania major state routes (Turnpike, interstate highways, and U.S. routes) having the top 20% of the truck traffic and AADTT $\geq$ 5,790 are the most important supply chain roads for truck transportation companies in Pennsylvania. Using such criteria, we have produced the following three maps, where routes are colored based on ranges of their AADTT and AADPTT values:

- Pennsylvania Truck Volume Map
  - Top 5% of AADTT (AADTT ≥ 10,960)
  - Between 5% and 20% of AADTT (5,790 ≤ AADTT < 10,960)
  - Between 20% and 50% of AADTT (1,430 ≤ AADTT < 5,790)
  - Bottom 50% of AADTT (AADTT < 1,430)
- Pennsylvania Truck Volume and Density Map
  - Top 20% of AADTT (AADTT ≥ 5,790) and AADPTT ≥ 20%
  - Top 20% of AADTT (AADTT ≥ 5,790) and AADPTT< 20%
  - Bottom 80% of AADTT (AADTT < 5,790) and AADPTT ≥ 20%
  - Bottom 80% of AADTT (AADTT < 5,790) and AADPTT ≥ 20%
- Pennsylvania Turnpike's Truck Volume Map
  - Top 5% of AADTT (AADTT ≥ 10,100)
  - Between 5% and 20% of AADTT (7,640 ≤ AADTT < 10,100)
  - Between 20% and 50% of AADTT (5,890 ≤ AADTT < 7,640)
  - Bottom 50% of AADTT (AADTT < 5,890)

In addition, PTC's 2010 Growth Report [25] provides traffic volume data for the Turnpike for the nine PTC vehicle classes. PTC vehicle classes are based on weight and can be converted to FHWA classes using the PTC pavement design matrix. [29] This traffic volume data has been used to generate a truck density map comparing AADTT values for truck traffic with Annual Average Daily Traffic (AADT) for all traffic using pie charts for various segments of the Turnpike. The area of the pie in each Turnpike segment is proportional to its AADT and the area of a piece of the pie corresponds to its AADTT.

The next major task was to determine the top 30 road segments with the highest AADTT values by county and road number. First, we filtered out from the PASDA database the road segments with AADTT ≤ 580. Then we computed the weighted mean AADTT values for the segments of each Pennsylvania road in each county using the segment lengths as weights. For example, if a 1 mile segment has an AADTT = 1,000 and a 2 mile segment has an AADTT = 2,000, then the weighted mean AADTT is 1,667. Lastly, we calculated the sum of the weighted mean AADTT for the two ways (EB/WB or NB/SB) and the sum of the segment lengths.

Figure 2.7 provides the work flow diagram for the work performed in this section.

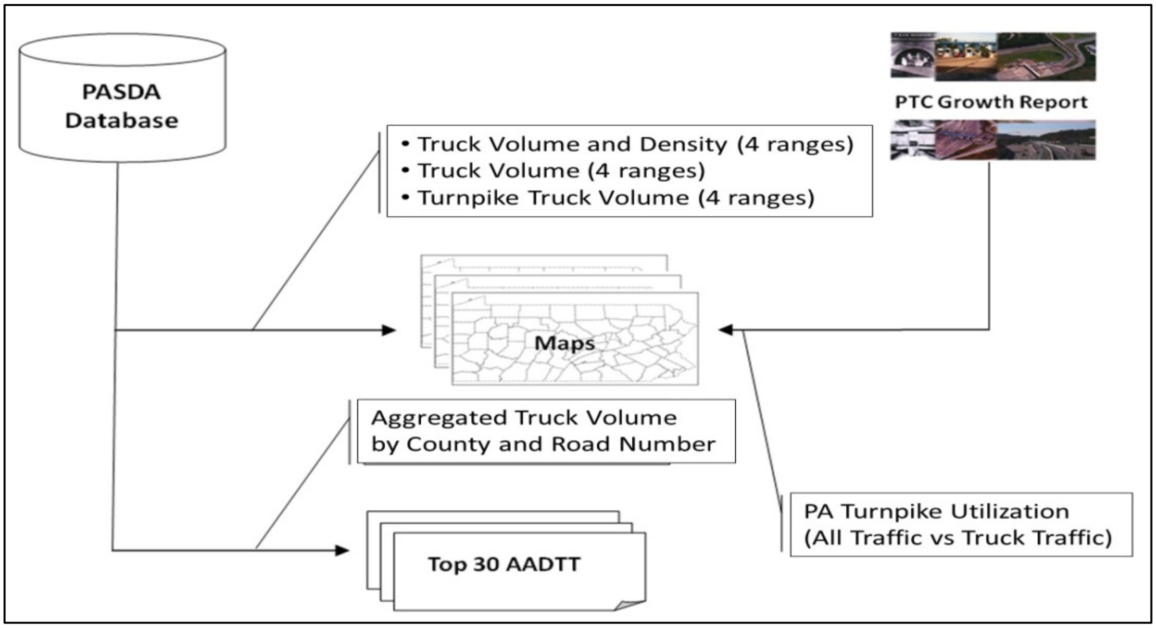

Figure 2.7. Work flow diagram for truck volume analysis on Pennsylvania roads

2.2 Truck Volume and Density Distribution Maps

Truck volume and density distribution maps for classes 4 to 13 are provided in Figures 2.8 and 2.9, respectively. The following observations can be made regarding these maps:

- Figure 2.8 shows the truck volumes in all major state routes. The top 5% of the truck traffic is 10,960 and the top 20% is 5,790. The highest truck traffic areas in Pennsylvania can be recognized in Clarion, Jefferson, Somerset, Clearfield, Bedford, Clinton, Union, Cumberland, Franklin, Dauphin, Lebanon, Berks, Lancaster, Lehigh, Northampton, Montgomery, Delaware, and Philadelphia Counties.
- Figure 2.9 characterizes the main supply chain routes of trucks in Pennsylvania, which comprise the Turnpike (I-70, I-76, I-276, I-376 and I-476), interstate highways, and U.S. routes. All these roads have heavy truck traffic and high truck density. Red lines (AADTT $\geq$ 5,790 and AADPTT $\geq$ 20%) indicate the road segments with the highest truck traffic and density. Note that the road segment between interchanges T75 in Westmoreland County and T161 in Bedford County has the heaviest truck traffic and the highest truck density in the Turnpike. In contrast, green lines showing higher truck volumes and lower truck densities appear near urban areas.

red	10960 ≤ AADTT	(Top 5%)
green	5790 ≤ AADTT < 10960	(5% - 20%)
blue	1430 ≤ AADTT < 5790	(20% - 50%)
gray	0 ≤ AADTT < 1430	(Bottom 50%)

Figure 2.8. Pennsylvania truck volume on the Turnpike (I-70, I-76, I-276, I-376, and I-476), interstate highways, and U.S. routes

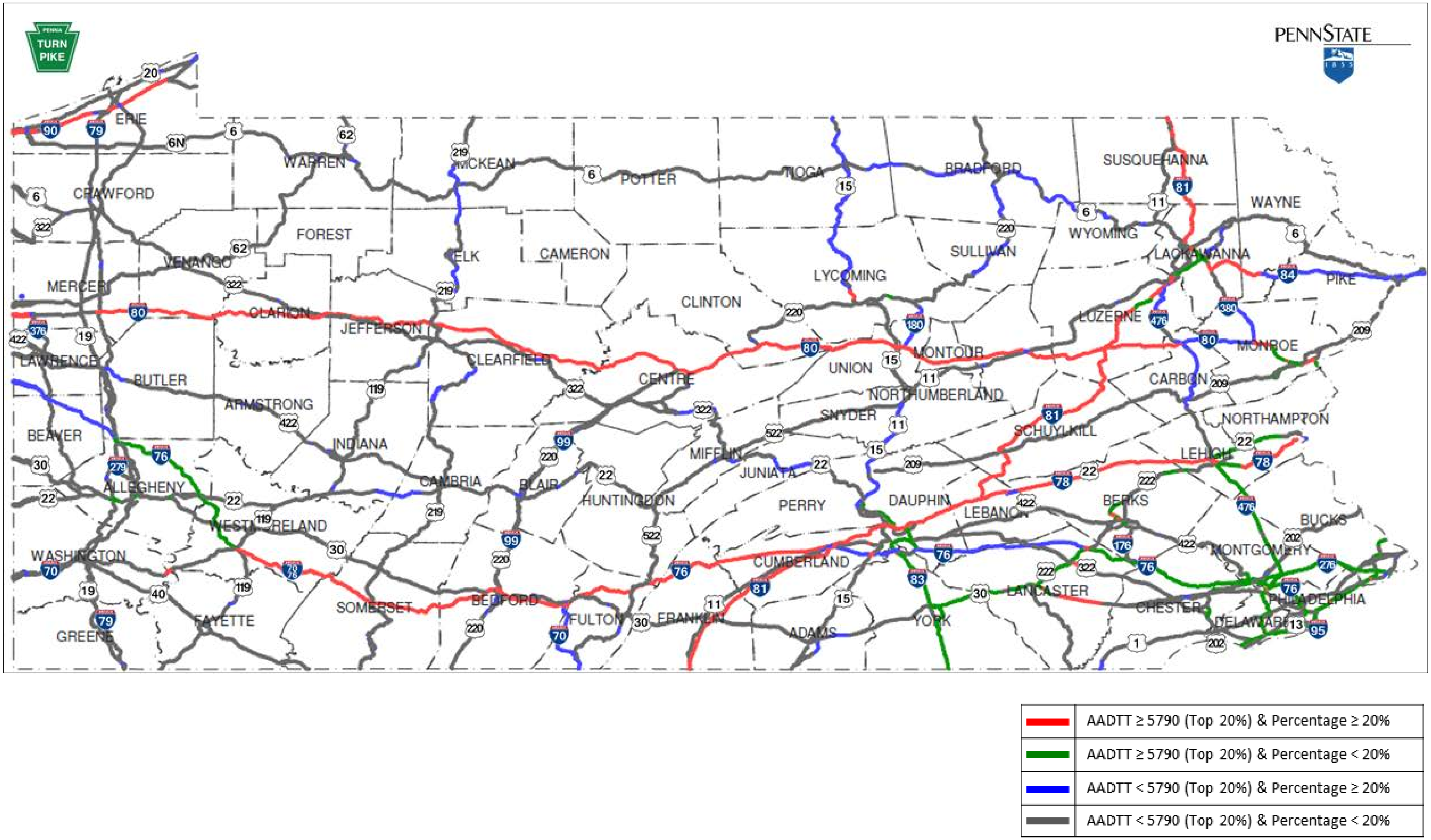

Figure 2.9. Pennsylvania truck volume and density on the Turnpike (I-70, I-76, I-276, I-376, and I-476), interstate highways, and U.S. routes

2.3 Truck Utilization Maps for the PA Turnpike System

Figure 2.10 shows truck volumes categorized in four ranges along the Pennsylvania Turnpike mainline (I-70, I-76, and I-276) and Northeast Extension (I-476). Also, a comparison of truck volumes versus total traffic volumes is provided in Figure 2.11 in the form of pie charts for the Turnpike. Based on Figure 2.11, Table 2.7 shows the top 10 Turnpike segments with the highest truck densities. The following observations can be made regarding truck volumes:

- The east-west mainline around Westmoreland, Montgomery, Bucks, and Philadelphia Counties carry the top 5 % of the Pennsylvania truck volume (AADTT ≥ 10,100), as shown in Figure 2.10.

- As shown in Figure 2.11 and Table 2.7, the Turnpike segment between interchanges T91 and T226 on the east-west mainline, from Westmoreland to Cumberland Counties has the highest densities of truck traffic (AADPTT ≥ 30% of trucks). In contrast, the lowest densities of truck traffic (AADPTT ≤ 11% of trucks) appear on the east-west mainline segment between interchanges T326 and T351.

- Even though the segment between interchanges T91 and T226 has the highest truck density and the segment between interchanges T326 and T351 has the lowest truck density, truck volumes in these two segments are similar.

- We have also observed that 54.06% of the PA Turnpike System (in miles) has a truck density of at least 20% (AADPTT ≥ 20% of trucks), 10.89% of the total length has an AADTT ≥ 10,000 trucks per day, and 22.11% of the entire Turnpike has an AADTT ≤ 10,000 trucks per day.

Table 2.7. Top 10 Turnpike segments with the highest truck densities

Rank	Turnpike segment (interchange pairs)	AADPTT (% of trucks)	AADT (vehicles/day)	AADTT (trucks/day)
1	T91-T110	31	32,467	10,065
2	T110-T146	31	30,666	9,506
3	T161-T226	31	21,545	6,679
4	T146-T161	29	34,683	10,058
5	T226-T236	25	21,117	5,279
6	T67-T91	24	35,025	8,406
7	A105-A115	23	10,594	2,437
8	T2-T10	22	11,148	2,453
9	T236-T242	21	27,313	5,736
10	T247-T286	20	26,551	5,310

Figure 2.10. Truck volume on the Pennsylvania Turnpike (east-west mainline and Northeast Extension)

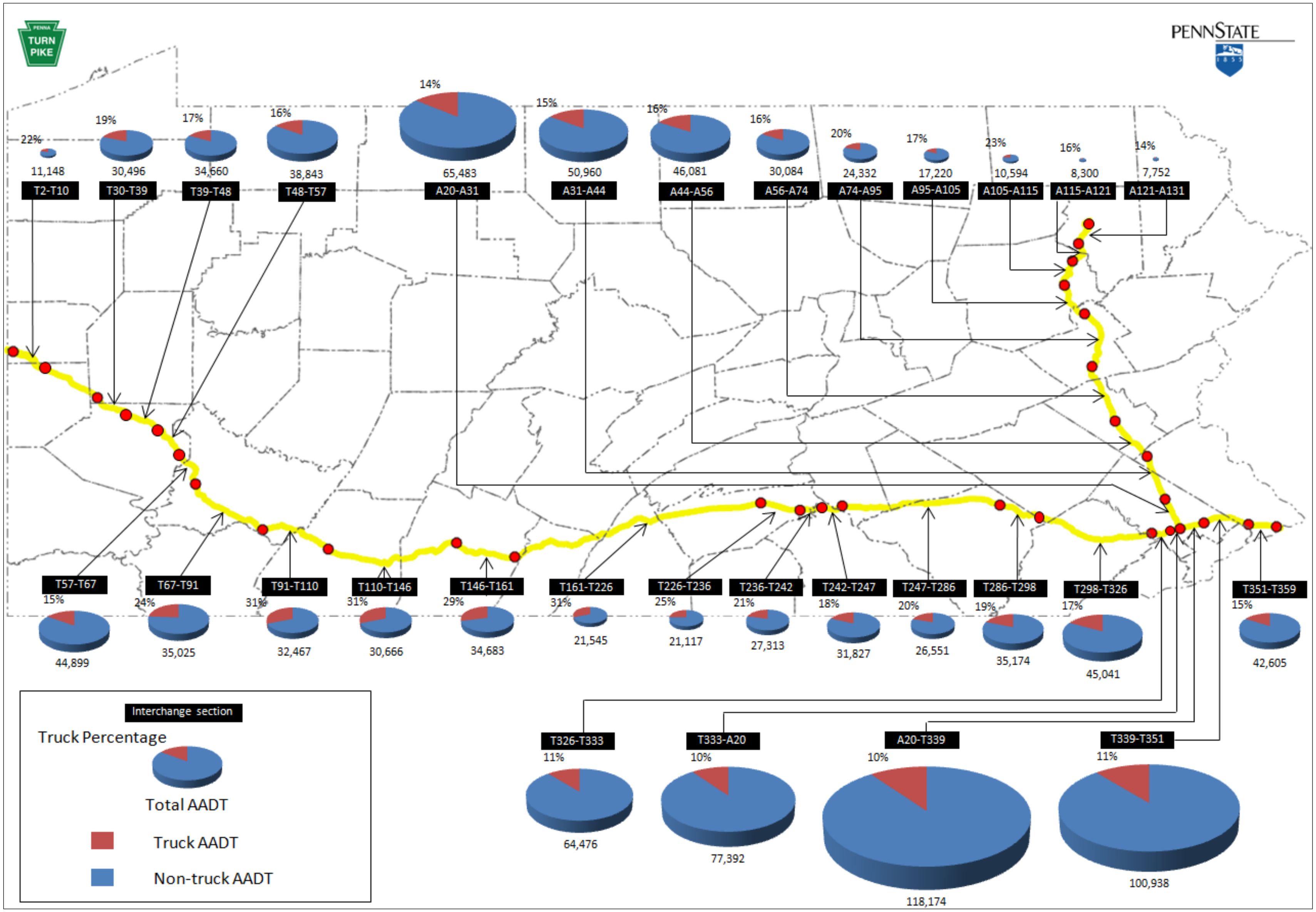

Figure 2.11. Road utilization on the Pennsylvania Turnpike (east-west mainline and Northeast Extension)

2.4 Top 30 Road Segments with the Highest AADTT in Pennsylvania

Table 2.8 provides the top 30 road segments with the highest AADTT on all state routes, including the Turnpike, interstate highways, U.S. routes, Pennsylvania routes and local roads. In the construction of this table, we used the weighted average of AADTT values from the PASDA database when combining adjacent segments in the same road in a given county to calculate the AADTT average values for truck classes 4-13. The following observations can be made from the results in the table:

- All top 30 road segments in PA belong to interstate highways, including the Turnpike. This infers that interstate highways are the main routes used by trucks. In particular, the 33.27 miles segment of I-81 in Dauphin County has the largest mean AADTT value. This suggests that Turnpike interchanges in Dauphine County should be considered as candidate LNG station locations to maximize truck coverage.

- Five Turnpike segments are included in top 30 road segments with the highest mean AADTT values. In particular, the 10.97 miles section of I-476 in Montgomery County has the highest mean AADTT value. Thus, Allentown Service Plaza (MP A55.90NS), which has already been identified as one of the main candidates to build an LNG fueling station in the Turnpike by the mathematical model discussed in Section 2.1, would be expected to cover many trucks.

- I-70 and I-76 segments in Somerset, Bedford, and Westmoreland Counties, and I-276 segment in Montgomery County should also be considered among the most important candidates to build LNG fueling stations due to their high truck volume.

- The sum of the mean AADTT values in the top 30 road segments is 333,764 trucks/day, while the sum of the mean AADTT values in the top five Turnpike road segments is 50,032 trucks/day. Thus, the Turnpike counts for about 15% of the truck volume among the top 30 road segments

- Given that the sum of the lengths of the top 30 road segments is 1,138.04 miles and the sum of the lengths of the top five Turnpike road segments is 137.11 miles, the Turnpike accounts for 12.05% of the total length of the top 30 road segments.

Table 2.8. Top 30 road segments with the highest AADTT in Pennsylvania

Rank	Mean AADTT (trucks/day)	Route	County	Linear Miles (EB/WB or NB/SB)	Note
1	18,991	I-81	Dauphin	33.27	
2	15,856	I-78	Northampton	24.36	
3	14,366	I-95	Philadelphia	43.40	
4	14,268	I-81	Cumberland	78.18	
5	13,384	I-78	Lehigh	38.38	
6	12,951	I-80	Jefferson	47.30	
7	12,734	I-95	Delaware	22.67	
8	12,456	I-78	Lebanon	16.86	
9	12,451	I-476	Montgomery	10.97	TURNPIKE
10	11,951	I-78	Berks	70.68	
11	11,309	I-81	Franklin	51.48	
12	10,597	I-80	Northumberland	10.93	
13	10,541	I-81	Lebanon	30.47	
14	10,448	I-80	Union	32.36	
15	10,303	I-80	Montour	23.34	
16	10,280	I-80	Clearfield	83.46	
17	10,204	I-80	Clinton	47.85	
18	9,891	I-81	Luzerne	78.04	
19	9,717	I-83	Dauphin	17.17	
20	9,692	I-70, 76	Somerset	29.79	TURNPIKE
21	9,651	I-276	Montgomery	20.21	TURNPIKE
22	9,508	I-80	Columbia	38.17	
23	9,491	I-70, 76	Bedford	35.23	TURNPIKE
24	9,474	I-80	Centre	65.39	
25	9,147	I-80	Butler	3.74	
26	8,935	I-80	Clarion	56.05	
27	8,870	I-83	Cumberland	4.84	
28	8,783	I-80	Venango	29.38	
29	8,768	I-81	Lackawanna	53.18	
30	8,747	I-70, 76	Westmoreland	40.91	TURNPIKE

2.5 Identification of the Key Supply Chain Routes of Major and Mid-size Trucking Companies

Despite sluggish economic growth, U.S. business logistics costs continued to rise in 2011. Logistics costs that year amounted to $1.28 trillion, an increase of $79 billion, or 6.6 percent, over the 2010 total. Costs rose in large part due to increased truck and rail rates along with higher costs for warehousing. [20] Considering truck transportation, the most effective way to stabilize transportation costs is to improve infrastructure in the main supply chain routes and to optimize truck movements and route shipments. In this section, we use county business patterns data from the U.S. Census Bureau [21] and truck volume data to identify and analyze the main supply chain routes used by major and mid-size trucking companies in Pennsylvania.

After collecting raw data on the number of trucking companies and their size by number of paid employees by county, the authors processed the data to classify trucking companies into three categories by employment-size and find out the distributions of major and mid-size trucking companies in Pennsylvania. By analyzing the results, we found that Bucks County has the largest number of small-size trucking companies and the overall largest number of trucking companies in Pennsylvania. However, among counties with most major and mid-size trucking companies, Allegheny County has the most companies in both categories. It is also worth noting that, although Cumberland County has the largest number of paid employees working for trucking companies in Pennsylvania, it only ranks 12th for the total number of trucking companies. We also noticed that both major and mid-size trucking companies are more densely concentrated in urban areas and more broadly dispersed or nonexistent in rural areas. Moreover, it is interesting to note that the PA Turnpike network passes through the counties where major and mid-size trucking companies are densely located. The next section presents the process that has been used to gather data, determine the distribution of truck transportation companies, and display the results.

Methodology

Finding the distribution truck transportation companies and their transportation-related activities is necessary for estimating the key supply chain routes of trucks in Pennsylvania. We cannot overstate the significance of this information, as it might influence the Commission's decision-making process about initiatives to improve the PA Turnpike infrastructure, including decisions on alternative fuels and location of new dispensing facilities.

We used county business patterns data for 2010 provided by the U.S. Census Bureau to find the number of trucking companies by employment-size for all of 67 counties in Pennsylvania. The original data was grouped into 9 ranges by employment-size: 1-4 employees, 5-9 employees, 10-19 employees, 20-49 employees, 50-99 employees, 100-249 employees, 250-499 employees, 500-999 employees, and 1,000 or more employees. We regrouped this data and organized trucking companies into three categories:

- Small-size trucking companies: 1-9 employees
- Mid-size trucking companies: 10-49 employees
- Major trucking companies: 50 or more employees

Figure 2.12 shows the work flow diagram for the work performed in this section.

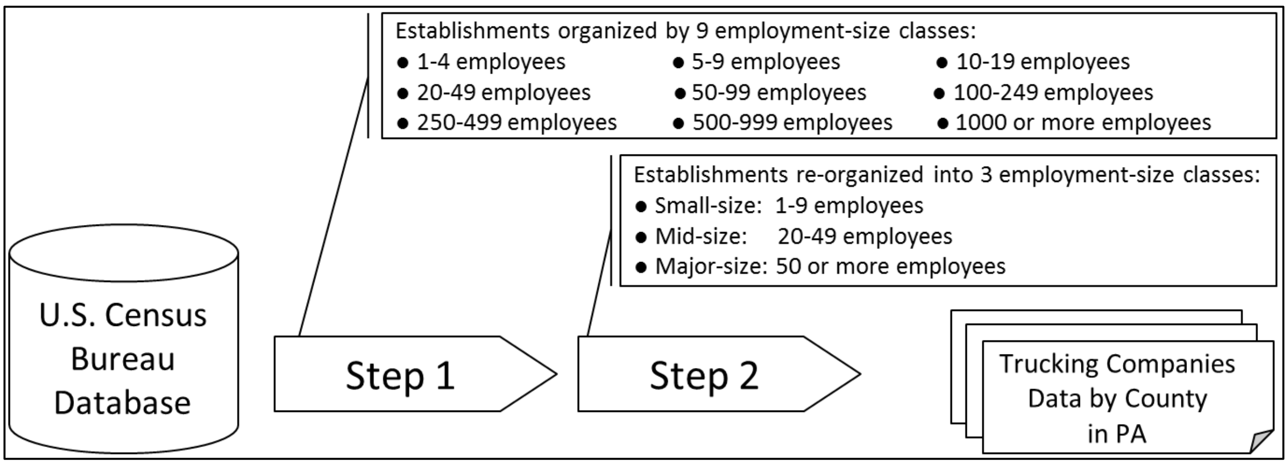

Figure 2.12. Work flow diagram for trucking company analysis

This trucking company data from the U.S. Census Bureau was also processed to produce distribution maps for both major and mid-size trucking companies using AutoCAD Map 3D software. For each distribution map, counties were partitioned into five categories depending on the number of companies in the employment-size class being considered. The categories in each class were defined according to the maximum number of companies per county in each class, which is 21 major companies and 57 mid-size companies, both in Allegheny County.

The trucking company data from the U.S. Census Bureau also comprised the number of paid employees in each county. Based on this data, similar distribution maps for major and mid-size trucking companies were produced.

Distribution of Truck Transportation Companies

The distribution of trucking companies in Pennsylvania for the calendar year of 2010 is shown in Figure 2.13. These results are based on the following data:

- There are 4,209 trucking companies in PA.
- 3,097 companies are small-size (1-9 employees)
- 890 companies are mid-size (10-49 employees).
- 222 companies are major companies (50 or more employees).

From the pie chart in Figure 2.13, we can easily figure out that about three quarters of the trucking companies in Pennsylvania are small-size companies, one fifth of the companies are mid-size companies, and only 5% of them are major companies.

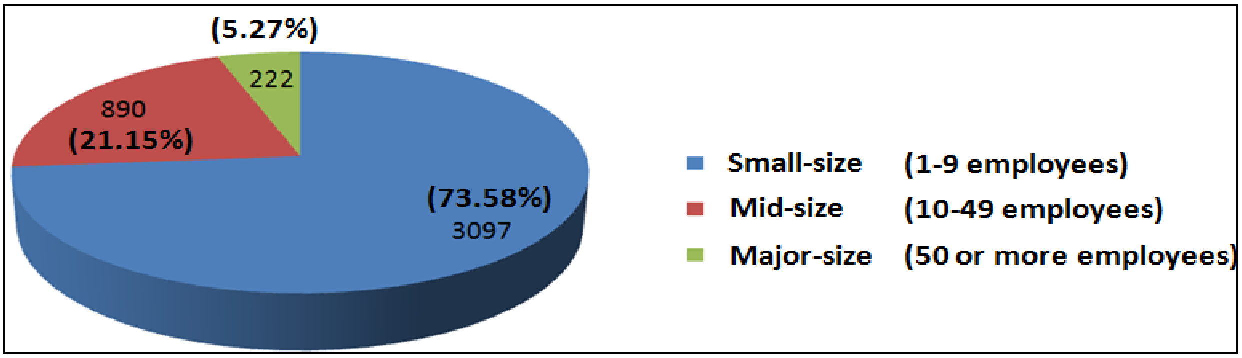

Figure 2.13. Distribution of truck transportation companies in PA for 2010

Table 2.9 shows a list of characteristics of truck transportation companies by county. The table shows the total number of companies, the number of companies by employment-size class, the total number of paid employees working in trucking companies, the average number of employees per company. Also, by using a ratio of 1.3 employees per truck, an estimate of the number of trucks is provided. This is an estimate of the number of trucks owned by truck transportation companies only in each county. Note that the top five values of each characteristic are yellow-highlighted.

Table 2.9 (a). List of characteristics of truck transportation companies by county

No.	County	No. of Companies	No. of Companies by Class: Small Size (1-9)	Mid-size (10-49)	Major (50 or more)	No. of Paid Employees	Avg. No. of Employees per Company	No. of Trucks (estimated)
1	Adams	38	32	5	1	269	7.08	207
2	Allegheny	216	138	57	21	3622	16.77	2786
3	Armstrong	33	24	8	1	245	7.42	188
4	Beaver	59	44	11	4	699	11.85	538
5	Bedford	27	20	7	0	201	7.44	155
6	Berks	139	96	39	4	1517	10.91	1167
7	Blair	54	32	18	4	913	16.91	702
8	Bradford	90	76	13	1	462	5.13	355
9	Bucks	274	231	35	8	1997	7.29	1536
10	Butler	78	47	24	7	1323	16.96	1018
11	Cambria	73	52	19	2	863	11.82	664
12	Cameron	2	2	0	0	7	3.50	5
13	Carbon	18	15	2	1	149	8.28	115
14	Centre	45	35	8	2	321	7.13	247
15	Chester	111	78	25	8	2120	19.10	1631
16	Clarion	30	23	6	1	251	8.37	193
17	Clearfield	110	94	12	4	1125	10.23	865
18	Clinton	13	9	4	0	108	8.31	83
19	Columbia	25	19	4	2	325	13.00	250
20	Crawford	30	28	2	0	103	3.43	79
21	Cumberland	110	63	27	20	7721	70.19	5939
22	Dauphin	82	54	20	8	1668	20.34	1283
23	Delaware	87	67	20	0	562	6.46	432
24	Elk	26	18	8	0	190	7.31	146
25	Erie	98	75	18	5	1041	10.62	801
26	Fayette	69	56	10	3	728	10.55	560
27	Forest	1	0	1	0	13	13.00	10
28	Franklin	53	42	10	1	549	10.36	422
29	Fulton	12	9	3	0	68	5.67	52
30	Greene	16	11	5	0	129	8.06	99
31	Huntingdon	21	19	2	0	77	3.67	59
32	Indiana	48	37	10	1	342	7.13	263
33	Jefferson	47	39	8	0	213	4.53	164
34	Juniata	16	13	2	1	256	16.00	197

Note: The top five values of each characteristic are yellow-highlighted.

Table 2.9 (b). List of characteristics of truck transportation companies by county (cont.)

No.	County	No. of Companies	No. of Companies by Class: Small Size (1-9)	Mid-size (10-49)	Major (50 or more)	No. of Paid Employees	Avg. No. of Employees per Company	No. of Trucks (estimated)
35	Lackawanna	82	54	22	6	1283	15.65	987
36	Lancaster	258	191	55	12	2750	10.66	2115
37	Lawrence	34	24	10	0	295	8.68	227
38	Lebanon	51	41	6	4	1448	28.39	1114
39	Lehigh	119	85	24	10	1817	15.27	1398
40	Luzerne	132	96	28	8	1377	10.43	1059
41	Lycoming	53	35	17	1	537	10.13	413
42	McKean	40	30	10	0	180	4.50	138
43	Mercer	49	38	8	3	1150	23.47	885
44	Mifflin	27	17	9	1	303	11.22	233
45	Monroe	41	35	4	2	511	12.46	393
46	Montgomery	168	120	35	13	3142	18.70	2417
47	Montour	11	9	2	0	47	4.27	36
48	Northampton	91	68	19	4	975	10.71	750
49	Northumberland	65	51	11	3	869	13.37	668
50	Perry	18	14	3	1	152	8.44	117
51	Philadelphia	127	96	28	3	1082	8.52	832
52	Pike	7	7	0	0	8	1.14	6
53	Potter	13	9	4	0	102	7.85	78
54	Schuylkill	86	64	18	4	995	11.57	765
55	Snyder	16	9	7	0	160	10.00	123
56	Somerset	77	52	24	1	692	8.99	532
57	Sullivan	5	3	2	0	26	5.20	20
58	Susquehanna	26	21	5	0	114	4.38	88
59	Tioga	32	25	7	0	139	4.34	107
60	Union	24	17	6	1	323	13.46	248
61	Venango	24	15	7	2	378	15.75	291
62	Warren	14	8	4	2	242	17.29	186
63	Washington	56	38	11	7	841	15.02	647
64	Wayne	23	19	4	0	113	4.91	87
65	Westmoreland	110	74	28	8	1439	13.08	1107
66	Wyoming	35	30	4	1	205	5.86	158
67	York	144	104	25	15	2505	17.40	1927
Sum		4209	3097	890	222	56377		43367

Note: The top five values of each characteristic are yellow-highlighted.

Table 2.10 shows rankings for the top 5 counties by the total number of companies and number of companies for each employment-size class. From these results, we can draw the following conclusions:

- Bucks County ranked first in both total number trucking companies and number of small-size trucking companies.
- Allegheny County ranked first in both number of mid-size trucking companies and number of major trucking companies.

Table 2.10. Top 5 counties ranked by number of trucking companies

Rank	Total		Small-size (1-9)		Mid-size (10-49)		Major (50 or more)	
	County	No. of Companies	County	No. of Companies	County	No. of Companies	County	No. of Companies
1	Bucks	274	Bucks	231	Allegheny	57	Allegheny	21
2	Lancaster	258	Lancaster	191	Lancaster	55	Cumberland	20
3	Allegheny	216	Allegheny	138	Berks	39	York	15
4	Montgomery	168	Montgomery	120	Bucks	35	Montgomery	13
5	York	144	York	104	Montgomery	35	Lancaster	12

Table 2.11 shows rankings for the top 5 counties by the total number of employees in truck transportation companies and average number of employees by company. From these results, we can draw the following conclusions:

- Although Cumberland County has the largest for number of paid employees in Pennsylvania, it only ranks 12th in total number of trucking companies.
- The top 5 counties in number of major trucking companies (see Table 2.10) were also top 5 in total number of employees in Pennsylvania.
- The rank by total number of employees is different from the rank by average number of employees per company. For example, Allegheny County is ranked higher than Montgomery County by total number of employees, but Allegheny is ranked lower than Montgomery by average number of employees by company. Thus, higher rank by total number of employees does not necessarily mean higher rank by average number of employees per company.
- The maximum average number of employees per company is 70.19 in Cumberland County. This implies that more employees were hired per trucking company in Cumberland than in any other county.

- The second largest average number of employees per company is only 28.39 in Lebanon County. The big gap between the two largest averages means that the size of trucking companies in Cumberland County is significantly larger than in any other county, including Lebanon.
- The minimum average number of employees by company in Pennsylvania is only 1.14 in Pike County.

Table 2.11. Top 5 counties ranked by number of paid employees

Rank	County	Number of Companies	Total Number of Employees	Average Number of Employees per Company
1	Cumberland	110	7721	70.19
2	Allegheny	216	3622	16.77
3	Montgomery	168	3142	18.70
4	Lancaster	258	2750	10.66
5	York	144	2505	17.40

Now, we focus on the distribution of both major and mid-size trucking companies in PA to establish the basis to find a relationship between the special distribution of trucking companies and key supply chain routes for these companies. Figure 2.14 and Figure 2.15 display the distribution maps for both employment-size classes in PA. From these maps, we can draw the following conclusions:

- Figure 2.14 reveals that mid-size trucking companies were more densely located in the urban area, such as Philadelphia, Harrisburg, and Pittsburgh, while they were sparsely or no located in the rural area.
- Allegheny County, the largest county for mid-size trucking companies, has 57 companies or, equivalently, 6.40% of all mid-size trucking companies in PA.
- Lancaster County, which houses 55 mid-sized trucking companies, follows on the heels of Allegheny County.
- Figure 2.15 discloses that the distribution of major trucking companies has a similar pattern than that of mid-size companies.
- Allegheny County, also the largest county for major trucking companies, has 21 major trucking companies, which counts for 9.46% of all major trucking companies in PA.
- Cumberland and York Counties with 20 and 15 major trucking companies rank second and third in this employment-size class.

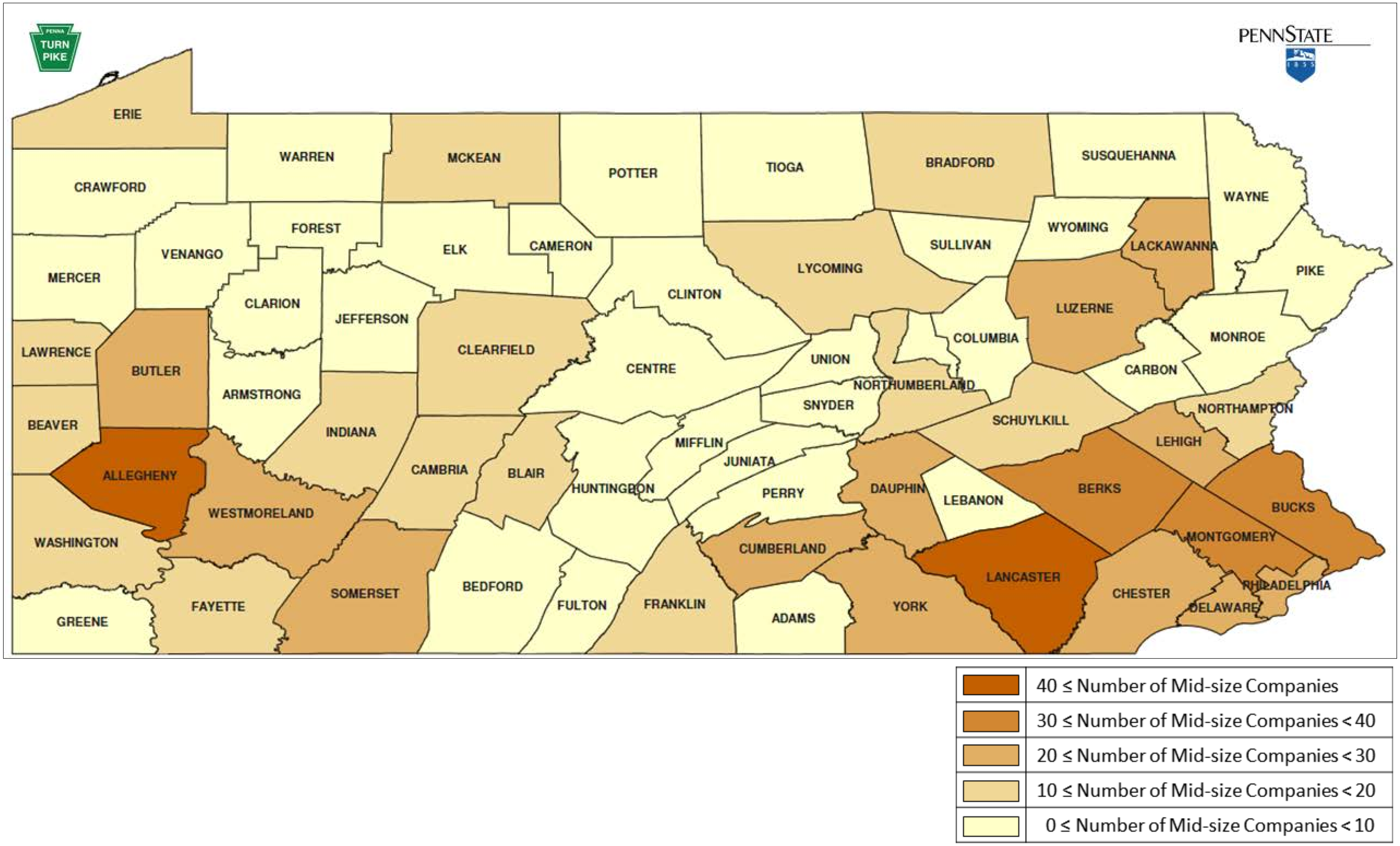

Figure 2.14. Distribution of mid-size truck transportation companies in PA

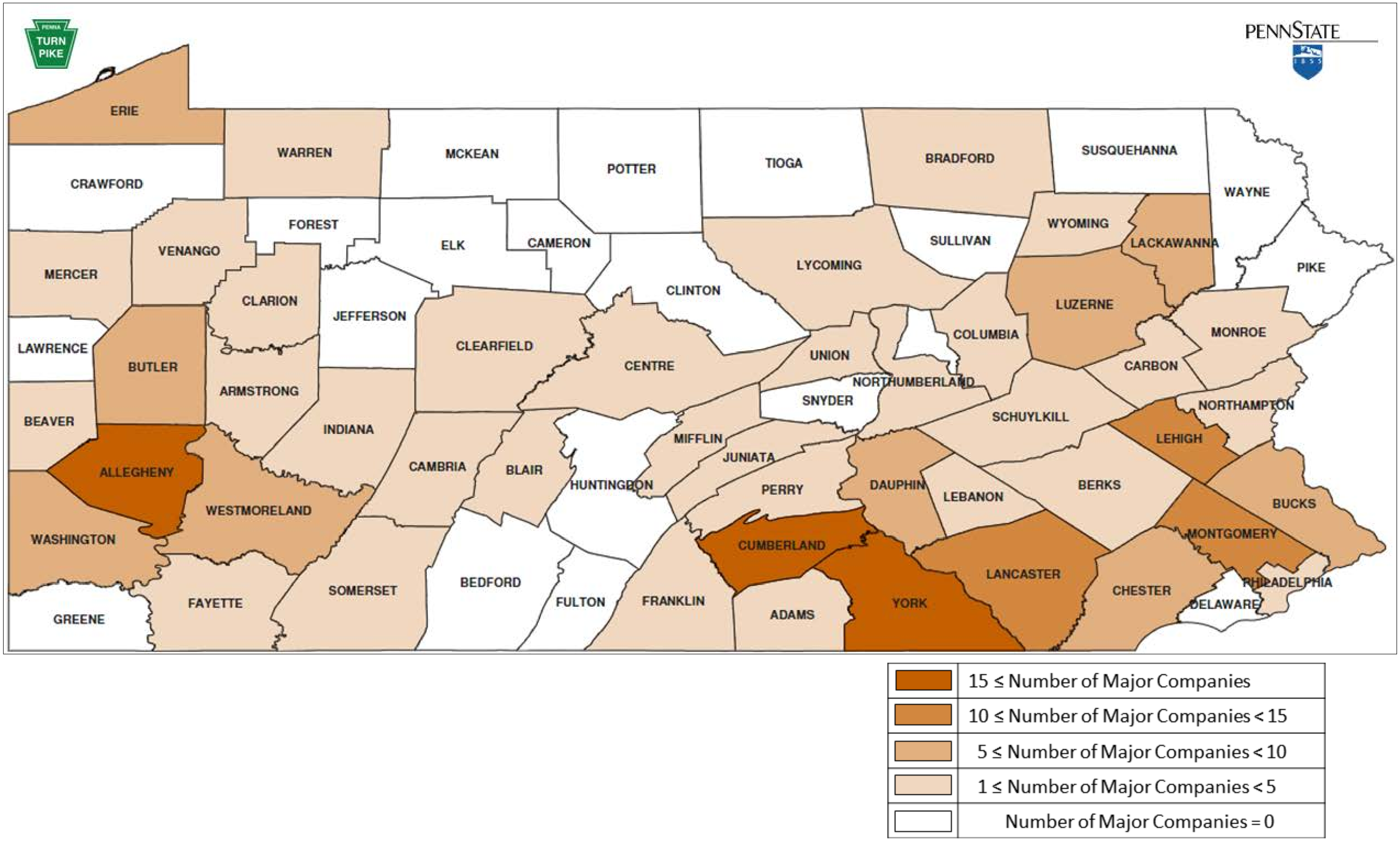

Figure 2.15. Distribution of major truck transportation companies in PA

Distribution of Truck Transportation Companies and Locations of Candidate LNG Fueling Stations

We have created a map to visually analyze the locations of candidate LNG fueling stations in the Turnpike relative to the distribution of trucking companies by county and truck volumes in the Turnpike. Figures 2.16 and 2.17 show maps of the 67 counties in Pennsylvania, where each county is colored by the total number of employees in trucking companies. The map also shows truck traffic in the PA Turnpike mainline and NE Extension, the locations of the 3 LNG fueling stations currently being constructed by Clean Energy, and the optimal locations of 4 fueling LNG stations for safe travel distances of 300 and 600 miles, respectively. The following observations can be made by analyzing these maps:

- The distribution of paid employees working for truck transportation companies is similar to the distributions of major and mid-size trucking companies. Furthermore, employees of trucking companies are densely populated in urban areas, but sparsely populated in rural areas.
- The PA Turnpike mainline passes through the 6 most densely populated counties with paid employees working for trucking companies (at least 2,000 employees per county), including Allegheny, Chester, Cumberland, Lancaster, Montgomery, and York.
- All candidate LNG stations for both R = 300 and R = 600 are located in densely-populated counties by paid employees or in Turnpike segments with high AADTT values.
- Oakmont-Plum service plaza (MP T49.33E), an optimal LNG station location for R = 300, is in Allegheny County, which has the 2nd largest number of employees working for trucking companies.
- King of Prussia service plaza (MP T328.40W), an optimal LNG station location for R = 300, is in Montgomery County, which ranks 3rd in number of employees working for trucking companies, and on the edge of a Turnpike segment with high AADTT value.
- The LNG station being built by Clean Energy in Carlisle is a densely populated by paid employees working for trucking companies, although its AADTT value in the Turnpike is low.
- Allentown service plaza (MP A55.90NS) and Sideling Hill service plaza (MP T172.27W) are respectively located in Lehigh and Fulton Counties, which are sparsely populated counties by paid employees, but these service plazas are located on the edge of Turnpike segments with large AADTT. Note that Allentown service plaza is an optimal location both for R = 300 and R = 600 while Sideling Hill service plaza is only an optimal location for R = 300.
- South Midway service plaza (MP T147.31E) and Peter J. Camiel service plaza (MP T304.84W), optimal solutions for R = 600, are located in Bedford and Chester Counties, respectively. Chester County has a high number of paid employees and the Turnpike segment near the plaza has high AADTT. Conversely, Bedford County has a lower

number of paid employees, but the Turnpike segment near the plaza also has high AADTT and connects east and west sides of the Turnpike.

- The location of the LNG station to be built by Clean Energy in Mill Hall, Clinton County, is sparsely populated by paid employees but has a large AADTT through I-80 and US-220.

Thus, we are able to conclude that one of the important factors that Clean Energy considers in the location of an LNG station is the number of paid employees working for trucking companies and the AADTT value in Turnpike or interstate highways close to the selected station location.

It is also reasonable to assume that, generally, the number of paid employees working for trucking companies directly relates to the size of trucking business.

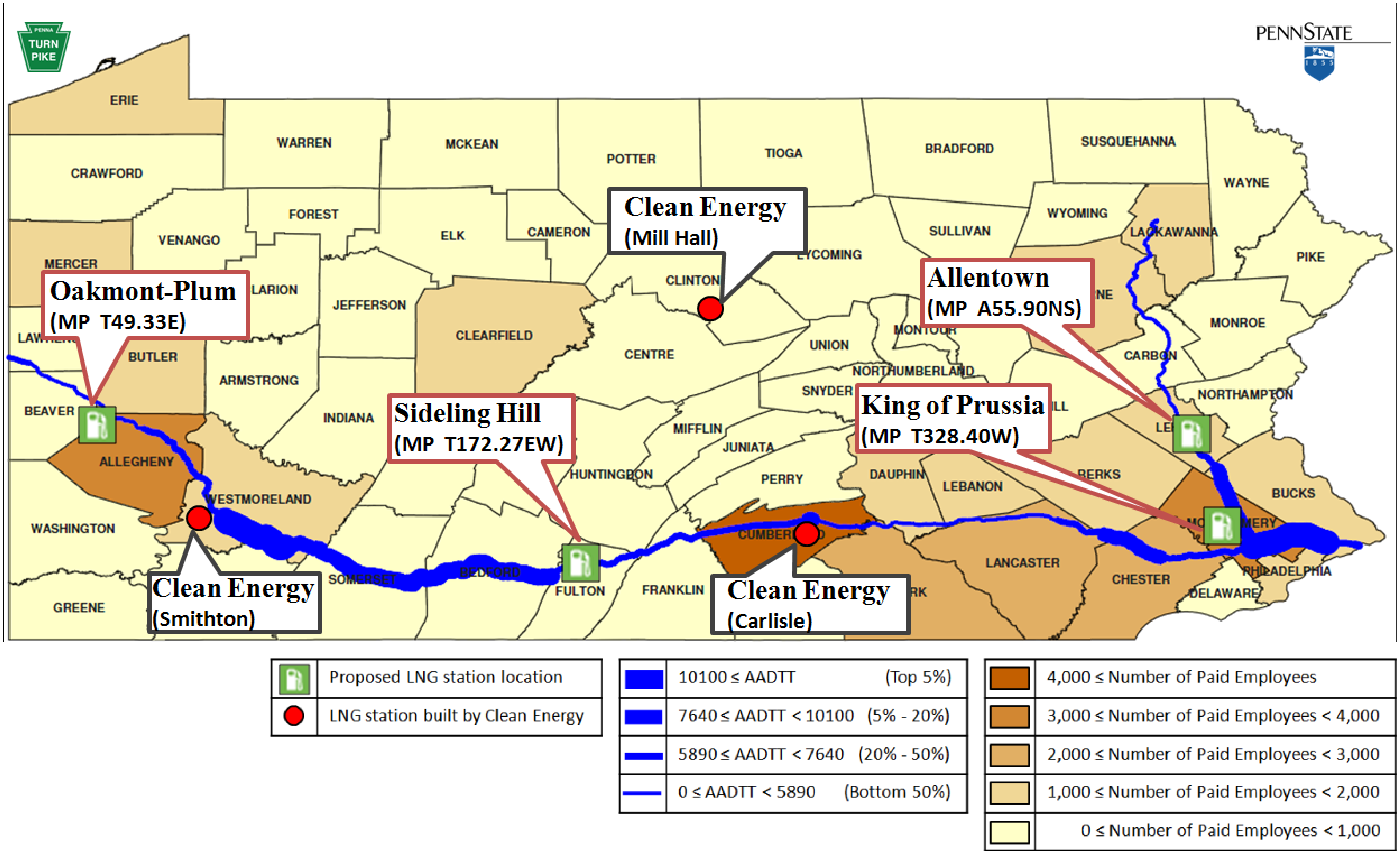

Figure 2.16. Distribution of paid employees with locations of the four best LNG fueling stations for a safe traveling distance of R=300

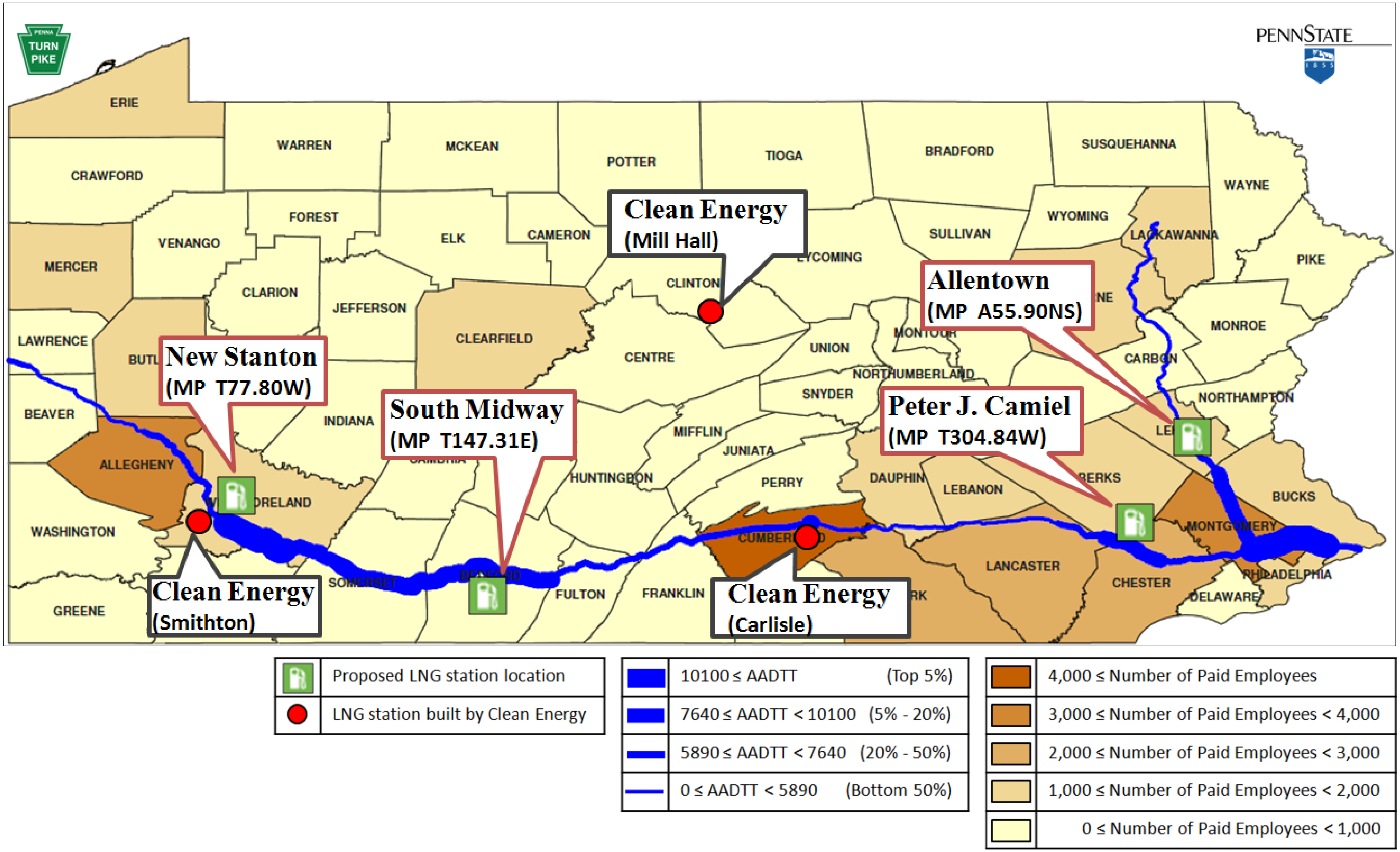

Figure 2.17. Distribution of paid employees with locations of the four best LNG fueling stations for a safe traveling distance of R=600 miles

Truck Volume and Density, Distribution of Truck Transportation Companies, and Locations of Candidate LNG Fueling Stations

Truck volume and density for classes 4 to 13 are provided in Figures 2.18-2.21. The maps in these figures also show the distribution of trucking companies per county. Truck volume is shown for two ranges of the annual average daily truck traffic (AADTT < 5790 and AADTT ≥ 5790) and truck density is displayed for two ranges of the annual average of daily percentage of truck traffic (AADPTT < 20% and AADPTT ≥ 20%). Figures 2.18 and 2.19 show the distribution of trucking companies based on the number of paid employees per county, and Figures 2.20 and 2.21 display the distribution of trucking companies based on the number of companies per county. These maps also show the optimal locations of four LNG fueling stations for safe driving distances of 300 miles (Figures 2.18 and 2.20) and 600 miles (Figures 2.19 and 2.21). From these maps, we can make the following observations:

- Figure 2.18 shows that the Oakmont-Plum service plaza (MP T49.33E) is selected to cover truck trips for a safe traveling distance is 300 miles. This service plaza is located in Allegheny County, where the number of paid employees in trucking companies and the truck traffic volume are very high.
- Figures 2.18 and 2.20 reveal that Allentown service plaza (MP A55.90NS) and King of Prussia service plaza (MP T328.40W) are selected to cover the truck trips for a safe traveling distance of 300 miles. These service plazas are respectively located in Lehigh and Montgomery Counties, where the density of trucking companies and the truck traffic volume are high.
- As shown in Figures 2.18 and 2.20, Sideling Hill service plaza (MP T172.27EW), located in Fulton County, is selected to cover the truck trips for a range of 300 miles. Although this county has a small number of trucking companies, this service plaza is necessary to connect the west and east sides of Pennsylvania, given that R = 300, and Assumptions A.1 and A.2.
- Figures 2.19 and 2.21 show that New Stanton service plaza (MP T77.80W), located in Westmoreland County, is close to the service plaza being built by Clean Energy in Smithton. Thus, we expect competition. Westmoreland County, however, has a high AADPTT, a high number of trucking companies, and high number of paid employees in these companies. Thus, this location is important to increase the coverage of truck on the Turnpike.
- In order to cover the trucks with a safe traveling distance of 600 miles, Peter J. Camiel service plaza (MP T304.84W) and Allentown service plaza (MP A55.90NS) are located in areas where AADPTT, number of paid employees, and number of trucking companies are high, as shown in Figures 2.19 and 2.21.

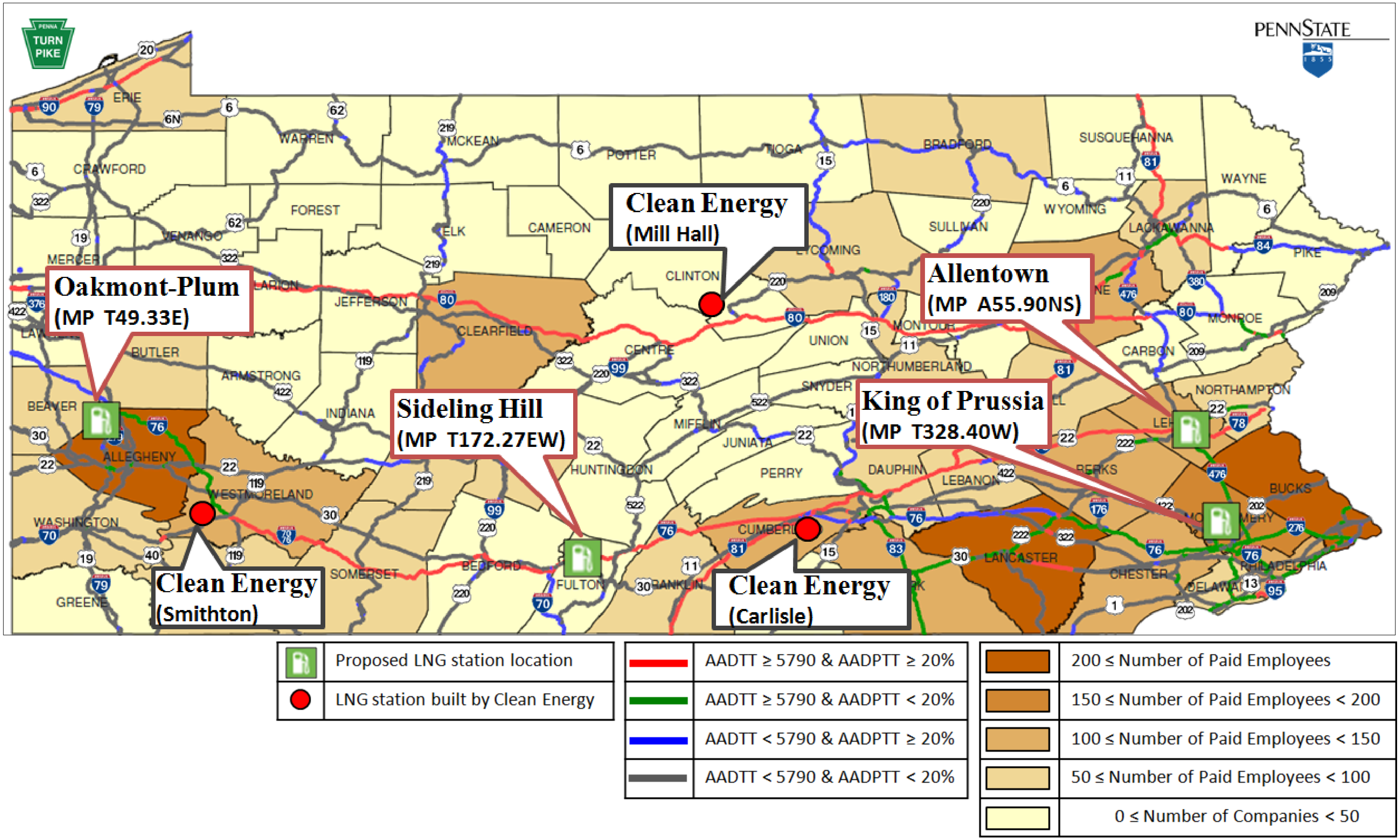

Figure 2.18. Truck volume and density, and distribution of paid employees with locations for the four best LNG fueling stations for a safe traveling distance of R=300 miles

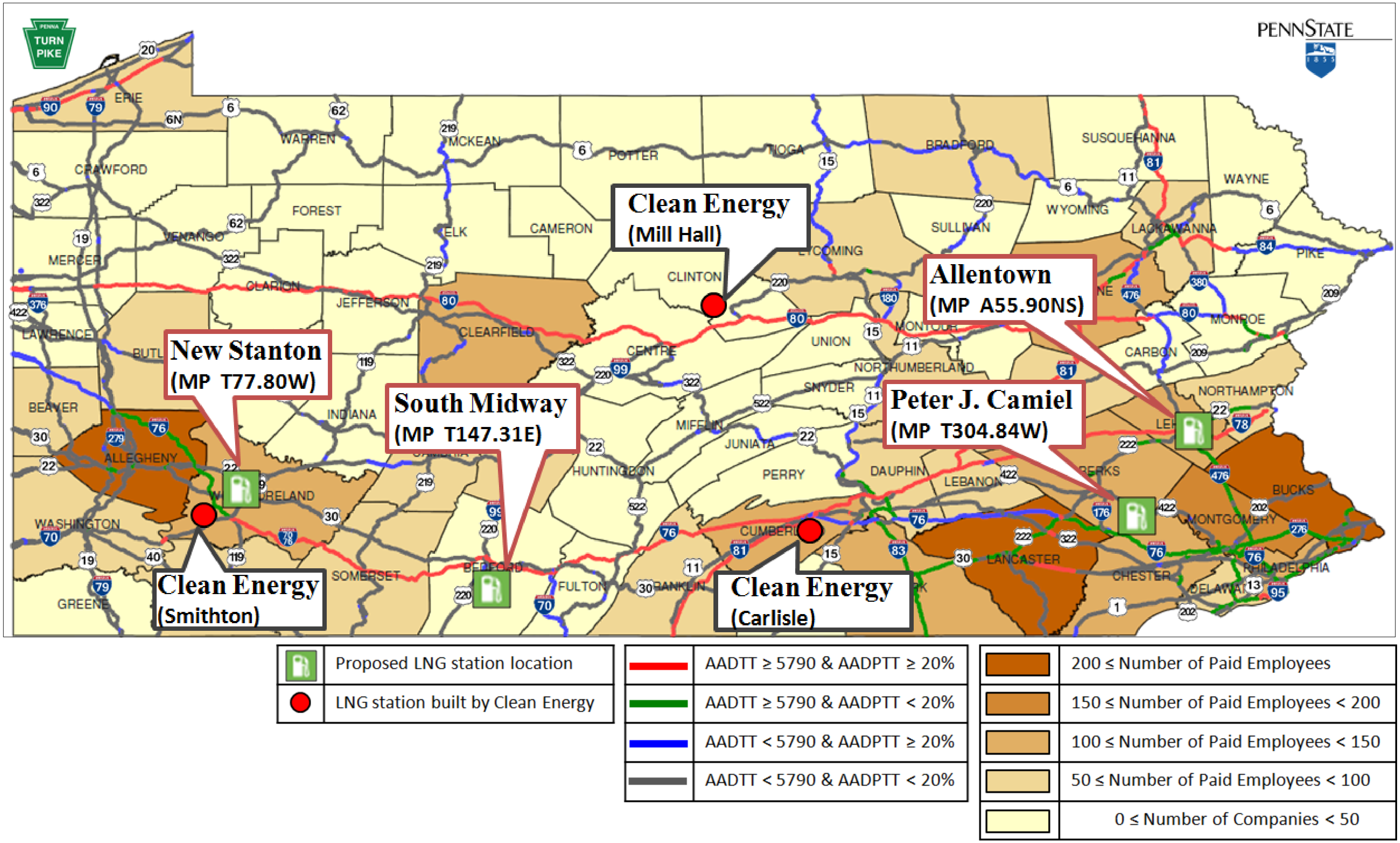

Figure 2.19. Truck volume and density, and distribution of paid employees with locations for the four best LNG fueling stations for a safe traveling distance of R=600 miles

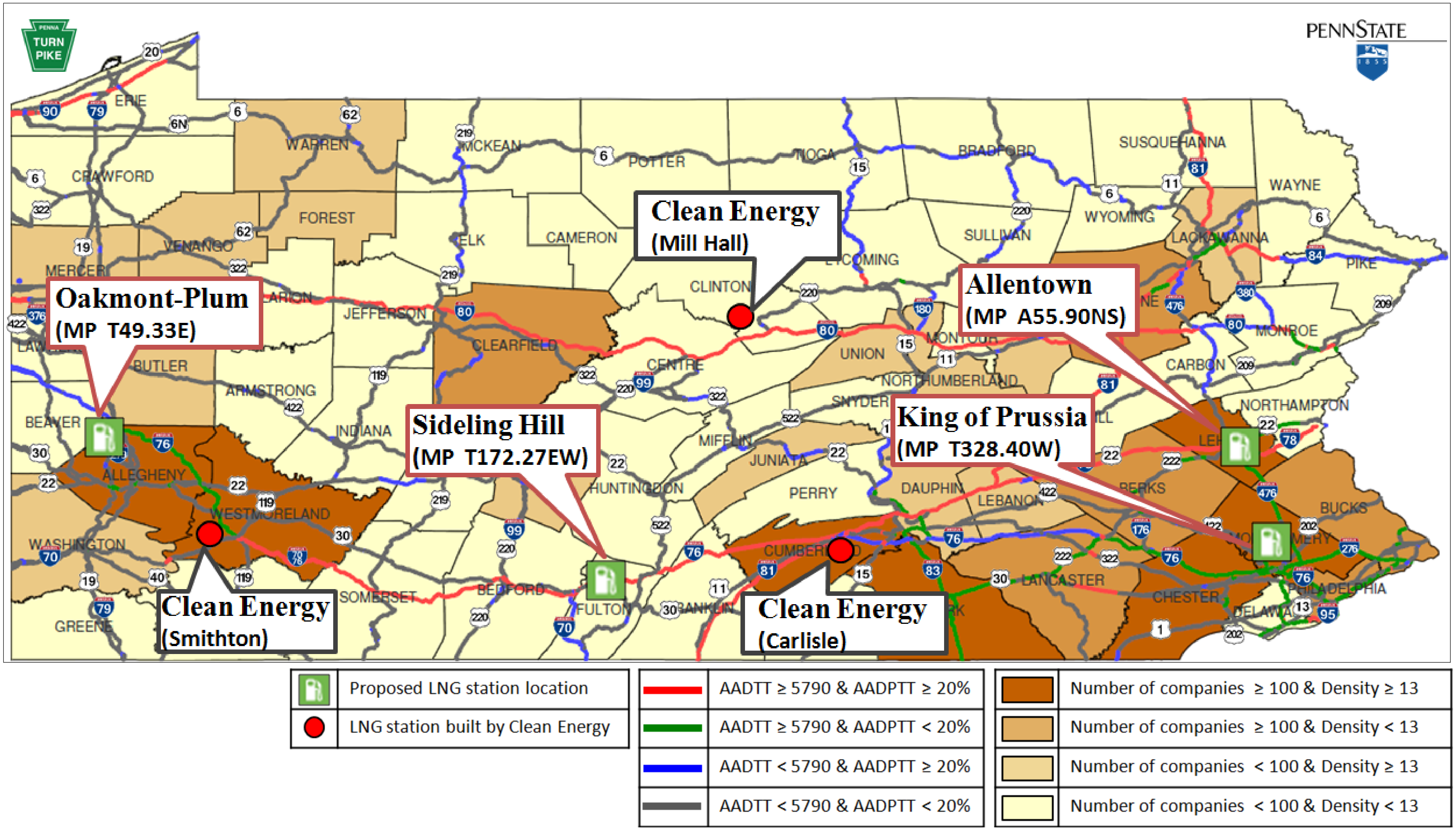

Figure 2.20. Truck volume and density, and distribution of number of trucking companies with locations for the four best LNG fueling stations for a safe traveling distance of R=300 miles

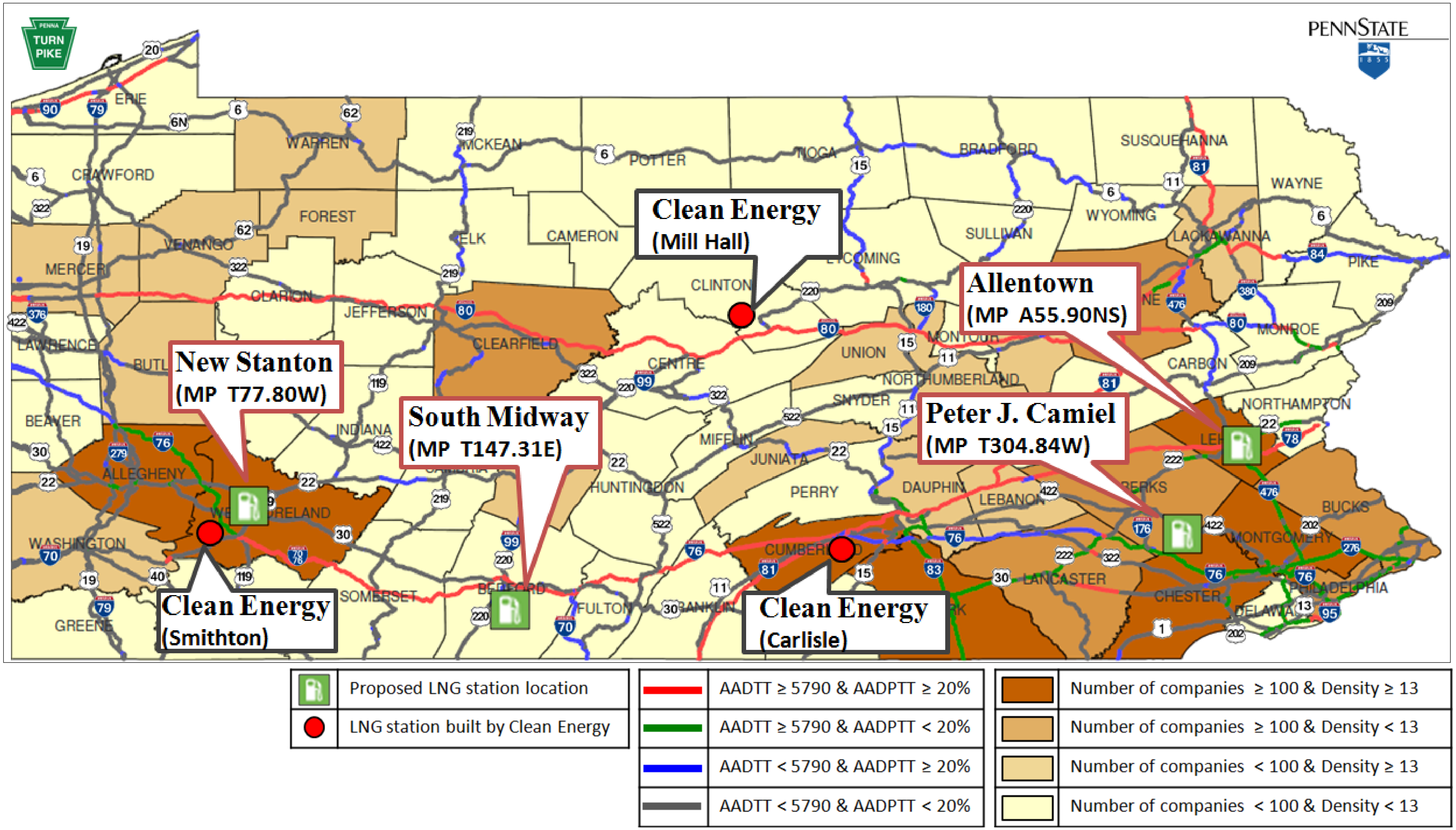

Figure 2.21. Truck volume and density, and distribution of number of trucking companies with locations for the four best LNG fueling stations for a safe traveling distance of R=600 miles

2.6 Overview of Natural Gas Engines and Technology

This portion of Chapter 2 focuses on task 6, the pathways by which the market for LNG-fueled vehicles will develop.

Commercial engines generally operate as either spark ignition (typically, gasoline fueled) or compression ignition (typically, diesel fueled) devices. Due to the nature of the combustion process, engine designs require fuels with particular performance and property specifications. Spark ignition engines, due to the need to avoid spontaneous pre-ignition events ("knock"), require fuels with a high resistance to auto-ignition (described by antiknock index or octane number) and operate within a restricted range of compression ratios, typically between 10:1 to 13:1 for commercial engines. Spark ignition engines have operated typically by injection of the fuel in the intake port ("PFI") or with intake fumigation when operating with gaseous fuels such as propane and natural gas. Compression ignition engines operate by initiating a spontaneous ignition of a portion of the injected fuel and then continuing to inject fuel. To achieve spontaneous ignition of the fuel, diesel engines require fuels with a high auto-ignition tendency (described by the cetane number) and operate with high compression ratios (from 15:1 to 22:1) or with a combination of moderate compression ratio and boosting of intake pressure via a turbocharger or supercharger. Most modern diesel engines operate by directly injecting the fuel into the combustion chamber as well. To use natural gas in such engine systems requires accommodation for the high antiknock character of natural gas; typical gasoline grades range from an octane number (ON) of 87-93. Natural gas composition is quite variable but typically provides an octane number ranging from 120-137 [22].

When converting spark ignition passenger cars from gasoline to natural gas, the engine compression ratio can be increased to improve efficiency relative to the gasoline vehicle baseline from the typical 10:1 to 13:1 or higher [22]. With a compression ratio increase, the fuel efficiency of the gasoline vehicle can be improved by as much as nearly 20%. Without a compression ratio increase the fuel efficiency of the vehicle will likely decrease due to a loss of volumetric efficiency. A higher compression ratio is advisable to capitalize on the higher antiknock capacity of natural gas.

When considering options to convert diesel vehicles to operation on natural gas, several pathways are available. These options have been thoroughly surveyed by Thomas and Staunton and many other authors. The options can be arrayed in order of their impact on thermal efficiency (fuel conversion efficiency) relative to the diesel baseline. Table 2.12 from Thomas and Staunton provides an excellent summary of the impacts that conversion to natural gas can have on energy efficiency, and clearly shows that to maintain diesel vehicle efficiency, natural gas engine technology needs to operate as closely to the diesel combustion process as possible. In this table, Thomas and Staunton base their comparison of the impact of natural gas engine strategies on a typical passenger PFI engine baseline. But, looking from the vantage point of the diesel engine as the baseline, only operation on the conventional compression ignition process can compete in terms of efficiency with diesel-fueled compression ignition engines. However, the latest technological advancement, directly injecting diesel and natural gas into the cylinder, is reported to maintain diesel engine performance and efficiency. To summarize, the options for diesel engine conversion (meaning conversion of an existing engine or design for operation in these configurations, but starting from a diesel engine base design) to natural gas include:

1. Conversion to spark ignition operation – involves decreasing the compression ratio from the compression ignition configuration (typically > 15:1) to a high compression ratio spark ignition configuration (< 15:1) and insertion of spark plugs into the combustion chamber.
2. Conversion to "dual fuel" operation via intake injection of natural gas – involves addition of natural gas (CNG or LNG) tanks onboard the vehicle and injection of natural gas into the intake air. Can readily achieve replacement of as much as 30% of the diesel fuel energy consumption with natural gas. Both OEM vehicle configurations and after-market conversions can be found that operate on this dual-fuel process. The natural gas charge is mixed with intake air and is ignited by the diesel fuel injection.
3. High pressure direct injection (HPDI) – this technology has been pioneered by Westport Innovations in partnership with the Cummins Inc. engine company. A single fuel injector (see http://www.westport-hd.com/technology for detailed information) provides an injection of a small amount of diesel fuel and then natural gas. The diesel serves to ignite the natural gas, and by directly injecting the natural gas rather than injecting into the intake port, diesel torque and efficiency are maintained while allowing up to 95% of the diesel fuel energy to be replaced by natural gas.

This last option, HPDI, appears to be the most energy efficient solution for using natural gas (as LNG) in heavy-duty applications. HPDI technology has recently been offered as an engine option on new trucks but has not yet been made available as an aftermarket retrofit kit for existing truck fleets. This has implications for the growth of LNG adoption given the long service life of class 6-10 trucks, ranging from 10-20 years. Another option would be to convert natural gas to liquid or liquefied gaseous fuels such as DME using synthetic fuel production processes and then operating diesel engines on such fuels. These options are not considered in depth here.

Table 2.12. Impacts on engine efficiency of natural gas technologies

Table 5. Expected relative efficiency changes due to selected engine technologies or engine and vehicle parameter changes (an FTP-75 duty cycle is assumed)

Selected engine design, engine parameter, or vehicle parameter	Energy efficiency change from baseline gasoline engine (%)
Base case gasoline engine and typical NG fleet vehicle engine	
1. Base case engine: SI, gasoline, NA, PFI, ~9.0:1 CR, TWC, in a LD vehicle	Base
2. NG engine very similar to case 1: SI, NA, PFI, ~9.0:1 CR, TWC, lower volumetric efficiency, lower peak power	–9 to –2
Selected design parameter	
3. LD NGV weight penalty, adding 68 kg to a 1360-kg vehicle	–3
4. CR increase from 9.0–10.0:1 to 12.0–13.0:1	+5 to 11
5. NG, control of air and fuel to avoid all rich conditions, use of reduced crevice volume piston, in a stoichiometric SI engine employing TWC	+2 to 4
Stoichiometric SI engines	
6. NG, SI, stoichiometric, turbocharged or DI, NGV with effects of cases 3, 4, and 5 included; compared with current fuel-efficient NA gasoline engine (base case)	+5 to 11
Lean-burn SI engines	
7. Gasoline, lean-burn, early-injection DI, homogeneous charge	+11 to 15
8. NG, lean-burn, turbocharged PFI or DI early-injection (essentially homogeneous charge), SI, with CR increase (case 4) and weight penalty (case 3)	+16 to 20
9. Gasoline, lean-burn, SI, DI stratified charge or IDI (prechamber)	+14 to 18
10. NG, DI stratified charge or IDI (prechamber), lean burn, with CR increase (case 3) and weight penalty (case 2)	+19 to 23
CI engines	
11. NG, CI, turbocharged, homogeneous charge, micropilot ignition (~19:1 CR), some throttling needed; weight penalty of 113 kg for 1360-kg vehicle included	+24 to 29
12. NG, CI, turbocharged, DI stratified charge or IDI (prechamber), micropilot ignition (~19:1 CR); weight penalty of 113 kg for 1360-kg vehicle included; a small amount of throttling is assumed to be required	+28 to 37
13. Diesel fueled, turbocharged, IDI, and DI engines	+30 to 44

Note: CI—compression ignition, DI—direct injection, IDI—indirect injection, SI—spark ignition, PFI—port fuel injection, NA—naturally aspirated, CR—compression ratio, NGV—natural gas vehicle.

Dual Fuel Conversion Kits

While in the long term, the primary LNG fueling options for heavy-duty tractor trailer rigs will be through new vehicle offerings that are EPA and/or CARB certified, rather than aftermarket conversions, aftermarket conversion of existing vehicles provides a means of immediately expanding the fleet of vehicles that can utilize CNG or LNG. However, aftermarket kits run into significant liability problems for vehicle owners, because most kits are not emissions certified and any operator that implements them could be found to have "tampered" with the vehicle and violated EPA rules. The regulatory aspects related to aftermarket conversions are complex and remain in flux as state governments such as Pennsylvania explore ways to expand transportation applications of natural gas. Nonetheless, because new diesel vehicles can be expected to have a long lifetime (depending on their application and duty cycle) of from 8-19 years of age and can accumulate from 30,000 to 130,000 miles annually, there are opportunities to utilize substantial amounts of natural gas through conversion of in-use vehicles [23]. However, with the uncertainty in the regulatory environment over certification of kits and vehicles to which such kits can be applied, the growth of natural gas usage along the Pennsylvania Turnpike is presently unclear.

Natural Gas Engine and Vehicle Products

According to the DOE Alternative Fuels Data Center (AFDC), only four LNG engines are available for new vehicles to adopt: Westport Innovations Westport HD, Westport Innovations GX, Cummins Westport Inc. ISL G, and Clean Air Power Integrated Dual-Fuel. [24] Clean Air Power provides scant information about its engine on its website. The company primarily does its business in the UK and it seems the company only has components for CNG engines rather than for an LNG engine. According to the AFDC, 22 types of heavy-duty LNG vehicles are available. A majority of them have the Cummins Westport ISL G engine, while a few use the Westport Innovations HD engines. Table 2.13 presents information collected on LNG engines obtained by searching manufacturers' websites.

Since Cummins engines appear in HD trucks sold by a variety of truck manufacturers, customers can obtain some of these vehicles through different truck manufacturers and in different truck configurations. In addition, Volvo Trucks now offers vehicles with its 13-liter engine that includes the Westport "HPDI"—high pressure direct injection of diesel and natural gas—fueled by LNG. They also offer a 12-liter Cummins Westport ISX12 G, which is a spark ignition engine fueled by CNG. Customers can purchase heavy-duty trucks from Freightliner, Kenworth, Peterbilt, Mack, Volvo, and others that include LNG and CNG fueling options in various application areas.

Table 2.13. Survey of natural gas HD vehicle offerings

Manufacturer	Engine	Models	LNG?	CNG?	Ignition	Other Info	Source
Cummins Westport Inc.	ISX12	320, 330, 350, 385, 400	yes	yes	SI	available 2013	http://www.cumminswestport.com/
Cummins Westport Inc.	ISL G	250, 260, 280, 300, 320	yes	yes	SI	13,000 currently in service	http://www.cumminswestport.com/
Westport Innovations	HD	400, 450, 475	yes	no	CI (diesel pilot)		http://www.westport-hd.com/
Westport Innovations	GX	400, 450	yes	no	CI (diesel pilot)		http://www.westport-hd.com/, http://www.ngvamerica.org/pdfs/marketplace/MP.Analyses.NGVs-a.pdf
Emissions Solutions Inc./International Truck	ESI-0308	195, 210, 225, 255, 285	TBD	yes	SI		http://www.emissionsolutionsinc.com/ESI/Emission_Solutions_Inc.html
Emissions Solutions Inc./International Truck	ESI-0313/326	210, 225, 255, 300	TBD	yes	SI		http://www.emissionsolutionsinc.com/ESI/Emission_Solutions_Inc.html

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Chapter 3: Fueling Station Characteristics, Considerations, and Costs

An LNG fueling station has several features that make it physically unique from the diesel and gasoline fueling stations that are currently found at the Commission's service plazas. The primary difference is due to the cryogenic properties of LNG fuel, which require specialized equipment to store, pump, and dispense a fuel with an approximate temperature of -260°F. This chapter of the study covers tasks 2-4 (see study task list in Table I.1) and will address the following:

- Introduce the basic components of a conventional LNG fueling station
- Discuss the costs and physical challenges that exist for the Commission to construct an LNG fueling station on the site of an existing service plaza
- Discuss the opportunity to construct a model LNG fueling station – a fueling station capable of providing complete service to the commercial trucks utilizing LNG fuel
- Discuss the opportunity to construct an independent LNG fueling station at one of the surplus service plazas or a surplus parcel of property
- Discuss the option to utilize an LNG mobile fueling station
- Discuss the business models to construct, operate, and maintain an LNG fueling station

3.1 Introduction to an LNG Fueling Station

The basic components of an LNG fueling station are presented in Figure 3.1.

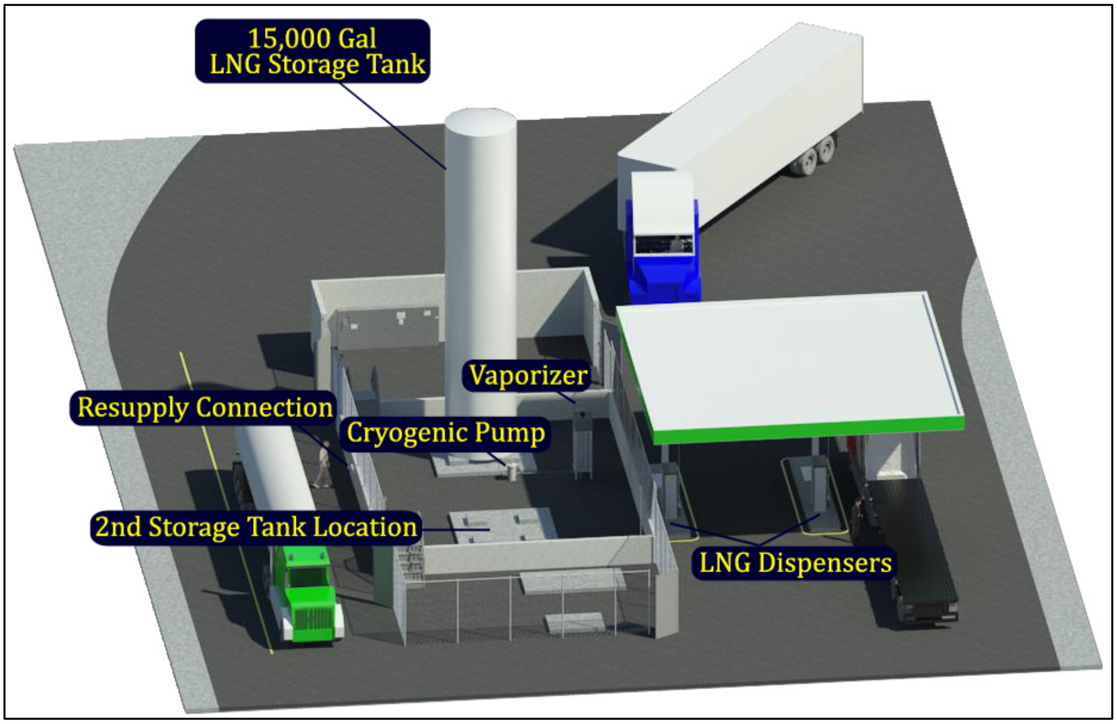

Figure 3.1. Basic components of an LNG fueling station

LNG can be stored above or below ground at fueling stations in vacuum-insulated storage tanks with typical storage volumes in the range of 10,000 to 20,000 gallons. The specialized storage tanks are necessary to minimize the temperature increase of the fuel so it will remain in a liquid form as long as practically possible without refrigeration. The tanks can be sized to meet the fuel demand at each location but, according to our observation, the tanks are typically found to have a 15,000-gallon capacity in order to accept delivery from a 10,000-gallon tanker truck. Since the demand for this type of fuel is difficult to predict over the next decade, many fueling station owners find it advantageous to construct the foundation for an additional fuel storage tank as part of the original construction operations. The height of a 15,000-gallon storage tank can be in excess of 40 feet above the traffic surface, thus making it the most prominent component of the fueling station.

The movement of the LNG fuel from the storage tank to the fuel dispenser begins with the aid of a cryogenic pump in order to overcome the pressure inside the vehicle fuel tanks. The pump pulls the liquid out of the tank and through a warming vaporizer until the pressure in the vaporizer is approximately 80 to 100 psi. This process is called saturation. The pressure of the liquid is now at a point where it can be dispensed to the vehicle.

The fueling equipment at the dispenser is similar to the pump and hose used for gasoline or diesel fuel; the major differences are the dispensing nozzle size and the locking requirements to ensure a proper seal and avoid leaks or spills. The LNG dispenser hoses are vacuum-jacketed for insulation purposes, and consumers should be required to wear PPE, including a safety mask and gloves while dispensing fuel in order to avoid cryogenic burns. Additionally, a grounding wire is connected between the fuel dispenser and the vehicle before any fueling can commence in order to eliminate static electricity as a source of ignition. The LNG fuel dispensing process is unique in comparison to the diesel fueling process; however, the training resources offered by LNG fuel suppliers and fueling station operators to train consumers on the proper dispensing of this fuel has proven to be a reliable and a successful program.

The LNG fueling process described above could not occur without the aid of a computer automation system to power, control, and manage the complete fueling process. Once programmed by the fuel station vendor, the automation system handles all of the complex tasks required to operate and monitor the fueling station while presenting a simple user interface to the consumer. This allows the consumer to simply insert payment and fill the vehicle with fuel as with any other filling station while the automation system operates in the background.
The installation of 15,000 gallon storage tanks at LNG fuel stations should provide service plazas with a 5 to 7 day reserve of fuel and the ability to overcome a majority of the limitations due to short-term fuel supply or transportation problems. The winter weather in Pennsylvania and hazardous material traveling restrictions imposed by the five tunnels along the Turnpike corridor are potential factors limiting LNG transport by truck. Given the current liquefaction production capacity in the region, there may be times when there is a short term tightening on

supply. An example of this is that extended cold winter weather may increase demand on natural gas and reduce the supply of LNG for some customers. However, the 15,000 gallon tank should mitigate these risks.

3.2 Construction Cost and Challenges at Existing Service Plaza Sites

In Chapter 2 of this study, the Commission is presented with recommendations for the optimal locations of LNG fueling stations at current and surplus service plazas. The complex analysis used to determine the optimal locations is invaluable, since it is based on safe traveling distances for single- and dual-tank vehicles utilizing LNG fuel as they travel along the Turnpike highway system. This portion of the study assesses the existing site conditions at several of the service plazas identified in Chapter 2 with regard to their ability to accommodate an LNG fueling station. The challenges posed by the existing site conditions are then used to determine the estimated cost of construction for an LNG fueling station. Additionally, the Commission is presented with options to construct an independent, alternative fuels station at surplus service plazas or install a mobile LNG fueling station.

The following service plaza locations were selected for conceptual site design for an LNG fueling station since they routinely appear as optimal locations based on the criteria established in Chapter 2. The sites are arranged in their order of prominence as determined by the traffic optimization model:

- Allentown Service Plaza
- Sideling Hill Service Plaza
- Oakmont-Plum Service Plaza
- King of Prussia Service Plaza (MP T328.40)
- New Stanton Service Plaza (MP T77.80)
- South & North Midway Service Plazas (MP T112.33 & 112.37)
- Peter J. Camiel (MP T304.84)

Based on our assessment of these locations, it became quite clear that the most challenging requirement to accommodate a new LNG fueling station at an existing service plaza is the availability of adequate space for the station and the proposed path of travel for semi-trailer trucks, rather than the infrastructure required to operate the fueling station. As compared to its gasoline and diesel-fuel station counterparts, an LNG fueling station has some distinct characteristics that require consideration when planning for the new location:

- Above-ground storage tanks: An LNG fueling station will typically utilize an above-ground containment area for storage tanks and fuel equipment. The underground tank storage system utilized for gasoline and diesel fuels is not common practice for the LNG industry. As a result, the above-ground footprint and obstructed path for vehicular traffic is much larger for an LNG fueling station. A typical fueling station comprised of a tank storage area and fuel island canopy will occupy an area of approximately 3,200 square feet.

- Cryogenic fuel distribution: The distance between an LNG storage tank and the fuel dispensing equipment (i.e., fuel island) should be kept to a minimum due to the additional piping costs and potential degradation of the fuel. Storage tanks for gasoline and diesel fuels are often found a considerable distance away from the fuel dispensing equipment, since there are no losses in fuel performance or special insulating requirements necessary to distribute these fuels. Infrastructure for LNG fuel distribution is very expensive to distribute because a special form of double-walled piping (referred to as vacuum-jacketed [VJ] piping) must be installed in an effort to maintain the cryogenic temperature of the fuel. As a result, the LNG fuel-dispensing equipment and storage tanks are typically kept in close proximity to each other to avoid the excessive cost and concerns of distributing the fuel through the VJ pipes.
- Existing truck parking: The Commission has made a considerable effort over the years to increase the amount of truck parking (i.e., heavy-duty and tractor trailer combinations) at the service plazas for the safety of all motorists. This measure is intended to reduce the amount of truck parking adjacent to the roadway shoulders and along the acceleration or deceleration lanes. As a result, the location of a new LNG fueling station at an existing service plaza will need to be considerate of the impact it will have on the truck parking area.
- Truck travel path: The existing service plazas, whether redeveloped or not, are well designed with regard to the travel path for light- and heavy-duty vehicles entering and exiting the property, but accommodating a safe travel path for trucks accessing a new LNG fueling station will be a challenge. The selection of a safe travel path must consider the increased width and turning radii of the truck traffic and the possibility that trucks utilizing high-pressure direct injection engine technology may also desire to access the diesel fueling station during the same visit. As a result, the location of a new LNG fueling station may need to be constructed on land adjacent to or on the perimeter of a service plaza to meet the safe travel path requirements. Alternatively, this issue could be resolved by installation of a low-volume, diesel fuel dispenser at the LNG fuel island, as discussed later in this chapter.

With these considerations in mind, the most prominent service plaza sites, based on the traffic optimization model, were identified and visited to determine the challenges that may exist for the construction of an LNG fueling station. This information, combined with the authors' knowledge from visiting the sites on an annual basis for facility condition assessments was utilized to develop the conceptual site plans which are presented on the following pages. The conceptual site plans utilize aerial photography and a scaled version of an LNG fueling station as depicted in Figure 3.1 to offer the Commission some perspective on the impact this construction will have on the existing site. Each conceptual site plan includes information pertaining to the estimated cost of construction as well as a list of the advantages and disadvantages associated with the proposed location. Whenever possible, the research team has provided the Commission with several options for the proposed location of a new LNG fueling station at a service plaza.

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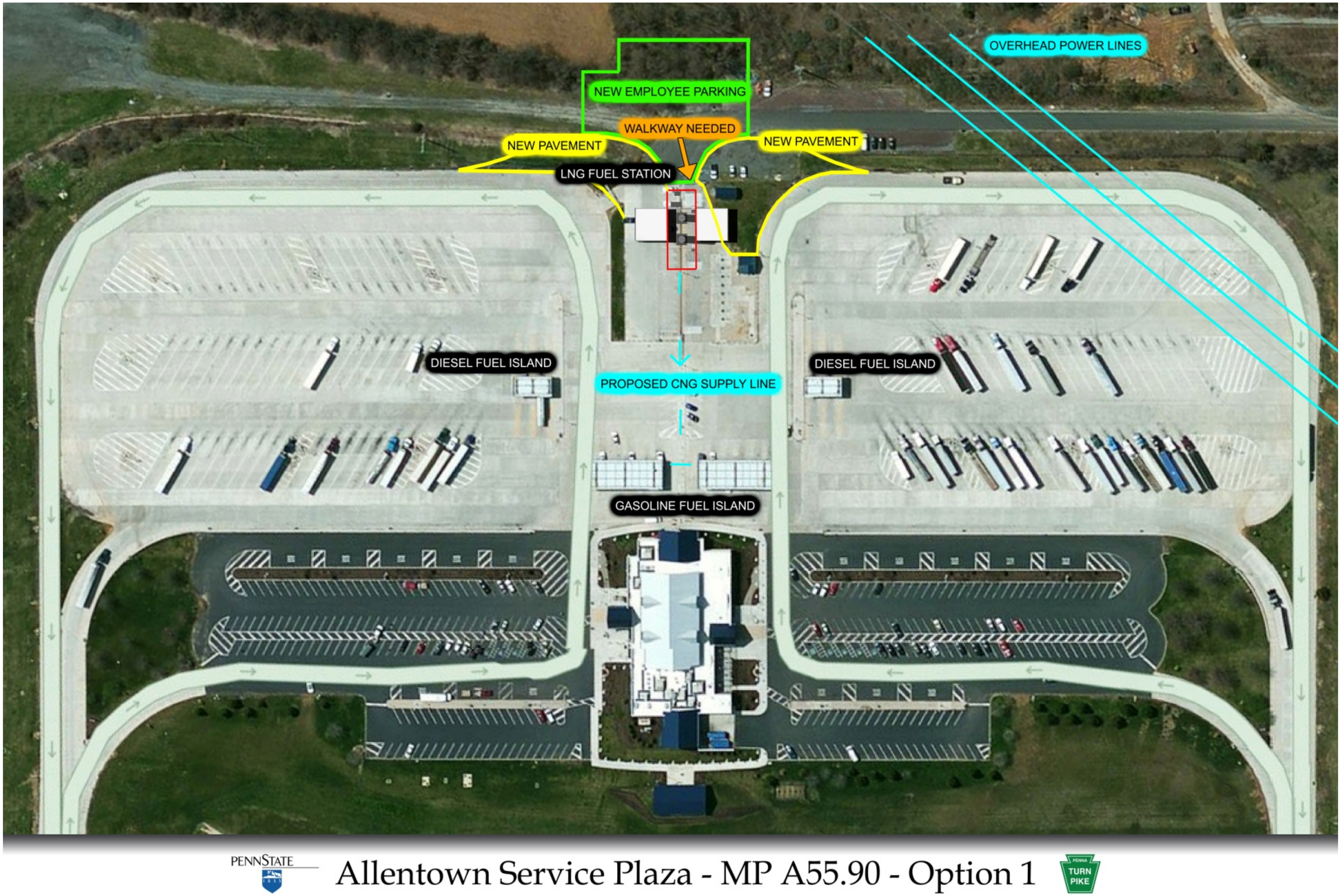

Figure 3.2. Conceptual Option 1 for LNG fueling station installation at the Allentown Service Plaza

Allentown Service Plaza (MP A55.90)

Estimated Cost to Construct - *$3.8 million w/o property acquisition**

<u>Option 1 – New LNG fuel station at west (rear) end</u>

Advantages

- Cost-effective construction utilizing one storage tank containment area to serve two fuel dispensing areas
- Safe travel path for easy access to both LNG and diesel fueling stations for trucks equipped with HPDI engines; No requirement to install low-volume diesel fuel dispenser at LNG fuel island
- Short distance to install optional, underground CNG fuel supply line to gasoline fuel island
- No loss of existing truck parking stalls

Disadvantages

- Approximately 3,500 square feet of additional property will need to be acquired
- Existing employee parking area will need to relocated
- Existing storage buildings will need to be relocated
- Considerable amount of concrete-paved surface to be constructed for new exit path from LNG fueling station and new employee parking area
- Existing underground storage tanks for gasoline and diesel fuel are in immediate vicinity of northbound truck refueling lane. Diesel and gasoline fuel delivery events will disrupt LNG fueling for these trucks

* An additional $750,000 should be added to each option above when considering an LCNG station with boil off gas collection.

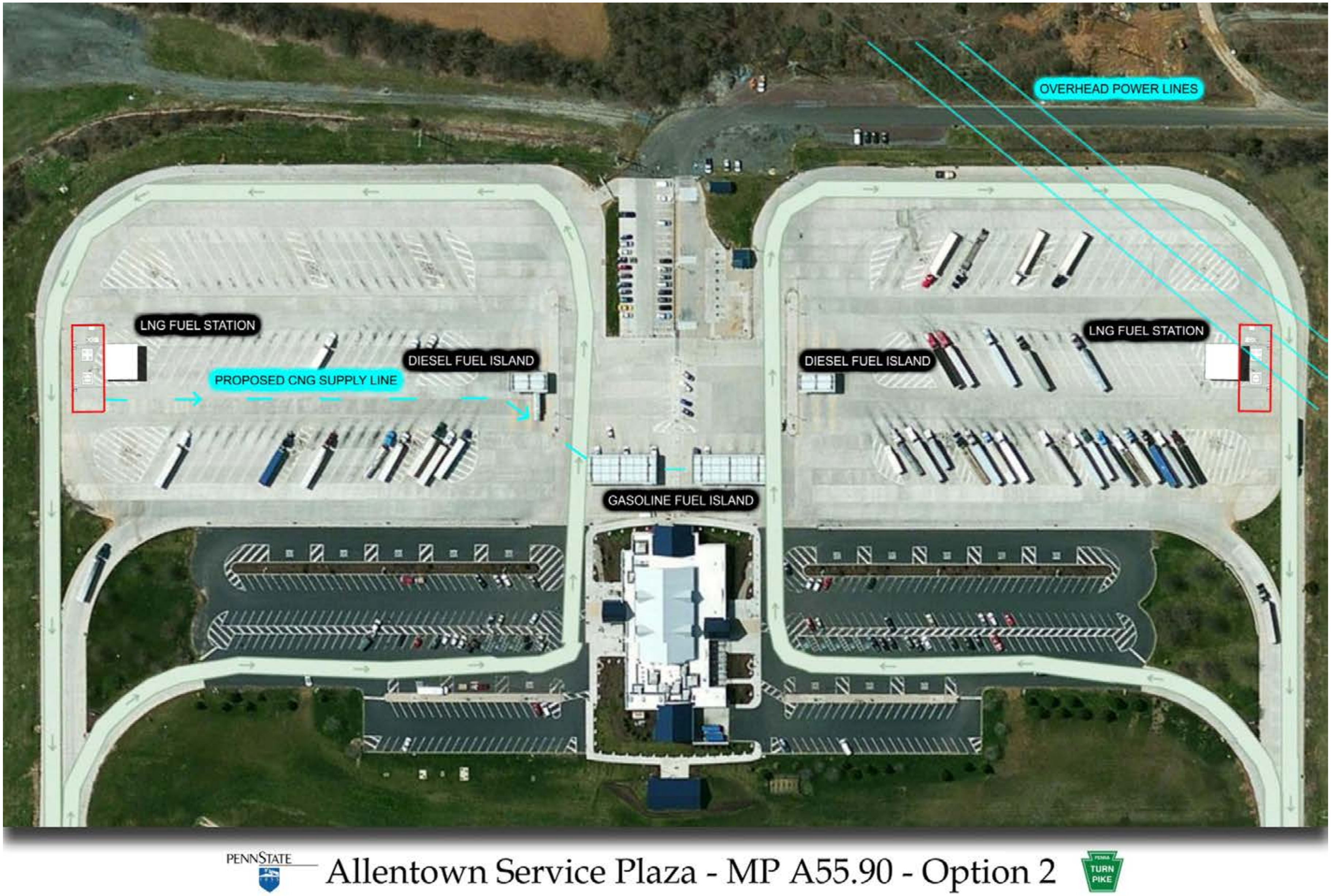

Figure 3.3. Conceptual Option 2 for LNG fueling station installation at the Allentown Service Plaza

Allentown Service Plaza (MP A55.90)

Option 2 – New LNG fuel stations at north and south ends

*Estimated Cost to Construct - $3.6 million**

Advantages

- No acquisition of additional property
- No loss of employee parking area or existing storage buildings
- No costs associated with additional paved areas
- Safe travel path for easy access to both LNG and diesel fueling stations for trucks equipped with HPDI engines; No requirement to install low-volume diesel fuel dispenser at LNG fuel island

Disadvantages

- Dual LNG fueling stations not cost effective
- Distance to existing gasoline fuel island may make option to install underground CNG fuel supply line cost prohibitive
- Cars and other light-duty vehicles in need of CNG fuel would need to access common area with trucks if a cost effective option were to be considered
- Selective demolition of existing concrete surface for installation of tank foundations and other items may add costs as compared to typical asphalt surface
- Loss of approximately 9 existing truck parking stalls at each end
- Location of existing overhead power lines on north end of the service plaza may require adjustment in LNG fuel station location

* An additional $750,000 should be added to each option above when considering an LCNG station with boil off gas collection.

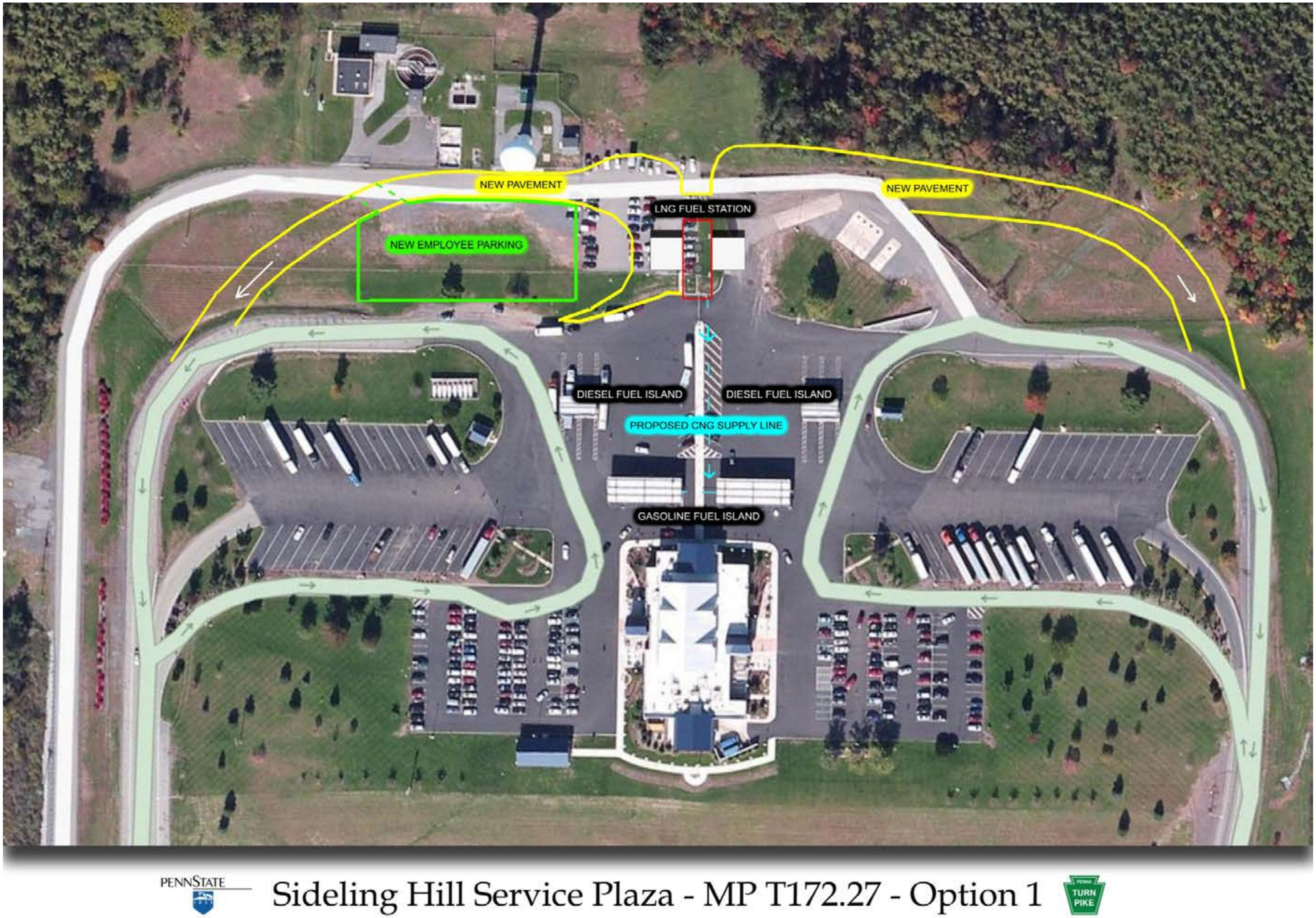

Figure 3.4. Conceptual Option 1 for LNG fueling station installation at the Sideling Hill service plaza

Sideling Hill Service Plaza (MP T172.27)

Option 1 – New LNG fuel station at north (rear) end

Estimated Cost to Construct - *$3.95 million**

Advantages

- Cost-effective construction utilizing one storage tank containment area to serve two fuel dispensing areas
- Safe travel path for easy access to both LNG and diesel fueling stations for trucks equipped with HPDI engines; No requirement to install low-volume diesel fuel dispenser at LNG fuel island
- Short distance to install optional, underground CNG fuel supply line to gasoline fuel island
- No loss of existing truck parking stalls

Disadvantages

- Existing employee parking area will need to be relocated. Employee access by vehicle to new parking area requires crossing path of trucks leaving the LNG fueling station.
- Considerable amount of asphalt-paved surface to be constructed for new exit path from LNG fueling station and new employee parking area
- Local access road will require realignment near existing wastewater treatment plant

* An additional $750,000 should be added to each option when considering an LCNG station with boil off gas collection.

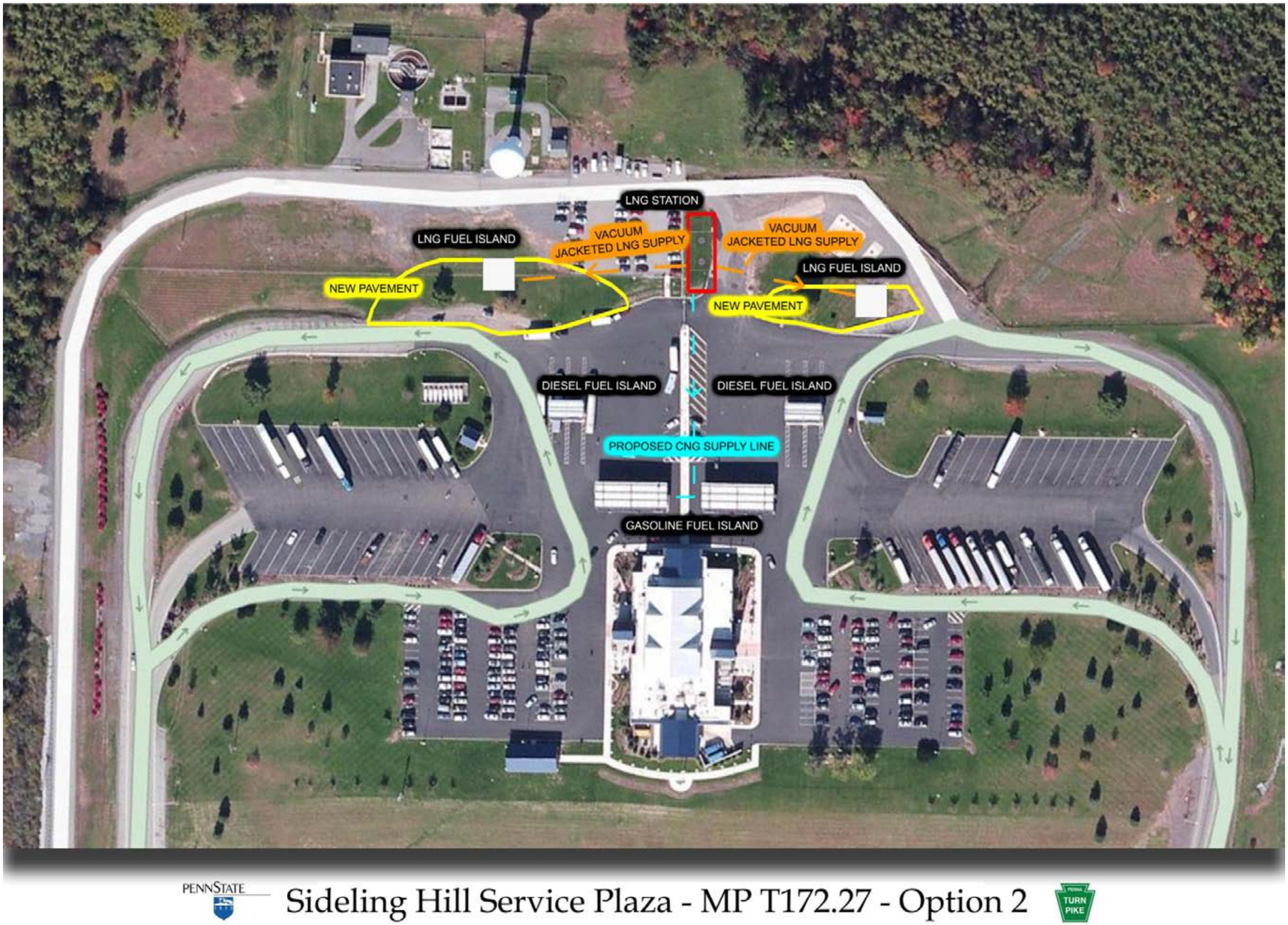

Figure 3.5. Conceptual Option 2 for LNG fueling station installation at the Sideling Hill service plaza

Sideling Hill Service Plaza (MP T172.27)

Option 2 – New LNG fuel station at north (rear) end with separated fuel islands

*Estimated Cost to Construct - $3.45 million**

Advantages

- In an effort to reduce the amount and cost of new asphalt pavement shown in Option 1, dual fuel dispenser islands are shown separated from the storage tank containment area
- Safe travel path for easy access to both LNG and diesel fueling stations for trucks equipped with HPDI engines; No requirement to install low-volume diesel fuel dispenser at LNG fuel island
- Short distance to install optional, underground CNG fuel supply line to gasoline fuel island
- No disruption to employee parking area or local road access
- No disruption to LNG fuel lanes during refueling operations due to multiple access points along tank containment area
- No loss of existing truck parking stalls

Disadvantages

- Vacuum-jacketed piping will need to be installed to distribute the cryogenic LNG fuel from the storage tanks to the fuel dispensers. The vacuum insulated piping material is expensive and may also pose an operational issue with LNG stored in the line between fueling events.

* An additional $750,000 should be added to each option above when considering an LCNG station with boil off gas collection.

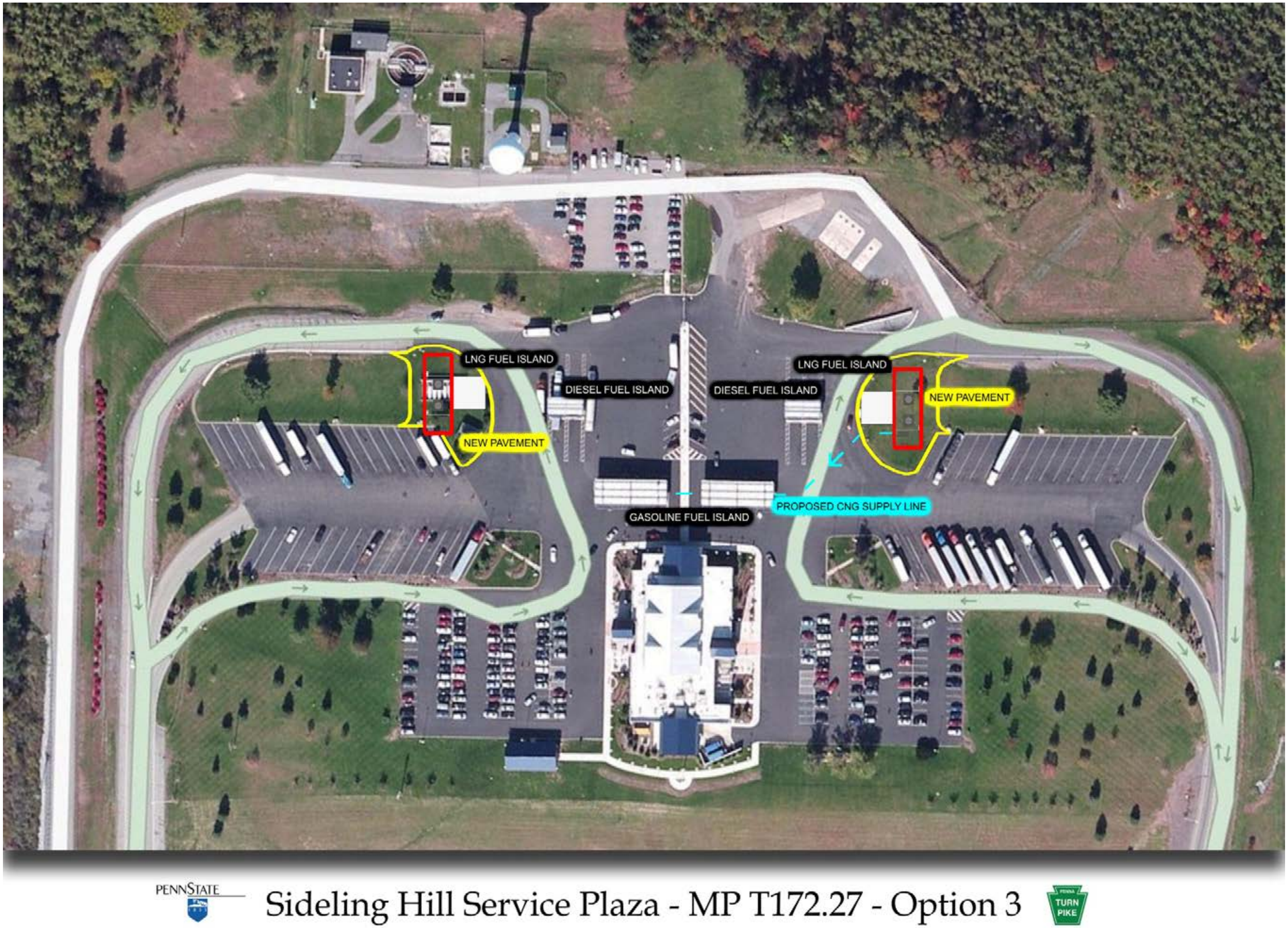

Figure 3.6. Conceptual Option 3 for LNG fueling station installation at the Sideling Hill service plaza

Sideling Hill Service Plaza (MP T172.27)

Option 3 – New LNG fuel stations at east and west ends

Estimated Cost to Construct - *$3.4 million**

Advantages

- In an effort to reduce the amount and cost of new asphalt pavement shown in Option 1 and the cost of vacuum-jacketed piping in Option 2, dual fueling stations are proposed on the east and west ends of the Service Plaza
- Short distance to install optional, underground CNG fuel supply line to gasoline fuel island
- No disruption to employee parking area or local road access
- Minor loss of existing truck parking stalls

Disadvantages

- Difficult travel path for trucks equipped with HPDI engines to access both LNG and diesel fueling stations during same visit due to site restrictions; Low-volume diesel fuel dispenser may be required at LNG fueling station to resolve issue
- LNG storage tank refueling will require closure of one LNG fuel lane since access is limited on rear and sides of tank containment area
- New asphalt pavement will need to be installed to assist with trucks leaving the LNG fueling station

* An additional $750,000 should be added to each option above when considering an LCNG station with boil off gas collection.

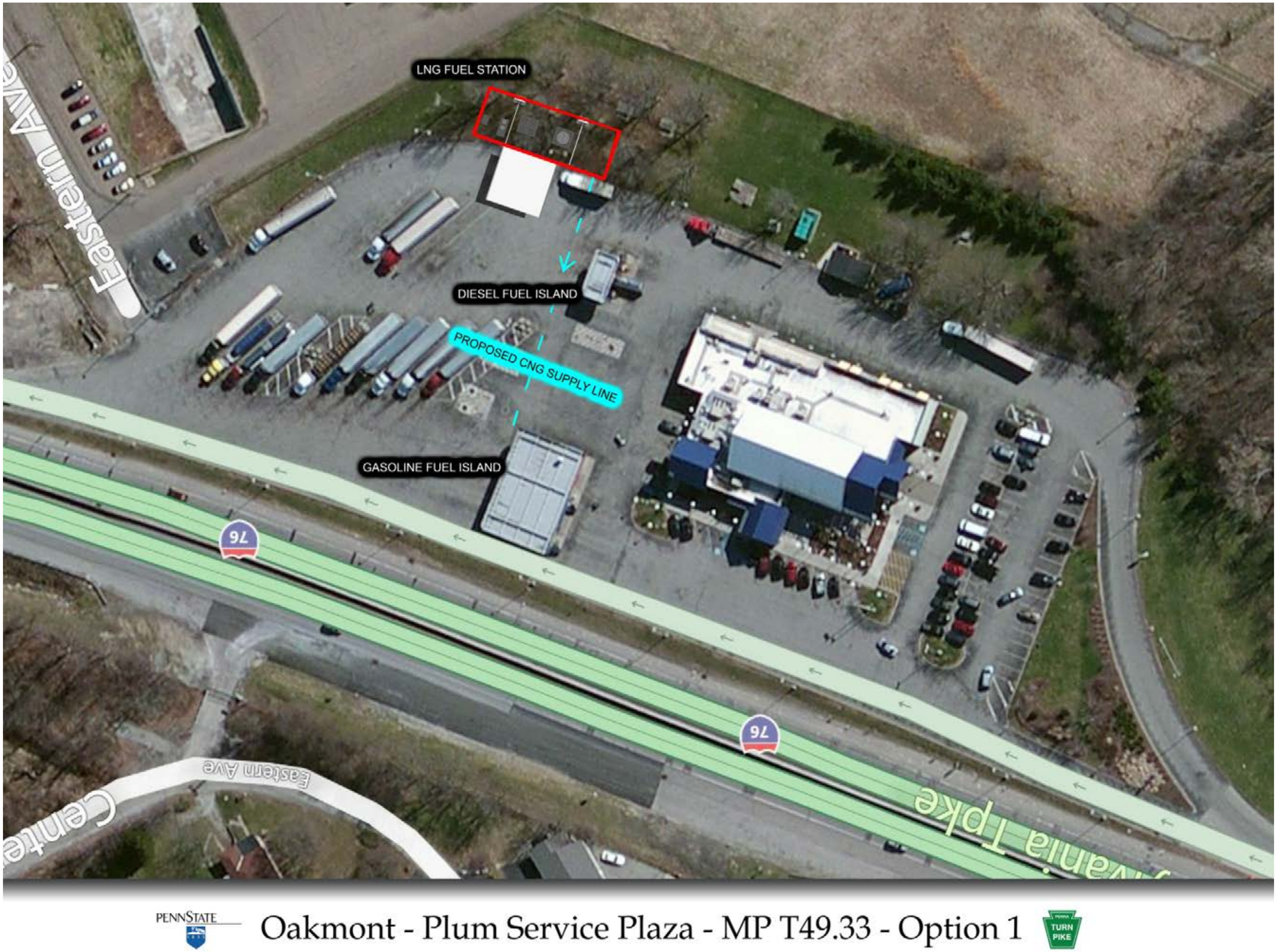

Figure 3.7. Conceptual Option 1 for LNG fueling station installation at the Oakmont-Plum service plaza

Oakmont-Plum Service Plaza (MP T49.33)

Option 1 – LNG fuel station at southeast corner

Estimated Cost to Construct - *$1.8 million**

Advantages

- Fueling station located within existing property boundaries
- Minimal disruption and restoration to existing paving
- Short distance to install optional, underground CNG fuel supply line to gasoline fuel island

Disadvantages

- Proposed location disrupts existing flow of truck traffic
- Multiple truck parking stalls would be lost due to new truck travel path
- LNG storage tank refueling will require closure of one LNG fuel lane since access is limited on rear and sides of tank containment area
- Difficult travel path for trucks equipped with HPDI engines to access both LNG and diesel fueling stations during same visit due to site restrictions; Low-volume diesel fuel dispenser may be required at LNG fueling station to resolve issue

* An additional $750,000 should be added to each option above when considering an LCNG station with boil off gas collection.

Figure 3.8. Conceptual Option 2 for LNG fueling station installation at the Oakmont-Plum service plaza

Oakmont-Plum Service Plaza (MP T49.33)

<u>Option 2 – LNG fuel station at rear</u>

*Estimated Cost to Construct - $2.6 million w/o property acquisition**

Advantages

- No disruption to existing traffic patterns
- Minimal loss of existing truck parking stalls
- No disruption to LNG fuel lanes during storage tank refueling operations due to multiple access points along tank containment area

Disadvantages

- Approximately 5,400 square feet of additional property will need to be acquired
- Additional cost due to new site paving and lighting
- Longer distance to install optional, underground CNG fuel supply line to gasoline fuel island
- Difficult travel path for trucks equipped with HPDI engines to access both LNG and diesel fueling stations during same visit due to site restrictions; low-volume diesel fuel dispenser may be required at LNG fueling station to resolve issue

* An additional $750,000 should be added to each option above when considering an LCNG station with boil off gas collection.

Figure 3.9. Conceptual plan for LNG fueling station installation at the King of Prussia service plaza

King of Prussia Service Plaza (MP T328.40)

Estimated Cost to Construct - *$1.9 million**

Advantages

- No additional property to be acquired
- Safe travel path for easy access to both LNG and diesel fueling stations for trucks equipped with HPDI engines; No requirement to install low-volume diesel fuel dispenser at LNG fuel island
- Short distance to install optional, underground CNG fuel supply line to gasoline fuel island

Disadvantages

- Loss of approximately 6 existing parking stalls for trucks
- LNG storage tank refueling will require closure of one LNG fuel lane since access is limited on rear and sides of tank containment area
- Proposed location on property has history of sink hole activity

* An additional $750,000 should be added to each option when considering an LCNG station with boil off gas collection.

Figure 3.10. Conceptual Option 1 for LNG fueling station installation at the New Stanton service plaza

New Stanton Service Plaza (MP T77.80)

<u>Option 1 – LNG fuel station at west end</u>

*Estimated Cost to Construct – $2.5 million**

Advantages

- Minimal disruption to existing traffic patterns
- No loss of existing truck parking stalls
- No disruption to LNG fuel lanes during storage tank refueling operations due to multiple access points along tank containment area
- Reasonable distance to install optional underground CNG fuel supply line to gasoline fuel island
- Safe travel path for easy access to both LNG and diesel fueling stations for trucks equipped with HPDI engines; No requirement to install low-volume diesel fuel dispenser at LNG fuel island

Disadvantages

- Additional property may need to be acquired
- Additional cost due to new site paving, retaining wall and site lighting
- May require minor realignment and possible extension of acceleration lane

* An additional $750,000 should be added to each option when considering an LCNG station with boil off gas collection.

Figure 3.11. Conceptual Option 2 for LNG fueling station installation at the New Stanton service plaza

New Stanton Service Plaza (MP T77.80)

Option 2 – LNG fuel station at east end of truck service electrification parking area

Estimated Cost to Construct - *$2.3 million**

Advantages

- Fueling station located within existing property boundaries
- No disruption to existing traffic patterns around service plaza;
- Location well suited for trucking customer
- Minor loss of existing truck parking stalls
- No disruption to fuel lanes during storage tank refueling operations due to multiple access points along tank containment area
- Safe travel path for easy access to both LNG and diesel fueling stations for trucks equipped with HPDI engines; No requirement to install low-volume diesel fuel dispenser at LNG fuel island

Disadvantages

- Potential issue with installation of new electric service panel at fueling station due to distance; additional costs may result
- Distance to existing gasoline fuel island may make option to install underground CNG fuel supply line cost prohibitive
- Cars and other light-duty vehicles in need of CNG fuel would need to access common area with trucks if a cost effective option were to be considered
- Selective demolition of existing concrete surface for installation of tank foundations and other items may add costs as compared to typical asphalt surface.

* An additional $750,000 should be added to each option when considering an LCNG station with boil off gas collection.

Figure 3.12. Conceptual Option 3 for LNG fueling station installation at the New Stanton service plaza

New Stanton Service Plaza (MP T77.80)

Option 3 – LNG fuel station at north end of truck service electrification parking area

*Estimated Cost to Construct - $3.4 million**

Advantages

- No disruption to existing traffic patterns around service plaza
- Location well suited for trucking customer
- Safe travel path for easy access to LNG fueling station with defined traffic pattern for trucks
- No loss of existing truck parking stalls
- No disruption to LNG fuel lanes during refueling operations due to multiple access points along tank containment area
- Safe travel path for easy access to both LNG and diesel fueling stations for trucks equipped with HPDI engines; No requirement to install low-volume diesel fuel dispenser at LNG fuel island

Disadvantages

- Additional property may need to be acquired
- Potential issue with installation of new electric service panel at fueling station due to distance, additional costs may result
- Distance to existing gasoline fuel island may make option to install underground CNG fuel supply line cost prohibitive
- Cars and other light-duty vehicles in need of CNG fuel would need to access common area with trucks if a cost effective option were to be considered

* An additional $750,000 should be added to each option when considering a combined LCNG station with boil off gas collection.

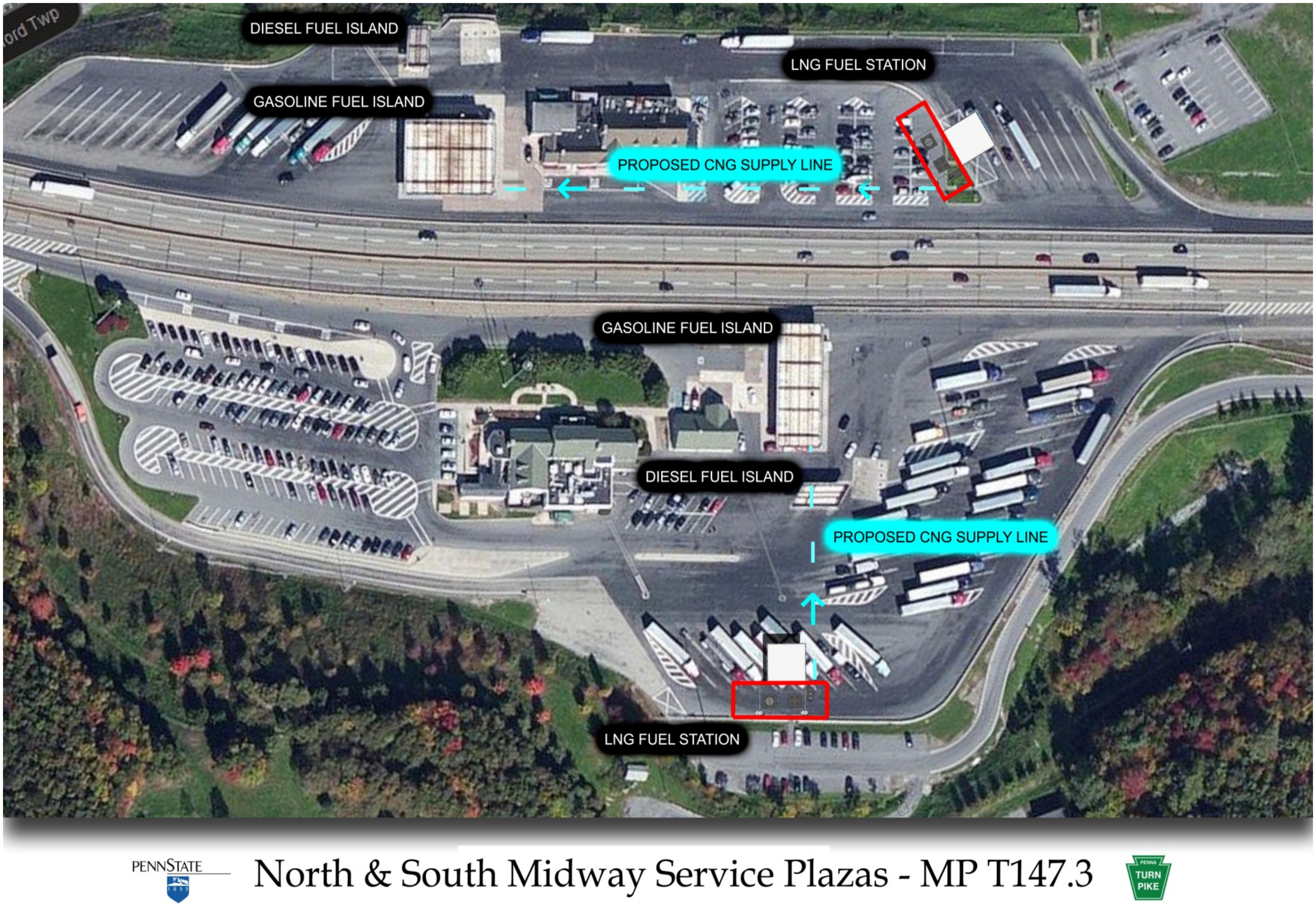

Figure 3.13. Conceptual plan for LNG fueling station installation at the North and South Midway service plazas

South Midway Service Plaza (MP T147.31) – *Currently under reconstruction*

*Estimated Cost to Construct - $1.8 million**

Advantages

- Minor disruption to existing traffic patterns around service plaza
- Short distance to install optional, underground CNG fuel supply line to gasoline fuel island
- No additional property to be acquired

Disadvantages

- Loss of approximately 10 existing parking stalls for trucks
- Difficult travel path for trucks equipped with HPDI engines to access both LNG and diesel fueling stations during same visit due to site restrictions; Low-volume diesel fuel dispenser may be required at LNG fueling station to resolve issue
- LNG storage tank refueling will require closure of one LNG fuel lane since access is limited on rear and sides of tank containment area

North Midway Service Plaza (MP T147.32)

*Estimated Cost to Construct - $1.8 million**

Advantages

- No additional property to be acquired
- Safe travel path for easy access to both LNG and diesel fueling stations for trucks equipped with HPDI engines; No requirement to install low-volume diesel fuel dispenser at LNG fuel island
- Short distance to install optional, underground CNG fuel supply line to gasoline fuel island

Disadvantages

- Loss of approximately 5 existing parking stalls for trucks and 12 existing parking stalls for cars
- Truck access to LNG fueling station will require use of existing “Cars Only” path of travel at end of deceleration lane
- LNG storage tank refueling will require closure of one LNG fuel lane since access should be limited on rear and sides of tank containment area to preserve car parking area

*An additional $750,000 should be added to each option when considering an LCNG station with boil off gas collection.

Peter J. Camiel Service Plaza - MP T304.84

Figure 3.14. Conceptual plan for LNG fueling station installation at the Peter J. Camiel service plaza

Peter J. Camiel Service Plaza (MP T304.84)

*Estimated Cost to Construct - $1.8 million**

Advantages

- No additional property to be acquired
- Safe travel path for easy access to both LNG and diesel fueling stations for trucks equipped with HPDI engines; No requirement to install low-volume diesel fuel dispenser at LNG fuel island
- Short distance to install optional, underground CNG fuel supply line to gasoline fuel island

Disadvantages

- Loss of 9 existing parking stalls for trucks
- LNG storage tank refueling will require closure of one LNG fuel lane since access is limited on rear and sides of tank containment area
- Truck turning radius for access to LNG fuel dispensers is poor but manageable
- Ability to increase lot size through acquisition of adjacent property from The Brandywine Conservancy may be difficult.

* An additional $750,000 should be added to each option when considering an LCNG station with boil off gas collection.

The values shown for the estimated cost to construct a new LNG fueling station are based on a competitive bidding process and inclusive to the cost for the LNG fuel equipment, dispensers, canopy, and site-related amenities. The Commission should be aware that many alternative-fuel vendors offer an operations and preventative maintenance program that is beneficial to the longevity of the facility. These programs are reported to cost in the range of $2,000 to $4,000 per month.

The construction options and challenges presented above are provided to the Commission with the intent of illustrating a few of the critical issues regarding the location of a new LNG fueling station. Each service plaza presents some unique advantages and disadvantages that will need to be further explored during prior to construction.

Although the physical challenges of the existing service plaza sites cannot be eliminated there are several options for the Commission to consider that could improve the installation of LNG fueling stations along the Turnpike. These options are described in the following sections and include:

- The model LNG fueling station
- An independent fueling station
- A mobile fueling station

3.3 Construction of a Model LNG Fueling Station – LNG, CNG, and Diesel Fuel at One Dispensing Location

While the construction of an LNG fueling station(s) along the Pennsylvania Turnpike would be a significant step in the creation of an alternative fuels corridor in Pennsylvania, several enhancements can be incorporated into the typical LNG fueling station that will allow the Commission to satisfy a broader range of the consumers utilizing natural gas as an alternative fuel with less environmental issues. These enhancements include:

- The ability to deliver both "saturated" and "unsaturated" LNG fuel to accommodate the two different types of LNG engines used by the trucking industry.
- The ability to offer a diesel fuel dispenser for truck engines utilizing both natural gas and diesel fuel.
- The ability to convert the LNG fuel and collected evaporated LNG to a CNG fuel to serve light- and heavy-duty vehicles as an LCNG fueling station.

Automotive fuels on the market today offer a wide variety of options to the consumer based on the level of octane for gasoline-fueled engines or the amount of bio-diesel additives for diesel-fueled engines. LNG also has two varieties for two applications. A "Cold" LNG is the *preferred* form of the fuel for the high-pressure direct injection engines, while the "Saturated" form of

LNG is *required* for the spark ignited (SI) engine types. The Commission should be aware that LNG fuel dispenser technology has evolved over the years and the equipment is now capable of offering both the “Cold” and “Saturated” fuels from the same dispenser. Capabilities for both fuel dispensing technologies should be a requirement for any fueling station constructed by the Commission.

Although this study is focused on the feasibility of constructing LNG fueling stations, it would be an oversight not to discuss the opportunity that exists to offer both LNG and CNG as alternative fuels at the service plazas with only modest adjustments to the LNG fueling station equipment. The opportunity is possible since the conversion from liquefied to compressed natural gas is produced by simply pumping LNG to a selected pressure level and then vaporizing the liquid through a heat exchanger. It is more efficient and faster to pressurize natural gas when it is in liquid form via a relatively small cryogenic pump. Other, more common methods of generating CNG require access to a natural gas utility line and a large compressor to achieve the same result. Once the CNG is generated it is stored on-site in storage vessels for quick dispensing to vehicles. A CNG fuel dispenser should be installed at the LNG fuel island as well as the existing gasoline fuel island to better service a wide variety of customers.

Another advantage of constructing an LCNG fueling station is the environmental and cost-effective benefit of capturing the BOG from the LNG storage tanks. When LNG is stored for long periods of time, there is a tendency for the lighter gases (specifically methane) to boil off and vent to the atmosphere. For this reason, LNG fuel should be treated as a perishable product that will degrade over time if not used. Capturing the methane BOG from the LNG storage tanks and compressing it into a CNG fuel is an effective way to make use of this natural process while providing another form of an alternative fuel. It should be noted that LNG fueling station vendors have made significant improvement in station technology to capture BOG and prevent release to the atmosphere, but this technology has yet to appear in the United States.

As previously mentioned in our site assessment of the existing service plazas, one disadvantage that frequently occurs is the inability of a truck to maneuver between the existing diesel fueling station and the new LNG fueling station. This feature is particularly important for trucks utilizing HPDI engine technology, since these engines require a small amount of diesel fuel to operate. This type of LNG customer will primarily fuel the truck with LNG but would require refueling with diesel every 3rd or 4th trip to the LNG fueling station. Installation of a low-volume, diesel fuel dispenser at the LNG fueling station would eliminate the issue of truck access between the two locations and hopefully deter conventional diesel trucks from using the fuel dispenser due to a slower pump rate of discharge.

The model LNG fueling station would be constructed at one of the existing service plazas, but it would offer several additional amenities as compared to the typical LNG fueling station. These amenities should be strongly weighed by the Commission against the additional costs that would be incurred for construction. In order to implement these amenities, the Commission should anticipate additional construction costs in the range of $750,000 to $1,000,000 above the basic construction costs previously listed with each of the service plazas.

The features of a model LNG fueling station are presented in Figure 3.15 for comparison with the conventional LNG Station presented in Figure 3.1.

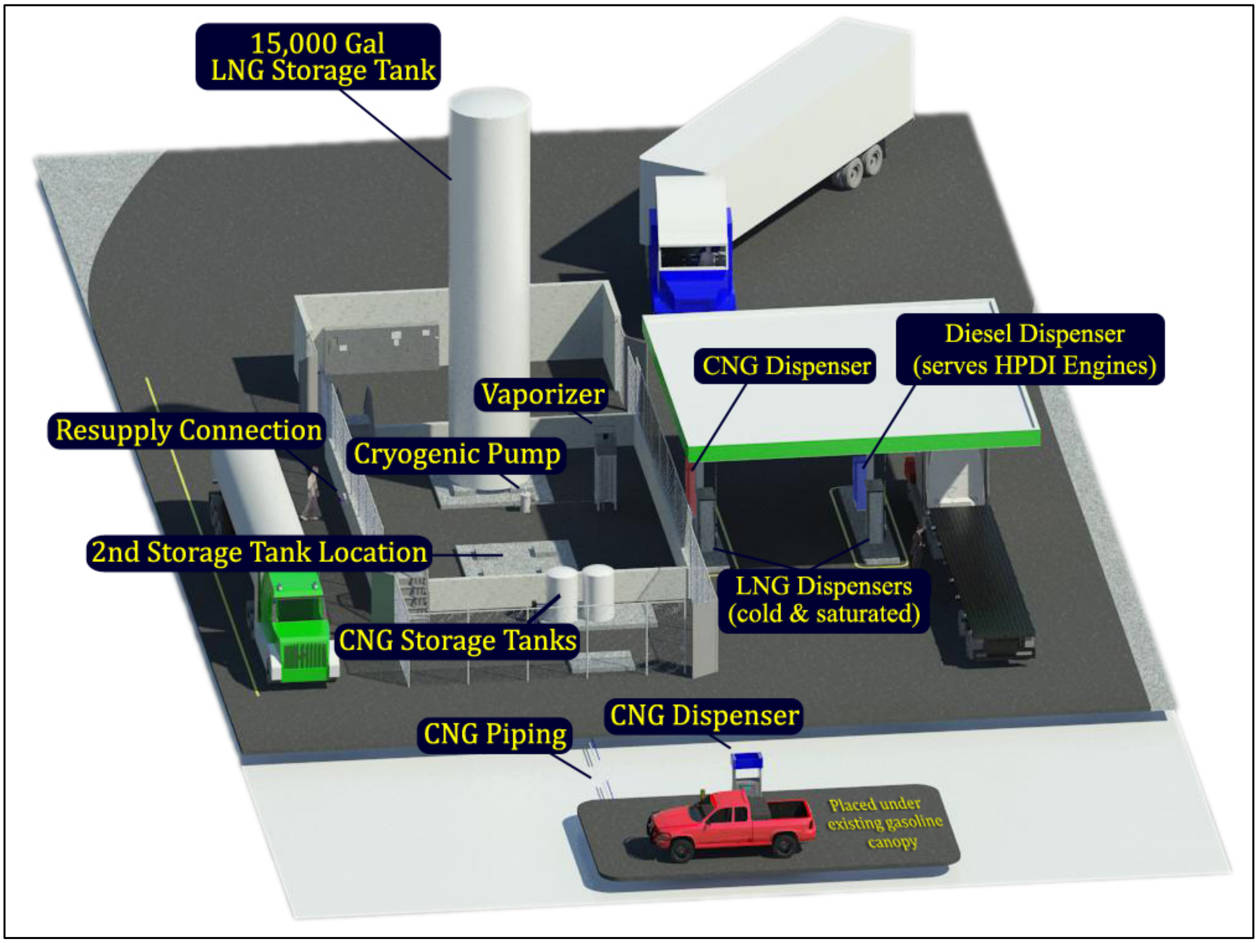

Figure 3.15. Basic components of the Model LCNG fuel station. Note the presence of multiple fuel dispensers capable of offering LNG, CNG, and Diesel to the commercial vehicles

3.4 Construction of an LNG Fueling Station Independent of a Service Plaza

The location of a new LNG fueling station at an existing service plaza is beneficial in many ways to the Commission and the LNG consumer but, as described in our assessment of the conceptual site plans, several challenges exist to physically locate the fueling station on the property. A possible solution to this problem would be the utilization of an undeveloped or surplus property to construct an independent fueling station that would offer both LNG and CNG alternative fuels. This option is referred to as an “independent LCNG fueling station” and is represented by the renderings in Figures 3.16, 3.17, and 3.18.

The intent of offering the independent LCNG fueling station option to the Commission is not to construct a facility that competes with the food and fuel services provided at the existing service plazas, but to work as a partner in providing easy access to alternative fuels for the customers traveling along the Turnpike. As pointed out in the renderings, the independent LCNG fueling station would be limited to providing LNG and CNG alternative fuels and thus would not be another resource for diesel-fueled trucks. A small restroom facility was added to the site based on the request of several trucking companies that were approached by the research team with the concept of the independent fueling station.

In order for the independent LCNG fueling station to be cost-effective for the Commission, the preferred location would be a surplus service plaza site in order to take advantage of the existing property available for acceleration and deceleration ramps as well as access to existing electric, water, sewer, and data utility lines. The access to utilities is essential since a facility of this type will require a 480-volt, three-phase electric service as well as cable data lines for remote monitoring of the alarm, fire, and fuel management control systems.

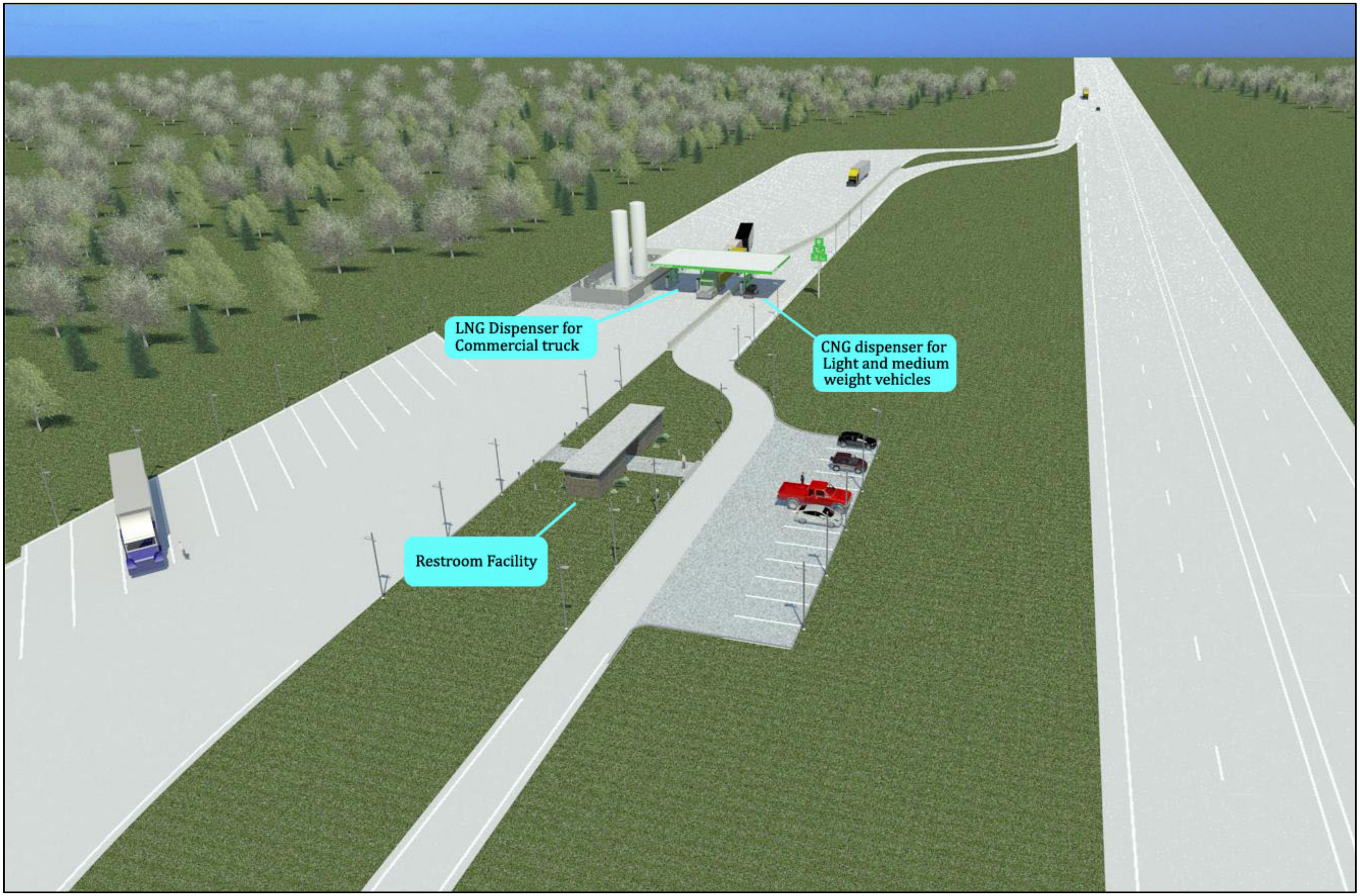

Figure 3.16. Conceptual aerial view of an LCNG fueling station independent of a service plaza location

Figure 3.17. Enlarged view of conceptual fuel dispensing area at an LCNG fueling station independent of a service plaza location

Figure 3.18. Enlarged view of basic restroom facility at an LCNG fueling station independent of a service plaza location

3.5 Installation of a Mobile LNG Fueling Station

The combination of supplying a "perishable" fuel such as LNG to a speculative market of trucking companies that are on the fringe of purchasing LNG engines has created demand for an innovative product known as the LNG mobile fueling station. Several companies in the drilling and construction industry utilize an LNG mobile fueling station due to the transient nature of their business but, in this case, the Commission could make wise use of this technology for initial installation of the LNG fueling stations until an anchor customer or defined customer base is determined.

As shown in Figure 3.19 below, the mobile fueling station has a much smaller footprint and requires much less infrastructure than a permanent fueling station but is still able to offer many of the same services. As an example, the mobile fueling station utilizes a small, onboard compressor to provide its own natural gas power and is typically constructed with a self-containment system. The requirement to supply a new electric service or construct containment walls around the storage tank is not necessary for this option.

Figure 3.19. Proposed installation of an LNG mobile fueling station at an existing service plaza. Note the reduced physical space and level of infrastructure to implement this option

The storage tank on a mobile fueling station is typically capable of containing 6,000 gallons of LNG fuel, which is managed by a control system that is aware of the onboard pressure and fuel levels. This is critical for a mobile fueling station, since an anchor customer with a modest-sized truck fleet could consume the entire tank of fuel in 3 to 4 days. This frequency of refueling is not ideal over the long-term, but is one option to be considered until a permanent fueling station is constructed with a 15,000-gallon storage tank.

The technology built into the mobile fueling station is as complex as the permanent fueling station. These stations have the ability to provide the “Cold” and “Saturated” forms of LNG and include environmental features to capture the BOG without release to the atmosphere.
In the opinion of the project team, installation of a mobile LNG fueling station by the Commission would require only a few basic items as follows:

- Construction of a concrete pad for tank support;
- Installation of perimeter steel bollards for vehicle impact protection
- Installation of site lighting for security and night time fueling
- Installation of an electronic card reader system for fuel purchases (underground data line would need to be installed)

The LNG mobile fueling station is an innovative product that suits many companies well as they explore the use of LNG as an alternative fuel. Industry resources informed us that the cost to purchase a mobile fueling station is approximately $400,000 to $500,000, but leasing options may be available.

This concludes our look into the characteristics, considerations, and costs of an LNG fueling station. In the course of this chapter the Commission was introduced to the basic components of an LNG fueling station, the costs and physical challenges of constructing a typical LNG fueling station at an existing service plaza, and the various options that exist to install these fueling stations along the Turnpike. This information is beneficial to the Commission but none is more important than understanding the perishable nature of the LNG fuel in the storage tank and the need for the Commission to acquire an anchor customer that is committed to purchasing a pre-determined amount of fuel.

3.6 Business Model to Construct, Operate, and Maintain an LNG Fuel Station

The business model used to construct a fueling station traditionally involves a capital expenditure and a “If we build it, they will come” approach with regard to the location. This approach is still valid for fueling stations that offer gasoline and diesel fuels to consumers but the model must change when LNG fuel is added to the equation. The perishable change of state property of the LNG fuel in the storage tank requires fueling station owners to make a concerted effort to use the fuel in a timely manner in order to avoid a monetary loss. For this reason, the business model in use by several leading alternative fuel vendors is to locate an anchor customer that will agree to use a pre-determined amount of LNG fuel over a given period of time.

The Commission may initially find it difficult to follow the LNG business model since many trucking companies are either waiting for the LNG infrastructure to be constructed before they convert their trucking fleet to LNG fuel or the existing companies with LNG trucks have already made commitments to other LNG fuel vendors. This scenario leaves many businesses with the question of "Who is willing to burden the risk of constructing an LNG fueling station without an anchor customer to purchase the fuel?"

In the process of researching information for this study, the research team met with several leading alternative fuel vendors that were willing to share some information regarding the estimated cost to construct an LNG fueling station. As one would expect, the cost to construct will vary based on the existing site conditions and whether the project is bid by the Commission using prevailing wage labor rates or through a private-sector fuel vendor approved by the Commission.

The project team also expressed to the vendors that the Commission may have concerns regarding the financial risk of constructing an LNG fueling station to promote the use of alternative fuel but without the benefits of an anchor customer to purchase the fuel. The alternative fuel vendors we met with were very quick to point out that there are several options to construct a fueling station which should be considered by the Commission:

- Commission ownership of the fueling station via a capital expenditure
  - Traditional business model
  - Commission retains ownership of the LNG fuel equipment
  - Financial risk is greater if an anchor customer is unknown at time of construction
  - If the fueling station is not successful, fuel station equipment must be salvaged
  - Maintenance program is established with alternative-fuel vendor for periodic and preventative maintenance of equipment

- Commission leases the fueling station from alternative-fuel vendor
  - Leasing option places less financial risk on the Commission if anchor customer is unknown at time of construction
  - Construction of fueling station looks permanent to potential customers but financial risk to Commission is greatly reduced if location is not successful
  - If the fueling station is not successful, fuel equipment will be removed by the vendor and financial arrangements will end per the agreement

    - Maintenance program is established with alternative-fuel vendor for periodic and preventative maintenance of equipment

- Commission purchases/leases an LNG mobile fueling station(s)
    - Option places less amount of financial risk on the Commission if anchor customer is unknown at time of deployment and fuel demand never materializes
    - Mobile fueling stations require limited infrastructure (i.e., concrete pad, steel bollards, additional site lighting) to implement
    - Option still allows capability to provide "cold" and "saturated" forms of LNG
    - Option is capable of communicating with electronic payment system at existing service plazas
    - Option allows the Commission to move the mobile fueling station to alternate locations along the Turnpike to gauge interest in the fuel
    - If the fueling station is not successful, it could be returned to the fuel station vendor or preserved for use by the Commission as a pilot project for its own maintenance fleet

- Commission releases ownership and operations to an alternative-fuel vendor (i.e. Sunoco)
    - Option is similar to the agreement for fuel services currently in place with Sunoco
    - Option allows the Commission to infuse capital money into the development of the infrastructure but places the management and construction oversight with the alternative-fuel vendor
    - Alternative-fuel vendor should be encouraged to explore the options of constructing a fueling station on an independent site or utilizing mobile fueling station technology

The Commission has been presented here with several business options for the possible installation of LNG fueling stations and formal discussions with alternative fuel vendors may reveal even more. Regardless of the business model selected, the research team cannot emphasize the importance of an anchor customer to the success of this program.

The preferred anchor customer, as described in other portions of this study, would be a large- or medium-sized trucking fleet with a defined path of travel that includes the Turnpike. Although this search may sound easy to accomplish, the customer base is currently small and in desperate need of incentives to switch from conventional diesel-fueled engines. This incentive could certainly appear in the form of higher diesel prices, but it can also appear in the form of a commitment from the Commission to build LNG fueling stations and offer incentives to purchase alternative fuels while traveling on the Turnpike.

It is the opinion of this research team that a campaign by the Commission to spur more activity in the LNG fuel market could possibly begin with the deployment of one or two mobile fueling stations at selected service plaza locations. The mobile fueling stations may require a lead time of four to six months to deploy due to the manufacturing process but may still offer the quickest form of an alternative fuels presence along the Turnpike with minimal financial risk. The installation of the mobile fueling station(s) could be used in conjunction with a marketing campaign to locate an anchor customer and gauge further interest in the LNG market. The LNG fuel customers should be informed during their stop to refuel that the mobile fueling stations are temporary and will be replaced with permanent fueling stations if the demand is present since the Commission is committed to promoting alternative fuels along the Turnpike. The potential anchor customers will also be faced with many LNG fueling options in the coming years as the infrastructure begins to grow. Therefore, it is critical that the Commission take an active and swift role in the decision to implement this program to ensure its success.

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Chapter 4: Safety Considerations for LNG Fueling Stations

Like any fuel, safe handling procedures and proper safety precautions must be followed when working with LNG. Many years of experience using natural gas vehicles have proven that natural gas can be used safely as a fuel for vehicles. However, using LNG, or any other alternative fuel, involves different safety procedures than most fuel providers and consumers are accustomed to following. This chapter addresses tasks 9 and 13 of the study as listed in Table I.1.

As discussed earlier in this report, LNG is a clear and odorless cryogenic liquid that is non-toxic, non-corrosive, and non-carcinogenic, and like other forms of natural gas, poses no threat to soil, surface water, or ground water. If LNG fuel is spilled, it will dissipate rapidly into the atmosphere, causing no lasting problems for the adjacent soil, plants, or animals. Still, the LNG fueling process does contain some potential hazards, such as the potential for leaking gas to collect in flammable concentrations or if personnel are exposed to the cryogenic temperatures of the fuel. Fortunately, standards organizations have developed and modified several codes over the years to provide guidelines for the design and production of LNG vehicles and fueling stations. These codes and standards include the following:

- Pennsylvania Uniform Construction Code (UCC)
- NFPA 57 – Liquefied Natural Gas Vehicular Fuel Systems Code
- NFPA 59A – Standard for the Production, Storage, and Handling of Liquefied Natural Gas
- SAE J2343 – Recommended Practice for LNG Medium and Heavy-Duty Powered Vehicles

The LNG industry has taken many steps over the years to develop technology and implement protocols for the safe use, transport, and dispensing of this fuel. An example of the typical safety measures in place at an LNG fueling station is presented in Figure 4.1.

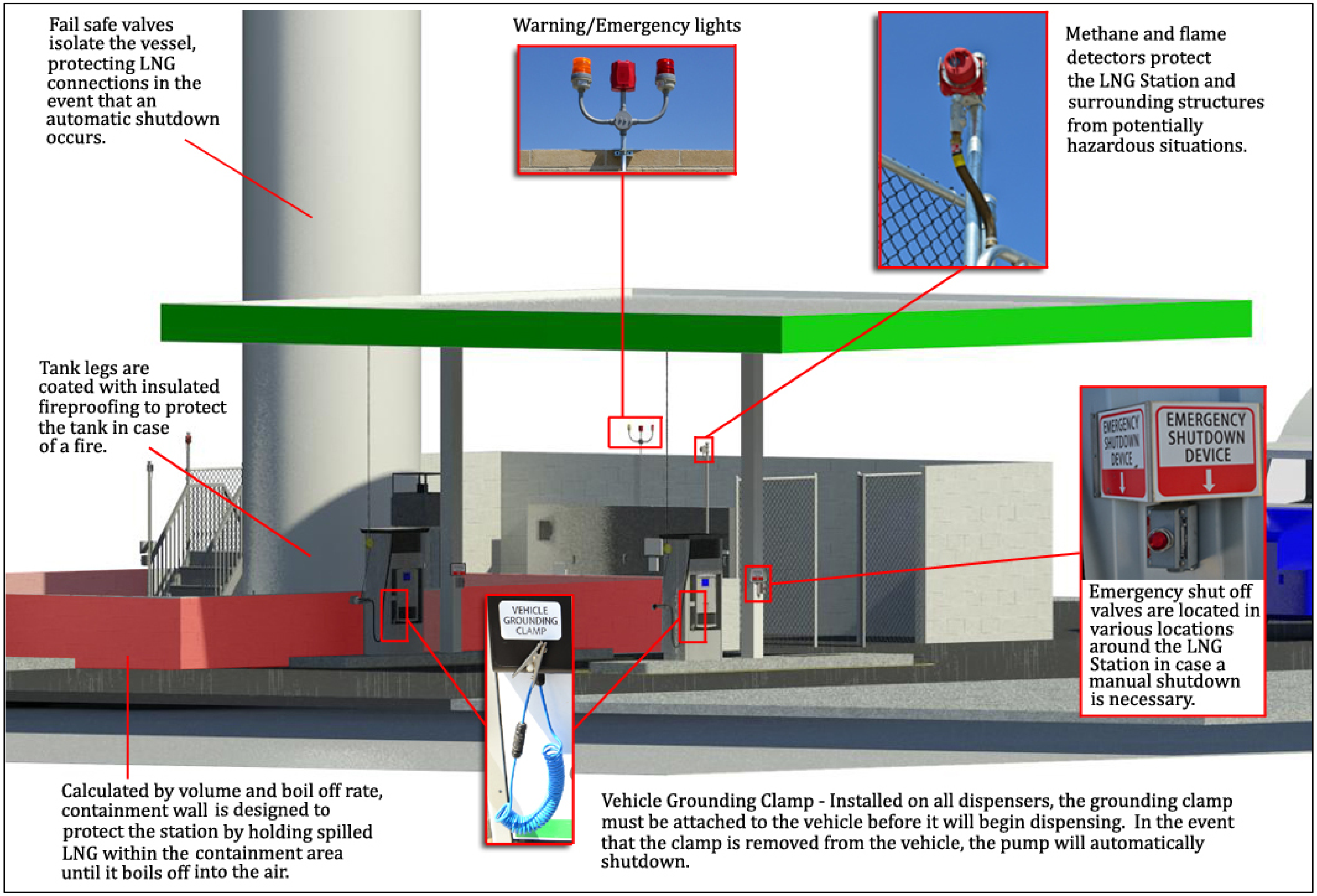

Figure 4.1. Typical safety features present at an LNG fueling station

4.1 General Properties Affecting Fire Hazards

Even though the end product of the use of CNG and LNG for vehicular applications is essentially the same, the general properties affecting safety are quite different. On one hand, LNG is a more refined and consistent product with none of the problems associated with corrosive effects on tank storage associated with water vapor and other contaminants. On the other, the cryogenic temperature makes it extremely difficult or impossible to add an odorant. Therefore, with no natural odor of its own, there is no way for personnel to detect leaks unless the leak is sufficiently large to create a visible condensation cloud or localized frost formation. It is essential that methane gas detectors be placed in any area where LNG is being transferred or stored.

The cryogenic temperature associated with LNG systems creates a number of generalized safety considerations for bulk transfer and storage. Most importantly, LNG is a fuel that requires intensive monitoring and control because of the constant warming of the fuel, which takes place due to the extreme temperature differential between ambient and LNG fuel temperatures. Even with highly insulated tanks, there will always be a continuous buildup of internal pressure and a need to eventually use the fuel vapor or safely vent it to the atmosphere.

The constant vaporization of the fuel also has an interesting effect on the properties of the fuel. The methane in the fuel will boil off before some of the heavier hydrocarbon components such as ethane, propane, and butane. Therefore, if LNG is stored over an extensive period of time without withdrawal and replenishment the methane content will continuously decrease and the actual physical characteristics of the fuel will change to some extent. This is known as "weathering" of the fuel.

4.2 Fire Hazards during Transport

The first concern with implementing an LNG fuel station program is the bulk transportation of the LNG fuel over the roadways from the liquefaction plant to the fueling station. LNG is transported in Motor Carrier (MC)-338 Class cryogenic liquid tanker trucks whose construction specifications are governed by 49 CFR 178.338. LNG tanker trucks, typically containing 10,000 to 12,000 gallons of fuel, would be utilized for the refueling process, which is similar to that for other fuels but with several additional safety mechanisms. The double-walled construction of the LNG tanker truck is inherently more robust than the equivalent tanker truck designed for the transport of other liquid fuels. Therefore, the transport of LNG is considered safer from the perspective of fuel spills resulting from a tank rupture during an accident. A rupture of the outer tank wall would cause the loss of insulation and result in the venting of LNG vapor. While this is of concern, it is relatively minor as compared to the prospect of an LNG spill.

In the event that the LNG tanker truck is ruptured in a transport accident and the LNG is spilled, there is a possibility of a fire because a flammable natural gas vapor/air mixture could be formed in the vicinity of the LNG pool. In an accident situation, there is a high likelihood of ignition sources due to electrical sparking, hot surface, or possibly a fuel fire created from the tanker truck engine fuel or other vehicles involved in the accident. The vapor cloud from an LNG pool will be denser than the ambient air; therefore, it will tend to flow along the ground surface, dispersed by any prevailing winds.

When spilled along the ground or any other warm surface, LNG boils quickly and vaporizes. A high volume spill could cause a pool of LNG to accumulate and the boiling rate will decrease from an initial high value to a low value as the ground under the pool cools. The heat release rate from an LNG pool fire will be approximately 60% greater than that of a gasoline pool fire of equivalent size.

LNG is classified as a Class 2.1 (Flammable Gas) hazardous material according to the United States Department of Transportation's Code of Federal Regulation (CFR) 49 CFR 172 and thus may not be transported in bulk form through the Allegheny, Tuscarora, Kittatinny, and Blue Mountain tunnels located along the Turnpike mainline and the Lehigh Valley tunnel along the Northeast Extension. A majority of the LNG bulk transport services are currently originating from facilities along the Atlantic coast or eastern Pennsylvania; therefore, delivery to service plazas located beyond these tunnels will require careful consideration of the means and methods for delivery.

Recent occurrences of hazards encountered during transport are evident with the June 4, 2012, incident in Pawtucket, Rhode Island. In this case, a malfunctioning valve was to blame for vapors escaping from the tanker, which led to the shutdown of traffic in the immediate vicinity and the request of residents to remain in their homes until the situation was under control. The truck driver's previous training and knowledge of the LNG fuel allowed for early detection and quick response by emergency responders.

4.3 Fire Hazards during Transfer to Storage Tanks

The transfer of LNG from a tanker truck to storage tanks is a complex process that involves the active participation of both the tanker truck driver and a representative of the fleet operator. A partial listing of some of the steps involved provides some indication of the safety precautions that are necessary.

After the truck wheels are chocked and the engine is shut off, a grounding cable is attached to the truck to ground any electrostatic discharge.
A flexible liquid transfer hose is attached to the tanker and purged of air. A fleet operator representative will open the storage vessel liquid fill line and the driver will open the trailer's main liquid valve.

The safety features that are typical of truck storage transfer of LNG include equipment design such as trailer liquid valves that are interlocked with the truck brake system to prevent fuel transfer before the truck is properly secured; remote-controlled, redundant liquid valves; storage vessel alarms to prevent overfill; and long drain lines for venting LNG vapor.

The complexity of the fuel transfer arrangement creates the potential for leaks and spills through human error and equipment failure. One of the particular concerns is that the fuel transfer equipment goes through a continuous cycle of cool down to cryogenic temperatures and warm up to ambient temperature. This type of thermal cooling can create additional stresses on equipment and sealing devices, which could result in decreased reliability over time.

4.4 Fire Hazards during Fleet Storage

LNG storage facility requirements for a total on-site storage capacity of 70,000 gallons or less are defined in the draft NFPA 57 -- Standard for Liquefied Natural Gas (LNG) Vehicular Fuel Systems. NFPA 59A -- Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG) is applicable to storage volumes above 70,000 gallons. Both of these standards address similar issues, including location of the storage tank, provision for spill and leak control, and the basic design of the storage container and LNG transfer equipment.

One of the major provisions at any LNG storage facility is the requirement to provide an impounding area surrounding the container to minimize the possibility of accidental discharge of LNG from endangering adjoining property, on important process equipment and structure, or reaching waterways. This requirement ensures that any size spill at a fleet storage facility will be fully contained and the risk of any fire damage will be minimized.

4.5 Other Hazards

LNG presents a unique safety hazard among alternative fuels because of the potential exposure of personnel to cryogenic temperatures. Workers and consumers can receive cryogenic burns from direct body contact with cryogenic liquids, metals, and cold gas. Exposure to LNG or direct contact with metal at cryogenic temperatures can damage skin tissue more rapidly than when exposed to vapor.

The risk of cryogenic burns through accidental exposure can be reduced by the use of appropriate protective clothing and PPE. Depending upon the risk of exposure, PPE can range from loose fitting, fire-resistant gloves and full face shields to special extra protection multi-layer clothing.

This concludes our assessment of the safety considerations for LNG fueling stations. In summary, the LNG industry has developed a comprehensive set of safety standards and technology, exhibited an excellent safety record and taken many other steps to ensure the safe use, transport, and dispensing of this fuel. The LNG fueling station includes many components as denoted in Figure 4.1 to ensure the safety of all personnel – employees and consumers. The Commission should be aware of the risks associated with LNG fuel but should not hesitate to deploy LNG fueling stations along the Turnpike due to safety considerations.

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Chapter 5: General Safety, Operation and Maintenance, and Training for LNG Stations

This chapter addresses Task 8 - safety related to LNG station deployment of the study task list in Table I.1.

5.1 General Safety Information for LNG Stations

General Fire and Explosion Hazard

LNG is stored at pressures up to 230 psi, and when vaporized it is not explosive in an uncontained environment. Although a large amount of energy is stored in LNG, it generally is not released rapidly enough to cause the overpressures associated with an explosion. LNG vapors (methane) mixed with air are combustible but not explosive in an unconfined environment.

LNG spills or leaks will quickly vaporize since LNG has a boiling point of -258.7^{o}F. Should a tank ever fail and a leak result, fire is possible, but only if there is the right concentration of LNG vapor in the air and a source of ignition. This concentration is a mixture containing 5% – 15% of natural gas in the air. Concentrations under 5% do not contain enough gas to burn, and concentrations over 15% do not contain enough oxygen to burn. This results in a fairly slow burn when any vaporized clouds of LNG are ignited in an open environment. [1] Small leaks in enclosed spaces present a fire and explosion hazard because of the potential for methane to gradually build up to the necessary 5%-15% combustible concentration. LNG vapors also have a higher ignition point than either gasoline or diesel (1004^{o}F, 500^{o}F, and 494.6^{o}F, respectively).

LNG fires should be extinguished using dry chemicals only (Purple–K). Water fog or high-expansion foam can be used to suppress or contain fires. Water should not be sprayed directly into an LNG pool, since it will increase the rate of LNG vaporization. [2, 3]

Freeze Burn Hazard

Because LNG is a cryogenic liquid with a boiling point of -258.7^{o}F, the liquid itself and any un-insulated hoses or containers will present a freeze burn or frostbite danger to exposed human skin.

Asphyxiation Hazard

The components of natural gas (methane, ethane, and propane) are classified as “simple asphyxiants,” meaning they are not dangerous or poisonous in themselves, but can displace oxygen in enclosed environments. In outdoor environments, any LNG vapors will naturally disperse and rise into the atmosphere, posing little asphyxiation hazard. In enclosed spaces, LNG vapors from spills or leaks present an asphyxiation hazard, as they will displace oxygen. [4] To alleviate this hazard, LNG vehicles are typically stored outside where vapors can dissipate. Any enclosed spaces such as workshops where LNG vehicles will be serviced should be equipped with methane detectors that are linked to automatically activate exhaust fans to clear the area in the event of a leak.

Spill Hazards

Should a large amount of LNG be release into the environment, such as a spill from a truck or tank, the pool of liquid would quickly boil off and dissipate into the atmosphere. Because of this, LNG spills pose no hazard to soil or water, and require no cleanup.

5.2 Driver Training

Drivers who stop to refuel at Turnpike LNG facilities must be properly trained. LNG fueling is relatively simple, although it contains more steps than typical gas or diesel fueling. The exact LNG fueling equipment and procedure also vary slightly from station to station. Although many new LNG refueling stations claim to be easy to use with "minimal or no training," it still makes sense to ensure that drivers who stop are aware of the safety precautions and fueling procedure for those specific stations. There are several possible options to ensure drivers are aware of proper LNG safety and fueling procedures:

1) Brief Instructional Video: Drivers could be required to view a brief tutorial video before fueling. Some LNG pumps incorporate this video into the pump itself. This type of video would be less than 2 minutes in length.
2) Instructional Video and "certification": Instead of requiring drivers to view a video each time they refuel, a longer video tutorial and "certification" program could be implemented. In this situation, drivers refueling for the first time would be required to watch an instructional and safety video (~10 minutes in length). The video could be located at the pump or at a separate kiosk. A simple "quiz" could even be included at the end of the video. After watching the video and passing the "quiz," that driver would be certified to refuel at all Turnpike LNG stations in the future without further training. The certification could be handled with a simple pin number system.

5.3 Training of LNG Station Staff

Because LNG stations and dispensing equipment present unique operational and safety considerations, education and training will be important. The topics below discuss various user groups and education/training considerations for each. See Appendix D for a summary table of existing trainings.

General Employee Education

Every Turnpike employee, from janitors to executives, should receive some form of *basic* LNG education. This basic education would be designed as an overview of the major physical properties and safety information about LNG and fueling stations in the form of either classroom training or an informational video. Approximate training/video duration would be about 30 minutes.

Fuel Handlers and Station Attendants

Because of the specialized storage and distribution equipment for LNG, each station installation will require station attendants at that service plaza to be trained in the basic operation and maintenance of the LNG station equipment. Training will be necessary for all station attendants whether they are PTC employees, Sunoco employees, or employees of an outside contractor. Various trainings are available for station attendants ranging from 1-3 days in length.

5.4 Emergency Responders

Because LNG has different properties from traditional gas and diesel fuels, local emergency responders around each station will need to be educated in how to respond to any potential emergencies at the LNG station or at the scene of LNG vehicle accidents. This process will vary significantly depending on the locality of each station. [4] Several trainings exist to educate emergency responders to the unique circumstances that may be encountered relating to LNG. These are intensive 2-day trainings with live fire demonstrations.

References

[1] CLNG, Center for Liquefied Natural Gas: (http://www.lngfacts.org/About-LNG/Safety.asp)

[2] MSDS, LNG Material Safety Data Sheet

[3] TEEX, Texas Engineering Extension Service, LNG Emergency Response, http://www.teex.com/teex.cfm?pageid=estiprog&area=esti&templateid=1536

[4] ANGA, America's Natural Gas Alliance, TIAX U.S. and Canadian Natural Gas Vehicle Market Analysis Liquefied Natural Gas Infrastructure: Final Report

Other Notes

UPS is converting some trucks to LNG:

- Drivers require certification and must view a 30-minute video
- Technicians require 3.5 days of training at UPS facility
- (http://pressroom.ups.com/Fact+Sheets/ci.LNG+Fact+Sheet.print)

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Chapter 6: Funding

This chapter covers work that was done as part of Tasks 5, 10, and 14 of study task list in Table I.1. The principal purpose of these tasks was to identify sources that the Commission could use to fund any planning, design, or operational elements for the proposed use of LNG as an alternative fuel on the Turnpike system. The work focused on three principal areas:

- Federal or state funding mechanisms available for infrastructure or vehicle development;
- Programs employed by other states, vehicle manufacturers, or natural gas companies to incentivize use of natural gas as a fuel source; and
- Public-private partnerships promoting natural gas fuel use.

Similar methods were used to gather information about each of these areas of interest. For each topic, extensive Web-based reviews of recently concluded, existing, and planned programs were conducted to check for relevance to the Commission's proposed use of LNG on the Turnpike. Once these reviews were performed, representatives from individual organizations (e.g, Air Products, Linde, Cryostar, EQT) were contacted to obtain further details about programs with which they were directly involved or of which they had knowledge.

All of our industry contacts generally pointed us in the same direction to find information on funding programs and P3 projects. Further, given that there is so much uncertainty relative to taking the first steps on the parts of many players in this industry, there seemed to be little point in conducting any type of large-scale survey in the hopes of finding additional information, as the major industry contacts we were in touch with all seemed to know the same information.

With that said, there is a great deal of information available on the Web; however, the principal problem in trying to uncover meaningful information is wading through that material to find information relevant to the work at hand. The research team did just that, and the results of that work are reported in the following sections.

6.1 Federal Programs

The United States Government is heavily involved in promoting the use of natural gas in a variety of ways. Some of the programs related to NG use as a vehicle fuel are described below.

Federal Natural Gas Vehicle Grants

Several federal programs that provide grants for the purchase of natural gas powered vehicles may have more relevance to the purchase of NG vehicles by the Commission for use as part of the Turnpike maintenance fleet, although there is some allowance made, in a few of these programs, for fueling stations.

Clean Cities Program
The Clean Cities Program is a coalition of nearly 100 different regions around the United States composed of businesses, fuel providers, vehicle fleets, state and local government agencies, and community organizations and led by a Clean City Coordinator. The main goal of the program is to reduce petroleum use in their respective regions through the implementation of alternative-fuel vehicles. Clean Cities provides grants to projects that increase the use of natural gas powered vehicles including school and transit buses, airport vehicles, taxis, and delivery fleets. Grants provided by the Clean Cities Program have also been used to fund the construction of alternative-fuel infrastructure, especially on those available for public use to encourage the continued expansion of alternative fuel use. Two Clean Cities Coalitions currently exist in Pennsylvania, one encompassing the City of Philadelphia as well as the counties of Bucks, Chester, Delaware, Montgomery, and Philadelphia. The other includes the City of Pittsburgh and Allegheny County. Clean Cities is overseen by the U.S. Department of Energy and is part of the Office of Energy Efficiency and Renewable Energy's Vehicle Technologies Program (http://www1.eere.energy.gov/cleancities/).

Congestion Mitigation and Air Quality Improvement Program
The Congestion Mitigation and Air Quality Improvement Program (CMAQ) began in 1991 to provide funding for alternative-fuel projects that help communities meet or maintain compliance with federal air quality standards. Between 2005 and 2009, this program provided $8.6 billion in funding to projects related to transportation that reduced emissions, including improving rail and transit services, implementing bike path programs, and supporting alternative-fuel projects. Specifically relating to AFV projects, the program can pay for the incremental cost of purchasing natural gas vehicles and can be used to fund alternative-fuel refueling projects. These projects must have 20 percent local or regional co-funding. Funding is also allowed for public-private partnerships. This program is administered by the Federal Highway Administration along with the Federal Transit Administration, and has continued to operate under the extensions of The Safe, Accountable, Flexible, and Efficient Transportation Act, a Legacy for Users (SAFETEA-LU); it is also part of the most recent surface transportation authorization, MAP-21 (Moving Ahead for Progress in the 21st Century). Funds are allocated to a state's department of transportation for distribution to local/regional metropolitan planning organizations for these projects with preference given to those areas with more significant ozone and carbon monoxide problems (http://www.fhwa.dot.gov/environment/air_quality/cmaq/).

National Clean Diesel Campaign
This program is also known as the Diesel Emission Reduction Program. Its primary purpose is to provide grants to government agencies, school districts, and other interested parties who intend to replace or retrofit their diesel-powered vehicle fleets with new low-emission ones. One option that is funded by this program is the replacement of these vehicles with natural gas powered ones in addition to retrofitting existing diesel engines with natural gas power. The program will cover 75 percent of the cost of an existing engine retrofit, or 50 percent of the cost

of a new bus or truck purchase, as long as the vehicles meet the 2010 engine standards outlined by the program. The program will also provide funding for the construction of fueling infrastructure with new vehicle purchases or existing vehicle retrofits. The funding is authorized up to $100 million but will vary yearly depending on funding appropriation (http://www.epa.gov/cleandiesel/#pagecontent).

6.2 State Programs

While the federal government is heavily involved in the promotion of natural gas as a vehicle fuel, there are many more state-related programs in this area. This section describes the programs sponsored by the Commonwealth of Pennsylvania along with a summary of the manifold programs in other states.

Pennsylvania Programs

The Alternative Fuels Incentive Grant (AFIG) Program was established in December 1992 under Act 166 by the Pennsylvania State Legislature. The program offers grants to "school districts and vocational schools, municipal authorities, political subdivisions, non-profit entities, corporations and partnerships incorporated or registered in the Commonwealth, and Commonwealth residents (PA DEP 2002)" that provide a portion of the purchase cost of alternatively fueled vehicles or for the conversion of conventionally fueled vehicles so that they can use alternative fuels. The program also allows for "constructing the refueling and recharging infrastructure, and advancing innovative alternative fuel technologies (PA DEP 2002)."

The Natural Gas Vehicle Grant Program was established under Pennsylvania Act 88 of 2012. Through the collection of natural gas drilling impact fees, the program will award $20 million over the next 3 years to purchase or convert vehicles to run on natural gas. Programmatically, the funding will be allocated as $10 million in FY 2012-2013 ($5 million for local transportation agencies), $7.5 million in FY 2013-2014 (50 percent for local transportation agencies), and $2.5 million in FY 2014-2015. The grants can be used for 50 percent of the initial purchase and retrofit costs, and they are capped at $25,000 per vehicle. Further, grant funds cannot be used to pay for project development costs, fueling stations or other fueling infrastructure.

Summary of State Incentives Relating to Natural Gas Powered Vehicles

There was a sizeable amount of information on programs in different states. Appendix E is a summary list of incentive programs and laws listed by state that encourage, promote, or fund the use of natural gas powered vehicles in some way. Most plans describe the use of alternative-fueled vehicles, which can describe other types of vehicles as well (e.g., electric vehicles, fuel cell vehicles, etc.). The table only includes plans where the term "alternative fuel vehicle" or "AFV" did not exclude natural gas vehicles (NGV). All information is from the U.S. Department of Energy Alternative Fuels Data Center at http://www.afdc.energy.gov/laws/state as linked through the Natural Gas Vehicles for America website at http://www.ngvc.org/.

Some states do not appear in the table because they currently have no program incentivizing the use of CNG or LNG vehicles. Special attention should be paid to the California and Texas-based incentives, as they are the most numerous and seem to be the strongest programs. Certain incentives that occurred commonly in many states include:

- AFV high occupancy vehicle lane exemption – AFVs can use HOV lanes regardless of the number of passengers.
- Tax credits for AFVs – Many states have a public program that provides tax credits for the purchase of new AFVs, the conversion of conventional gasoline-powered vehicles to AFVs, and the installation of AFV refueling infrastructure for both businesses and individuals.
- Tax exemptions – Many states provide tax exemptions for registration, fueling, and emission inspections of AFVs.
- Bus and transit AFV funding - Many programs provide municipalities and transit operators with significant amounts of funding for the purchase of NG-fueled buses.

6.3 Public-Private Partnerships

There are some examples of public-private partnerships related to the use of natural gas as a vehicle fuel. Also, the recent passage of Pennsylvania Act 88 of 2012, which allows for P3 projects in the Commonwealth, gives some indication of how the Commission might move forward using P3 arrangements to further this endeavor. Of course, one condition of Act 88 PA is the prohibition of the Commission from engaging in any P3 relationships with respect to granting substantial oversight and control over the Turnpike Mainline to another entity without further approval from the state legislature; however, the requirements of the new law are applicable to non-Mainline sections of the Turnpike and even for Mainline sections the conditions of the law will likely be paralleled in any arrangement that the Commission is successfully able to pursue. Therefore, a brief summary of the bill is included below.

Summary of Pennsylvania Act 88 of 2012

Pennsylvania Act 88 of 2012, an act amending Title 74 of the Pennsylvania Consolidated Statues, was approved by PA Governor Corbett on July 5, 2012, after it was unanimously approved by the state senate and approved by majority in the state house of representatives. The purpose of the bill is to allow for the formation of public-private partnerships on transportation projects in Pennsylvania. The bill defines a public-private transportation partnership (PPTP) agreement as a "contract for a transportation project which transfers the rights for the use or control, in whole or in part, of a transportation facility by a public entity to a development entity for a definite term during which the development entity will provide the transportation project to the public entity in return for the right to receive all or a portion of the revenue generated from the use of the transportation facility, or other payment."

A board known as the Public-Private Transportation Partnership Board is to be established, consisting of the following seven members:

- The secretary of transportation, or a designee member of the department;
- The secretary of the budget, or a designee from the office of the budget;
- A governor's appointee;
- An appointee by the president of the senate;
- An appointee by the minority leader of the senate;
- An appointee by the speaker of the house of representatives; and
- An appointee by the minority leader of the House of Representatives.

The purpose of the board is to approve or reject proposals for transportation projects and PPTPs. Any public entity owning a transportation facility in Pennsylvania may solicit a transportation project through request. Offerors may respond to the request for transportation projects, and if the public entity determines the project is in the best interest of the public, it can submit to the board for approval. If the board approves, a request for proposals is then solicited by the public entity. Once all proposals are received by an established deadline, the public entity determines which offeror to award the proposal based on a number of weighted factors including cost, financing, design, feasibility, public reputation, compatibility, and public commitment, and other factors that are included at its discretion. The board then approves or denies the proposal as forwarded by the public entity. If the transportation facility is owned by the Commonwealth, the legislature can reject the project (even if the board approves), but they must do so within 20 calendar days or 9 legislative days, whichever is longer. The Pennsylvania Department of Transportation must receive detailed reports of all partnership projects approved by the board, and it has the right to oversee all aspects of the project throughout its duration. Once a proposal is approved, the partnership is defined in an agreement between the public entity and the development entity (the private entity) and any other public entities involved. This agreement includes all plans relating to the project's capacity, rehabilitation, modernization, and operation, in addition to any environmental impacts and a defined term for the partnership. At the end of the term, the facility is to be returned to the public entity in the same or better condition than it was in at the start of the term.

As mentioned above, the Pennsylvania Turnpike Commission is exempt from this bill for any partnership arrangements that would grant substantial oversight and control over the Turnpike Mainline to another entity. It will remain to be seen how this condition will be interpreted, but one can surmise that the principal intent of this language is to prohibit long-term leasing of the Turnpike to a private vendor for the purposes of operating, maintaining, and managing the Turnpike without legislative approval. This means the Commission can pursue other types of PPTP arrangements that are more limited in scope than a long-term leasing contract.

Public-Private Partnerships Relating to Natural Gas Vehicles

While there are many descriptions of P3 relationships related to the development and use of natural gas, there were only two that seemed to be particularly germane to this project. These are described below.

Weld County, Colorado CNG Fueling Station

Mansfield Energy Corporation opened its first CNG vehicle refueling station on June 29, 2012, in Weld County, Colorado. The retail brand of the fuel was named SkyBlu. The project is a public-private partnership, partially funded by Congestion, Mitigation, and Air Quality (CMAQ) funds from the Denver Regional Council of Governments, matched to funding from the energy companies Mansfield Energy, Anadarko, Noble Energy, and Encana, which are all members of a local natural gas coalition. Mansfield was enlisted to design and build this CNG station at a Firestone Convenience LLC existing retail fueling location. Mansfield owns and operates the facility, which is open 24 hours a day and can fuel light-, medium-, and heavy-duty CNG vehicles. The station is open for public use, as well as private and government sector customers, and most credit cards and fleet card payments are accepted. Another CNG fueling site is set to open later this year in Weld County (http://www.weldsmartenergy.org/assets/70aa86C81099b227169B.pdf).

Leon County, Florida

The Florida-based company, Nopetro, recently constructed a natural gas refueling station in Leon County, Florida through a public-private partnership. The station, built with private funds, is owned and operated by Nopetro, but the county school district has plans to use this station to fuel all of the buses in its fleet. The school district will also benefit from royalty payments and private-sector sales. The station is open to the public, as well as government agencies and business fleets. Nopetro claims that this is the first station in a network of natural gas refueling stations that they intend to open in Florida as well as all along the East Coast (http://www.nopetro.com/news12_02_07.shtml).

6.4 Conclusions

While there are many options for funding the conversion of existing and the purchase of new natural gas powered vehicles along with the construction of natural gas fueling facilities, there is no single option that would meet the needs of the Commission's anticipated program. The best alternative will be to pursue multiple options in the hope of securing as much funding as possible to implement the planned program in stages.

As mentioned above, the federal Clean Cities Program provides resources to increase the use of natural gas powered vehicles and fund the construction of alternative fuel infrastructure. The Commission should approach both the Philadelphia-based (http://phillycleancities.org/) and Pittsburgh-based (http://www.pgh-cleancities.org/wordpress/) programs to explore the possibility of obtaining grants for fueling station construction. There should also be some discussion of vehicle conversion and purchase, although the Commission's vehicles may not qualify as part of this program. Clean Cities Pittsburgh has already funded many projects similar in character and scope (http://www.pgh-cleancities.org/wordpress/?page_id=462) to what the Commission wants to do. Further, many of the organizations already funded could be potential "collaborators" for the Commission as users, vendors, or P3 partners (e.g., EQT, Giant-Eagle, Waste Management). The Congestion Mitigation and Air Quality Improvement Program (CMAQ) can pay for costs related to the purchase of natural gas vehicles and alternative fuel refueling projects. As described above, these projects have to provide 20 percent local or regional co-funding, which the Commission could provide directly or with the assistance of partners. Funding can also be used for public-private partnerships. The Commission should approach PennDOT regarding the applicability of these funds for use in conjunction with local metropolitan planning organizations that abut the Turnpike with significant ozone or carbon monoxide issues.

The Commission should consider seeking funding through the Diesel Emission Reduction Program to replace or convert the PTC vehicle fleet to natural gas fuel use. As the program covers 75% of the cost of an existing retrofit or 50% of the cost to purchase a new truck and also provides funds for the construction of fueling infrastructure to be used in conjunction with "new" vehicles, this program could offer significant resources for a planned program.

There are programs within Pennsylvania that can provide some element of the costs to put in place natural gas refueling infrastructure and costs for vehicle conversion. The Commission should attempt to secure some of the resources available from AFIG for the purchase cost of alternatively fueled or converted vehicles that are part of its fleet and constructing of refueling stations. There should also be some attempt to use the Natural Gas Vehicle Grant Program to procure funds for natural gas vehicles. However, in the context of building natural gas fueling stations along the Turnpike, state funding may prove to be highly restricted and highly competitive if the Commission focuses on the aforementioned competitive programs. It may make the most sense, and be the best use of Commission staff time, to consider submitting an unsolicited proposal to DEP. The PA DEP formally advertises its willingness to consider unsolicited proposals (http://files.dep.state.pa.us/Energy/Enintech%20Temp/lib/enintech/Unsolicted_proposal_public.pdf), and this may be an effective means of obtaining support for natural gas infrastructure and bypassing the per-project funding limits that are part of programs such as AFIG (limited to no more than ~$400,000 per project).

Given the few successful examples of public private partnerships described above, such as those in Colorado and Florida described earlier in this chapter, the Commission should explore the possibility of PPTP arrangements, as allowed by Act 88, with all reasonably qualified private partners.

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Chapter 7: Environmental Considerations

This chapter covers the environmental considerations and issues of the operation of LNG fueling stations, particularly with respect to carbon footprint of the facilities. These issues arise from inadvertent release of natural gas from the handling and storage of LNG, and from the operation of vehicles on natural gas.

7.1 Greenhouse Gas Tailpipe Emissions

One of the promises of natural gas vehicle advocacy groups is that operation of vehicles on natural gas leads to a net reduction in tailpipe greenhouse gas emissions (CO_2 equivalent emissions). For instance, the Marcellus Shale Coalition commissioned a report titled "NGV Roadmap for Pennsylvania Jobs, Energy Security and Clean Air," in which the coalition proposes the development of the "PCTC," Pennsylvania Clean Transportation Corridor, which includes installations along the Pennsylvania Turnpike in the Pittsburgh, Harrisburg, and Philadelphia areas. The NGV Roadmap includes a "developed" case in which 17 stations would be installed around the Commonwealth and would lead to an estimated 21,000 metric tons reduction of greenhouse gas emissions. Such projections are frequently based solely on the lower carbon content of the natural gas fuel and ignore the inevitable release of unburned methane in the tailpipe.

An alternate view of the net greenhouse gas emissions impact is seen in an older set of comparative data from a study by McCormick et al. [1], in which a fleet of diesel-fueled transit buses were compared head-to-head with natural gas conversions of these same diesel vehicles. Table 1 presents some data from the McCormick et al. study. [1] These results show that the inferior thermal efficiency of the CNG vehicle negates the CO_2 emissions benefits one would expect by burning a high hydrogen to carbon ratio (H/C) fuel (H/C=4 for CNG and H/C~2 for diesel). The methane (CH_4) emissions are nearly 100 times higher for CNG, and methane has 20 times higher global warming effect than CO_2 according to the US Environmental Protection Agency. [2] Applying this principle, the additional CH_4 emissions from the CNG vehicle produce effective CO2 equivalent emissions of 2,090 g/mi, compared to the 1,785 g/mi of CO_2 emitted by the diesel vehicle. One must note that the particulate matter emissions from the CNG vehicle are negligible and the NO_x emissions are 1/3 lower for the CNG vehicle.

Table 7.1: Comparison of emissions of low emissions vehicle-certified RTD buses [2]

Vehicle	Cycle	THC (g/mi)	**NMHC (g/mi)**	**NO_x (g/mi)**	**CO (g/mi)**	CO_2 (g/mi)	PM (g/mi)	Btu/mi
RTD Bus 1014-CNG	CBD	20.04	2.19	9.06	0.34	1690	0.02	27018
RTD Bus 1011-Diesel	CBD	0.18	-----	16.12	11.18	1785	1.02	22908

Therefore, the promise of lower greenhouse emissions from natural gas vehicles will depend on how well the vehicle system is designed to control methane emissions. At the present time, the EPA regulates only non-methane hydrocarbon emissions. Vehicle methane emissions are not directly regulated by the EPA and therefore are not directly controlled by vehicle manufacturers.

More recent studies confirm these concerns over the tailpipe emissions of natural gas vehicles and offer potential solutions. D'Ambrosia et al. observed that the majority of hydrocarbon emissions from a turbocharged CNG-fueled engine were from methane, because methane is more difficult to oxidize using a conventional three-way catalytic converter, given the high chemical stability of methane and the risk of generating formaldehyde by partial oxidation of the methane. [3] Noipheng et al. observed that tailpipe methane emissions from a dual-fuel (diesel and natural gas) vehicle could be reduced effectively through injection of a small quantity of diesel fuel into the engine exhaust upstream of the diesel oxidation catalyst, to raise catalyst temperature and improve methane oxidation efficiency. [4] In contrast, Arteconi et al. demonstrated, through a detailed life-cycle analysis comparison between diesel fuel and LNG, that LNG trucks equipped with HPDI fuel injection systems could result in a reduction of CO_2 equivalent greenhouse gas emissions of 10%, accounting for fuel production, processing, transport, dispensing, utilization, and exhaust emissions. [5] Overall, the current information in the literature suggests that tailpipe methane emissions need not be a weakness of a natural gas vehicle, if appropriate technologies are employed. But, if measures are not taken to ensure that tailpipe methane emissions are controlled, then significant increases in GHG emissions may accompany expanded use of natural gas.

7.2 Fugitive Greenhouse Emissions from Fuel Handling and Storage Facilities

Both LNG-fueled vehicles and the operation of LNG fueling stations on the Turnpike will have environmental consequences with regard to methane emissions. Besides the vehicle exhaust emissions, it is also important to consider BOG. LNG is stored and transported as a liquid at atmospheric pressure and approximately -260°F [6]. Because no storage or transport container is perfectly insulated, the temperature will rise and some liquid will change phase to gas. When it becomes gas, the tank will vent it to the atmosphere in order bring the pressure down and maintain the low temperature creating BOG [7].

According to a study carried out by Adom et al., a large LNG tank loses between 0.03-0.08% volume/day, meaning a 52.8 million gallon tank could lose between 15,000 and 43,000 gallons of liquid every day. [8] Furthermore, as the percentage of methane in the LNG increases, the volume of BOG per day increases, as seen in the Figure 7.1 from Adom et al. This increased BOG can be a problem as higher percent methane composition may not be as desirable as the losses increase.

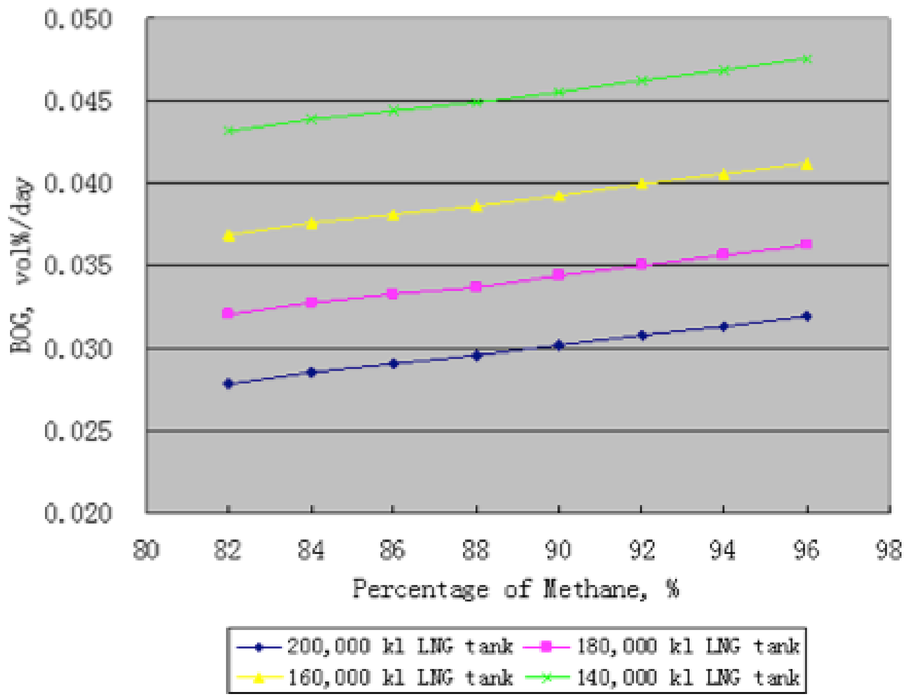

Figure 7.1. Relationship between BOG and methane composition [4]

Another study by Jaramillo et al., which looks at life-cycle air emissions of different fuels intended for electricity production, estimates the BOG somewhat higher.[9] As the storage for use in a power plant or for vehicle fuel has few, if any, differences, this study is useful for the current investigation. The study measures an LNG boil-off rate of between 0.15% and 0.25% per day on board LNG tankers that use the BOG to power their steam engines [9]. It may be that these higher rates are acceptable because the BOG is being used and not lost to the atmosphere. On board vehicles or at fuel stations the BOG could be collected and then reused as CNG. Alternately, BOG can be collected and re-condensed by piping it through coils in cold LNG within the fueling station.

A recent report from America’s Natural Gas Alliance and the American Petroleum Institute ANGA/API, which focuses on the sources of methane emissions from natural gas production, provides some meaningful information for this investigation. These organizations collected data from industry to compare with EPA estimates. The report finds that the industry data for metric tons of methane emissions in the production phase of LNG (4,420,677 metric tons) is 50% less than the values reported by the EPA (8,799,670 metric tons) [10]. The EPA report is from 2010 while the ANGA/API is current (as of 2012). This difference in emission levels hopefully indicates that the process is becoming cleaner. It also reports data for methane emissions during processing, specifically in the compressors used to compress the gas to a liquid. The ANGA/API report finds that of the 38 centrifugal compressors in the study, 79% of compressors have dry seals and emit 51,370 scfd methane/compressor and the remaining compressors are wet sealed and emit 25,189 scfd methane/compressor [10]. The ANGA/API report does not include data for BOG in storage tanks.

7.3 Other Considerations Affecting Fugitive Emissions of Natural Gas

Finally, the fueling process provides an additional opportunity for release of natural gas. Small amounts of natural gas venting will occur during the fueling process due to the coupling and decoupling of connecting hoses. Proper fueling station design should also include the capability to return BOG from the trucks as they vent to lower tank pressures in preparation to be filled with LNG, rather than simply venting truck fuel tanks to the atmosphere. Including these considerations in the design and planning of fueling stations installed by the Commission will minimize the carbon footprint associated with Turnpike operations.

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Appendix A: PTC White Paper

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Appendix B: Computational Results of LNG Station Location Analysis

This appendix provides notation for the problem parameters, a detailed list of the assumptions to build the LNG station location model, the formulation of the mathematical model, and additional details of the computational results discussed in Section 2.1.

B. 1 Notation for sets and parameters

$G = (N, A)$: undirected graph representing the simplified PA Turnpike network,

$N = \{1, 2, ..., 37\}$: set of nodes of G (service plazas or aggregated intersections), where $n = 37$ is the number of nodes,

$A = \{(i, j): i, j \in N\}$: set of arcs of G representing Turnpike segments between service plazas or aggregated interchanges,

$K = \{2, 4, 6, 8, 9, 11, 12, 14, 16, 17, 19, 20, 22, 24, 26, 28, 32, 34, 36\} \subset N$: set of service plazas, where $n_K = 19$ is the number of service plazas,

$P = \{1, 3, 5, 7, 10, 13, 15, 18, 21, 23, 25, 27, 29, 30, 31, 33, 35, 37\} \subset N$: set of aggregated interchanges, where $n_P = 18$ is the number of aggregated interchanges,

Note that $N = P \cup K$,

$P_1 = \{1, 3, 5, 7, 10, 13, 15, 18, 21, 23, 25, 27, 29, 33\} \subset P$: set of aggregated interchanges in routes I-70, I-76, and I-276,

$P_2 = \{1, 3, 5, 7, 10, 13, 15, 18, 21, 23, 25, 27, 31, 35, 37\} \subset P$: set of aggregated interchanges in routes I-70, I-76, and I-476,

$P_3 = \{30, 33, 35, 37\} \subset P$: set of aggregated interchanges in routes I-276 and I-476,

Note that $P = P_1 \cup P_2 \cup P_3$,

$Q = \{(i, j): i < j, \text{ and } (i, j \in P_1, i, j \in P_2, \text{ or } i, j \in P_3)\}$: set of origin/destination (O/D) pairs,

$R = 300\ miles$: safe distance for LNG trucks,

d_{ij}: distance (in miles) between node i and node j. Note that $d_{ij} = d_{ji}$,

f_{ij}: traffic volume (in trucks of classes 6-10 per year) from origin i to destination j,

$Q^{(1)} = \left\{(i, j) \in Q : 0 < d_{ij} \le \frac{R}{4}\right\}$: set of O/D pairs of case 1,

$I_1^{(1)}(i, j) = \{k \in K : k \text{ is located in path } i \to j\},\ \forall (i, j) \in Q^{(1)}$,

$I_2^{(1)}(i, j) = \{k \in K : k \text{ is located in path } j \to i\},\ \forall (i, j) \in Q^{(1)}$,

$Q^{(2)} = \left\{(i, j) \in Q : \frac{R}{4} < d_{ij} \le \frac{R}{2}\right\}$: set of O/D pairs of case 2,

$I_1^{(2)}(i, j) = \{k \in K : k \text{ is located in path } i \to j\},\ \forall (i, j) \in Q^{(2)}$,

$I_2^{(2)}(i, j) = \{k \in K : k \text{ is located in path } j \to i\},\ \forall (i, j) \in Q^{(2)}$,

$Q^{(3)} = \left\{(i, j) \in Q : \frac{R}{2} < d_{ij} \le R\right\}$: set of O/D pairs of case 3,

$I_1^{(3)}(i, j) = \left\{k \in K : k \text{ is located in path } i \to j,\ d_{ik} \le \frac{R}{2}\right\},\ \forall (i, j) \in Q^{(3)}$,

$I_2^{(3)}(i, j) = \left\{k \in K : k \text{ is located in path } i \to j,\ d_{kj} \le \frac{R}{2}\right\},\ \forall (i, j) \in Q^{(3)}$,

$I_3^{(3)}(i, j) = \left\{k \in K : k \text{ is located in path } j \to i,\ d_{kj} \le \frac{R}{2}\right\},\ \forall (i, j) \in Q^{(3)}$,

$$I_4^{(3)}(i, j) = \left\{ k \in K : k \text{ is located in path } j \rightarrow i, d_{ik} \leq \frac{R}{2} \right\}, \ \forall (i, j) \in Q^{(3)},$$

$$Q^{(4)} = \left\{ (i, j) \in Q : R < d_{ij} \leq \frac{3R}{2} \right\} \text{ : set of O/D pairs of case 4.}$$

$$I_1^{(4)}(i, j) = \left\{ k \in K : k \text{ is located in path } i \rightarrow j, d_{ik} \leq \frac{R}{2} \right\}, \ \forall (i, j) \in Q^{(4)},$$

$$I_2^{(4)}(i, j, k) = \left\{ s \in K : s \text{ is located in path } k \rightarrow j, d_{ks} \leq R, d_{sj} \leq \frac{R}{2} \right\}, \ \forall\ k \in I_1^{(4)}(i, j), (i, j) \in Q^{(4)},$$

$$I_3^{(4)}(i, j) = \left\{ k \in K : k \text{ is located in path } j \rightarrow i, d_{kj} \leq \frac{R}{2} \right\}, \ \forall (i, j) \in Q^{(4)},$$

$$I_4^{(4)}(i, j, k) = \left\{ s \in K : s \text{ is located in path } k \rightarrow i, d_{sk} \leq R, d_{is} \leq \frac{R}{2} \right\}, \ \forall\ k \in I_3^{(4)}(i, j), (i, j) \in Q^{(4)},$$

B.2 Assumptions

In order to cover a truck trip between its entrance and exit points on the Turnpike, an LNG truck may need to refuel multiple times in various LNG stations (service plazas) depending on the truck's safe distance, the length of the trip, the locations of the LNG stations between the two interchanges, the amount of fuel in the tank when the truck enters the Turnpike, and the desirable amount of fuel when the truck leaves it. Thus, a number of reasonable assumptions need to be considered to formulate the constraints of the model to determine when a truck trip between two interchange points is covered. The following assumptions are similar to those made in other studies to locate refueling stations. [18, 20] They are necessary to formulate the constraints of the optimization model.

A.1 The safe travel distance of an LNG truck, R, is the maximum distance that the truck can travel without refueling. In the first scenario solved in Section 2.1, R=300 miles.

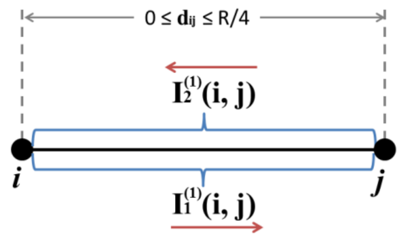
A.2 A truck enters the Turnpike with its tank at least half full.

A.3 A truck leaves the Turnpike with its tank at least half full.

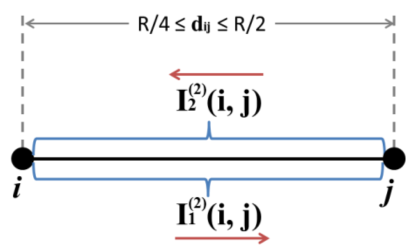
A.4 A truck trip between origin (entrance) *i* and destination (exit) *j* is considered covered if the truck can be refueled in its round trip from *i* to *j*, and from *j* to *i*.

A.5 Let d_{ij} be the travel distance (in miles) between origin *i* and destination *j* of a trip. Then, given that $0 < d_{ij} \leq 450$ miles for any pair of interchanges i and j in the PA Turnpike mainline and Northeast Extension, four cases need to be evaluated to consider a trip covered:

Case 1: If $0 < d_{ij} \leq R/4$, where $R/4 = 75$ miles in the first scenario solved in Section 2.1, trip (i, j) is covered if there is an LNG station in the trip from i to j, or from j to i. In this case it is not necessary to have an LNG station each way. Since d_{ij} is a short distance, the fuel consumption will be low, and Assumption A.3 can be relaxed in the direction where no LNG station is available. Based on the following figure, at least one service plaza in sets $I_1^{(1)}(i, j)$ or $I_2^{(1)}(i, j)$ needs to be selected to cover the trip.

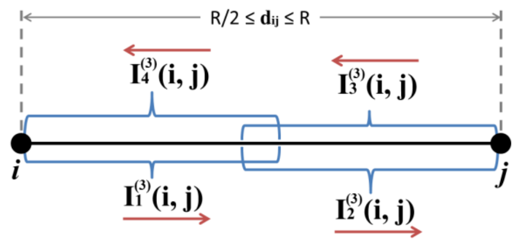


Case 2: If $R/4 < d_{ij} \leq R/2$, where $R/2 = 150$ miles in the first scenario, truck trip (i, j) is covered if there is an LNG station in the trip from i to j, and another LNG station from j to i. Note that, if there is a dual LNG station between i and j, this single station can cover the round trip in both directions. Based on the figure below, at least one service plaza in set $I_1^{(2)}(i, j)$ and another in set $I_2^{(2)}(i, j)$ need to be selected to cover the trip.

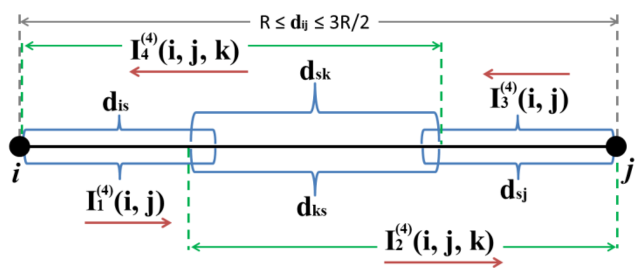


Case 3: If $R/2 < d_{ij} \leq R$, where $R = 300$ miles, the truck trip from i to j is covered if there is an LNG station within 150 miles of i and another station within 150 miles of j. Note that, since

the distance between i and j is at most 300 miles, a single LNG station within a distance of less than 150 miles from i and j would satisfy both conditions. Similarly, the truck trip from j to i is covered if there is an LNG station within 150 miles of j and another station within 150 miles of i. Based on the figure below, in the trip from i to j, at least one service plaza in set $I_1^{(3)}(i, j)$ and another in set $I_2^{(3)}(i, j)$ need to be selected to cover the trip in this direction. A single service plaza common to both sets satisfies the requirement. A similar requirement is necessary for the trip from j to i to cover the trip.



Case 4: If $R < d_{ij} \le 3R/2$, where $3R/2 = 450$ miles, the truck trip from i to j is covered if there is an LNG station within 150 miles of i. Let k be the position of that station. Then, there must be another station within 300 miles of k and 150 miles of j. Similar conditions have to be imposed in order to cover the truck trip from j to i. Given the sets in following figure, the trip from i to j is covered if a service plaza in set $I_1^{(4)}(i, j)$ and another in set $I_2^{(4)}(i, j, k)$ are selected to cover the trip in this direction. Note that k is the service plaza selected in $I_1^{(4)}(i, j)$. A similar requirement is necessary for the trip from j to i.



B.3 Mathematical Model

In this subsection we define the variables that are necessary to formulate the mathematical model. After that, the model is presented followed by a description of the objective function and all sets of constraints.

Definition of the variables:

$$x_k = \begin{cases} 1 & \text{if an LNG station is assigned to service plaza } k, \\ 0 & \text{otherwise,} \end{cases}$$

$$y_{ij} = \begin{cases} 1 & \text{if flows } f_{ij} \text{ and } f_{ji} \text{ are captured,} \\ 0 & \text{otherwise,} \end{cases}$$

$$y_{ijk} = \begin{cases} 1 & \text{if } x_k = 1 \text{ and flow } f_{ij} \text{ is captured,} \\ 0 & \text{otherwise.} \end{cases}$$

Integer Linear Programming (ILP) Model:

$$\text{Maximize } TC = \sum_{(i,j)\in Q} \left(f_{ij} + f_{ji}\right) y_{ij}, \tag{1}$$

Subject to

$$\sum_{k\in I_1^{(1)}(i,j)\cup I_2^{(1)}(i,j)} x_k \ge y_{ij}, \qquad \forall (i,j) \in Q^{(1)}, \tag{2}$$

$$\sum_{k\in I_1^{(2)}(i,j)} x_k \ge y_{ij}, \qquad q \forall (i,j) \in Q^{(2)}, \tag{3}$$

$$\sum_{k\in I_2^{(2)}(i,j)} x_k \ge y_{ij}, \qquad \forall (i,j) \in Q^{(2)}, \tag{4}$$

$$\sum_{k\in I_1^{(3)}(i,j)} x_k \ge y_{ij}, \qquad \forall (i,j) \in Q^{(3)}, \tag{5}$$

$$\sum_{k\in I_2^{(3)}(i,j)} x_k \ge y_{ij}, \qquad \forall (i,j) \in Q^{(3)}, \tag{6}$$

$$\sum_{k\in I_3^{(3)}(i,j)} x_k \ge y_{ij}, \qquad \forall (i,j) \in Q^{(3)}, \tag{7}$$

$$\sum_{k\in I_4^{(3)}(i,j)} x_k \ge y_{ij}, \qquad \forall (i,j) \in Q^{(3)}, \tag{8}$$

$$\sum_{k\in I_1^{(4)}(i,j)} x_k \ge y_{ij}, \qquad \forall (i,j) \in Q^{(4)}, \tag{9}$$

$$\sum_{s\in I_2^{(4)}(i,j,k)} x_s + 1 - x_k \ge y_{ijk}, \quad \forall\, k \in I_1^{(4)}(i,j), (i,j) \in Q^{(4)}, \tag{10}$$

$$x_k \geq y_{ijk}, \qquad \forall\, k \in I_1^{(4)}(i,j),\ (i,j) \in Q^{(4)}, \qquad (11)$$

$$\sum_{k \in I_1^{(4)}(i,j)} y_{ijk} \geq y_{ij}, \qquad \forall\, (i,j) \in Q^{(4)}, \qquad (12)$$

$$\sum_{k \in I_3^{(4)}(i,j)} x_k \geq y_{ij}, \qquad \forall\, (i,j) \in Q^{(4)}, \qquad (13)$$

$$\sum_{s \in I_4^{(4)}(i,j,k)} x_s + 1 - x_k \geq y_{ijk}, \qquad \forall\, k \in I_3^{(4)}(i,j),\ (i,j) \in Q^{(4)}, \qquad (14)$$

$$x_k \geq y_{ijk}, \qquad \forall\, k \in I_3^{(4)}(i,j),\ (i,j) \in Q^{(4)}, \qquad (15)$$

$$\sum_{k \in I_4^{(4)}(i,j)} y_{ijk} \geq y_{ij}, \qquad \forall\, (i,j) \in Q^{(4)}, \qquad (16)$$

$$\sum_{k \in K} x_k = p, \qquad (17)$$

$$x_k \in \{0,1\}, \qquad \forall\, k \in K, \qquad (18)$$

$$y_{ij} \in \{0,1\}, \qquad \forall\, (i,j) \in Q, \qquad (19)$$

$$y_{ijk} \in \{0,1\}, \qquad \forall\, k \in I_3^{(4)}(i,j),\ (i,j) \in Q^{(4)}. \qquad (20)$$

The objective function (1) maximizes the truck volume for truck classes 6-10 that can be covered if they were using LNG engines when p LNG stations are located along the Turnpike. Constraint set (2) is related to the truck trips for case 1. Note that set $Q^{(1)}$ includes all pairs of aggregated interchanges for which distance d_{ij} satisfies the conditions: $0 < d_{ij} \leq R/4$, where $R/4 = 75$ miles If there is at least one LNG station in the path from i to j, or in the path from j to i, then $y_{ij} = 1$ and the trip will be covered. Similarly, constraint sets (3) and (4) are set up to determine the trips covered for case 2, constraint sets (5) - (8) are used to detect the trips captured by case 3, and finally constraint sets (10) - (16) are used to identify the trips covered by case 4. Constraint (17) allows the model to select exactly p station locations. Lastly, constraint sets (18) - (20) define all the decision variables to be binary.

B.4 Computational Results

Table B.1 shows a comparison of the results of the model for p station locations, p = 1, 2, …, 8, and a safe distance R=300 miles, for the following two scenarios. In the first four columns, only the top eight station locations found for a safe distance R=300 miles are considered as potential solutions; in the next four columns, all 19 service plazas are allowed as potential solutions. Since the first scenario is restricted to only eight plazas, the solutions of the second scenario outperform the solutions of the first. Figure B.1 graphically displays the effective coverage of truck trips of the solutions for the two scenarios.

Tables B.2 (a) and (b) display a comparison of the model solutions for four scenarios with different truck safe distances: R=300, 350, 400, and 450 miles. Scenarios with large safe distance may represent average values of R when some trucks have a large fuel tank (see Table B.4) or dual tanks. Obviously, as the safe distance increases, more truck trips can be covered with the same number of refueling stations, because trucks can drive longer distances without refueling. Table B.3 and Figure B.2 graphically display the effective coverage of truck trips of the solutions for all four scenarios. Finally, Table B.5 shows an interesting comparison of the effective coverage for p = 8 stations when the four sets of optimal service plazas are considered as station locations for all four scenarios. Note that the solutions for R=400 and 450 miles are identical. Also, by taking the average of the four rows, the solutions for R=300 and 350 appear to be the less robust with an average effective coverage of 83.61% while the identical solutions for R = 400 and 450 have a higher average (83.98%).

Detailed results for scenarios with two types of LNG trucks are provided in Tables B.6 (a) to (e). Some LNG trucks carry a single tank (R=300 miles) and the remaining LNG trucks have dual tanks (R=600 miles). The model is run for a percentage of LNG trucks with a single tank that ranges from 0 to 100, in 10% intervals. For each case, the number of LNG stations increases from 1 to 15, one station at a time. These scenarios have already been discussed in Section 2.1, but the tables here provide the specific solution for p=1, … , 15 stations. Table B.7 provides the effective coverage for all runs.

Table B.1. Comparison between solutions with respect to top eight optimal fueling station locations and overall optimal solutions for a safe traveling distance of R=300 miles

No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Overall Coverage (%)	Service Plaza(s)	Captured Flow (trips/year) (Unrestricted)	Effective Coverage (%) (Unrestricted)	Overall Coverage (%) (Unrestricted)	Service Plaza(s) (Unrestricted)
0	0	0.00	0.00	-	0	0.00	0.00	-
1	2,066,994	21.48	17.89	Allentown	2,066,994	21.48	17.89	Allentown
2	3,417,414	35.51	29.58	King of Prussia, Allentown	3,580,184	37.20	30.99	Sideling Hill, Allentown
3	4,467,880	46.43	38.68	South Midway, North Midway, Allentown	4,930,604	51.23	42.68	Sideling Hill, King of Prussia, Allentown
4	5,818,300	60.46	50.37	South Midway, North Midway, King of Prussia, Allentown	5,972,866	62.06	51.70	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
5	6,900,002	71.70	59.73	South Midway, North Midway, Highspire, Peter J. Camiel, Allentown	6,996,119	72.70	60.56	Oakmont-Plum, Sideling Hill, Highspire, Peter J. Camiel, Allentown
6	7,942,264	82.53	68.75	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, Allentown	7,942,264	82.53	68.75	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, Allentown
7	8,876,487	92.24	76.84	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, North Neshaminy, Allentown	8,876,487	92.24	76.84	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, North Neshaminy, Allentown
8	9,623,615	100.00	83.31	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown	9,623,615	100.00	83.31	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown

Total Flow	11,552,005

Note: Highlighted rows 2 through 5 represent scenarios where the unrestricted solution outperforms the restricted solution.

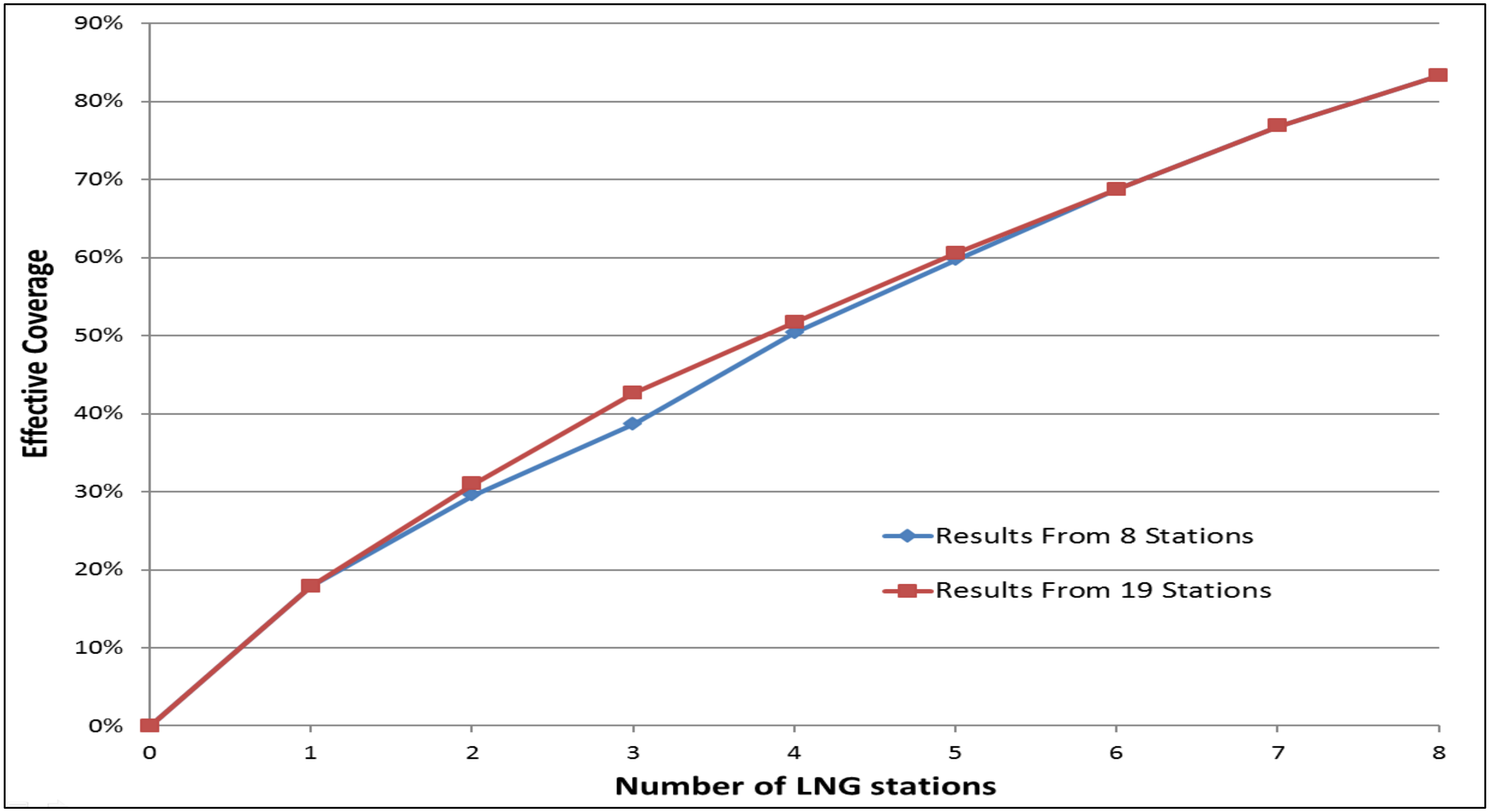


Figure B.1. Effective coverage of truck trips with respect to top eight optimal fueling station locations and overall optimal solutions for a safe traveling distance of R=300 miles

Table B.2 (a). Optimal LNG fueling station locations for safe traveling distances of R=300 and 350 miles

	R=300			R=350		
No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Service Plaza(s)	Captured Flow (trips/year)	Effective Coverage (%)	Service Plaza(s)
1	2,066,994	17.89	Allentown	2,568,985	22.24	Allentown
2	3,580,184	30.99	Sideling Hill, Allentown	4,377,616	37.89	Sideling Hill, Allentown
3	4,930,604	42.68	Sideling Hill, King of Prussia, Allentown	5,728,036	49.58	Sideling Hill, King of Prussia, Allentown
4	5,972,866	51.70	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown	6,770,298	58.61	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
5	6,996,119	60.56	Oakmont-Plum, Sideling Hill, Highspire, Peter J. Camiel, Allentown	7,713,162	66.77	Oakmont-Plum, Sideling Hill, Bowmansville, King of Prussia, Allentown
6	7,942,264	68.75	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, Allentown	8,671,966	75.07	Zelienople, New Stanton, South Midway, Lawn, Valley Forge, Allentown
7	8,876,487	76.84	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, North Neshaminy, Allentown	9,463,657	81.92	Zelienople, New Stanton, South Midway, Highspire, Peter J. Camiel, King of Prussia, Allentown
8	9,623,615	83.31	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown	10,003,896	86.60	Zelienople, Oakmont-Plum, New Stanton, South Midway, Highspire, Peter J. Camiel, King of Prussia, Allentown
9	10,184,353	88.16	Zelienople, Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown	10,538,456	91.23	Zelienople, Oakmont-Plum, New Stanton, South Midway, Highspire, Peter J. Camiel, King of Prussia, Allentown, Hickory Run
10	10,718,913	92.79	Zelienople, Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run	11,027,892	95.46	Zelienople, Oakmont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, Allentown, Hickory Run
11	11,249,221	97.38	Zelienople, Oakmont-Plum, New Stanton, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run	11,383,506	98.54	Zelienople, Oakmont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
12	11,407,846	98.75	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run	11,435,695	98.99	Zelienople, Oakmont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
13	11,460,035	99.20	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run	11,479,062	99.37	Zelienople, Oakmont-Plum, New Stanton, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
14	11,509,253	99.63	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run	11,521,814	99.74	Zelienople, Oakmont-Plum, New Stanton, South Midway, Sideling Hill, Blue Mountain, Highspire, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
15	11,552,005	100.00	Zelienople, Oakmont-Plum, New Stanton, South Somerset, North Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run	11,552,005	100.00	Zelienople, Oakmont-Plum, New Stanton, North Somerset, South Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run

Table B.2 (b). Optimal LNG fueling station locations for safe traveling distances of R=400 and 450 miles

	R=400			R=450		
No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Service Plaza(s)	Captured Flow (trips/year)	Effective Coverage (%)	Service Plaza(s)
1	2,568,988	22.24	Allentown	2,569,106	22.24	Allentown
2	4,457,161	38.58	Sideling Hill, Allentown	4,457,161	38.58	Sideling Hill, Allentown
3	5,890,741	50.99	Sideling Hill, Peter J. Camiel, Allentown	6,087,563	52.70	Sideling Hill, Peter J. Camiel, Allentown
4	6,975,903	60.39	Oakmont-plum, Sideling Hill, Peter J. Camiel, Allentown	7,259,171	62.84	New Stanton, South Midway, Peter J. Camiel, Allentown
5	8,156,106	70.60	Oakmont-plum, New Stanton, Sideling Hill, Peter J. Camiel, Allentown	8,352,928	72.31	Oakmont-plum, New Stanton, Sideling Hill, Peter J. Camiel, Allentown
6	9,239,926	79.99	Oakmont-plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown	9,240,964	79.99	Oakmont-plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown
7	9,800,664	84.84	Zelienople, Oakmont-plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown	9,801,702	84.85	Zelienople, Oakmont-plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown
8	10,335,224	89.47	Zelienople, Oakmont-plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown, Hickory Run	10,336,262	89.48	Zelienople, Oakmont-plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown, Hickory Run
9	10,772,453	93.25	Zelienople, Oakmont-plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, Allentown, Hickory Run	10,773,491	93.26	Zelienople, Oakmont-plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, Allentown, Hickory Run
10	11,128,067	96.33	Zelienople, Oakmont-plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, North neshaminy, Allentown, Hickory Run	11,129,105	96.34	Zelienople, Oakmont-plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, North neshaminy, Allentown, Hickory Run
11	11,383,506	98.54	Zelienople, Oakmont-plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North neshaminy, Allentown, Hickory Run	11,383,506	98.54	Zelienople, Oakmont-plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North neshaminy, Allentown, Hickory Run
12	11,435,695	98.99	Zelienople, Oakmont-plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North neshaminy, Allentown, Hickory Run	11,435,695	98.99	Zelienople, Oakmont-plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North neshaminy, Allentown, Hickory Run
13	11,479,062	99.37	Zelienople, Oakmont-plum, New Stanton, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North neshaminy, Allentown, Hickory Run	11,479,062	99.37	Zelienople, Oakmont-plum, New Stanton, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North neshaminy, Allentown, Hickory Run
14	11,521,814	99.74	Zelienople, Oakmont-plum, New Stanton, South Midway, Sideling Hill, Blue Mountain, Highspire, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North neshaminy, Allentown, Hickory Run	11,521,814	99.74	Zelienople, Oakmont-plum, New Stanton, South Midway, Sideling Hill, Blue Mountain, Highspire, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North neshaminy, Allentown, Hickory Run
15	11,552,005	100.00	Zelienople, Oakmont-plum, New Stanton, North Somerset, North Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North neshaminy, Allentown, Hickory Run	11,552,005	100.00	Zelienople, Oakmont-plum, New Stanton, North Somerset, North Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North neshaminy, Allentown, Hickory Run

Table B.3. Effective coverage of truck trips for four safe traveling distances (R=300, 350, 400, and 450 miles)

Safe Distance	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
300	0.00	17.89	30.99	42.68	51.70	60.56	68.75	76.84	83.31	88.16	92.79	97.38	98.75	99.20	99.63	100.00
350	0.00	22.24	37.89	49.58	58.61	66.77	75.07	81.92	86.60	91.23	95.46	98.54	98.99	99.37	99.74	100.00
400	0.00	22.24	38.58	50.99	60.39	70.60	79.99	84.84	89.47	93.25	96.33	98.54	98.99	99.37	99.74	100.00
450	0.00	22.24	38.58	52.70	62.84	72.31	79.99	84.85	89.48	93.26	96.34	98.54	98.99	99.37	99.74	100.00

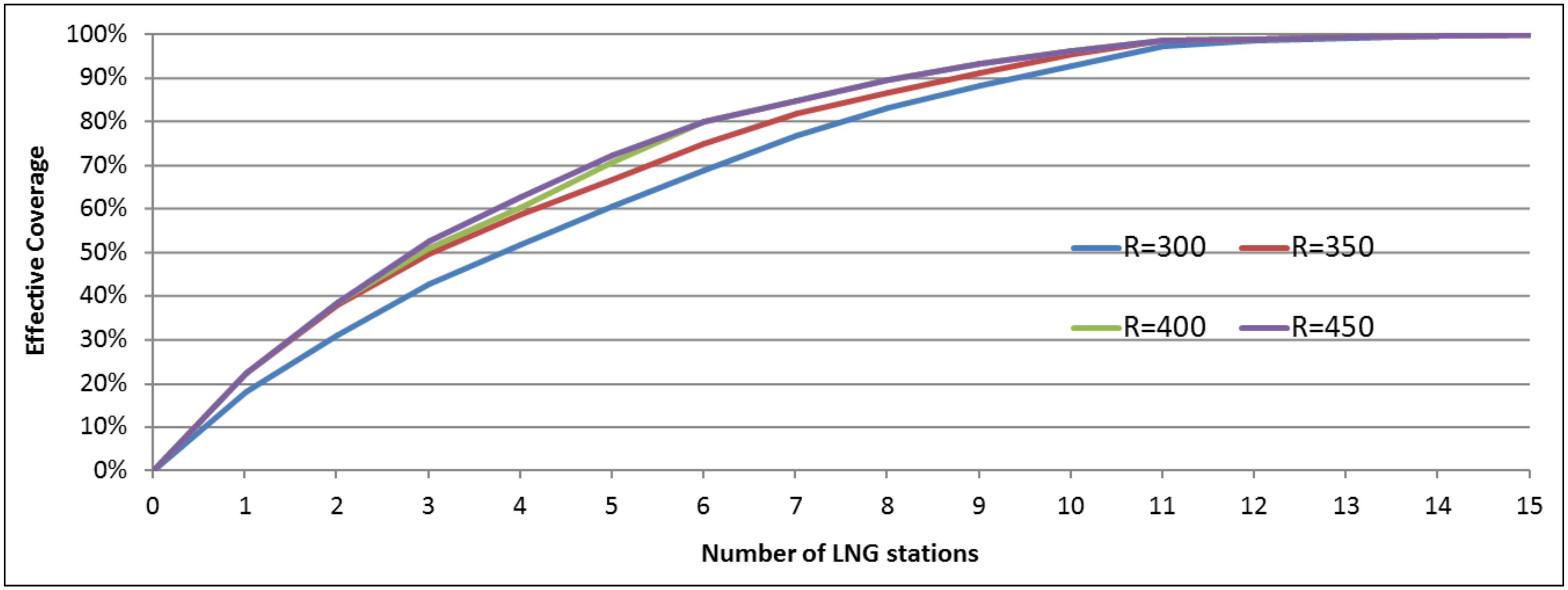


Figure B.2. Effective coverage of truck trips for four safe traveling distances (R=300, 350, 400, and 450 miles)

Table B.4. LNG tank capacities and truck safe traveling distances [21]

LNG Tank Capacity (gallons)	Amt. of Gas Actually Stored (gallons)	Diesel Equivalent (Energy Stored) (gallons)	Safe Distance (miles)
119	102	63	300 to 350
149	128	78	350 to 400

Table B.5. Solution matrix with respect to eight LNG fueling stations

Number of Stations: 8

	Safe Traveling Distance			
Service Plazas	R=300	R=350	R=400	R=450
Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown (Optimal SPs when R = 300)	83.31%	83.38%	83.78%	83.97%
	9,623,615	9,632,177	9,678,522	9,700,213
Zelienople, Oakmont-Plum, New Stanton, South Midway, Highspire, Peter J. Camiel, King of Prussia, Allentown (Optimal SPs when R = 350)	71.55%	86.60%	87.92%	88.38%
	8,265,922	10,003,896	10,156,007	10,210,125
Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown, Hickory Run (Optimal SPs when R = 400)	74.87%	82.08%	89.47%	89.48%
	8,649,002	9,482,452	10,335,224	10,336,262
Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown, Hickory Run (Optimal SPs when R = 450)	74.87%	82.08%	89.47%	89.48%
	8,649,002	9,482,452	10,335,224	10,336,262

Total Flows	11,552,005

Notes: Yellow blocks represent optimal solutions. Values represent percent effective coverage and annual trips covered of class 6-10 trucks.

Table B.6 (a). Optimal LNG fueling station locations for two pairs of mixed safe traveling distances: R=300 (90%) and R=600 (10%) on left, and R=300 (80%) and R=600 (20%) on right

	R=300 (90%) R=600 (10%)		
No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Service Plaza(s)
1	2,117,207	18.33	Allentown
2	3,667,882	31.75	Sideling Hill, Allentown
3	5,058,674	43.79	Sideling Hill, King of Prussia, Allentown
4	6,119,358	52.97	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
5	7,078,064	61.27	Oakmont-Plum, Sideling Hill, Highspire, Peter J. Camiel, Allentown
6	8,003,408	69.28	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, Allentown
7	8,887,432	76.93	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, North Neshaminy, Allentown
8	9,634,560	83.40	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
9	10,195,298	88.26	Zelienople, Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
10	10,729,858	92.88	Zelienople, Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
11	11,262,650	97.50	Zelienople, Oakmont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
12	11,408,431	98.76	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
13	11,460,620	99.21	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
14	11,509,253	99.63	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
15	11,552,005	100.00	Zelienople, Oakmont-Plum, New Stanton, South Somerset, North Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run

	R=300 (80%) R=600 (20%)		
No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Service Plaza(s)
1	2,167,419	18.76	Allentown
2	3,755,579	32.51	Sideling Hill, Allentown
3	5,186,743	44.90	Sideling Hill, King of Prussia, Allentown
4	6,265,851	54.24	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
5	7,160,010	61.98	Oakmont-Plum, Sideling Hill, Highspire, Peter J. Camiel, Allentown
6	8,064,552	69.81	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, Allentown
7	8,898,377	77.03	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, North Neshaminy, Allentown
8	9,645,505	83.50	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
9	10,206,243	88.35	Zelienople, Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
10	10,741,518	92.98	Zelienople, Oakmont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
11	11,276,078	97.61	Zelienople, Oakmont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
12	11,409,016	98.76	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
13	11,461,205	99.21	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
14	11,509,253	99.63	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
15	11,552,005	100.00	Zelienople, Oakmont-Plum, New Stanton, South Somerset, North Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run

Table B.6 (b). Optimal LNG fueling station locations for two pairs of mixed safe traveling distances: R=300 (70%) and R=600 (30%) on left, and R=300 (60%) and R=600 (40%) on right

	R=300 (70%) R=600 (30%)		
No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Service Plaza(s)
1	2,217,632	19.20	Allentown
2	3,843,277	33.27	Sideling Hill, Allentown
3	5,314,813	46.01	Sideling Hill, King of Prussia, Allentown
4	6,412,343	55.51	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
5	7,280,295	63.02	Oakmont-Plum, Sideling Hill, Valley Forge, King of Prussia, Allentown
6	8,125,697	70.34	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, Allentown
7	8,949,443	77.47	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, Allentown
8	9,656,450	83.59	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
9	10,220,903	88.48	Zelienople, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
10	10,755,463	93.10	Zelienople, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
11	11,289,507	97.73	Zelienople, Oakmont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
12	11,409,601	98.77	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
13	11,461,790	99.22	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
14	11,509,253	99.63	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
15	11,552,005	100.00	Zelienople, Oakmont-Plum, New Stanton, South Somerset, North Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run

	R=300 (60%) R=600 (40%)		
No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Service Plaza(s)
1	2,267,844	19.63	Allentown
2	3,930,975	34.03	Sideling Hill, Allentown
3	5,442,882	47.12	Sideling Hill, King of Prussia, Allentown
4	6,558,836	56.78	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
5	7,412,405	64.17	Oakmont-Plum, Sideling Hill, Bowmansville, King of Prussia, Allentown
6	8,230,724	71.25	Oakmont-Plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown
7	9,010,587	78.00	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, Allentown
8	9,667,395	83.69	Oakmont-Plum, South Midway, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
9	10,236,397	88.61	Zelienople, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
10	10,770,957	93.24	Zelienople, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
11	11,302,935	97.84	Zelienople, Oakmont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
12	11,410,186	98.77	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
13	11,462,375	99.22	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
14	11,509,253	99.63	Zelienople,Oakmont-Plum, New Stanton, South Somerset, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
15	11,552,005	100.00	Zelienople, Oakmont-Plum, New Stanton, South Somerset, North Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run

Table B.6 (c). Optimal LNG fueling station locations for two pairs of mixed safe traveling distances: R=300 (50%) and R=600 (50%) on left, and R=300 (40%) and R=600 (60%) on right

	R=300 (50%) R=600 (50%)		
No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Service Plaza(s)
1	2,318,057	20.07	Allentown
2	4,018,673	34.79	Sideling Hill, Allentown
3	5,570,952	48.22	Sideling Hill, King of Prussia, Allentown
4	6,705,328	58.04	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
5	7,558,846	65.43	Oakmont-Plum, New Stanton, Sideling Hill, King of Prussia, Allentown
6	8,399,979	72.71	Oakmont-Plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown
7	9,091,806	78.70	Oakmont-Plum, South Somerset, North Midway, Highspire, Peter J. Camiel, King of Prussia, Allentown
8	9,698,416	83.95	Oakmont-Plum, South Somerset, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
9	10,259,154	88.81	Zelienople, Oakmont-Plum, South Somerset, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
10	10,793,714	93.44	Zelienople, Oakmont-Plum, South Somerset, North Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
11	11,316,364	97.96	Zelienople, Oakmont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
12	11,410,772	98.78	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
13	11,462,961	99.23	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
14	11,509,253	99.63	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
15	11,552,005	100.00	Zelienople, Oakmont-Plum, New Stanton, South Somerset, North Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run

	R=300 (40%) R=600 (60%)		
No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Service Plaza(s)
1	2,368,270	20.50	Allentown
2	4,106,370	35.55	Sideling Hill, Allentown
3	5,699,022	49.33	Sideling Hill, King of Prussia, Allentown
4	6,851,820	59.31	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
5	7,742,409	67.02	Oakmont-Plum, New Stanton, Sideling Hill, King of Prussia, Allentown
6	8,569,234	74.18	Oakmont-Plum, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown
7	9,204,585	79.68	Oakmont-Plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, Allentown
8	9,765,323	84.53	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, Allentown
9	10,321,734	89.35	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown
10	10,856,294	93.98	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
11	11,329,792	98.08	Zelienople, Oakmont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
12	11,411,357	98.78	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
13	11,463,546	99.23	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
14	11,509,253	99.63	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
15	11,552,005	100.00	Zelienople, Oakmont-Plum, New Stanton, South Somerset, North Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run

Table B.6 (d). Optimal LNG fueling station locations for two pairs of mixed safe traveling distances: R=300 (30%) and R=600 (70%) on left, and R=300 (20%) and R=600 (80%) on right

	R=300 (30%) R=600 (70%)		
No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Service Plaza(s)
1	2,418,482	20.94	Allentown
2	4,194,068	36.31	Sideling Hill, Allentown
3	5,827,091	50.44	Sideling Hill, King of Prussia, Allentown
4	6,998,313	60.58	Oakmont-Plum, Sideling Hill, King of Prussia, Allentown
5	7,932,536	68.67	Zelienople, New Stanton, Sideling Hill, King of Prussia, Allentown
6	8,745,052	75.70	Zelienople, New Stanton, Sideling Hill, Bowmansville, King of Prussia, Allentown
7	9,329,550	80.76	Zelienople, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, Allentown
8	9,883,725	85.56	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, Allentown
9	10,418,285	90.19	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, Allentown, Hickory Run
10	10,924,497	94.57	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
11	11,343,221	98.19	Zelienople, Oakmont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
12	11,411,942	98.79	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
13	11,464,131	99.24	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
14	11,509,253	99.63	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
15	11,552,005	100.00	Zelienople, Oakmont-Plum, New Stanton, South Somerset, North Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run

	R=300 (20%) R=600 (80%)		
No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Service Plaza(s)
1	2,468,695	21.37	Allentown
2	4,281,766	37.07	Sideling Hill, Allentown
3	5,963,685	51.62	Sideling Hill, Peter J. Camiel, Allentown
4	7,153,329	61.92	Oakmont-Plum, Sideling Hill, Peter J. Camiel, Allentown
5	8,136,154	70.43	Zelienople, New Stanton, Sideling Hill, Peter J. Camiel, Allentown
6	8,959,900	77.56	Zelienople, New Stanton, Sideling Hill, Peter J. Camiel, King of Prussia, Allentown
7	9,502,545	82.26	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Peter J. Camiel, King of Prussia, Allentown
8	10,037,105	86.89	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Peter J. Camiel, King of Prussia ,Allentown, Hickory Run
9	10,536,687	91.21	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, Allentown, Hickory Run
10	10,992,699	95.16	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
11	11,356,649	98.31	Zelienople, Oakmont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
12	11,412,527	98.79	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
13	11,464,716	99.24	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
14	11,509,253	99.63	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
15	11,552,005	100.00	Zelienople, Oakmont-Plum, New Stanton, South Somerset, North Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run

Table B.6 (e). Optimal LNG fueling station locations for two pairs of mixed safe traveling distances: R=300 (10%) and R=600 (90%) on left, and R=300 (0%) and R=600 (100%) on right

	R=300 (10%) R=600 (90%)		
No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Service Plaza(s)
1	2,518,907	21.80	Allentown
2	4,369,463	37.82	Sideling Hill, Allentown
3	6,131,717	53.08	Sideling Hill, Peter J. Camiel, Allentown
4	7,339,785	63.54	Oakmont-Plum, Sideling Hill, Peter J. Camiel, Allentown
5	8,371,210	72.47	Zelienople, New Stanton, Sideling Hill, Peter J. Camiel, Allentown
6	9,194,956	79.60	Zelienople, New Stanton, Sideling Hill, Peter J. Camiel, King of Prussia, Allentown
7	9,729,516	84.22	Zelienople, New Stanton, Sideling Hill, Peter J. Camiel, King of Prussia, Allentown, Hickory Run
8	10,260,632	88.82	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Peter J. Camiel, King of Prussia ,Allentown, Hickory Run
9	10,666,445	92.33	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
10	11,060,902	95.75	Zelienople, Oakmont-Plum, New Stanton, Sideling Hill, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
11	11,370,078	98.43	Zelienople, Oakmont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
12	11,422,267	98.88	Zelienople, Oakmont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
13	11,466,219	99.26	Zelienople, Oakmont-Plum, New Stanton, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
14	11,509,253	99.63	Zelienople, Oakmont-Plum, New Stanton, South Somerset, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
15	11,552,005	100.00	Zelienople, Oakmont-Plum, New Stanton, South Somerset, North Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run

	R=300 (0%) R=600 (100%)		
No. of Stations	Captured Flow (trips/year)	Effective Coverage (%)	Service Plaza(s)
1	2,569,120	22.24	Allentown
2	4,457,161	38.58	Sideling Hill, Allentown
3	6,299,750	54.53	Sideling Hill, Peter J. Camiel, Allentown
4	7,566,645	65.50	New Stanton, South Midway, Peter J. Camiel, Allentown
5	8,609,301	74.53	Zelienopleienople, New Stanton, Cumberland Valley, Peter J. Camiel, Allentown
6	9,433,047	81.66	Zelienopleienople, New Stanton, Cumberland Valley, Peter J. Camiel, King of Prussia, Allentown
7	9,967,607	86.28	Zelienopleienople, New Stanton, Cumberland Valley, Peter J. Camiel, King of Prussia, Allentown, Hickory Run
8	10,490,740	90.81	Zelienopleienople, Oakmont-Plummont-Plum, New Stanton, Cumberland Valley, Peter J. Camiel, King of Prussia, Allentown, Hickory Run
9	10,846,354	93.89	Zelienopleienople, Oakmont-Plummont-Plum, New Stanton, Cumberland Valley, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
10	11,176,379	96.75	Zelienopleienople, Oakmont-Plummont-Plum, New Stanton, South Midway, Highspire, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
11	11,383,506	98.54	Zelienopleienople, Oakmont-Plummont-Plum, New Stanton, South Midway, Cumberland Valley, Lawn, Peter J. Camiel, King of Prussia, North Neshaminy, Allentown, Hickory Run
12	11,435,695	98.99	Zelienopleienople, Oakmont-Plummont-Plum, New Stanton, South Midway, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
13	11,479,062	99.37	Zelienopleienople, Oakmont-Plummont-Plum, New Stanton, South Midway, Sideling Hill, Blue Mountain, Highspire, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
14	11,521,814	99.74	Zelienopleienople, Oakmont-Plummont-Plum, New Stanton, South Midway, Sideling Hill, Blue Mountain, Highspire, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run
15	11,552,005	100.00	Zelienopleienople, Oakmont-Plummont-Plum, New Stanton, North Somerset, North Midway, Sideling Hill, Cumberland Valley, Lawn, Bowmansville, Peter J. Camiel, Valley Forge, King of Prussia, North Neshaminy, Allentown, Hickory Run

Table B.7. Effective coverage with respect to different proportions of safe traveling distances R=300 and R=600 (in %)

No. of Stations	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
R=300 (90%) R=600 (10%)	0.00	18.33	31.75	43.79	52.97	61.27	69.28	76.93	83.40	88.26	92.88	97.50	98.76	99.21	99.63	100.00
R=300 (80%) R=600 (20%)	0.00	18.76	32.51	44.90	54.24	61.98	69.81	77.03	83.50	88.35	92.98	97.61	98.76	99.21	99.63	100.00
R=300 (70%) R=600 (30%)	0.00	19.20	33.27	46.01	55.51	63.02	70.34	77.47	83.59	88.48	93.10	97.73	98.77	99.22	99.63	100.00
R=300 (60%) R=600 (40%)	0.00	19.63	34.03	47.12	56.78	64.17	71.25	78.00	83.69	88.61	93.24	97.84	98.77	99.22	99.63	100.00
R=300 (50%) R=600 (50%)	0.00	20.07	34.79	48.22	58.04	65.43	72.71	78.70	83.95	88.81	93.44	97.96	98.78	99.23	99.63	100.00
R=300 (40%) R=600 (60%)	0.00	20.50	35.55	49.33	59.31	67.02	74.18	79.68	84.53	89.35	93.98	98.08	98.78	99.23	99.63	100.00
R=300 (30%) R=600 (70%)	0.00	20.94	36.31	50.44	60.58	68.67	75.70	80.76	85.56	90.19	94.57	98.19	98.79	99.24	99.63	100.00
R=300 (20%) R=600 (80%)	0.00	21.37	37.07	51.62	61.92	70.43	77.56	82.26	86.89	91.21	95.16	98.31	98.79	99.24	99.63	100.00
R=300 (10%) R=600 (90%)	0.00	21.80	37.82	53.08	63.54	72.47	79.60	84.22	88.82	92.33	95.75	98.43	98.88	99.26	99.63	100.00

Appendix C: Economic analysis for LNG truck payback

This section estimates the economic benefits accrued by a trucking company when purchasing an LNG truck instead of a diesel truck, and keeping the truck for a period of 6 years. The analysis is performed under the following assumptions:

- While the price of the diesel truck is $140,000, an equivalent LNG truck costs $240,000. This is a realistic difference for an LNG truck with two fuel tanks [1].
- The annual average mileage of a truck is 120,000 miles, representing an annual consumption of 20,000 DGE of fuel.
- The overall tax rate for the trucking company is 32%.
- The tax depreciation system for a truck is based on the Modified Accelerated Cost Recovery System (MACRS).
- The value of a truck decreases by half every four years. Thus, the salvage value of a six year old truck is 37.5% of its original price.

Since 1986, the MACRS method has been used to depreciate properties for tax purposes in the U.S. MACRS has different recovery periods according to the asset classes, and different depreciation rates are applied based on the recovery period of the corresponding asset class. Under MACRS, trucks have the depreciation rates shown in Table C.1.

Table C.1. Annual depreciation percentage of a truck under MACRS [2]

Year	1	2	3	4	5	6
Percentage (%)	20	32	19.20	11.52	11.52	5.76

Based on the above assumptions, Table C.2 compares the cash flow of a diesel truck with that of an LNG truck for a period of 6 years. In the table, X represents the annual average income generated by a truck, DP is the price of one gallon of diesel, and LP is the price of one DGE of LNG. For example, the cash flow in year 2 for a diesel truck includes the annual income, X, minus the fuel cost, 20,000*DP, and minus the annual corporate taxes, which are the product of the taxable income, X-20,000*DP-0.32*140,000, times the tax rate, 0.32.

Table C.2. Comparison of cash flow between a diesel truck and an LNG truck for 6 years (in dollars)

Year	Diesel Truck	LNG Truck
0	-140,000	-240,000
1	X-20,000*DP -(X-20,000*DP-0.20*140,000)*0.32	X-20,000*LP -(X-20,000*LP-0.20*240,000)*0.32
2	X-20,000*DP -(X-20,000*DP-0.32*140,000)*0.32	X-20,000*LP -(X-20,000*LP-0.32*240,000)*0.32
3	X-20,000*DP -(X-20,000*DP-0.192*140,000)*0.32	X-20,000*LP -(X-20,000*LP-0.192*240,000)*0.32
4	X-20,000*DP -(X-20,000*DP-0.1152*140,000)*0.32	X-20,000*LP -(X-20,000*LP-0.1152*240,000)*0.32
5	X-20,000*DP -(X-20,000*DP-0.1152*140,000)*0.32	X-20,000*LP-(X-20,000*LP -0.1152*240,000)*0.32
6	X-20,000*DP -(X-20,000*DP-0.0576*140,000)*0.32 -140,000*0.375*0.32+140,000*0.375	X-20,000*LP -(X-20,000*LP-0.0576*240,000)*0.32 -240,000*0.375*0.32+240,000*0.375

Under MACRS and the table above, we are able to calculate the cash flow of economic benefits by replacing a diesel truck by a LNG truck. Table C.3 shows the expected cash flows over a period of 6 years that can be additionally gained by replacing a diesel truck by a LNG truck with respect to the difference between diesel and LNG prices.

Table C.3. Cash flows based on differences between a diesel truck and an LNG truck over 6 years (in dollars)

Diesel and LNG Price Difference	Now	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
0.4	-100,000	11,840	15,680	11,584	9,126	9,126	32,783
0.6	-100,000	14,560	18,400	14,304	11,846	11,846	35,503
0.8	-100,000	17,280	21,120	17,024	14,566	14,566	38,223
1.0	-100,000	20,000	23,840	19,744	17,286	17,286	40,943
1.2	-100,000	22,720	26,560	22,464	20,006	20,006	43,663
1.4	-100,000	25,440	29,280	25,184	22,726	22,726	46,383
1.6	-100,000	28,160	32,000	27,904	25,446	25,446	49,103
1.8	-100,000	30,880	34,720	30,624	28,166	28,166	51,823
2.0	-100,000	33,600	37,440	33,344	30,886	30,886	54,543
2.2	-100,000	36,320	40,160	36,064	33,606	33,606	57,263
2.4	-100,000	39,040	42,880	38,784	36,326	36,326	59,983
2.6	-100,000	41,760	45,600	41,504	39,046	39,046	62,703
2.8	-100,000	44,480	48,320	44,224	41,766	41,766	65,423
3.0	-100,000	47,200	51,040	46,944	44,486	44,486	68,143

Return on Investment (ROI), Net Present Value (NPV), and Internal Rate of Return (IRR) are the major financial metrics used to analyze an investment. Each metric provides a different investment message. ROI is one of the most well-known economic analytical tools in measuring financial results in the business field; it is also called **cash-on-cash** analysis. [3] It is derived as incremental gains from an investment divided by the investment cost:

$$\mathrm{ROI} = \frac{(Gains - \ Costs)}{Costs}.$$

A positive ROI, greater than 0%, means the investment returns are more than its costs. Especially, when comparing to other investments, a higher ROI is a better investment than others. Next, NPV evaluates investments at present value according to their values during the investment periods, meaning that the higher NPV is the more desirable investment. [4] Given cash inflows and outflows over an investment, NPV is derived as

$$\mathrm{NPV} = \sum_{n=0}^{periods} \frac{inflows\ or\ outflows}{(1 + interest\ rate)^n}.$$

ROI is simple and intuitively applied, but has a weakness in that it does not consider interest rate at all for the next years. Lastly, Internal Rate of Return (IRR) is another important metric to analyze cash flow. Given the cash flow of an investment, we find a rate that makes NPV equal to zero. It is derived as

$$0 = \sum_{n=0}^{periods} \frac{inflows\ or\ outflows}{(1 + IRR)^n}.$$

Since the rate is determined by the internal relationship between outflows and inflows in an investment, we call it as IRR. That is, it is defined internally without environmental factors. Comparing it to NPV, IRR indicates the efficiency of an investment. If IRR is greater than the minimum rate of return, it can be a good possible investment. Now, using the three financial metrics, we analyze the cash flows based on differences between diesel and LNG prices in DGE.

Using the cash flows in Table C.3, ROI with respect to differences in fuel prices for the next 6 years are derived in Table C.4. Also, Figure C.1 describes ROI with respect to these fuel price differences.

Table C.4. ROI for cash flow differences between a diesel truck and an LNG truck over 6 years (in dollars)

Diesel and LNG Price Difference	Total Cash Inflows	Total Cash Outflows	Net Cash Flows	ROI
0.4	90,140	-100,000	-9,860	-9.86%
0.6	106,460	-100,000	6,460	6.46%
0.8	122,780	-100,000	22,780	22.78%
1.0	139,100	-100,000	39,100	39.10%
1.2	155,420	-100,000	55,420	55.42%
1.4	171,740	-100,000	71,740	71.74%
1.6	188,060	-100,000	88,060	88.06%
1.8	204,380	-100,000	104,380	104.38%
2.0	220,700	-100,000	120,700	120.70%
2.2	237,020	-100,000	137,020	137.02%
2.4	253,340	-100,000	153,340	153.34%
2.6	269,660	-100,000	169,660	169.66%
2.8	285,980	-100,000	185,980	185.98%
3.0	302,300	-100,000	202,300	202.30%

From ROI analysis, we can figure out that using an LNG truck is more beneficial than using a diesel truck when the difference between diesel and LNG prices is at least $0.52.

Considering that in September 2012, the average retail diesel price was $4.13 per gallon in the U.S., and the retail LNG prices at LNG stations in Ohio and Connecticut were $3.00 and $2.75 per DGE, respectively, the difference between diesel and LNG prices was over $1.00 per DGE, which implies that a truck transportation company can expect at least 39.10% ROI by using LNG trucks instead of diesel trucks.

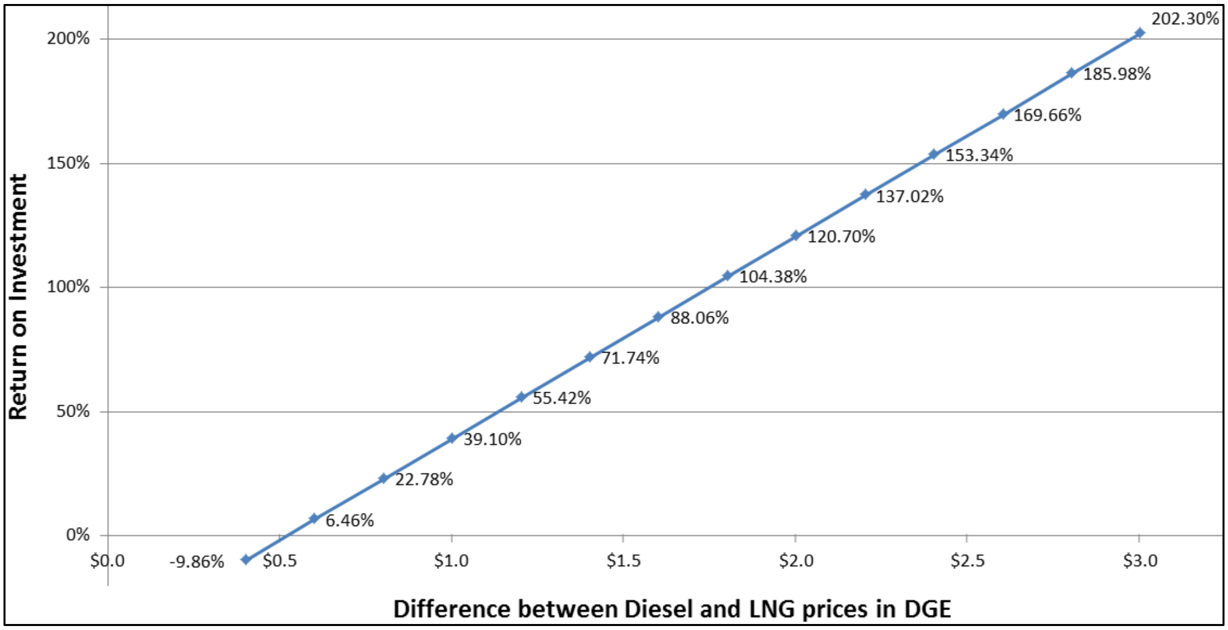


Figure C.1. ROI for cash flow differences between a diesel truck and an LNG truck over 6 years

Now, we perform NPV analysis to illustrate how an LNG truck is more beneficial than a diesel truck according to a given interest rate. To prepare for various market situations, we have increased the annual interest rate for investments from 5% to 25% in 5% intervals. Using the cash flows in Table C.3, Table C.5 and Figure C.2 are created to show the results of NPV according to various interest rates.

Table C.5. NPV results for cash flow differences between a diesel truck and an LNG truck over 6 years (in dollars)

	Interest Rate				
Diesel and LNG Price Difference	5%	10%	15%	20%	25%
0.4	-25,372.5	-37,169.0	-46,302.8	-53,492.8	-59,239.2
0.6	-11,566.6	-25,322.7	-36,009.0	-44,447.4	-51,211.3
0.8	2,239.3	-13,476.3	-25,715.2	-35,402.0	-43,183.4
1.0	16,045.2	-1,630.0	-15,421.4	-26,356.6	-35,155.5
1.2	29,851.1	10,216.3	-5,127.6	-17,311.2	-27,127.7
1.4	43,656.9	22,062.6	5,166.2	-8,265.8	-19,099.8
1.6	57,462.8	33,908.9	15,460.0	779.5	-11,071.9
1.8	71,268.7	45,755.2	25,753.8	9,824.9	-3,044.0
2.0	85,074.6	57,601.5	36,047.6	18,870.3	4,983.8
2.2	98,880.5	69,447.8	46,341.4	27,915.7	13,011.7
2.4	112,686.3	81,294.1	56,635.1	36,961.1	21,039.6
2.6	126,492.2	93,140.4	66,928.9	46,006.5	29,067.4
2.8	140,298.1	104,986.7	77,222.7	55,051.9	37,095.3
3.0	154,104.0	116,833.1	87,516.5	64,097.3	45,123.2

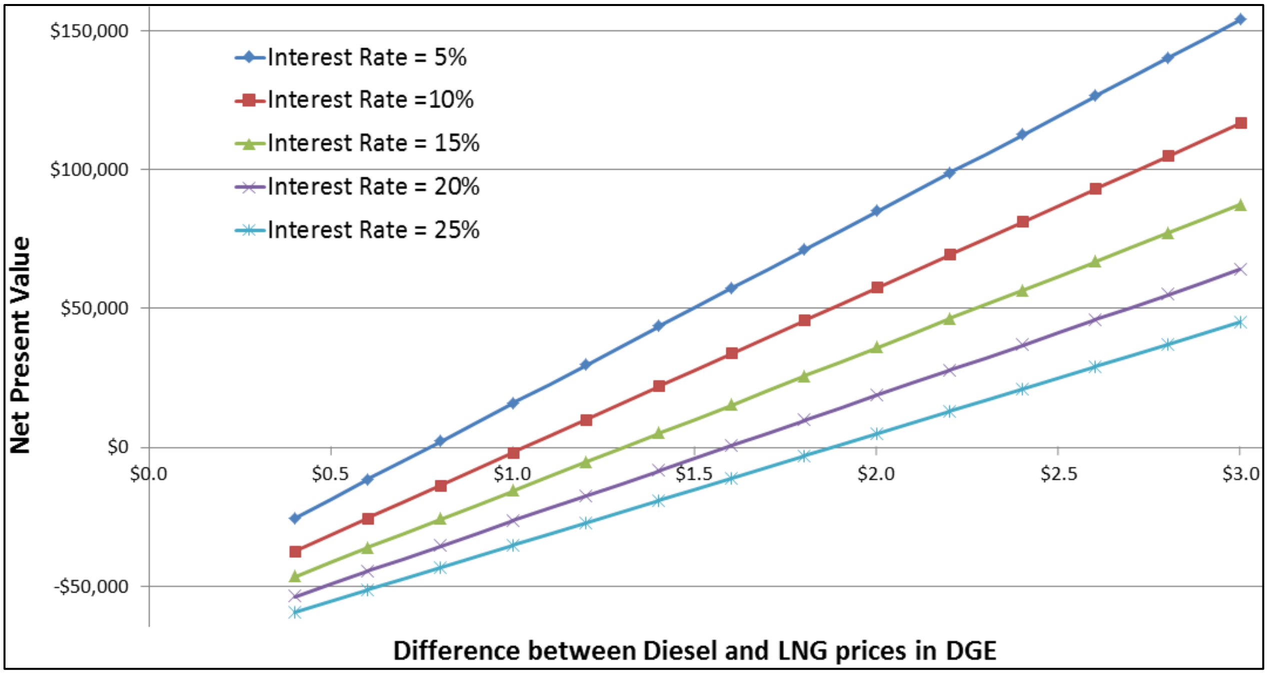


Figure C.2. NPV results for cash flow differences between a diesel truck and an LNG truck over 6 years (in dollars)

When the interest rate is 10% and the difference between diesel and LNG prices in DGE is at least $1.20, truck transportation companies with LNG trucks can save $10,216 per truck over six years. If the interest rate is 5% and the fuel price difference is at least $2, the companies can increase their profit by $85,074 per truck in six years.

Lastly, to identify reasonable rates of return internally for truck transportation companies, Table C.6 and Figure C.3 show IRR values for several fuel price differences using the cash flows in Table C.3.

Table C.6. IRR results for cash flow differences between a diesel truck and an LNG truck over 6 years (in dollars)

Difference between diesel and LNG Prices	IRR
0.4	-2.56%
0.6	1.64%
0.8	5.64%
1.0	9.48%
1.2	13.19%
1.4	16.79%
1.6	20.30%
1.8	23.72%
2.0	27.07%
2.2	30.36%
2.4	33.60%
2.6	36.79%
2.8	39.93%
3.0	43.04%

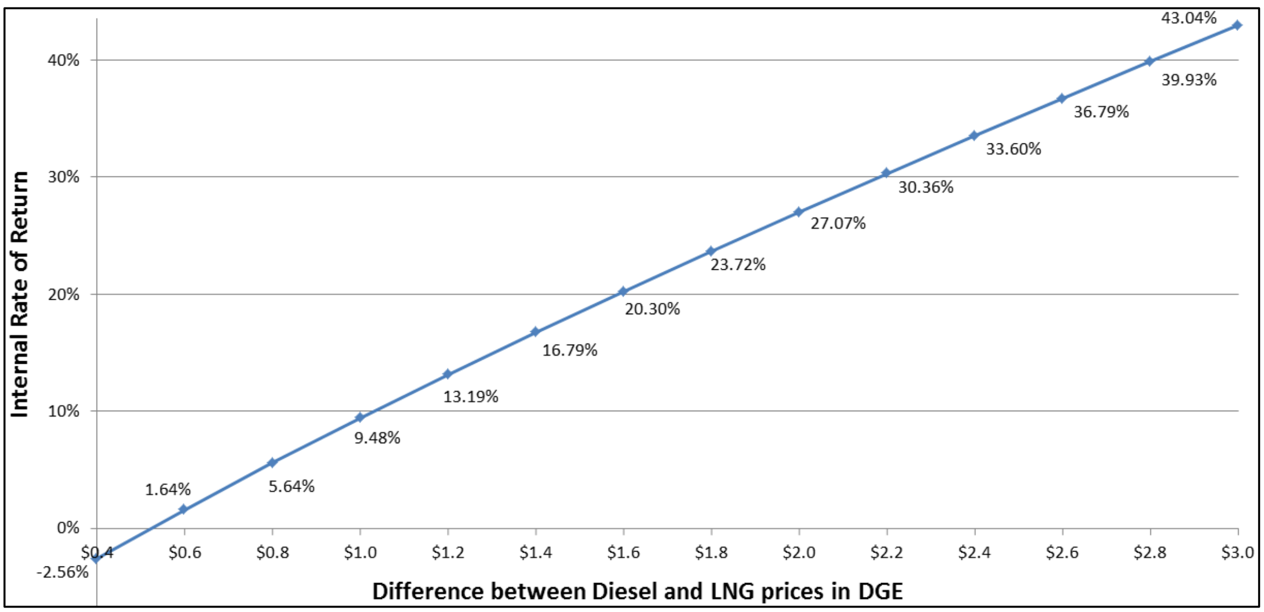


Figure C.3. IRR results for cash flow differences between a diesel truck and an LNG truck over 6 years (in dollars)

In all cases except when the fuel price difference is at $0.40, truck transportation companies do not incur any loss if they use LNG trucks instead of diesel trucks. Since the current fuel price difference is about $1.30, companies can expect an internal rate of return of more than 14% over 6 years.

In conclusion, given that the price of diesel is on an upward trend in the world oil market and LNG prices are expected to remain low and stable based on the growing availability of natural gas from shale formations, the price difference between diesel and LNG will widen in the future. In this situation, the above three financial metrics simultaneously reveal that it is a great investment opportunity for truck transportation companies to buy LNG trucks if an LNG fueling infrastructure becomes available.

References

[1] Hoopes, P. (2012). Private communication.

[2] Park, S.C. (2008). *Fundamentals of Engineering Economics, 2nd ed.* Pearson Education, Cranbury Township, NJ.

[3] Solution Matrix Ltd (2012). Return on Investment - Meaning and Use: http://www.solutionmatrix.com/return-on-investment.html.

[4] Luenberger, G. D. (1997). *Investment Science*. Oxford University Press, New Delhi.

Appendix D: Available Training Programs for LNG Station and Truck Operators

Audience	Training	Training Provider	Format	Length	Cost/person	*Ref*	notes
All Turnpike Employees	Online LNG Videos	Various	Video	30 min	free		Various general LNG info/safety videos available
Drivers	Online LNG Fueling Instruction	Westport-HD	Video	25-min	free		General overview videos available from various sources. Generic as fuel systems differ slightly.
Drivers & Technicians	Driver, Technician & Fuel Handler Safety Training for LNG Powered Vehicles	Natural Gas Vehicle Institute	In-person Training	1-day	$595	*1*	Offered at various locations
Fuel Handlers & Technicians	Westport-Kenworth GX and LNG System Training	Long Beach College	In-person Training	3 days	$800	*2*	Offered in Long Beach, CA
Emergency Responders	LNG Emergency Response	Texas Engineering Extension Service	In-person Training	2-days	$2,085	*3*	Offered in Austin, TX
Emergency Responders	LNG/LP Safety and Emergency Response Training Program	Northeast Gas Association	In-person Training	2-days	$1,295	*4*	Offered in Stow, MA

References:

1 http://www.ngvi.com/lng_safety.html
2 http://www.lbcc.edu/attc/documents/Westport%20GX%20Spring%202012.pdf
3 http://www.teex.com/teex.cfm?pageid=estiprog&area=esti&templateid=1536
4 http://www.northeastgas.org/index.php/training-a-qualification/lnglp-firefighting-and-safety-training

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Appendix E: Summary of State Incentives Relating to Natural Gas Powered Vehicles

STATE	INCENTIVE/PROGRAM	TARGET	PUBLIC/ PRIVATE	SUMMARY	REFERENCE
AK	State CNG Study	CNG, Multiple	n/a	January 2011 report by Mercury Associates, Inc. "State of Alaska Vehicle Fleet CNG Pilot Program Recommendations/Cost," broad overview of CNG field	www.legis.state.ak.us/basis/get_documents.asp?docid=401
AK	Alt. Fuel Vehicle Acquisition Requirement	Vehicles, Fuels	Public	AK DOT and Public Facilities Dept. must evaluate cost, efficiency, and commercial availability for alternative fuels every 5 years, and purchase or convert vehicles whenever practical	AK Statute 44.42.020
AZ	AFV HOV Lane Exemption	Vehicles	Public	Qualified alternative fuel vehicles (AFVs) are permitted to use high occupancy vehicle (HOV) lanes regardless of number of passengers	AZ Revised Statutes 28-337 and 28-2416
AZ	AFV Parking Incentive	Vehicles	Public	Individuals driving a qualified AFV may park in areas designated for carpool operators	AZ Revised Statute 28-887
AZ	Reduced AFV Tax	Vehicles	Public	Initial annual vehicle license tax for an AFV is significantly less than that of a conventional vehicle	AZ Revised Statutes 28-5805 and 28-5801
AZ	AF and AFV Tax Exemption	Fuel, Vehicles	Public	AZ use tax does not apply to natural gas used in an AFV, AFVs, or vehicles and equipment converted from diesel power to use natural gas	AZ Revised Statute 42-5159

AR	AF Grants and Rebates	CNG, Producers Distributors	Public	AR Alternative Fuels Development Program provides grants to AF producers, distributors, and feedstock processors utilizing AFs, also partial rebates for the cost of converting diesel school buses to CNG	AR Code 15-13-101 (multiple)
CA	AF and Vehicle Incentives	Multiple	Public	The CA Energy Commission administers the Alternative and Renewable Fuel and Vehicle Technology Program, which adopts an annual Investment Plan to establish funding priorities and opportunities for commercial AFV deployment, AF production, AF research and development, AFV manufacturing, training, and public education, outreach, and promotion	http://www.energy.ca.gov/drive/funding/
CA	HOV Lane Exemption	CNG Vehicles	Public	Qualified CNG vehicles may use HOV lanes regardless of the number of passengers	CA Vehicle Code 5205.5 and 21655.9
CA	AFV and Fueling Infrastructure Grants	Multiple	Public	The Motor Vehicle Registration Fee Program provides funding for projects that reduce air pollution through AFV use or AF infrastructure development	http://www.arb.ca.gov/planning/tsaq/mvrfp/mvrfp.htm
CA	Emission Reduction Grants	Multiple	Public	The Carl Moyer Memorial Air Quality Standards Attainment Program provides incentive funding to help cover costs of engines and equipment that provide cleaner than law required emission standards	http://www.arb.ca.gov/msprog/moyer/moyer.htm

CA	Heavy-Duty Vehicle Emission Reduction Grants	Heavy-Duty Vehicles	Public	The Goods Movement Emission Reduction Program provides funding for projects reducing emissions from freight movement, primarily heavy-duty vehicle replacement or retrofits	http://www.arb.ca.gov/bonds/gmbond/gmbond.htm
CA	Low Emissions School Bus Grants	School Buses	Public	The Lower-Emission School Bus Program provides funding for replacement or retrofit of existing buses with lower emission AF buses	http://www.arb.ca.gov/msprog/schoolbus/schoolbus.htm
CA	CNG Tax Exemption for Transit Use	Transit Vehicle Fuel	Public	Local agencies or public transit operators utilizing CNG as a fuel are exempt from applicable user taxes in their respective county	CA Revenue and Taxation Code 7284.2
CA	Vehicle Emissions Reduction Grants (Sacramento)	Multiple	Public	The Sacramento Emergency Clean Air and Transportation Program provides grants to offset costs associated with reducing emissions of nitrogen oxide, including vehicle upgrades and conversions	http://www.airquality.org/
CA	Employer Invested Emissions Reduction Funding (South Coast)	Multiple	Public	The Air Quality Investment Program provides funding for projects that reduce emissions, including conversion of conventional vehicles to AFVs	http://www.aqmd.gov/trans/aqip.html
CA	Technology Advancement Funding (South Coast)	Multiple	Public	The Clean Fuels Program provides funding for research, development, demonstration, and deployment projects that are intended to advance low-emission transportation technologies, including vehicles, fuel storage, and other infrastructure	http://www.aqmd.gov/tao/Demonstration/index.htm

CA	AF and Advanced Vehicle Rebate (San Joaquin Valley)	Vehicles	Public	The Drive Clean! Rebate Program provides rebates up to $3,000 for purchasing or leasing qualified natural gas powered vehicles	http://www.valleyair.org/grant_programs/grantprograms.htm#DriveCleanRebateProgram
CA	AFV and Fueling Infrastructure Incentives (San Joaquin Valley)	Multiple	Public	The Public Benefit Grant Program provides funding to cities, counties, districts, and public education institutions for the purchase of new AFVs as well as equipment and infrastructure	http://www.valleyair.org/Grant_Programs/GrantPrograms.htm#PublicBenefitGrantProgram
CA	Heavy-Duty Diesel Vehicle Vouchers (San Joaquin Valley)	Heavy-Duty Vehicles	Public	The Air Pollution Control District of San Joaquin Valley provides two different voucher incentive programs to fund the replacement/conversion of current heavy-duty truck fleets with lower emission vehicles, one for fleets of 3 vehicles or less, the other for fleets of 4 to 10 vehicles	http://www.valleyair.org/Grant_Programs/GrantPrograms.htm#On-Road%20Voucher%20Incentive%20Program
CA	Low Emission Vehicle Incentives and Technical Training (San Joaquin Valley)	Light Vehicles	Public	The REMOVE II Program provides incentives of $1,000 to $3,000 for the purchase of passenger vehicles, light-duty trucks, small buses, and trucks with a GVWR of 14,000 lbs or less, and also provides a training program for personnel on various aspects of alternative fueling	http://www.valleyair.org/Grant_Programs/GrantPrograms.htm#RemoveII
CA	Air Quality Improvement Program Funding (Ventura County)	Multiple	Public	The Clean Air Fund is a broad program that will supply grants to approved projects showing to significantly reduce emissions	http://www.afdc.energy.gov/laws/law/CA/4216
CA	AFV and Hybrid Electric Vehicle (HEV) Insurance Discount	Vehicles	Private	Farmers Insurance provides a discount up to 10% on insurance coverage of AFVs and HEVs	http://www.farmers.com/california_insurance_discounts.html

CA	Clean Vehicle Electricity and NG Rate Reduction by PG&E	Fuel	Private	Pacific Gas & Electric provides discounted rates for natural gas used to fuel AFVs	http://www.pge.com/
CA	Electric Vehicle and NG Charging Rate Reduction by SDG&E	Fuel	Private	San Diego Gas and Electric provides discounted rates for natural gas used to fuel AFVs	http://sdge.com/clean-energy/electric-vehicles/ev-rates
CA	Natural Gas Rate Reduction by SoCalGas	Fuel	Private	Southern California Gas Company provides discounted rates for natural gas used to fuel AFVs	www.socalgas.com/innovation
CO	AF, Advanced Vehicle, and Idle Reduction Equipment Tax Credit	Vehicles	Public	CO Dept of Revenue provides income tax credits on AFVs or conventional vehicles converted to AFVs based on the vehicle category and technology used	House Bill 1018, CO Revised Statutes 39-22-516
CO	Low Emission Vehicle (LEV) Sales Tax Exemption	Vehicles	Public	LEVs, power sources, or parts used for conversion for vehicles over 10,000 GVWR to LEV are exempt from state sales tax	CO Revised Statutes 39-26-719
CO	AFV Weight Limit Exemption	Vehicles	Public	GVWR limits for AFVs are 1,000 lbs greater than those of conventional vehicles	CO Revised Statutes 25-7-106.8 and 42-4-508
CT	AF and Advanced Technology Vehicle Grants	CNG Vehicles	Public	The Connecticut Clean Fuel Program provides funding to municipalities and public agencies that purchase, operate and maintain AFVs (CNG)	http://www.ct.gov/dot/cwp/view.asp?a=1386&q=415022
DE	Alternative Fuel Tax Exemption	Fuel	Public	Taxes on alternative fuels used in US gov't vehicles or vehicles for any DE state gov't agency are waived	DE Code Title 30 Ch 51

DC	Reduced Registration Fee for Fuel-Efficient Vehicles	Vehicles	Public	New motor vehicles achieving an average fuel economy of at least 40 mpg or equivalent are eligible for a reduced registration fee for 2 years	DC Code 50-150.03
DC	AF and Fuel-Efficient Vehicle Title Tax Exemption	Vehicles	Public	Qualified AFVs are exempt from the excise tax imposed on an original certificate of title	DC Code 50-2011.03
DC	AFV Exemption from Driving Restrictions	Vehicles	Public	AFVs part of a fleet of at least 10 vehicles are exempt from certain time-of-day and day-of-week restrictions and commercial vehicle bans, as well as restricted HOV lane use if certified by the EPA	DC Code 50-702 and 50-714
FL	HOV Lane Exemption	Vehicles	Public	Any Inherently Low Emission Vehicle as set by qualifying CA standards is permitted to use any HOV regardless of the number of passengers and without paying a toll	FL Statute 316.0741
GA	AFV Tax Credit	Vehicles	Public	An income tax credit of 10% of vehicle cost up to $2,500 is available to individuals purchasing or leasing an AFV	GA Code 48-7-40.16
GA	AF Production Assistance	Production	Public	The GA Division of Energy Resources and the Georgia Environmental Finance Authority provide assistance to companies considering locating AF production fuel facilities in GA	http://www.gefa.org/Index.aspx?page=367
GA	AFV HOV Lane Exemption	Vehicles	Public	AFVs may used HOV lanes regardless of the number of passengers	GA Code 32-9-4 and 40-2-76

GA	Reduced CNG Fueling Infrastructure Lease by AGL	Infrastructure	Private	Atlanta Gas Light offers a reduced cost lease on home CNG vehicle refueling equipment	http://www.atlantagaslight.com/Repository/Files/9784_Phill_Fact_Sheet.pdf
ID	AF Tax Refund	Fuel	Public	State excise tax paid on LNG or CNG fuel used in vehicles owned by the state or federal government may be refunded	ID Statutes
IL	AFV and AF Rebates	Vehicles, Fuel	Public	The IL Alternate Fuel Rebate Program provides a rebate of 80% (up to $4,000) for the cost of purchasing an AFV or converting a conventional vehicle to an AFV, and for the incremental cost of the fuel, part of the IL Green Fleets Program	http://www.illinoisgreenfleets.org/
IL	AFV Fleet Incentives	Marketing	Public	The Illinois Green Fleets Program recognizes and provides additional marketing incentives for fleets in IL that have a significant number of AFVs	http://www.illinoisgreenfleets.org/
IL	School Bus Retrofit Reimbursement	School Buses	Public	The IL Dept of Education will reimburse qualifying conversions of school buses to engines using AFs	IL Compiled Statutes 5/29-5
IN	Alternative Fueling Station Grant Program	Infrastructure	Public	This program provides grants up to $20,000 for installing new AF stations or converting existing conventional fueling stations (Only mentions CNG)	IN Code 4-4-32.2
IN	AFV Grant Program	Vehicles	Public	This program offers grants up to $2,000 to counties, cities, towns, townships, or schools to purchase AFVs or convert conventional vehicles to AFVs (only mentions CNG)	IN Code 4-4-32.3

IN	AFV Manufacturer Tax Credit	Vehicle Production	Public	The Hoosier AFV Manufacturer Tax Credit allows tax credits up to 15% of investments to manufacturers of AFVs in IN	IN Code 6-3.1-31.9
IN	Vehicle Research and Development Grants	Research, Production	Public	The Indiana 21st Century Research and Technology Fund can provide grants and loans for companies researching and producing AFs and AFVs	IN Code 5-28-16-2
IN	NGV Rebate	Vehicles	Private	Citizens Gas and Coke Utility offers rebates for CNG vehicle conversions or the purchase of new CNG or qualified used CNG vehicles to fleet operators	Citizens Energy Group
IO	AFV Demonstration Grants	Vehicles	Public	IO Dept of Natural Resources will award demonstration grants towards the purchase of AFVs	IO Code 214A.19
IO	AF Production Loans	Production	Public	The Value-Added Agricultural Program offers forgivable and low-interest loans to projects involving the production of AFs	http://www.iowaeconomicdevelopment.com/business/vap.aspx
IO	AF Production Tax Credits	Production	Public	The Enterprise Zone Program and the High Quality Jobs Program offer state tax incentives of various degrees to projects involving production of AFs	http://www.iowaeconomicdevelopment.com/business/enterprise_zones.aspx
LA	AFV and Fueling Infrastructure Tax Credit	Vehicles, Infrastructure	Public	The state offers tax credits of 50% of the cost of converting a conventional vehicle to an AFV, 50% of the incremental cost of purchasing a new AFV, 10% of the cost of a new AFV, and 50% of the cost of constructing an AF station	LA Revised Statute 47:6035

LA	Green Jobs Tax Credit	Infrastructure	Public	The state offers a corporate or income tax credit for capital infrastructure projects related to the energy efficient vehicle industry ranging from 10% to 25% of the project cost (Up to $1M), and may be eligible for up to 10% of the payroll of employees involved with the construction of the project	LA Revised Statute 47:6037
MI	AF and Vehicle Research, Development, and Manufacturing Tax Credits	Production	Public	Qualified taxpayers may claim a non-refundable credit for tax liability attributable to research, development, or manufacturing of qualified AFVs	MI Compiled Laws 207.821-207.827 and 208.1429
MI	AF Development Property Tax Exemption	Production	Public	A tax exemption may apply to industrial property that is used for high-technology activities such as the development of alternative fuel vehicles and their components	MI Compiled Laws 207.552 and 207.803
MI	AFV Tax Exemption	Vehicles	Public	Qualified and certified AFVs are exempt from personal property taxes	MI Compiled Laws 207.82 and 211.9i
MI	AFV Emissions Inspection Exemption	Vehicles	Public	Dedicated AFVs are exempt from emissions inspection requirements	MI Compiled Laws 324.6311 and 324.6512
MO	AF Infrastructure Tax Credit	Infrastructure	Public	An income tax credit is available for up to 20% of the cost of constructing a qualified alternative fueling station, up to $20,000, and the total amount claimed may not exceed $1 million	http://www.dnr.mo.gov/energy/transportation/Missouri-AFITC.htm

MO	AFV Emission Inspection Exemption	Vehicles	Public	AFVs are exempt from motor vehicle emission inspections under federal regulation as well as state emission inspection requirements	MO Revised Statutes 643.315
MT	AFV Conversion Tax Credit	Vehicles	Public	Businesses or individuals are eligible for a tax income credit up to 50% of the cost of converting conventional vehicles to operate on AFs, the maximum is $500 for GVWR < 10k lbs, and $1,000 for GVWR > 10k lbs	MT Code Annotated 15-30-2320
NE	AFV and Fueling Infrastructure Loans	Vehicles, Infrastructure	Public	The Dollar and Energy Saving Loan Program offers low-cost loans for a variety of AFV projects including conversion, new AFV purchases, and AF infrastructure construction to a maximum of $750k with an interest rate of 5% or less	http://www.neo.ne.gov/loan/index.html
NE	AF Tax Refund	Buses	Public	NE Dept of Revenue offers a refund for taxes paid on CNG or LNG used to carry at least 7 passenger within or near a municipality	NE Statutes 66-6,100 and 66-6,109.01
NE	CNG Vehicle Rebate - Metro Utilities District	Vehicles	Private	Gas customers of Metropolitan Utilities District who purchase a dedicated CNG vehicle are eligible for a rebate of $500	http://www.livegreenthinkblue.com/
NV	AFV Parking Fee Exemption	Vehicles	Public	AFVs with a decal, not to exceed a $10 per year fee, may park in metered spaces without paying a fee	NV Assembly Bill 511, 2011
NV	AFV Emissions Inspection Exemption	Vehicles	Public	AFVs are exempt from the NE Emissions Control Program requirements	NE Revised Statutes 445B.770-445B.825

NH	AF and Advanced Vehicle Funding	Projects	Public	NH Dept of Environmental Sciences and the Granite State Clean Cities Coalition provides cost reimbursements for AF and advanced vehicle projects	http://www.granitestatecleancities.nh.gov/
NM	AFV and Fueling Infrastructure Grants	Vehicles, Infrastructure	Public	The NM Energy, Minerals and Natural Resources Dept provides grants on a competitive basis for projects using clean energy technologies	NM Statutes 71-7-1 to 71-7-7
NM	AF Tax Exemption	Fuel	Public	AF distributed or used by US gov't, state gov't, or Indian nation, tribe, or pueblo is exempt from the state excise tax	NM Statutes 7-16B-5
NY	AF Bus and Infrastructure Funding	Buses, Infrastructure	Public	The Clean Fueled Bus Program provides funds to state and local transit agencies, municipalities, and schools for up to 100% of the incremental cost of purchasing new AF buses and related infrastructure	http://www.nyserda.ny.gov/Programs/Research-and-Development/Transportation-and-Power-Systems.aspx
NY	New York City Private Fleet Program	Private Fleets, Infrastructure	Public	The NYC Private Fleet AF/Electric Vehicle Program provides funding to private sector companies for various AFV investments including up to 50% of the incremental cost of acquiring new light, medium and heavy duty vehicles, up to 80% of the cost of converting medium and heavy duty vehicles, and up to 50% of the cost of fueling infrastructure	http://www.nyserda.ny.gov/Page-Sections/Research-and-Development/Alternative-Fuel-Vehicles/New-York-City-Private-Fleet-Program.aspx

NC	AF and Idle Reduction Grants	Vehicles, Infrastructure	Public	The NC Dept of Environment and Natural Resources Division of Air Quality provides grants for the replacement of diesel vehicles with AFVs, conversions of conventional vehicles to AFVs, and the installation of public AF facilities	http://www.ncair.org/motor/DERG/
NC	HOV Lane Exemption	Vehicles	Public	Dedicated NG vehicles may use NC HOV Lanes regardless of the number of occupants	HB 222, SB 194, NC General Statutes 20-4.01 and 20-146.2
NC	AFV and HEV Support	Vehicles, Infrastructure	Public	The Clean Fuel Advanced Technology project provides financial support for AFVs, AF infrastructure, and AFV conversions	http://ncsc.ncsu.edu/index.php/clean-transportation/clean-transportation-projects/clean-fuel-advanced-technology-project/
NC	AF and AFV Fund	Vehicles, Infrastructure	Public	The Energy Policy Act Credit Banking and Selling Program allows the state to place funds in an account which can be used to AFVs and AF infrastructure for state agencies	NC General Statutes 143-58.4, 143-58.5, 143-341(8)i and 136-28.13
NC	AF Tax Exemption	Fuels	Public	The retail sale, use, storage, and consumption of AFs is exempt from state retail sales and use tax	NC General Statutes 105-164.13(11)
NC	AFV Loans	Loans for AFV Purchases	Private	The State Employee's Credit Union and Local Government Federal Credit Union provide low interest rate loans for the purchase of qualifying AFVs	https://www.lgfcu.org/loans/pages/greenCar.php

OH	AF and Fueling Infrastructure Grants	Vehicles, Infrastructure	Public	The Alternative Fuel Transportation Grant Program provides funding for up to 80% of the cost of installing AF infrastructure as well as up to 80% of the incremental cost of purchasing and using AFVs for businesses, nonprofit organizations, public schools, and local governments	OH Revised Code 122.075
OK	AFV Tax Credit	Vehicles	Public	A one-time tax credit for up to 50% of the incremental cost of purchasing an AFV is available to individuals, and if an AFV is resold a tax credit of up to 10% or $1,500 is available if no tax credit has yet been taken on the vehicle	OK Statutes 68-2357.22
OK	AF Infrastructure Tax Credit	Infrastructure	Public	A tax credit is available for up to 75% of the cost of new AF infrastructure, and for up to 50% of the cost of a new residential CNG fueling system, up to $2,500	OK Statutes 68-2357.22
OK	AFV and AF Infrastructure Loans	Vehicles, Infrastructure	Public	The OK Department of Central Services' Alternative Fuels Conversion Loan Program provides gov't fleets with 0% interest loans of up to $10,000 for conversion of conventional vehicles to AFVs or new AFV purchases, as well as 0% interest loans up to $150,000 for AF infrastructure construction	Ok Statutes 74-130.4 and 74-130.5
OK	AFV Loans	Vehicles	Public	OK Dept of Commerce, State Energy office provides 3% interest loans for the conversion of private fleets to us AFs, purchase new AFVs, and installation of AFV fueling infrastructure	http://www.afdc.energy.gov/laws/law/OK/4668

OR	AF Infrastructure Tax Credit for Residents	Infrastructure	Public	The Residential Energy Tax Credit program provides residents with a tax credit of 25%, up to $750 for the cost of installing alternative fueling infrastructure in their homes	http://cms.oregon.gov/ENERGY/RESIDENTIAL/Pages/residential_energy_tax_credits.aspx
OR	AF Infrastructure Tax Credit for Businesses	Infrastructure	Public	Business owners may be eligible for a tax credit of up to 35% of the costs of installing AF infrastructure facilities for mixing, storing, compressing, or dispensing alternative fuels	OR HB 3672
OR	AF School Bus Grant and Loan Program	Buses	Public	School districts may be eligible for grants and loans to retrofit their bus fleets with AF buses through either conversion or replacement	OR HB 2960
OR	AF Loans	Multiple	Public	The State Energy Loan Program offers low-interest loans for qualified AF projects including those focusing on facilities, infrastructure, and vehicle	http://cms.oregon.gov/ENERGY/LOANS/Pages/selphm.aspx
OR	Pollution Control Equipment Exemption	Vehicles	Public	Dedicated original manufacturer AFVs are not required to be equipped with a certified pollution control system	OR Revised Statutes 815.300
PA	AF Production Tax Credits	Fuel	Public	The Alternative Energy Production Tax Credit Program provides a credit of 15% up to $1M per taxpayer for the next cost of projects related to AF production or research	Title 73 PA Statutes Ch 18G Section 1649.701-1649.711

PA	AFV and HEV Funding	Multiple	Public	The Alternative Fuels Incentive Grant Program provides financial assistance programs for new AFVs as well as AFV technology research, development, and demonstration, and it also provides rebates to eligible individuals purchasing AFVs, up to $1,000 for NGVs	Title 73 PA Statutes Ch 18E Section 1647.3
PA	AF Development and Deployment Grants	Multiple	Public	The Pennsylvania Energy Development Authority provides grants up to $1M for alternative energy projects that can be used for equipment purchases, construction, contractor expenses, and engineering design related to the project	http://www.portal.state.pa.us/portal/server.pt/community/peda-move_to_grants/10496
PA	AF Project Grants	Multiple	Public	The Pennsylvania Energy Harvest Grant is for funding alternative energy projects (including clean fuel for transportation) that address both energy and environmental concerns	http://www.elibrary.dep.state.pa.us/dsweb/View/Collection-9169
RH	AFV Tax Exemption (Warren)	Vehicles	Public	The town of Warren may allow excise tax exemptions of up to $100 for qualified AFVs registered there	RH General Laws 44-34-14
TN	AF Infrastructure Development Program	Infrastructure	Public	The FastTrack Infrastructure Development Program may provide funding to eligible projects that intend to provide alternative fueling infrastructure improvements	http://www.tn.gov/ecd/BD_FIDP.html

TN	HOV Lane Exemption	Vehicles	Public	Vehicles that qualify as Low Emission and Energy-Efficient Vehicles by the EPA and have a GVWR under 26,000 lbs are permitted to use HOV lanes regardless of the number of passengers	TN Code 55-8-188
TX	AF Infrastructure Grants	Infrastructure	Public	The Alternative Fueling Facilities Program provides grants for 50% or eligible costs up to $500,000 to construct, reconstruct or acquire facilities with the purpose of storing, compressing, or dispensing AFs	Senate Bill 20 2011, TX Statutes Health and Safety Code 394
TX	NGV and Fueling Infrastructure Grants	Vehicles, Infrastructure	Public	The NGV Grant program provides grants to replace medium and heavy-duty vehicles with GVWR of at least 8,500 lbs with new, converted, or repowered NGVs, and the program may provide grants to build NGV fueling stations along particular areas of interstate highways	Senate Bill 20 2011, TX Statutes Health and Safety Code 393
TX	Clean Vehicle and Infrastructure Grants	Multiple	Public	The Emissions Reduction Incentive Grants Program provides grants to approved projects that work to improve air quality in nonattainment areas, including alternative fuel use in transportation	http://www.tceq.texas.gov/airquality/terp/erig.html
TX	AF and Advanced Vehicle Research and Development Grants	Research and Development	Public	The New Technology Research and Development Program provides grants for projects researching, developing, and commercializing new alternative fuel projects	http://www.tceq.texas.gov/airquality/terp/ntrd.html

TX	Clean Fleet Grants	Vehicles	Public	The Texas Clean Fleet Program uses grants to cover incremental costs to encourage fleet owners to convert part or all of their fleets to AFVs	http://www.tceq.texas.gov/airquality/terp/tcf.html
TX	Heavy-Duty NGV Grants	Vehicles	Public	The NGV Initiative Grant Program encourages public-sector fleets and certain private-sector fleets that work under contract with the government to increase their use of heavy-duty NGVs through approved grants	http://www.glo.texas.gov/what-we-do/energy-and-minerals/alternative_fuels/natural-gas-vehicle-grant-program.html
TX	Clean Vehicle Replacement Vouchers	Vehicles	Public	The AirCheckTexas Drive a Clean Machine program provides qualified individuals with a rebate of $3,500 towards the purchase of an AFV to replace their current conventional vehicle	http://www.tceq.texas.gov/airquality/mobilesource/vim/driveclean.html
TX	NGV and Fueling Infrastructure Rebates (Texas Gas Service)	Vehicles, Infrastructure	Private	Texas Gas Service Conservation Program offers a $2,000 rebate for the purchase of an NGV, $3,000 for the conversion of a conventional vehicle to an NGV, and $2,000 for residential or commercial natural gas refueling infrastructure	http://www.texasgasservice.com/en/SaveEnergyAndMoney/NaturalGasVehicles.aspx
UT	AF and Fuel Efficient Vehicle Tax Credit	Vehicles	Public	The Clean Fuel Vehicle Tax Credit provides an income tax credit of 35% of the cost of a new NGV, up to $2,500	http://www.cleanfuels.utah.gov/taxcredits/taxcreditsintro.htm
UT	AFV and Fueling Infrastructure Grants and Loans	Vehicles, Infrastructure	Public	The Utah Clean Fuels and Vehicle Technology Grant and Loan Program provides grants and loans to businesses and government entities purchasing AFVs, converting current vehicles to AFVs, and installing AFV fueling infrastructure	http://www.cleanfuels.utah.gov/grants/grantsintro.htm

UT	AF Tax Rate Reduction	Fuel	Public	A reduced tax on CNG and LNG of $0.085 per gasoline gallon equivalent is imposed	UT Code 59-13-102, 59-13-201, 59-13-301
UT	AFV HOV Lane Exemption	Vehicles	Public	Vehicles operating on CNG or LNG are permitted to use HOV lanes regardless of the number of passengers	UT Code 41-1a-416
VT	NGV and Infrastructure Funding	Vehicles, Infrastructure	Public	The Clean Energy Development Fund provides funding for projects involving the purchase of NGVs and/or installing NG fueling infrastructure	http://publicservice.vermont.gov/energy/ee_cleanenergyfund.html
VA	AF Grants and Loans	Multiple	Public	The Alternative Fuels Revolving Fund is used to provide loans and grants to municipal, county, and state government agencies in support of projects implementing AFVs, including their maintenance, operation, testing, conversion, or for the installation of refueling infrastructure	VA Code 33.1-233.4 and 33.1-233.7