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Economic Viability of a Natural Gas Refueling Infrastructure for Long-Haul Trucks

JULY 2019



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AUTHORS

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Fan Tong Postdoctoral Research Associate, Dept. of Engineering and Public Policy, Carnegie Mellon Univ., 5000 Forbes Ave., Pittsburgh, PA 15213; Postdoctoral Research Scientist, Dept. of Global Ecology, Carnegie Inst. for Science, 260 Panama St, Stanford, CA 94305; (corresponding author). Email: ftong@cmu.edu

Ines Azevedo Professor, Dept. of Engineering and Public Policy, Carnegie Mellon Univ., 5000 Forbes Ave., Pittsburgh, PA 15213. Email: iazevedo@cmu.edu

Paulina Jaramillo Associate Professor, Dept. of Engineering and Public Policy, Carnegie Mellon Univ., 5000 Forbes Ave., Pittsburgh, PA 15213. Email: paulina@cmu.edu

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ABSTRACT

Low natural gas prices offer an opportunity to expand the use of this fuel in new sectors, such as powering long-haul trucks. The non-return-to-base nature of long-haul trucks requires a large natural gas refueling infrastructure, for which the costs and benefits have not yet been assessed.

This paper assesses the spatial distribution, capacity, and economic feasibility of a national natural gas refueling infrastructure for long-haul trucks in the United States. For a small share of natural gas powered trucks in the total fleet (1-5%), a national liquefied natural gas (LNG) refueling infrastructure would require 105-193 refueling stations at a capital investment of \$263-483 million (assuming truck range of 320-960 km or 200-600 miles). The share of LNG trucks has to be greater than 15.2% (assuming the minimum truck range is 320 km or 200 miles), 12.4% (480 km or 300 miles), or 9.5% (960 km or 600 miles), so that the national infrastructure achieves net profits for baseline economic assumptions (\$0.05/diesel gallon equivalent (DGE) profit margin, 7% discount rate, and 20 years).

Building a national compressed natural gas (CNG) refueling infrastructure requires more investment because a fast-fill CNG refueling station costs more and has lower capacity compared to an LNG counterpart. However, the CNG refueling infrastructure achieves better economic returns due to a higher assumed profit margin (\$0.1/DGE).

As the diesel price has the largest effect on the adoption of natural gas trucks, plans to build natural gas refueling infrastructure face significant challenges during times of low diesel prices. A practical strategy is to first target regional highway networks (such as those in California and Texas) to take advantage of high truck activities within regions, favorable market conditions, and supportive government policies.

Contents



INTRODUCTION	05
METHOD	08
TRUCK CHARACTERISTICS	09
REFUELING STATION CHARACTERISTICS	10
HIGHWAY NETWORK AND TRUCK FLOW ESTIMATES	11
ALTERNATIVE POWERTRAIN VEHICLES	14
ECONOMIC ANALYSIS	15
RESULTS	18
CONCLUSIONS AND POLICY RECOMMENDATIONS	29
SOURCES	32
APENDIX	36
ABOUT THE FUELS INSTITUTE	84

Introduction

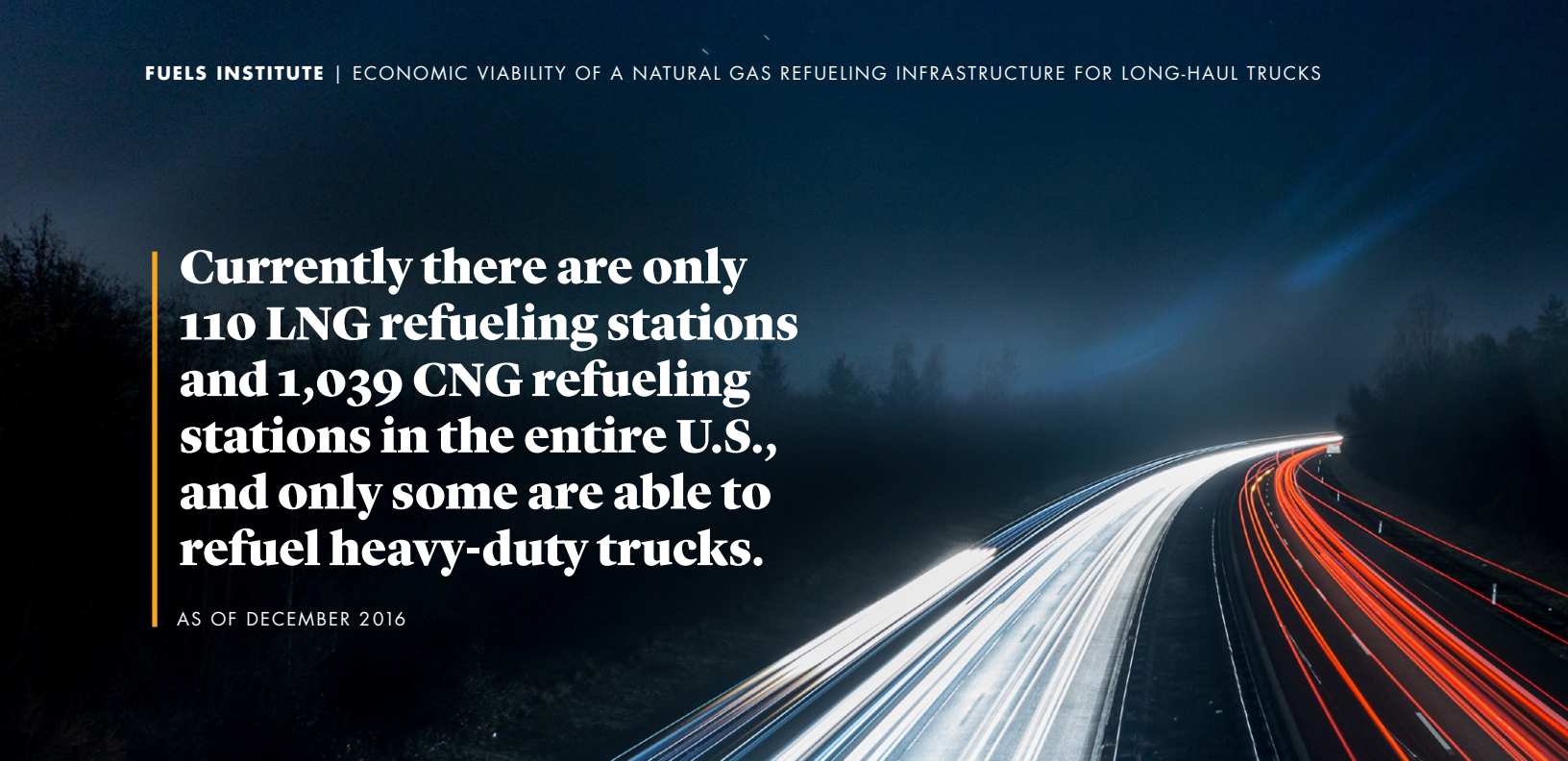
Trucks form the backbone of the U.S. freight transportation system.

In 2012, trucks in the U.S. transported more than 12.5 billion tons of goods, or about three quarters of all good shipments across the U.S. In 2014, the U.S. Department of Transportation (DOT) projected a more than 40% increase in shipment weight by trucks between 2012 and 2040 (U.S. FHWA 2014).

While heavy-duty trucks and other heavy-duty vehicles represent less than 5% of registered on-road vehicles in the U.S., they account for 24% of energy consumption and 25% of greenhouse gas (GHG) emissions associated with on-road vehicles (Davis et al. 2016; U.S. EIA 2015). As a result, the U.S. Environmental Protection Agency (EPA) and the U.S. National Highway Traffic Safety Administration (NHTSA) have jointly issued regulations to reduce fuel consumptions and GHG emissions from medium- and heavy-duty vehicles (MHDVs) by 2018. With modest compliance burdens, EPA and NHTSA expect fuel saving to be six times higher than the costs of compliance, as well as sizable environmental benefits from mitigated GHG emissions, reduced ambient concentrations of particulate matter and ground-level ozone, and improved energy security (U.S. EPA and U.S. NHTSA 2011). The agencies expect the majority of fuel use reductions will come from efficiency-improving technologies such as improved

aerodynamics, low-resistance tires, vehicle weight reduction, extended engine idling technologies, and reduction of vehicle speeds. Yet, alternative fuels, including natural gas fuels and biodiesel, could also play a role (U.S. EPA and U.S. NHTSA 2011).

The successful development of shale gas resources has increased natural gas supply dramatically, which in turn has lowered and stabilized natural gas prices. In addition to price advantages, natural gas fuels, such as liquefied natural gas (LNG) and compressed natural gas (CNG), have lower tailpipe GHG and air pollutant emissions than diesel, further increasing their attractiveness to the trucking industry that faces stringent environmental regulations (Thiruvengadam et al. 2015; Tong et al. 2015a; b, 2017). Recognizing these benefits, the trucking industry has invested in natural gas fuels. UPS has purchased hundreds of LNG-powered trucks (Cardwell and Krauss 2013). Vehicle manufacturers such as Cummings, Westport, and Volvo have either developed or are developing new natural gas engines for heavy-duty trucks (U.S. NRC 2014). Fuel suppliers such as Clean Energy, BluLNG, and Shell have started building CNG or LNG refueling stations along major freight corridors and at key freight distribution centers (Americas Commercial Transportation Research; 2012). Furthermore, the U.S. Energy Information Administration (EIA) and energy consulting firms have all produced forecasts with a significant penetration of CNG and LNG in heavy-duty trucks in the next two decades (Morse et al. 2013; TIAX LLC 2012a; U.S. EIA 2014).



Currently there are only 110 LNG refueling stations and 1,039 CNG refueling stations in the entire U.S., and only some are able to refuel heavy-duty trucks.

AS OF DECEMBER 2016

For instance, in 2013, Citi Global Research projected a 25% penetration rate of natural gas trucks in Class 8 tractor trailers by 2020 (Morse et al. 2013). In 2012, the U.S. National Petroleum Council (NPC) projected that share of natural gas trucks in Class 7&8 combination trucks could reach 15% (reference case) or 37% (high oil case) in 2020 (U.S. National Petroleum Council (NPC) 2012). In 2014, the U.S. EIA projected a 55-fold increase in natural gas consumption by medium-duty and heavy-duty vehicles from 2012 to 2040 (U.S. Energy Information Administration (EIA) 2014). The subsidy case in TIAX's study (TIAX LLC 2012a) projected similar natural gas fuel consumptions by heavy-duty trucks as U.S. EIA (U.S. Energy Information Administration (EIA) 2014) but the reference case projections in TIAX's study were almost flat between 2012 and 2040. More recently, however, low oil prices have slowed the adoption of natural gas trucks. As a result, the latest U.S. EIA projections suggested diesel will remain the dominant fuel for trucks through 2040 (U.S. Energy Information Administration (EIA) 2017).

An expanded use of natural gas for long-haul trucks would require a nationwide refueling infrastructure. Indeed, there are currently only 110 LNG refueling

stations and 1,039 CNG refueling stations in the entire U.S., and only some of these refueling stations are able to refuel heavy-duty trucks (California Air Resources Board (CARB) 2015; U.S. Department of Energy (DOE) 2018). The lack of natural gas refueling stations is obvious when compared to the approximately 160,000 gasoline stations and 5,000-10,000 diesel stations for heavy-duty trucks in the U.S. (Jaffe and Dominguez-faus 2013; TIAX LLC 2012b). To refuel long-haul trucks, a refueling station has to meet the following conditions: (1) it should be located on or near highway systems; (2) it should allow fast refueling; (3) it should be publicly accessible; (4) it should be designed for heavy-duty trucks (e.g. wider refueling lanes and larger parking lots). The CNG and LNG refueling stations that meet these criteria are only a small fraction of the current refueling stations. The resulting limited coverages of the CNG and LNG refueling infrastructure are widely seen as one of the primary barriers for truck fleets to adopt natural gas trucks (Morse et al. 2013; TIAX LLC 2012a; U.S. National Petroleum Council (NPC) 2012; Werpy et al. 2010; Whyatt 2010).

A number of existing studies have estimated the capacities and/or locations of alternative fuel

refueling infrastructure using two distinct methods. The first group of studies relies on simple metrics or heuristics, such as population density, numbers of vehicles, distance of roads, or number of existing refueling stations, to estimate the number of alternative fuel refueling stations (Melaina and Bremson 2008; Schraven et al. 2012; TIAX LLC 2012c; Wakeley et al. 2008; Yeh 2007). These estimates are easy to use but are only valid for order-of-magnitude estimation purposes and cannot provide detailed information such as locations and capacities for individual refueling stations. The second group of studies uses mathematical models such as mixed-integer linear programming (MILP) to optimize capacities and locations of refueling stations. Depending on data availability and the method used to model refueling demands, three types of MILP models - median-based models (such as p-median, fixed charge models), covering-based models (such as set covering, max covering, p-center), and flow capturing models - can be used (Current et al. 2001; Upchurch and Kuby 2010). Compared to the first group, these studies are able to provide more detailed estimates, at the cost of increased data needs (road network distance and topology, vehicle flow, or origin-destination trip data) and increased computational complexity, thus limiting their use for complex road networks. A particular type of MILP models, the flow-capturing refueling model (FRLM) proposed by Kuby and Lim (2005) and its variations have been used to optimize alternative fuel refueling

infrastructure for highway networks in Orlando, Florida (Upchurch and Kuby 2010), Arizona (Kuby et al. 2004), Florida (Kuby et al. 2009), Pennsylvania (Myers et al. 2012), United States (Fan et al. 2017), and European countries (Kuby et al. 2015). Still, few studies have rigorously examined what a national alternative fuel refueling infrastructure looks like and how much economic benefits or costs it entails.

This paper contributes to the body of literature by conducting an economic feasibility analysis of a national natural gas (LNG or CNG) refueling infrastructure for long-haul trucks. It estimates economic costs and benefits from the perspective of refueling infrastructure investors. It develops a refueling infrastructure model that prioritizes building refueling stations at highway intersections and ensures highway network coverage to determine the locations and capacities of a natural gas refueling network for long-haul trucks in the U.S.

A BENEFIT OF THE MODEL DEVELOPED IN THIS PAPER, COMPARED TO THE MILP MODELS PREVIOUSLY DESCRIBED, IS THAT IT REQUIRES LESS DETAILED TRIP DATA AND IS MORE COMPUTATIONALLY EFFICIENT.



Method

This paper presents a model to assess the locations, capacities, capital investments, and net profits of a natural gas refueling infrastructure for long-haul trucks in U.S.

The model has the following characteristics:

1. it relies on truck flow estimates;
2. it ensures refueling coverage of any truck traveling within the selected highway network no matter where its trip starts and ends;
3. it prioritizes building refueling stations at highway intersections.

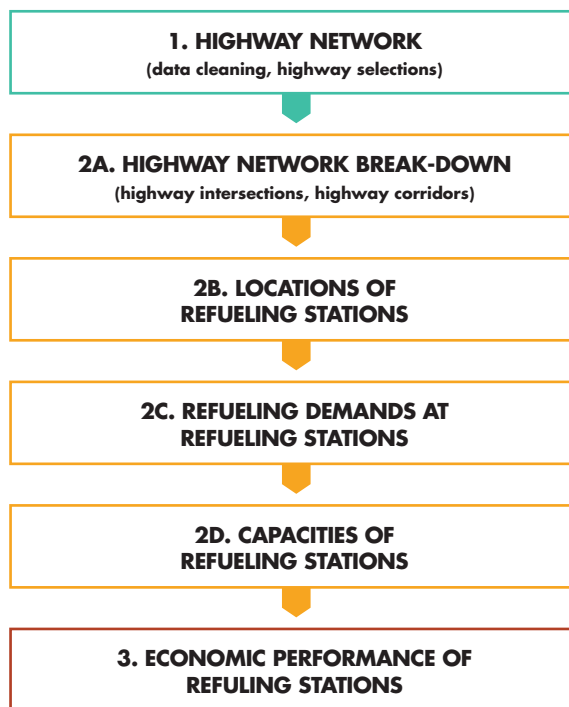
The paper includes two scenarios analyzed using the model: (i) a national scenario where the infrastructure is built for the entire U.S., and (ii) a regional scenario that only considers Texas and California because both states have high truck flows within regions as well as state incentives for the deployment of natural gas trucks (U.S. DOE 2016). Furthermore, natural gas in both states enjoys larger price advantages over diesel, thus motivating the conversion of diesel trucks to natural gas trucks (Jaffe et al. 2015; U.S. EIA 2016a).

To estimate refueling demands for natural gas fuels, the model relies on highway truck flow estimates (Freight Analysis Framework version 4.3 (FAF4)) (U.S. Federal Highway Administration (FHWA); 2017) and shares of natural gas trucks in the long-haul truck fleet. Furthermore, this analysis assumes a uniform adoption of natural gas trucks in the highway network. For both national and regional

scenarios the share of natural gas trucks varies parametrically from 1% to 100% to assess how refueling infrastructure evolves at different levels of refueling demands.

Fig. 1 shows the flow diagram of the refueling infrastructure model. The model has three major steps. The first step is to decide the boundary of the highway network and prepare the truck flow data. The second step is to determine the locations and capacities of refueling stations. Finally, the last step is to examine the economics of the refueling infrastructure. Before detailing the refueling infrastructure model, the following sections describe the assumptions on natural gas trucks and refueling stations.

FIGURE 1: FLOW DIAGRAM OF THE REFUELING INFRASTRUCTURE MODEL USED IN THIS PAPER.



TRUCK CHARACTERISTICS

This paper assumes long-haul trucks account for all the “long-distance truck flows” estimated in the FAF4 (U.S. Federal Highway Administration (FHWA); 2017). According to Table 1, natural gas trucks have a vehicle range (with a full tank of fuels) of 540-1,080 km (335-670 miles), depending on fuel tank specifications. The actual distance between two refueling stops, however, may be less than the vehicle range due to trip planning. This paper thus assumes the range of the trucks as either 320, 460, or 960 km (200, 300, or 600 miles) and tests the effect of these assumptions in the sensitivity analysis.



TABLE 1: TRUCK SPECIFICATIONS

FUEL TYPE	DIESEL		CNG		LNG	
Engine technology	Compression Ignition		Sparkling Ignition		High-Pressure Direct Ignition (HPDI)	
Fuel economy (unit: km per liter diesel equivalent, and mile per gallon diesel equivalent in parenthesis)	2.5 (5.8)		2.4 (5.3)		2.7 (5.7) ^a	
Fuel tank (unit: diesel liter equivalent, and diesel gallon equivalent in parenthesis)	570 (150)		270 (70)	530 (140)	230 (60)	450 (120)
Vehicle range (unit: km, and mile in parenthesis) ^b	1,400 (870)		540 (335)	1,070 (670)	550 (340)	1,100 (680)
Vehicle price premium (\$ premium relative to diesel)	0		35,000	62,000	70,000	89,000

Source: Adapted from Tong et al. 2015a and Deal 2012.

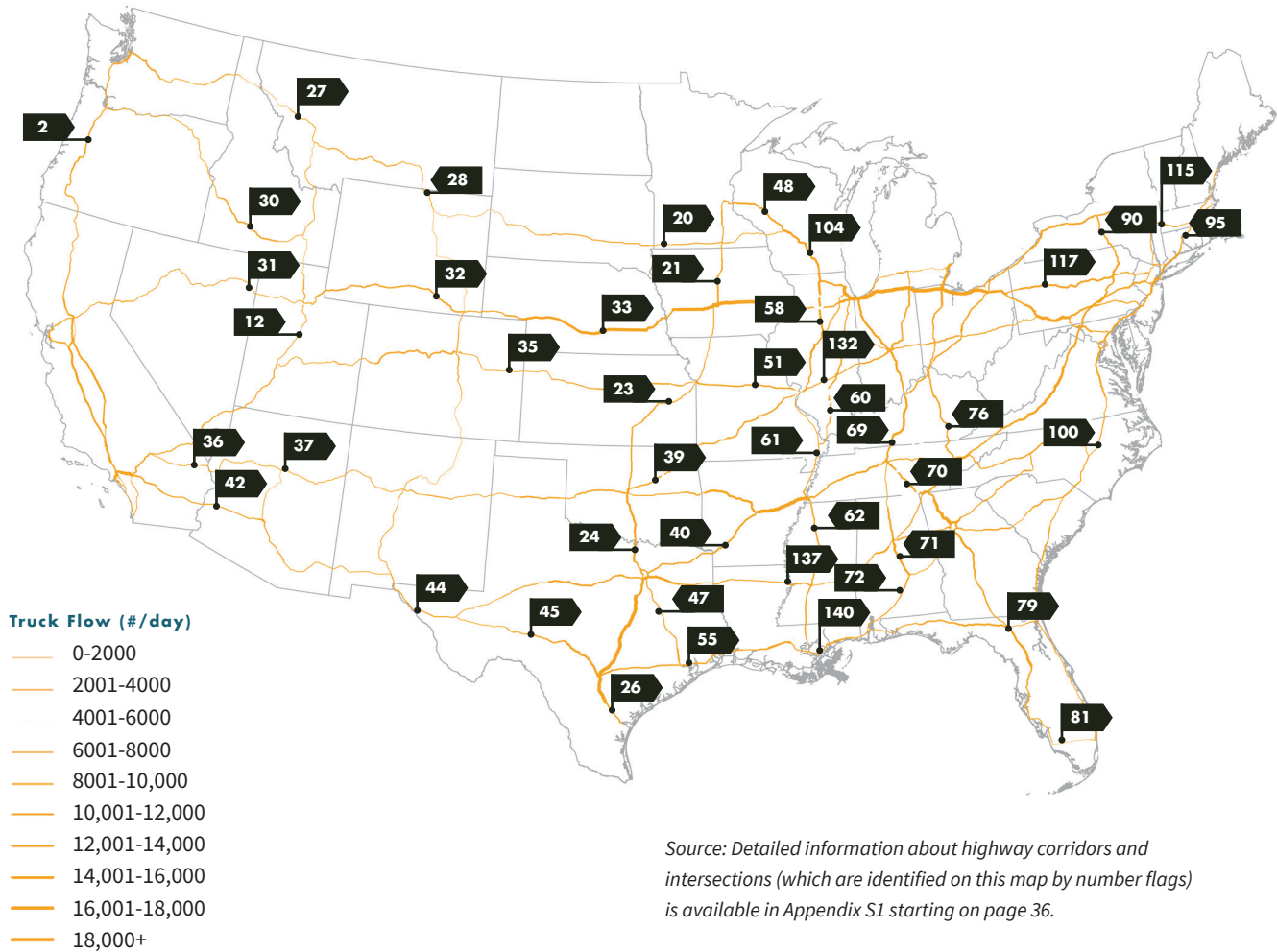
Note: ^a LNG-HPDI engine uses diesel to ignite the compression ignition, so only 95% of its fuel consumption is LNG. ^b Vehicle range = fuel economy × fuel tank × fraction of usable fuel. The fractions of usable fuel for LNG and CNG are assumed to be 0.95 and 0.9.

REFUELING STATION CHARACTERISTICS

This paper assumes standardized refueling stations. At locations with high refueling demands, the model will choose to build multiple refueling stations. It is further assumed that the LNG refueling station has two refueling lanes, each of which has one dispenser (the refueling rate is 54 diesel liter equivalent (DLE) per minute or 14 diesel gallon equivalent (DGE) per minute), a 57,000 liter (15,000 gallon) LNG storage tank, and other supporting equipment (Myers et al. 2012). The capital cost of the LNG refueling station is \$2.5 million (Myers et al. 2012). A review of recent literature on CNG refueling station assumptions shows that a fast-fill CNG refueling station with redundant compressors can refuel at 10 DGE/minute for a cost of \$3.35 million (Section IV in Appendix S1). The model assumes the refueling station has a maximum capacity factor of 40%, so the practical maximum refueling capacity is 11.7 million DLE/year (6.0 million DGE/year) for the assumed LNG station and 6.8 million DLE/year (4.2 million DGE/year) for the CNG station. This limit in the capacity factor accounts for practical limitations such as refueling congestion, idling between refuels, and low refuels at night. The capital cost of the refueling station includes equipment costs but excludes site-specific cost such as construction cost and land cost (Section IV in Appendix S1). The sensitivity analysis includes a scenario with a small-scale standardized LNG refueling station, which costs \$1.25 million for a practical maximum refueling capacity of 3 million DGE per year.



FIGURE 2: SELECTED HIGHWAY NETWORKS, INDEXED CORRIDORS, AND LONG-HAUL HEAVY-DUTY TRUCK FLOWS IN 2012.

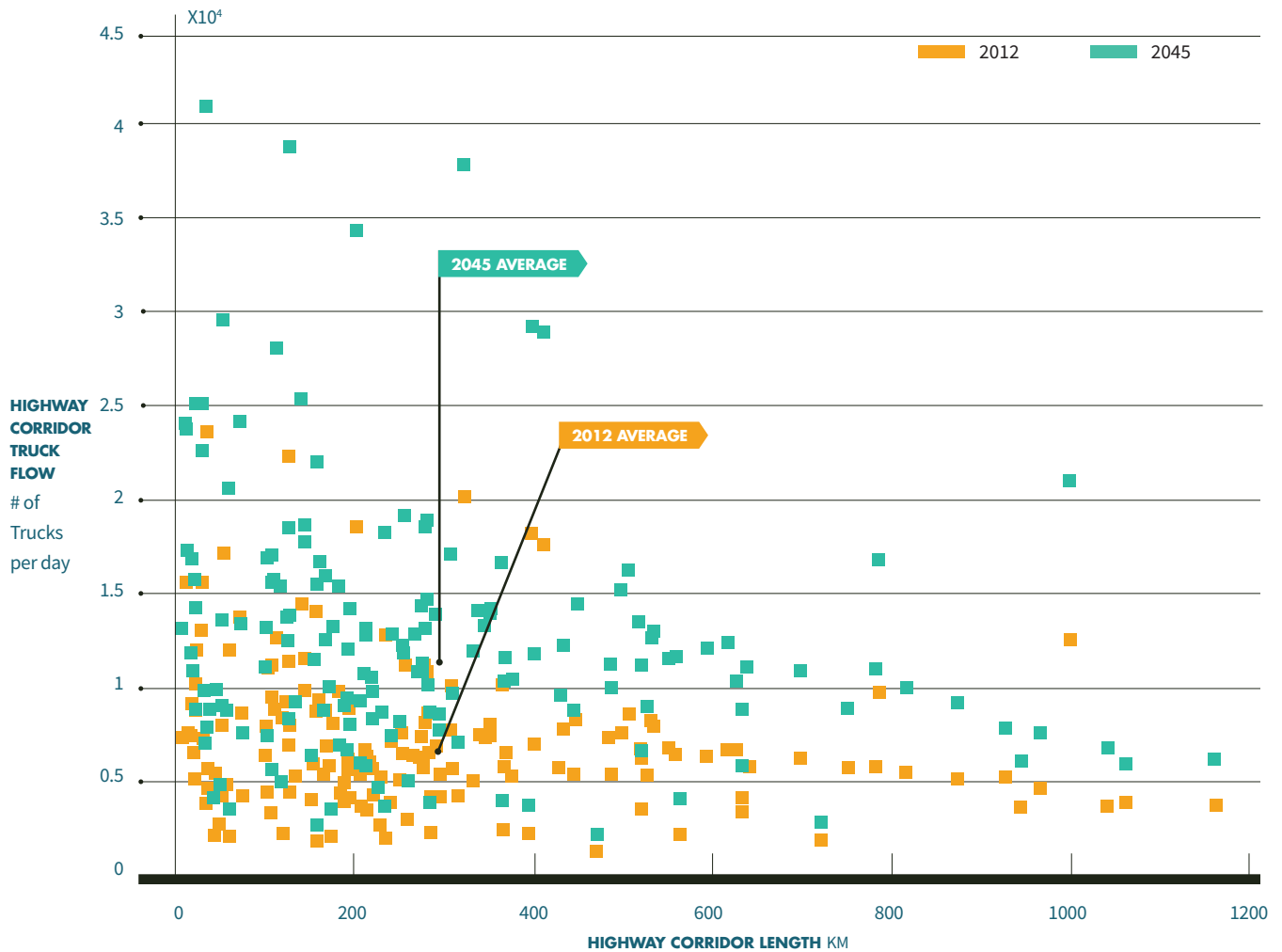


HIGHWAY NETWORK AND TRUCK FLOW ESTIMATES

This paper uses truck flow estimates from the FAF4, which is estimated by attributing freight flows (based on the 2012 U.S. Commodity Flow Survey, trade freight flows, and other data sources) to U.S. road networks (U.S. Federal Highway Administration (FHWA); 2017). The original FAF database models freight trucks on all types of roads in the U.S. The use of natural gas fuels is unlikely to happen on all of these roads. It is also computationally inefficient to consider all roads in the U.S. This analysis thus focuses on a reduced boundary of the national highway network to include a selection of interstate and state highways in the

U.S. The selection criteria include the ranking of weighted-average truck flows and coverage of major cities and freight centers (See Section I in Appendix S1). Fig. 2 shows the FAF4 truck flows for year 2012 on the selected highway network and Fig. 3 shows large variance in road length and weight-average truck flow across corridors. As the FAF4 dataset also projects truck flows for year 2045, this paper includes a sensitivity analysis on the refueling infrastructure model using truck flows in 2045. Intuitively, as all highway corridors see larger truck flows in 2045 (35-142% higher than 2012), more refueling stations will be built to meet the increasing refueling demands for the same share of natural gas trucks.

FIGURE 3: CORRIDOR LENGTH AND WEIGHTED-AVERAGE LONG-HAUL HEAVY-DUTY TRUCK FLOWS IN EACH CORRIDOR IN 2012 AND 2045.



The FAF data includes the number of long-haul trucks per day for any road segment across the U.S. road network. A road segment, defined in the FAF database, has a variable road length on the order of 0.1 to 10 km. FAF truck flows are converted to vehicle distance traveled (VDT) estimates for any road segment. Using fuel economy assumptions of diesel trucks (Table 1), it is possible to estimate

fuel consumption of long-haul trucks for all road segments in the selected highway network. Note that since FAF4 is a snapshot of highway truck flows in 2012, it should not include any significant use of natural gas for long-haul transportation. Equations (1)-(3) calculate fuel consumption of natural gas trucks for any road segment at a given share of natural gas trucks.

EQUATIONS 1-3: CALCULATE FUEL CONSUMPTION OF NATURAL GAS TRUCKS

1	$VDT_{road\ segments\ s} = \text{number of trucks}_s \times \text{road length}_s$
2	$\text{fuel consumption}_{road\ segments\ s,\ diesel} = VDT_s / \text{fuel economy}_{diesel}$
3	$\text{fuel consumption}_{road\ segments\ s,\ NG\ fuel} = \text{share}_{NG\ truck} \times VDT_s / \text{fuel economy}_{NG\ truck}$

Table 2 shows vehicle distance traveled and fuel consumption estimates of long-haul trucks calculated using Equations (1)-(3) as well as a national estimate from Transportation Energy Data Book (TEDB) (Davis et al. 2016). The TEDB estimates are 2.3 times higher than this paper’s because of the

different scopes considered. For instance, the truck flows estimated in the FAF4 database only include long-distance trucks; the highways selected for this analysis cover more than two thirds, but not all, of truck flows in the FAF4; the FAF4 data is for 2012 while the TEDB data is for 2013.

TABLE 2: VEHICLE DISTANCE TRAVELED (VDT) AND FUEL CONSUMPTION ESTIMATES IN THIS PAPER AND OTHER SOURCES

METRICS	TRANSPORTATION ENERGY DATA BOOK (DAVIS ET AL. 2016)	FAF4 (U.S. FHWA 2017)	THIS PAPER
Vehicles considered	Class 7-8 combination trucks	long-haul trucks	
Data year	2013	2012	
Road distance (unit: 1,000 km and 1,000 miles in parenthesis)	urban & public paved roads: 1,771 & 4,186 (1,100 & 2,600)	718 (446)	48 (30)
Number of trucks (million)	2.5	1.6 ^a	1.1 ^a
VDT (unit: billion km and billion miles in parenthesis)	262 (163)	171 (106)	115 (71)
Fuel consumption (unit: billion diesel liter equivalent and billion diesel gallon equivalent in parenthesis)	106 (28)	69 (18) ^b	46 (12) ^b

Note: ^a Assuming the only fuel consumed by long-distance trucks is diesel. ^b Fuel consumption is back-calculated using the fuel economy of an average diesel Class 7-8 combination truck, which is 5.8 mile per gallon (2.5 km per liter) (Davis et al. 2016).

ALTERNATIVE POWERTRAIN VEHICLES

The refueling infrastructure model takes refueling demand of natural gas trucks as the input and determines the locations and capacities of natural gas refueling stations. For simplicity, the model assumes refueling stations refuel trucks moving in both directions. The siting of refueling stations should ensure that any truck with any origin and any destination within the selected highway network has enough fuel at any point during its trip. In other words, the maximum road distance between two adjacent refueling stations should be less than the minimum range of trucks served. The model prioritizes building a refueling station at every major highway intersection to capture high refueling demands. Existing research found that refueling stations at road intersections see significantly larger vehicle visits than other refueling stations (Kelley 2015). As a result, the model determines the locations of refueling stations in two steps. First, it builds refueling stations at highway intersections. Second, if the length of a corridor - defined as the portion of a highway between two adjacent intersections - is longer than the range of a truck, the model chooses to build a minimum number of equally spaced refueling stations within the corridor to make sure the nearest road distance between two refueling stations is no larger than the vehicle range. For instance, if a corridor has a length of 1,600 km (1,000 miles) and a truck’s range is 480 km (300 miles), the model then chooses to build three refueling stations that are 400 km (250 miles) apart from each other in the corridor.

The model then proceeds to determine refueling capacities. It assumes that trucks refuel at every refueling station along their trips until they reach destinations, and trucks refuel the same amount of fuel consumed since their last refuel. For computational simplicity, the model does not account for refueling demands outside the selected highway network and assumes the trucks have full tanks when they first enter the highway network. This assumption is necessary as the available dataset does not include origin-destination data for trucks using the highway network. In practice, this assumption means that either trucks use local refueling stations near warehouses or the freight is transported outside the highway network by local trucks. Furthermore, the FAF4 truck flow data aggregates truck flows over moving directions. Without further information, the model assumes symmetrical truck flows in two directions. Finally, Equation (4) calculates the refueling demands at any refueling station location selected in the previous step.

Where the first summation sums up refueling demands from truck flows in all highways that intersect at a refueling station location r , the second summation sums up refueling demands between a refueling station location r and one of its adjacent refueling station locations r' , and “1/2” accounts for the driving direction of truck flows. If the refueling demand at a location is larger than the practical maximum capacity of the standardized refueling station, the model chooses to build another refueling station at the same location. The number of co-located refueling stations is calculated by Equation (5).

EQUATION 4: CALCULATES THE REFUELING DEMANDS AT ANY REFUELING STATION LOCATION

$$4 \quad \text{Refueling demand}_{\text{refueling station location } r} = \frac{1}{2} \times \sum_{\text{any refueling station location } r' \text{ that have a highway connection with } r} \sum_{\text{any highway segment } s \text{ that falls between } r' \text{ and } r} \text{fuel consumptions}_{s, \text{ NG fuels}}$$

EQUATION 5: CALCULATES THE NUMBER OF CO-LOCATED REFUELING STATIONS

5

$$\text{number of co-located refueling stations}_{\text{refueling station location } r} = \left\lceil \frac{\text{refueling demand}_r}{\text{capacity of a standardized refueling station}} \right\rceil$$

Where $\lceil \cdot \rceil$ is the ceiling function, defined as $\lceil x \rceil = \min\{n \in \mathbb{Z} | n \geq x\}$.

ECONOMIC ANALYSIS

This paper performs economic analysis from the perspective of refueling infrastructure investors. It treats all natural gas refueling stations as though they are owned by one single investor. Antitrust Laws would prevent this situation from occurring in reality, but this analysis provides an overall assessment of the economic viability of natural gas (CNG or LNG) refueling infrastructure.

For this analysis, it is assumed that the refueling infrastructure investor asks for positive returns for the investment on the refueling infrastructure. Since the investor can invest in both natural gas refueling infrastructure and diesel refueling infrastructure, the returns on the natural gas refueling infrastructure should be no smaller than those on the diesel refueling infrastructure. Since the diesel infrastructure is well established and is part of a competitive market, the analysis in this paper assumes the boundary condition where the net returns on the diesel infrastructure are zero (Biba 2017). As a result, the net returns on the natural gas refueling infrastructure should be larger than zero (boundary condition). In reality, if the investor can make the investment in other markets, the alternative investment may yield a high positive return, which would require an even higher return on the natural gas refueling infrastructure.

The cash flow of the natural gas refueling infrastructure investment consists of the upfront investment, which the model assumes happens all at once and at year 0, fuel procurement costs,

revenues from fuel sales, fuel excise tax and other taxes, and other costs such as those related to operation and maintenance (Section III in Appendix S1). For simplicity, the model assumes that except for the upfront investment cost, all other cash flow components are proportional to the fuels sold. In this analysis, the profit margin represents the difference between the per-unit revenues and the per-unit costs. The actual business models of refueling stations are much more complex than the simple engineering economic model assumed here. For instance, convenience stores co-located with refueling stations can contribute more to the overall profits than the refueling business (Biba 2017). The simple model used in this paper aims to illustrate the fundamental factors that determine the economic viability of the refueling infrastructure investment.



The engineering economic model consisting of Equations (6)-(8) calculates capital investment and net present value (NPV) of the net profit. Table 3 lists key assumptions used. In addition to baseline values, it includes wide sensitivity ranges for each assumption to analyze their impacts on the economic viability of the refueling infrastructure.

EQUATION 6-8: CALCULATES CAPITAL INVESTMENT AND NET PRESENT VALUE (NPV) OF THE NET PROFIT.

6	$\text{capital investment} = \sum_{r \in \text{all refueling stations}} \text{capital cost of a refueling station } r$ $= \text{number of refueling stations} \times \text{capital cost of a refueling station}$
7	$\text{net profit NPV} = - \text{capital investment} + \sum_{t=1}^{\text{lifetime}} \sum_{\text{refueling station } i} \text{fuel sales profits}_{i, \text{year } t} \times (1 + \text{discount rate})^{-t}$ $= - \text{capital investment} + \sum_{t=1}^{\text{lifetime}} \sum_{\text{refueling station } i} \text{fuel sales profits}_{i,t} \times \text{profit margin} \times (1 + \text{discount rate})^{-t}$ $= - \text{capital investment} + \text{annuity factor}_{\text{lifetime, discount rate}} \times \sum_{\text{refueling station } i} \text{fuel sales}_i \times \text{profit margin}$
8	$\text{annuity factor}_{\text{lifetime, discount rate}} = \frac{1 - (1 + \text{discount rate})^{-\text{lifetime}}}{\text{discount rate}}$



TABLE 3: KEY ECONOMIC ASSUMPTIONS

VARIABLE	BASELINE VALUE	REFERENCE FOR BASELINE VALUES	THIS PA SENSITIVITY RANGE PER
Discount rate	7%	U.S. OMB 2015	3%-11%
Lifetime	20 years	U.S. NPC 2012	10-30 years
LNG refueling station capital cost	\$2.5 million	Myers et al. 2012	\$0.5-4.5 million
LNG profit margin per unit fuel sold	\$0.05/DGE	U.S. NPC 2012	\$0.01-0.10/DGE
CNG refueling station capital cost	\$3.35 million	GNA 2012	\$1.35-5.35 million
CNG profit margin per unit fuel sold	\$0.10/DGE	U.S. NPC 2012	\$0.02-0.20/DGE





Results

LOCATIONS AND CAPACITIES OF THE LNG REFUELING INFRASTRUCTURE

Highway topology and vehicle range determine refueling station locations. The selected national highway network has 100 highway intersections, so there are at least 100 refueling stations at intersections. The number of refueling stations built within highway corridors depends on the vehicle range: if the assumed truck range is 960 km (600 miles), only 5 more refueling station sites are chosen to ensure corridor coverage, but if the truck range is reduced to 320 km (200 miles), then 72 more refueling station locations have to be selected within corridors (Table 4). Furthermore, the results suggest large variations in refueling demands across refueling stations and that most high-demand refueling stations are located at highway intersections (Section II in Appendix S1).

The results show that the share of long-haul trucks powered by natural gas fuels largely drives the capacity expansion of the refueling infrastructure

(Fig. 4). When the share of natural gas trucks is higher than 3%, the total refueling capacity grows almost linearly with respect to the share of natural gas trucks. However, if the share of natural gas trucks is less than 3%, the total refueling capacity needed is fairly constant, suggesting overcapacity of the built infrastructure. This is a result of discrete capacity for refueling stations and the modeling requirement to ensure network refueling coverage. The impact of vehicle range on the total refueling capacity is only noticeable at low shares of natural gas trucks; it becomes negligible when shares of natural gas trucks are high.

Faced with a very low share of natural gas trucks (1%), a national natural gas refueling infrastructure would require only 105-172 refueling stations for vehicle range assumptions of 320-960 km (200-600 miles) (see Fig. 4 and Table 4). On the other hand, a complete conversion of the existing truck fleet to natural gas trucks would require a national infrastructure consisting of 2,135-2,172

refueling stations. To put these numbers in context, there are about 5,000-10,000 heavy-duty diesel refueling stations on interstate highways (Jaffe and Dominguez-faus 2013; TIAX LLC 2012b). The number of existing diesel refueling stations is significantly larger than the model’s estimates because the model does not account for competitive market behaviors.

Fig. 4 and Table 4 report the calculated locations and capacities for a regional natural gas refueling infrastructure in California and Texas. Because these two states have much smaller and relatively denser highway networks than the entire U.S., fewer refueling station locations are needed – 18-25 refueling stations depending on vehicle

range assumptions. However, 11.5% of the U.S. total trucks’ VDTs take place in California and Texas (which have total highway length of 4,400 km (2,733 miles) within the scope of the network in this analysis). As a result, to serve the same amount of VDTs driven by natural gas trucks (e.g. 1.15% of the total truck VDT), a national refueling infrastructure requires building 105-172 refueling stations, while a regional refueling infrastructure in California and Texas would require only 33-39 refueling stations. This implies that, if the goal is to replace certain amount of diesel consumption, building refueling stations in high-demand regions such as California and Texas would significantly reduce capital investments required.

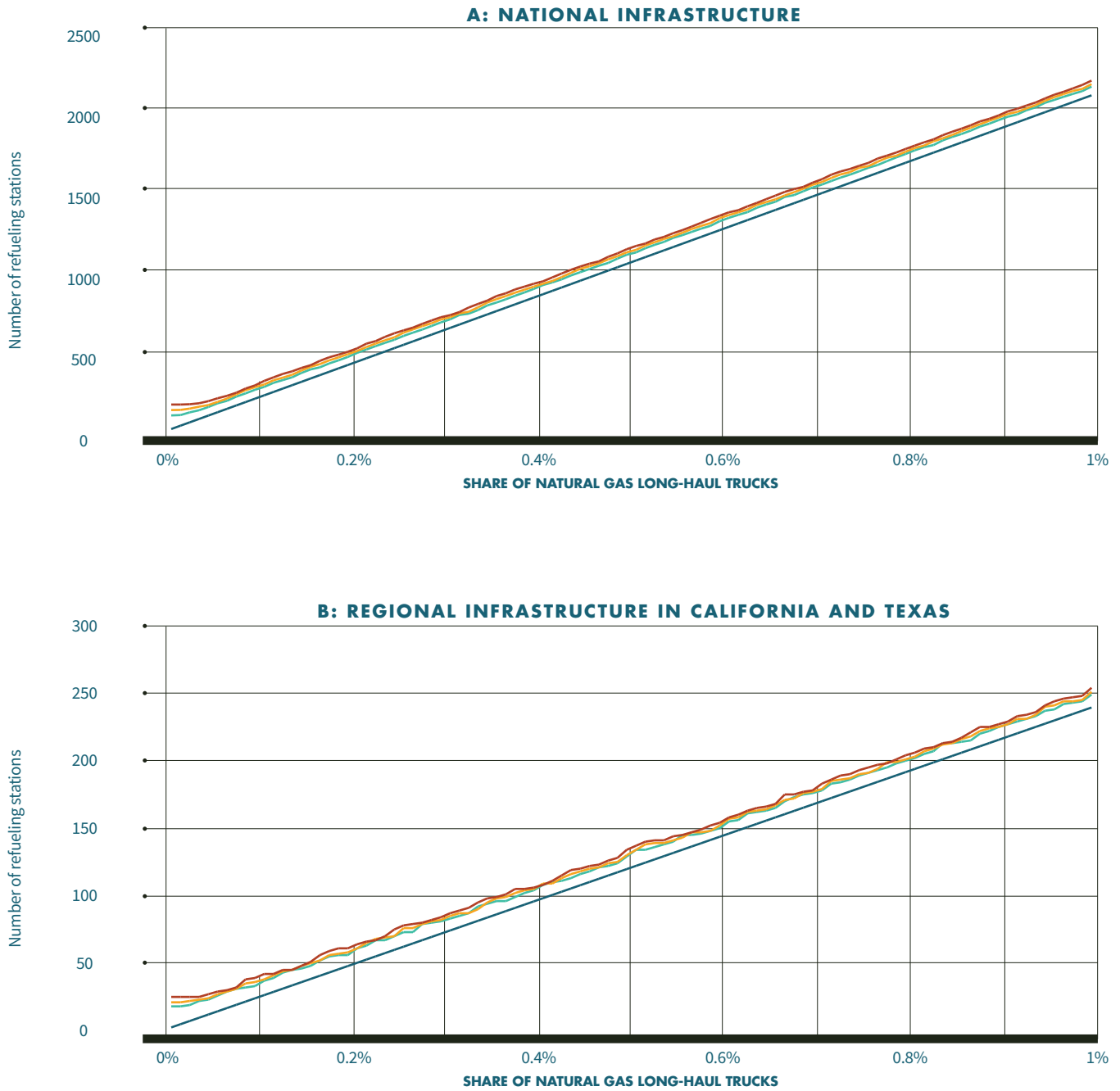
TABLE 4: NUMBER OF REFUELING STATIONS TO SERVE 1%, 5% AND 10% OF THE TOTAL TRUCK FLEET IN THE U.S., AND IN CALIFORNIA AND TEXAS

GEOGRAPHIC SCOPE AND VEHICLE RANGE		NUMBER OF REFUELING STATION LOCATIONS			NUMBER OF REFUELING STATIONS (SHARE OF NATURAL GAS TRUCKS: 1%/5%/10%)		
		AT INTER-SECTIONS	WITHIN CORRIDORS	TOTAL	AT INTER-SECTIONS	WITHIN CORRIDORS	TOTAL
U.S. NATIONAL	320 km (200 miles)	100	72	172	100/116/182	72/77/108	172/193/290
	480 km (300 miles)		38	138	100/128/211	38/41/68	138/169/279
	960 km (600 miles)		5	105	100/150/250	5/7/13	105/157/263
CALIFORNIA & TEXAS	320 km (200 miles)	18	7	14	18/19/26	7/8/13	25/27/39
	480 km (300 miles)		3	11	18/21/30	3/3/6	21/24/36
	960 km (600 miles)		0	10	18/23/33	0/0/0	18/23/33

Note: According to Table 2, a 10% share of the truck fleet corresponds to 110 thousand trucks, 7.1 billion vehicle miles (11.5 billion vehicle km) per year, and 1.2 billion DGE (4.6 billion DLE) of fuels per year.

FIGURE 4: NUMBER OF LNG REFUELING STATIONS AS FUNCTIONS OF SHARE OF NATURAL GAS TRUCKS AND VEHICLE RANGE FOR (A) A NATIONAL INFRASTRUCTURE AND (B) REGIONAL INFRASTRUCTURE IN CALIFORNIA AND TEXAS.

320 km (200 miles) 480 km (300 miles) 960 km (600 miles) Refueling demand



The “refueling demand” line shows the actual refueling demands at the refueling station locations (represented as multiples of a standardized refueling station).



ECONOMIC ANALYSIS OF THE LNG REFUELING INFRASTRUCTURE

For a 1-10% of the national truck fleet as natural gas trucks and vehicle ranges of 320-960 km (200-600 miles), the initial investment on the refueling infrastructure ranges from \$263-430 million to \$658-725 million (See Section VIII in Appendix S1 for detailed numerical results). We identify, again, a non-linearity in investment at low shares of natural gas trucks, which is due to the over-capacity issue discussed earlier. To capture an equivalent 1.2% of the nationwide VDT, the capital investment of refueling infrastructure in California and Texas is about a quarter (\$83-98 million) of that required for a national LNG refueling system. Similarly, Jaffe et al. suggested that “the costs to provide dedicated coverage for LNG across California are estimated to be less than \$100 million” (Jaffe et al. 2015). The National Petroleum Council (NPC) estimated that an investment of \$10-20 billion would be needed for a national LNG refueling infrastructure to replace one third of the diesel fuel market (U.S. NPC 2012). For that share of natural gas truck, this paper’s estimate ranges from \$1.8 to \$1.9 billion. As these cited work only presented aggregate estimates, it is not possible to provide more detailed comparisons.

WHILE THE CAPITAL EXPENDITURE ON BUILDING A NATURAL GAS REFUELING INFRASTRUCTURE IS SEEMINGLY LOW, THE NET PROFIT (IN NPV) FOR THE REFUELING INFRASTRUCTURE IS MORE LIKELY TO BE NEGATIVE WHEN NATURAL GAS TRUCKS CONSTITUTE A SMALL PORTION OF THE TOTAL TRUCK FLEET.

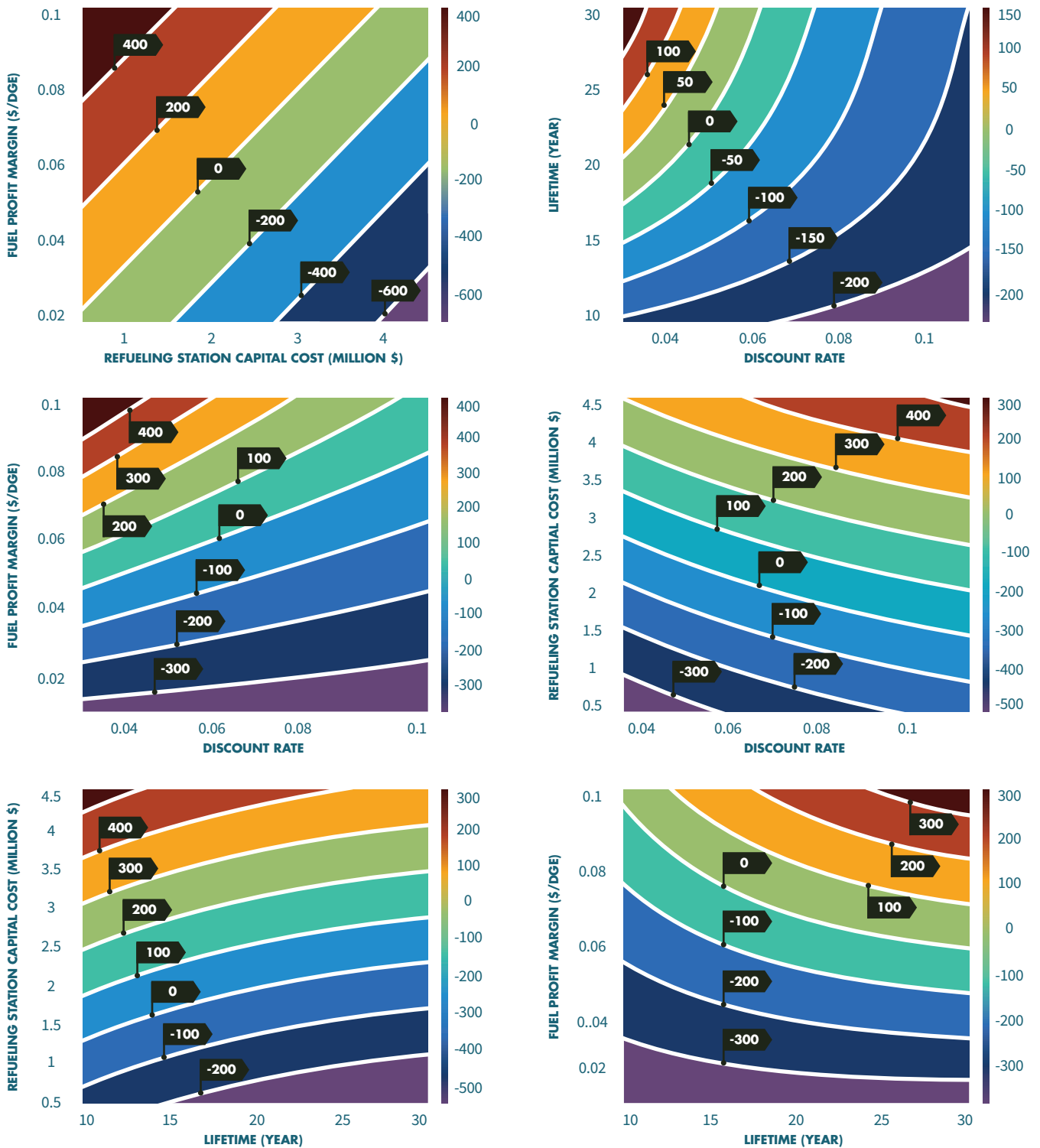
For the baseline economic assumptions shown in Table 3, the net profits (in NPV) for the national refueling infrastructure at 1%, 5%, and 10% natural gas truck shares are -\$364 million to -\$196 million, -\$152 million to -\$62 million, and -\$64 million to \$4 million. Higher shares of natural gas trucks improve the net profit for the refueling infrastructure. For vehicle range assumptions of 320 km (200 miles), 480 km (300 miles), and 960 km (600 miles), the break-even shares of natural gas trucks are 15.2%, 12.4%, and 9.5%, respectively. When the actual share of natural gas trucks is larger than these values, the investors will see positive returns.

These break-even shares are larger than that for a single LNG refueling station (which is 11% for a 300-mile range LNG truck as discussed in Section V in Appendix S1). The difference in the break-even estimates is due to several reasons: (1) there is significant variance in truck flows across corridors; (2) the distribution of refueling stations in the highway network is not spatially uniform; and (3) the two-dimensional connection of highways means that multiple refueling stations collectively refuel trucks traveling in connected corridors.

Fig. 5 and Fig. 6 illustrate how the four economic variables (refueling station capital cost, profit margin, discount rate, and lifetime) affect the net profit (NPV) for the refueling infrastructure. Each figure displays the trade-offs between a pair of economic variables for a given share of natural gas trucks (5% or 15%). While the baseline net profits show different signs (negative and positive) for a 5% or a 15% share of natural gas trucks, the effects of economic variables at a 5% share of natural gas trucks are similar to those at a 15% share of natural gas trucks. The net profit of the refueling infrastructure investment is more sensitive to profit margin per unit fuel and capital cost of a refueling station than to lifetime and discount rate assumptions. Furthermore, fuel profit margin and capital cost of a refueling station exhibit a linear substitution relationship. This is expected because the upfront capital cost of the refueling infrastructure is assumed to be paid for by sales of LNG fuels in our simple model.

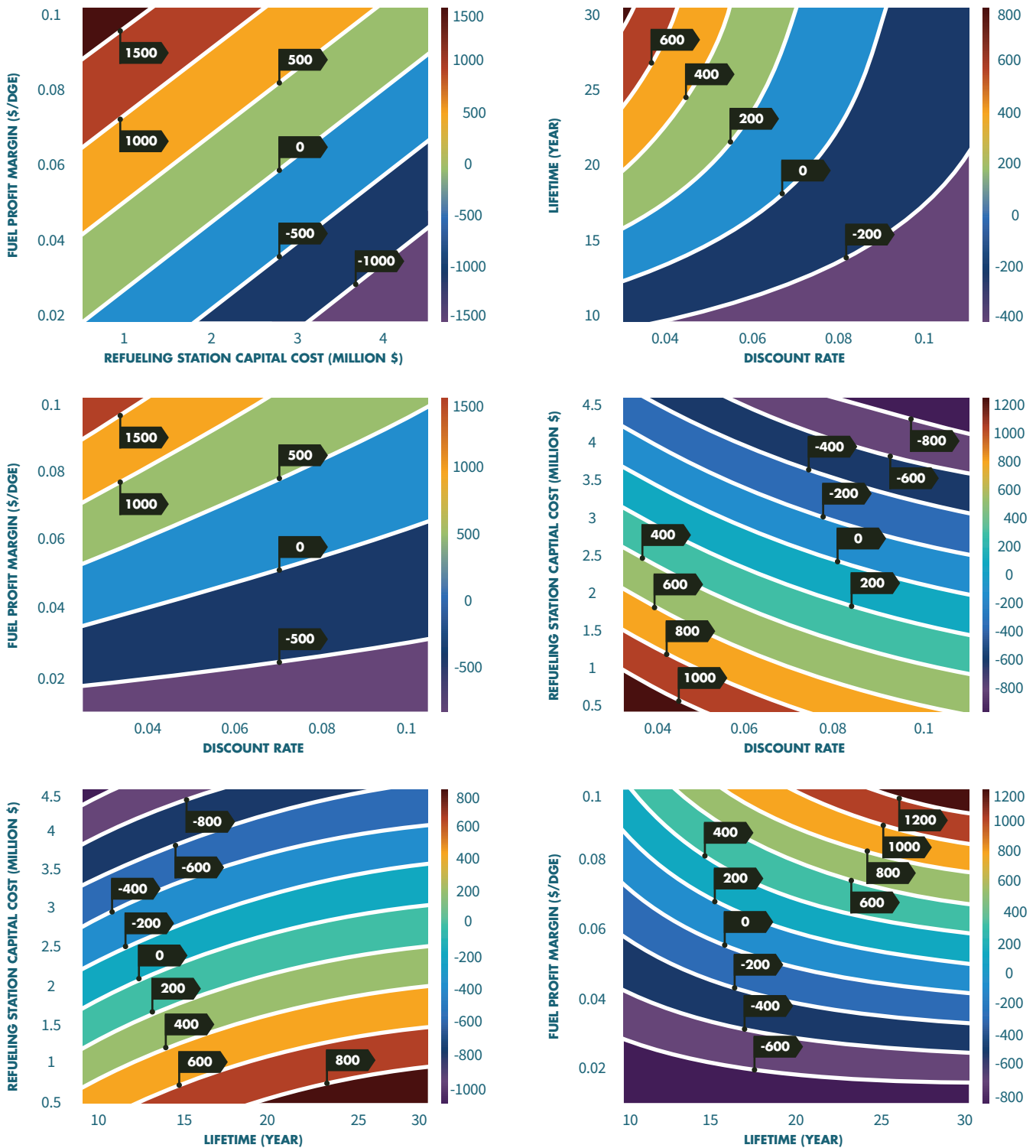


FIGURE 5: NET PROFIT (IN MILLION \$ NPV) FOR ALL REFUELING STATIONS AT DIFFERENT COMBINATIONS OF REFUELING STATION CAPITAL COST, DISCOUNT RATE, FUEL PROFIT MARGIN, AND LIFETIME.



We assume 5% of national long-haul trucks as natural gas trucks, a 480-km (300-mile) vehicle range and baseline economic assumptions. Contour lines that achieve the same net profits are marked. One color is filled in each interval of the net profits. The same color may represent different net profits in different figures.

FIGURE 6: NET PROFIT (IN MILLION \$ NPV) FOR ALL REFUELING STATIONS AT DIFFERENT COMBINATIONS OF REFUELING STATION CAPITAL COST, DISCOUNT RATE, FUEL PROFIT MARGIN, AND LIFETIME.



We assume 15% of national long-haul trucks as natural gas trucks, a 480-km (300-mile) vehicle range and baseline economic assumptions. Contour lines that achieve the same net profits are marked. One color is filled in each interval of the net profits. The same color may represent different net profits in different figures.

IMPACTS OF TRUCK FLOWS AND REFUELING STATION ASSUMPTIONS

In addition to the share of natural gas trucks and economic assumptions, this analysis also examined the sensitivity of the results to highway truck flows and refueling station assumptions. As shown in Fig. 2, the FAF4 data projects significant increase in truck flows from 2012 to 2045. Using the truck flow data in 2045 instead of those in 2012, the results suggest that the LNG refueling infrastructure sees much better economic returns: the break-even shares become smaller (9.1%, 6.7%, and 5.2% for an assumed vehicle range of 320 km (200 miles), 480 km (300 miles), and 960 km (600 miles)) and the net profits become better for the same economic assumptions. Intuitively, the natural gas refueling infrastructure requires break-even refueling demands (and equivalently break-even truck flows) to pay for the capital investment. As highway truck flows on highways increase, the share of natural gas trucks needed to break even decreases.


One potential concern with the previous results in this paper is that the capacity factors of the refueling stations are pretty high except for scenarios assuming low shares of natural gas trucks (See Section II in Appendix S1 for detailed results). As a result, this analysis includes two alternative set of refueling station assumptions. The first scenario assumes the maximum capacity factor as 20% instead of 40% and assumes the capital cost remains the same. The refueling infrastructure has negative returns regardless of shares of natural gas trucks when economic assumptions remain unchanged. Intuitively, this represents a waste of capital investment. The second scenario scales down both maximum capacity and capital cost of the refueling station by half. In other words, this scenarios assumes a smaller-scale refueling station that has the same ratio between capital cost and capacity as the larger one. The results for this scenarios suggest that the new refueling infrastructure has slightly better economic returns than the baseline refueling



infrastructure scenario. This is because smaller discrete size in refueling capacity tracks refueling demands better than larger ones, particularly when the share of natural gas trucks is low. Theoretical analysis and model results are available in Appendix S1 (Sections V and VIII).

CNG REFUELING INFRASTRUCTURE IMPLICATIONS

Assuming the profit margin of CNG is the same as LNG (\$0.05/DGE), the results suggest that a national CNG refueling infrastructure will never make a positive return regardless of the share of CNG trucks (Sections V and IX in Appendix S1). However, historical price trends (Section III in Appendix S1) and literature values (U.S. National Petroleum Council (NPC) 2012) suggest that CNG refueling stations can have larger profit margins than their LNG counterparts. Assuming a \$0.1/DGE profit margin, the national CNG refueling infrastructure has better economic returns than the LNG refueling infrastructure (See Section IX in Appendix S1 for numerical results). The break-even shares of CNG trucks are 8.6%, 6.6%, and 5.3% for an assumed vehicle range of 320 km (200 miles), 480 km (300 miles), and 960 km (600 miles).

An aerial photograph of a multi-lane highway cutting through a lush green landscape. A blue semi-truck is driving in the left lane, and a white semi-truck is driving in the right lane. The highway is flanked by green grass and trees. A road curves to the left on the left side of the highway, and another road curves to the right on the right side. The sky is not visible, suggesting a high-angle shot.

**Smaller discrete size
in refueling capacity
tracks refueling demands
better than larger ones,
particularly when the share
of natural gas trucks is low.**

TRUCK FLEET DECISIONS AND THE ADOPTION OF NATURAL GAS TRUCKS

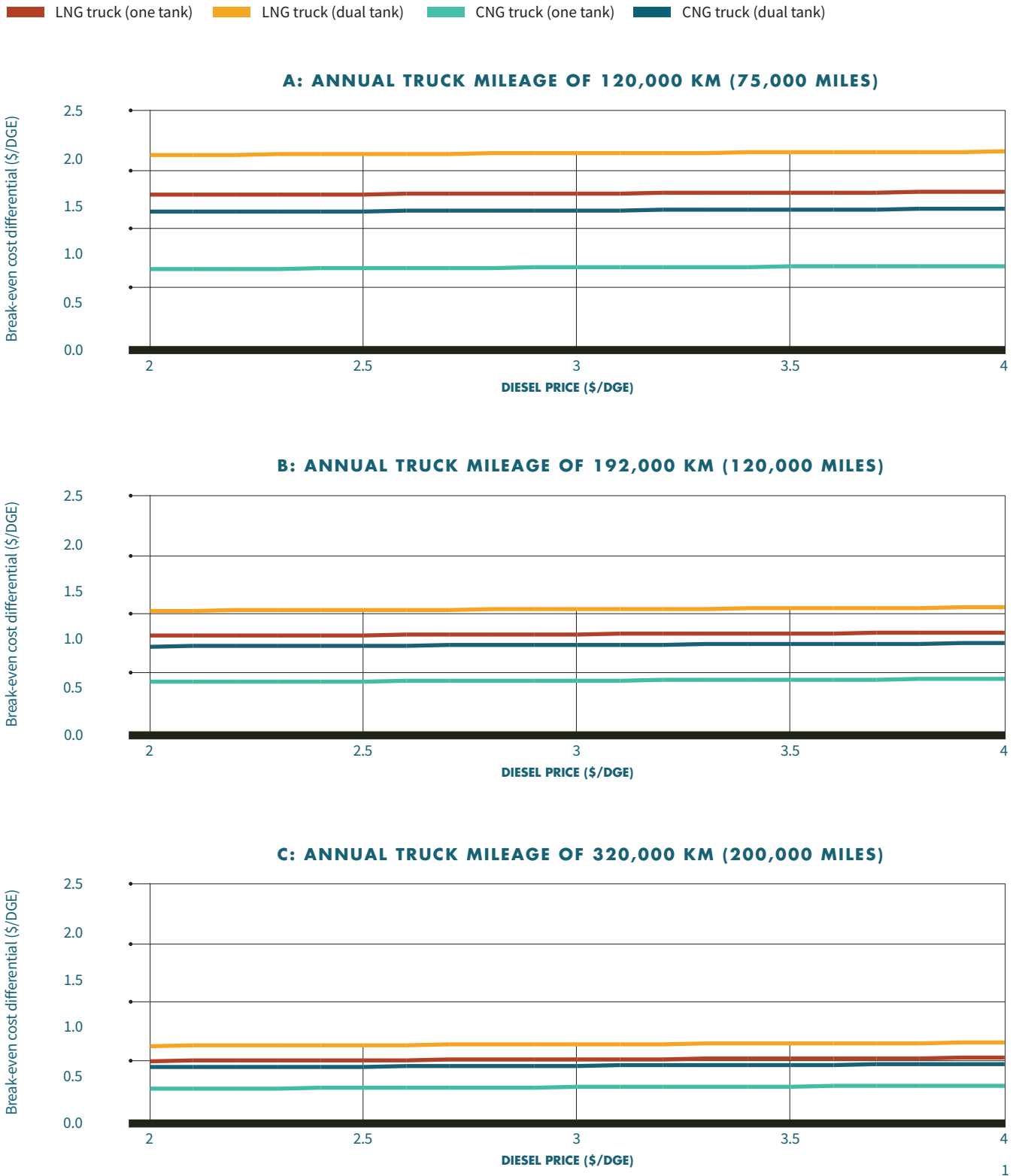
The previous results on the refueling infrastructure show that the assumed share of natural gas trucks in the long-haul truck fleet significantly affects the size, capacity, investment, and economics of the refueling infrastructure. The share of natural gas trucks reflects the decision-making of truck fleet owners. These owners have to decide whether they invest in and operate the natural gas trucks based on economic, environmental, infrastructure, and other considerations (U.S. National Petroleum Council (NPC) 2012). Fig. 7 shows the break-even fuel cost differentials between diesel fuel and natural gas fuels (defined as the diesel fuel price minus natural gas fuel price) so that the lifetime ownership costs of diesel and natural gas trucks are the same over four years (See Section VI in Appendix S1 for more details). These results suggest that the break-even fuel cost differentials are sensitive to annual truck mileage and premium in the cost of natural gas trucks over diesel trucks. At a baseline assumption of 193,000 km/year (120,000 miles/year), the break-even cost differential between diesel and LNG is \$1/DGE (single-tank LNG trucks) or \$1.3/DGE (dual-

tank LNG trucks). The break-even cost differentials between diesel and CNG are lower (\$0.5/DGE for a single-tank truck and \$0.9/DGE for a dual-tank truck) because CNG trucks are cheaper than LNG trucks for similar functions (Table 1). Higher or lower annual truck mileage decreases or increases the break-even fuel cost differential.

When the actual cost differentials between diesel and natural gas fuels are larger than the break-even differentials, natural gas trucks cost less than diesel trucks over the lifetime, making them more favorable to be used. However, historical data suggests large variations in the cost differentials between natural gas fuels and diesel over the past two decades due to high volatility in diesel price (Section III in Appendix S1). Using historical fuel prices, the cost savings between diesel and natural gas fuels range from -\$1.8/DGE to \$1.5/DGE for LNG and -\$1.6/DGE to \$1.8/DGE for CNG from 2000 to 2017. For the same period, truck fleet investors would only find natural gas trucks more economically attractive during times of high oil prices, such as in 2008 and 2011-2014.



FIGURE 7: BREAK-EVEN COST DIFFERENTIAL BETWEEN DIESEL AND NATURAL GAS FUELS (LNG OR CNG) AS A FUNCTION OF DIESEL FUEL PRICE FOR ANNUAL TRUCK MILEAGE OF: (A) 120,000 KM (75,000 MILES); (B) 192,000 KM (120,000 MILES); AND (C) 320,000 KM (200,000 MILES).



The cost differential is defined as the diesel fuel price minus the natural gas fuel price. The typical annual truck mileage is 192,000 miles (Tong et al. 2015a), but it can range from 120,000 km to 320,000 km (NRC 2010).



Conclusions and Policy Recommendations

This paper presents a refueling infrastructure model to determine the locations, capacities, and economic performance for a natural gas refueling infrastructure for long-haul trucks in the U.S.

The total refueling capacity needed is relatively constant when the share of natural gas trucks is 1-3% of the total long-haul truck fleet. For shares higher than 3%, the total refueling capacity is almost linear with respect to the share of natural gas trucks. For low shares of the truck fleet powered by LNG (1-10%), a national refueling infrastructure would require only 105-290 LNG refueling stations and a

capital investment of \$263-725 million. However, if the share of LNG trucks is lower than 15.2% (assuming the minimum truck range is 320 km or 200 miles), 12.4% (480 km or 300 miles), or 9.5% (960 km or 600 miles), building a national natural gas infrastructure may lead to financial losses under baseline economic assumptions (\$0.05/DGE profit margin, 7% discount rate, and 20 years). The results suggest that the CNG refueling infrastructure can achieve better economic returns than the LNG infrastructure with a higher assumed profit margin (\$0.1/DGE). Technology innovation or policy actions that reduce capital cost of a refueling station or increase profit margin improve the economic viability of the refueling infrastructure.

MODELING CHARACTERISTICS AND LIMITATIONS

The model assumes a perfect coordination between the refueling behavior of natural gas trucks (demand side) and the construction of the natural gas refueling infrastructure (supply side). In reality, such coordination is hard to achieve because both sides are independent decision makers, each of which faces unique objectives and constraints. We note, however, that the trucking industry and the refueling industry have strong interdependencies and they use market tools such as long-term contracts to lock in refueling demands and fuel supplies. Federal and state governments have also stepped in to help overcome market and non-market barriers and encourage the use of natural gas fuels (U.S. NPC 2012; Werpy et al. 2010; Whyatt 2010).

The model ignores the time dimension needed to build up either the natural gas truck fleets or the natural gas refueling infrastructure. This analysis assumes the infrastructure is built overnight in order to quantify the economic viability of the whole refueling infrastructure. In reality, the penetration of a new fuel takes a long time. For example, it took more than half a century for gasoline and diesel, which virtually dominate transportation fuel markets now, to overtake the market share of the previous fuel, kerosene (Fouquet 2010; Melaina 2007).

The model in this paper prioritizes building refueling stations at highway intersections. While this decision rule may forbid the model to find the optimal solution, it captures market behaviors. Indeed, market force has produced towns (e.g., Breezewood, PA) at highway intersections whose sole existence is to provide highway services including refueling stations, restaurants, convenience stores, repair shops, and hotels.

The model does not consider the existing natural gas infrastructure that refuels long-haul heavy-duty trucks and it ignores the refueling demands



of long-haul trucks outside the selected highway network. However, using U.S. Department of Energy's alternative fuel refueling station database (U.S. Department of Energy (DOE) 2018), we found that existing LNG refueling stations (74 in total) are located as part of the complete refueling network that we have identified. One notable characteristics of the existing LNG refueling stations is clustering in urban and industrial regions (29 LNG refueling stations in seven cities). Specifically, 11 and seven LNG refueling stations are already available in the greater Los Angeles area and Dallas-Fort Worth metro area. An interesting research direction is to investigate the dynamics between the highway refueling infrastructure studied in this paper and the local refueling infrastructure in urban areas and freight centers.

This paper only considers engineering cost estimates for building refueling stations. Other factors, such as land acquisition, supporting infrastructure, and refueling market competition may lead to different refueling infrastructure designs. Fuel price differences across regions, congestions at refueling stations, driving hour regulations, are also ignored in this work and should be the focus of future work.

CAPITAL INVESTMENT OF THE REFUELING INFRASTRUCTURE

The total capital investment needed to build a national natural gas refueling infrastructure (\$270-435 million for 1% share of natural gas trucks) is in the same order-of-magnitude as the recurring investment needed (\$150 million per year, estimated based on Melaina et al. 2013 values) to maintain the existing gasoline and diesel refueling infrastructure. This is because the studied refueling infrastructure for long-haul trucks represents only a small fraction of the overall existing refueling infrastructure. However, for any share of natural gas trucks ($\geq 5\%$), the total incremental investment on natural gas trucks compared to diesel trucks is an order-of-magnitude larger than the total overnight investment needed to build the natural gas refueling infrastructure. While CNG refueling stations require slightly higher investment than LNG refueling stations, the investment on CNG trucks is much lower than LNG trucks. (See Section VII in Appendix S1 for more details.)

ECONOMIC VIABILITY OF THE NATURAL GAS REFUELING INFRASTRUCTURE

This paper shows that the share of natural gas trucks has to be greater than a threshold (9.5%-15.2% for LNG trucks and 5.3-8.6% for CNG trucks) for a national natural gas infrastructure to achieve positive profits under baseline economic assumptions. However, the attractiveness of natural gas trucks over diesel trucks requires a minimum fuel cost saving of \$1.3/DGE (LNG trucks) and \$0.5/DGE (for CNG trucks). These conditions have not been seen since 2015, when the diesel price dropped significantly (U.S. EIA 2016b). As a result, the share of natural gas vehicles is still below 3% of the heavy-duty trucks and buses fleet (CARB 2015), and the previous plans for building natural gas refueling stations have not materialized (U.S. Department of Energy (DOE) 2018).

However, opportunities for natural gas fuels may still exist in regional markets. Indeed, this paper shows that far fewer refueling stations are needed to ensure highway coverage in California and Texas. Furthermore, regional factors that are not taken into account in this paper – such as higher price savings from natural gas fuels (Jaffe et al. 2015; U.S. Department of Energy (DOE) 2017), attractive state incentives, and/or strong environmental regulations (U.S. Department of Energy (DOE) 2016) – would support a swifter adoption of natural gas fuels in California and Texas. Finally, technology innovation and policy interventions that reduce capital costs of refueling stations or increase fuel profit margin would improve the economic viability of the refueling infrastructure, especially for low shares of natural gas trucks in the long-haul truck fleet.

THE COMPETITIVE STRENGTH OF LNG AND CNG IN THE LONG-HAUL TRUCKING MARKET

The competition between CNG and LNG refueling stations has been a tug of war for the past decade. While LNG fuel has better physical properties suited for long-haul trucks, such as higher fuel density (thus more range per refuel) and higher refueling rate, long-haul CNG trucks are much cheaper than their LNG counterparts, and can share the refueling infrastructure with local-haul CNG trucks in urban areas and freight centers. In contrast, the results in this paper suggest that the overall economic performance of LNG and CNG refueling stations is similar but the LNG refueling infrastructure requires 50% less capital investment except for low shares of natural gas trucks ($< 10\%$). It is possible that while the industry has expressed an interest in using both fuels for long-haul trucks, there has not been a significant growth in trucks or refueling infrastructure. As a result, the future of long-haul trucking market remains uncertain.

Sources

SUPPLEMENTAL DATA

Appendix S1 is available online in the ASCE Library: www.ascelibrary.org

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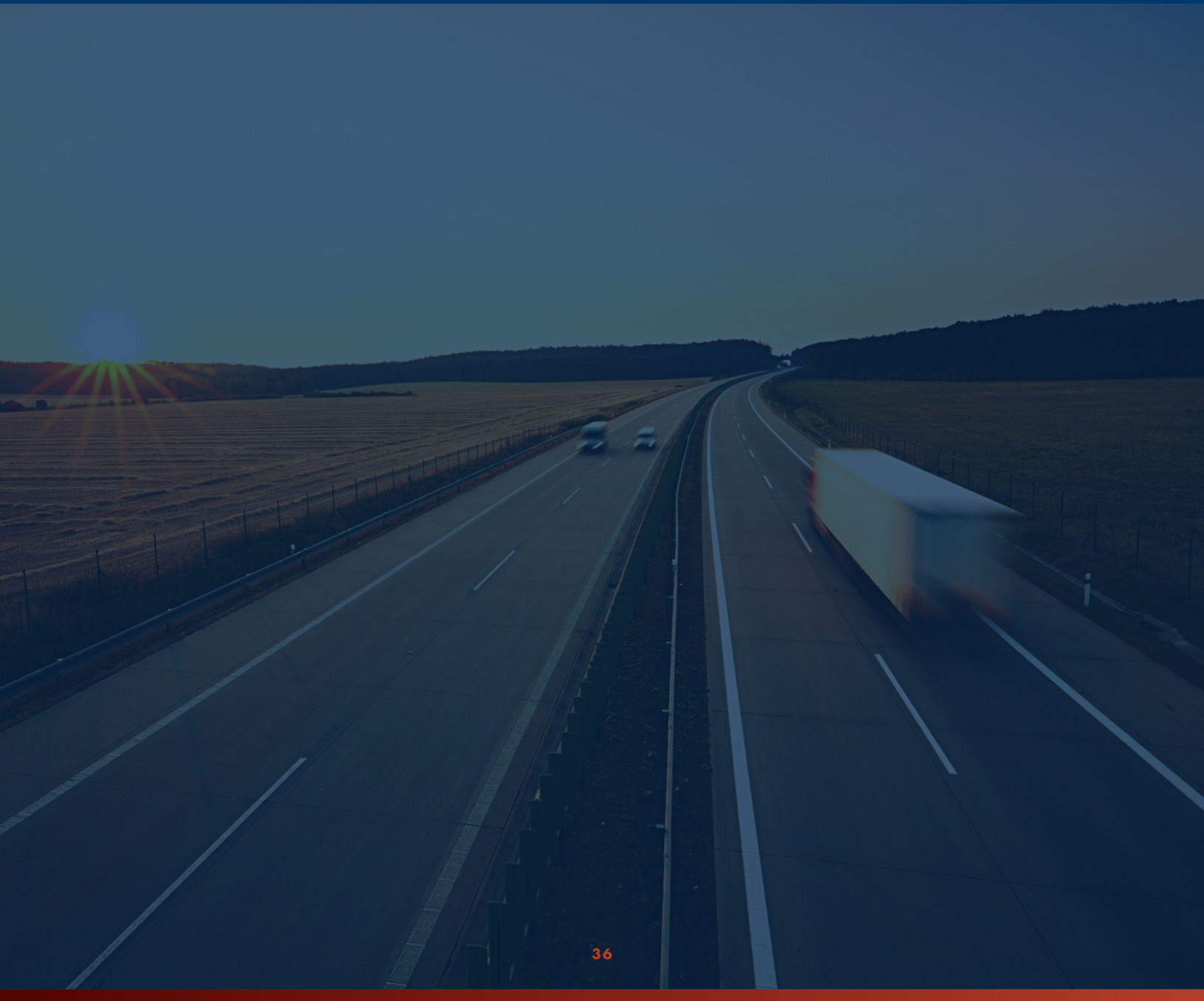
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Appendix S1

PAGES 37-82

Appendix for Figure 2 (shown on page 11): Selected highway networks, indexed corridors, and long-haul heavy-duty truck flows in 2012. Appendix S1 is also available online in the ASCE Library: www.ascelibrary.org



Supporting Information for

***Engineering Economic Analysis of a Natural Gas
Refueling Infrastructure for Long-haul Trucks***

Fan Tong^{1,2 *} ; Ines Azevedo²; and Paulina Jaramillo²

¹ Department of Global Ecology, Carnegie Institution for Science, 260 Panama St, Stanford, CA 94305

² Department of Engineering and Public Policy, Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh, PA 15213

* Corresponding author. Email: ftong@carnegiescience.edu

This document includes 45 pages, 6 figures, and 24 tables.

Table of Contents

I. Highway selection	3
II. Refueling demands across regions	12
III. Comparison of LNG, CNG, and diesel fuel prices	15
IV. Summary of LNG and CNG refueling station assumptions in literature	17
V. Economic analysis of a one-refueling-station system	19
VI. Economic analysis of a one-truck fleet.....	24
VII. Capital investment on natural gas trucks and refueling stations	25
VIII. Additional numerical results for the LNG refueling infrastructure.....	27
IX. Additional numerical results for the CNG refueling infrastructure	35
X. Reference	45

I. Highway selection

The FAF4 dataset was created by attributing regional origin-destination freight flows, which were estimated based on data sources such as U.S. Commodity Flow Survey, U.S. census, and out-of-scope data sources, to highway networks (U.S. Federal Highway Administration (FHWA); 2017). The full dataset has 670,428 data records for a U.S. road network of 446,144 miles (**Fig. S1**).

We determined our highway network based on the following criteria: (1) we choose interstate and state highways that have high weighted-average truck flows; (2) we make sure the selected highways form a connected network that covers all 48 states in the Contiguous U.S. and connects major urban areas and industrial centers; (3) we include the ring highways around major cities if such highways have large truck flows. For instance, Atlanta, Dallas, and San Antonio all have high-volume ring highways surrounding them, so these ring highways are considered in our network. The inclusion of such highways slightly increase the number of highway intersections and the number of refueling stations but they ensure the selected highway networks retain practical relevance. In **Fig. S1**, we present the selected highway network against the full FAF4 network. While the selected highway network looks much simpler, it still has 61,342 records covering 30,042 miles. The other statistics of the selected highway network is summarized in **Table 2** in the main text.

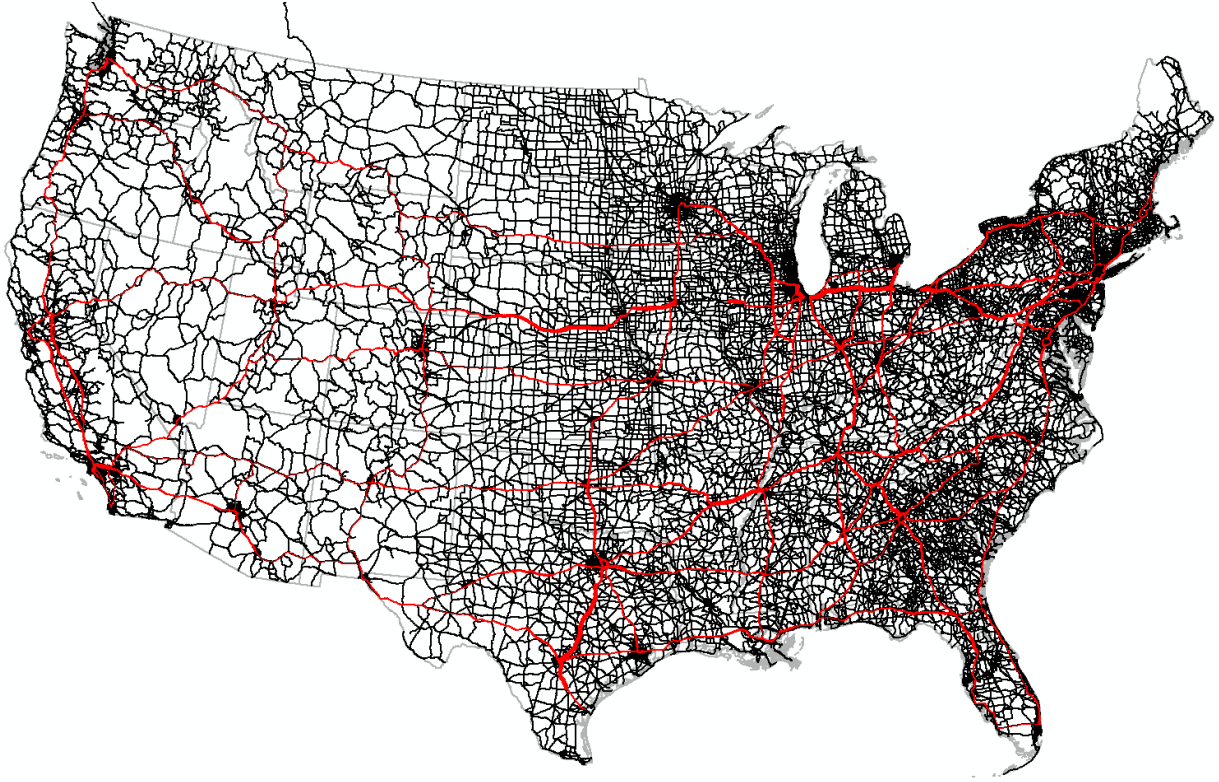


Fig. S1. The selected highway network in this paper and the road network in the full FAF4 dataset.

Table S1 and **Table S2** below summarize key geographic information about the highway intersections and corridors identified in the studied highway network. **Table S2** also includes the connection information between highway intersections and corridors. In total, 100 highway intersections and 165 highway corridors are identified.

Table S1. Intersection database for the studied highway network.

Intersection index	Nearby city or township	State	County	Region
1	Seattle	WA	King	West
2	Portland	OR	Multnomah	West
3	Bay area	CA	Alameda	West
4	Sacramento	CA	Sacramento	West
5	i5-i580	CA	San Joaquin	West
6	Kern (i5-S99)	CA	Kern	West
7	LA, NE	CA	Los Angeles	West

8	San Diego	CA	San Diego	West
9	Butte (i15-i90)	MT	Silver Bow	West
10	Pocatello (i15-i84)	ID	Bannock	West
11	Salt Lake City	UT	Salt Lake	West
12	(i15-i70)	UT	Millard	West
13	San Bernardino	CA	San Bernardino	West
14	Flagstaff	AZ	Coconino	West
15	Phoenix	AZ	Maricopa	West
16	Buffalo (i25-i90)	WY	Johnson	West
17	Cheyenne	WY	Laramie	West
18	Denver	CO	Denver	West
19	Albuquerque	NM	Bernalillo	West
20	Las Cruces (i25-i10)	NM	Doña Ana	West
21	(i10-i20)	TX	Reeves	West
22	Minneapolis	MN	Ramsey	Midwest
23	Albert Lea (i35-i90)	MN	Freeborn	Midwest
24	Des Moines (i35-i80)	IA	Polk	Midwest
25	Kansas City	MO	Jackson	Midwest
26	Oklahoma City	OK	Oklahoma	South
27	Dallas, NW	TX	Dallas	South
28	San Antonio, west (i10-i35)	TX	Bexar	South
29	Houston	TX	Harris	South
30	Corpus Christi	TX	Nueces	South
31	Little Rock	AR	Pulaski	South
32	Tomah (i94-i90)	WI	Monroe	Midwest
33	Portage (i39-i90)	IL	Winnebago	Midwest
34	Peru & LaSalle (i39-i80)	IL	LaSalle	Midwest
35	Bloomington (i39-i55-i74)	IL	McLean	Midwest
36	St. Louis	MO	St. Louis City	Midwest
37	Sikeston (i55-i57)	MO	Scott	Midwest
38	Memphis	TN	Crittenden	South
39	Jackson	MS	Hinds	South
40	Hammond (i10-i55)	MS	St. John the Baptist	South
41	Chicago (i55-i294/i90)	IL	Cook	Midwest
42	Chicago (i57-i80/i90)	IL	Cook	Midwest
43	Champaign	IL	Champaign	Midwest
44	Effingham	IL	Effingham	Midwest
45	Chicago (i65-i94/i80/i90)	IL	Lake	Midwest
46	Indianapolis	IN	Marion	Midwest
47	Louisville	KT	Jefferson	South
48	Nashville	TN	Davidson	South
49	Birmingham	AL	Jefferson	South

50	Montgomery	AL	Montgomery	South
51	Mobile (i65-i10)	AL	Mobile	South
52	Marshall (i69-i94)	MI	Calhoun	Midwest
53	Detroit	MI	Wayne	Midwest
54	Toledo	OH	Wood	Midwest
55	Cincinnati	OH	Hamilton	Midwest
56	Knoxville	TN	Knox	South
57	Chattanooga	TN	Hamilton	South
58	Atlanta, NW	GA	Cobb	South
59	Atlanta, West	GA	Fulton	South
60	Atlanta, SW	GA	Fulton	South
61	Atlanta, South	GA	Clayton	South
62	Atlanta, East	GA	DeKalb	South
63	Atlanta, NE	GA	DeKalb	South
64	Lake City (i75-i10)	FL	Columbia	South
65	Tampa	FL	Hillsborough	South
66	Cleveland, West	OH	Lorain	Midwest
67	Youngstown (i76-i80)	OH	Mahoning	Midwest
68	Columbus	OH	Franklin	Midwest
69	Pittsburgh	PA	Westmoreland	Northeast
70	Greensboro	NC	Iredell	South
71	Syracuse	NY	Onondaga	Northeast
72	(i81-i80)	PA	Luzerne	Northeast
73	Breezewood (i76-i70)	PA	Bedford	Northeast
74	Harrisburg	PA	Cumberland	Northeast
75	Albany	NY	Albany	Northeast
76	Suffern (i87-i287)	NY	Rockland	Northeast
77	Parsippany - Troy Hills (i80-i287/i87)	NJ	Morris	Northeast
78	(i87/i287-i78)	NJ	Somerset	Northeast
79	Portland	ME	Cumberland	Northeast
80	Worcester	MA	Worcester	Northeast
81	Port Chester (i287-i95)	NY	Westchester	Northeast
82	Edison (i78/i287-i95)	NJ	Middlesex	Northeast
83	Philadelphia	NJ	Camden	Northeast
84	Baltimore	MD	Baltimore	Northeast
85	Wilson (i95-i40)	NC	Johnson	South
86	Florence (I95-I20)	SC	Florence	South
87	Jacksonville	FL	Duval	South
88	Miami	FL	Broward	South
89	San Antonio, East (i10-i35)	TX	Bexar	South
90	Dallas, SW	TX	Bexar	South
91	Dallas, South	TX	Bexar	South

92	Dallas, SE	TX	Bexar	South
93	Dallas, NE	TX	Bexar	South
94	Farragut (i40-i75)	TN	Loudon	South
95	i40-i81	TN	Jefferson	South
96	i495-i95, West	MA	Middlesex	Northeast
97	Cleveland, South	OH	Summit	Midwest
98	Cleveland, NE	OH	Lake	Midwest
99	LA, downtown	CA	Orange	West
100	Irvine	CA	Los Angeles	West

Table S2. Corridor database for the studied highway network.

Corridor number	Highway sign	Nearby city or township		Intersection index	
		Start point	End	Start point	End point
1	i5	Seattle	Portland	1	2
2	i5	Portland	Sacramento	2	4
3	i5	Sacramento	i5-i580	4	5
4	i5	i5-i580	Kern (i5-S99)	5	6
5	i5	Kern (i5-S99)	LA, NE	6	7
6	i5	Irvine	San Diego	100	8
7	S99	Sacramento	Kern (i5-S99)	4	6
8	i880	Bay area	Sacramento	3	4
9	i80	Bay area	i5-i580	3	5
10	i15	Butte (i15-i90)	Pocatello (i15-i84)	9	10
11	i15	Pocatello (i15-i84)	Salt Lake City	10	11
12	i15	Salt Lake City	(i15-i70)	11	12
13	i15	(i15-i70)	San Bernardino	12	13
14	i15	San Bernardino	San Diego	13	8
15	i17	Flagstaff	Phoenix	14	15
16	i25	Buffalo (i25-i90)	Cheyenne	16	17
17	i25	Cheyenne	Denver	17	18
18	i25	Denver	Albuquerque	18	19
19	i25	Albuquerque	Las Cruces (i25-i10)	19	20
20	i35	Minneapolis	Albert Lea (i35-i90)	22	23
21	i35	Albert Lea (i35-i90)	Des Moines (i35-i80)	23	24
22	i35	Des Moines (i35-i80)	Kansas City	24	25
23	i35	Kansas City	Oklahoma City	25	26
24	i35	Oklahoma City	Dallas, NW	26	27
25	i35	Dallas, SW	San Antonio, East (i10-i35)	90	89
26	i37	San Antonio, west (i10-i35)	Corpus Christi	28	30
27	i90	Seattle	Butte (i15-i90)	1	9

28	i90	Butte (i15-i90)	Buffalo (i25-i90)	9	16
29	i90	Buffalo (i25-i90)	Albert Lea (i35-i90)	16	23
30	i84	Portland	Pocatello (i15-i84)	2	10
31	i80	Sacramento	Salt Lake City	4	11
32	i80	Salt Lake City	Cheyenne	11	17
33	i80	Cheyenne	Des Moines (i35-i80)	17	24
34	i70	(i15-i70)	Denver	12	18
35	i70	Denver	Kansas City	18	25
36	i40	San Bernardino	Flagstaff	13	14
37	i40	Flagstaff	Albuquerque	14	19
38	i40	Albuquerque	Oklahoma City	19	26
39	i40	Oklahoma City	Little Rock	26	31
40	i30	Dallas, NE	Little Rock	93	31
41	i20	(i10-i20)	Dallas, SW	21	90
42	i10	LA, NE	Phoenix	7	15
43	i10	Phoenix	Las Cruces (i25-i10)	15	20
44	i10	Las Cruces (i25-i10)	(i10-i20)	20	21
45	i10	(i10-i20)	San Antonio, west (i10-i35)	21	28
46	i10	San Antonio, East (i10-i35)	Houston	89	29
47	i45	Dallas, South	Houston	91	29
48	i94	Minneapolis	Tomah (i94-i90)	22	32
49	i90	Albert Lea (i35-i90)	Tomah (i94-i90)	23	32
50	i80	Des Moines (i35-i80)	Peru & LaSalle (i39-i80)	24	34
51	i70	Kansas City	St. Louis	25	36
52	i44	Oklahoma City	St. Louis	26	36
53	i40	Little Rock	Memphis	31	38
54	i20	Dallas, SE	Jackson	92	39
55	i10	Houston	Hammond (i10-i55)	29	40
56	i39	Portage (i39-i90)	Peru & LaSalle (i39-i80)	33	34
57	i39	Peru & LaSalle (i39-i80)	Bloomington (i39-i55-i74)	34	35
58	i55	Chicago (i55-i294/i90)	Bloomington (i39-i55-i74)	41	35
59	i55	Bloomington (i39-i55-i74)	St. Louis	35	36
60	i55	St. Louis	Sikeston (i55-i57)	36	37
61	i55	Sikeston (i55-i57)	Memphis	37	38
62	i55	Memphis	Jackson	38	39
63	i55	Jackson	Hammond (i10-i55)	39	40
64	i57	Chicago (i57-i80/i90)	Champaign	42	43
65	i57	Champaign	Effingham	43	44
66	i57	Effingham	Sikeston (i55-i57)	44	37
67	i65	Chicago (i65-i94/i80/i90)	Indianapolis	45	46
68	i65	Indianapolis	Louisville	46	47
69	i65	Louisville	Nashville	47	48

70	i65	Nashville	Birmingham	48	49
71	i65	Birmingham	Montgomery	49	50
72	i65	Montgomery	Mobile (i65-i10)	50	51
73	i69	Marshall (i69-i94)	Indianapolis	52	46
74	i75	Detroit	Toledo	53	54
75	i75	Toledo	Cincinnati	54	55
76	i75	Cincinnati	Knoxville	55	56
77	i75	Farragut (i40-i75)	Chattanooga	94	57
78	i75	Chattanooga	Atlanta, NW	57	58
79	i75	Atlanta, South	Lake City (i75-i10)	61	64
80	i75	Lake City (i75-i10)	Tampa	64	65
81	i75	Tampa	Miami	65	88
82	i24	Nashville	Chattanooga	48	57
83	i59	Chattanooga	Birmingham	57	49
84	i85	Atlanta, SW	Montgomery	60	50
85	i85	Greensboro	Atlanta, NE	70	63
86	i71	Cincinnati	Louisville	55	47
87	i71	Columbus	Cincinnati	68	55
88	i71	Cleveland, South	Columbus	97	68
89	i76	Youngstown (i76-i80)	Pittsburgh	67	69
90	i81	Syracuse	(i81-i80)	71	72
91	i81	(i81-i80)	Harrisburg	72	74
92	i81	Harrisburg	i40-i81	74	95
93	i78	Harrisburg	(i87/i287-i78)	74	78
94	i87	Albany	Suffern (i87-i287)	75	76
95	i95	Portland	i495-i95, West	79	96
96	i95	Worcester	Port Chester (i287-i95)	80	81
97	i95	Port Chester (i287-i95)	Edison (i78/i287-i95)	81	82
98	i95	Edison (i78/i287-i95)	Philadelphia	82	83
99	i95	Philadelphia	Baltimore	83	84
100	i95	Baltimore	Wilson (i95-i40)	84	85
101	i95	Wilson (i95-i40)	Florence (I95-I20)	85	86
102	i95	Florence (I95-I20)	Jacksonville	86	87
103	i95	Jacksonville	Miami	87	88
104	i90	Tomah (i94-i90)	Portage (i39-i90)	32	33
105	i90	Portage (i39-i90)	Chicago (i55-i294/i90)	33	41
106	i90	Chicago (i55-i294/i90)	Chicago (i57-i80/i90)	41	42
107	i90	Chicago (i57-i80/i90)	Chicago (i65-i94/i80/i90)	42	45
108	i94	Chicago (i65-i94/i80/i90)	Marshall (i69-i94)	45	52
109	i94	Marshall (i69-i94)	Detroit	52	53
110	i80	Peru & LaSalle (i39-i80)	Chicago (i57-i80/i90)	34	42
111	i80	Chicago (i65-i94/i80/i90)	Toledo	45	54

112	i80	Toledo	Cleveland, West	54	66
113	i90	Cleveland, NE	Syracuse	98	71
114	i90	Syracuse	Albany	71	75
115	i90	Albany	Worcester	75	80
116	i80	Cleveland, South	Youngstown (i76-i80)	97	67
117	i80	Youngstown (i76-i80)	(i81-i80)	67	72
118	i80	(i81-i80)	Parsippany - Troy Hills (i80-i287/i87)	72	77
119	i287	Suffern (i87-i287)	Parsippany - Troy Hills (i80-i287/i87)	76	77
120	i287	Suffern (i87-i287)	Port Chester (i287-i95)	76	81
121	i74	Bloomington (i39-i55-i74)	Champaign	35	43
122	i74	Champaign	Indianapolis	43	46
123	i70	Indianapolis	Columbus	46	68
124	i70	Columbus	Pittsburgh	68	69
125	i70	Pittsburgh	Breezewood (i76-i70)	69	73
126	i70	Breezewood (i76-i70)	Harrisburg	73	74
127	i76	Harrisburg	Philadelphia	74	83
128	i70	Breezewood (i76-i70)	Baltimore	73	84
129	i287	Parsippany - Troy Hills (i80-i287/i87)	(i87/i287-i78)	77	78
130	i287	(i87/i287-i78)	Edison (i78/i287-i95)	78	82
131	i70	St. Louis	Effingham	36	44
132	i70	Effingham	Indianapolis	44	46
133	i40	Memphis	Nashville	38	48
134	i40	Nashville	Farragut (i40-i75)	48	94
135	i40	i40-i81	Greensboro	95	70
136	i40	Greensboro	Wilson (i95-i40)	70	85
137	i20	Jackson	Birmingham	39	49
138	i20	Birmingham	Atlanta, West	49	59
139	i20	Atlanta, East	Florence (I95-I20)	62	86
140	i10	Hammond (i10-i55)	Mobile (i65-i10)	40	51
141	i10	Mobile (i65-i10)	Lake City (i75-i10)	51	64
142	i10	Lake City (i75-i10)	Jacksonville	64	87
143	i285	Atlanta, NW	Atlanta, West	58	59
144	i285	Atlanta, West	Atlanta, SW	59	60
145	i285	Atlanta, SW	Atlanta, South	60	61
146	i285	Atlanta, South	Atlanta, East	61	62
147	i285	Atlanta, NE	Atlanta, East	63	62
148	i285	Atlanta, NW	Atlanta, NE	58	63
149	i35	San Antonio, west (i10-i35)	San Antonio, East (i10-i35)	28	89
150	i35	Dallas, NW	Dallas, SW	27	90
151	i10	Dallas, SW	Dallas, South	90	91
152	i10	Dallas, South	Dallas, SE	91	92

153	i635	Dallas, NE	Dallas, SE	93	92
154	i635	Dallas, NW	Dallas, NE	27	93
155	i710	LA, downtown	LA, NE	99	7
156	i40	Farragut (i40-i75)	Knoxville	94	56
157	i40	Knoxville	i40-i81	56	95
158	i495	i495-i95, West	The other end of the outer-Boston ring road	96	101
159	i95	i495-i95, West	Worcester	96	80
160	i495	Baltimore	The other end of the DC ring road	84	102
161	i80	Cleveland, West	Cleveland, South	66	97
162	i90	Cleveland, West	Cleveland, NE	66	98
163	i271	Cleveland, NE	Cleveland, South	98	97
164	i5	LA, NE	Irvine	7	100
165	i405	LA, downtown	Irvine	99	100

II. Refueling demands across regions

Fig. S2 shows the distributions of refueling demands faced by LNG refueling stations at four representative shares of natural gas trucks in the long-haul truck fleet (1%, 5%, 10%, and 100%). In **Fig. S4**, we reproduced the fuel sale distribution at existing diesel refueling stations reported by an industry survey (TIAX LLC 2012a). We note that the refueling demands the existing diesel refueling stations exhibit larger variability than our results. This is due to our simplified assumption that all refueling stations have the same size, and, to a lesser extent, that our studied network is a high-volume subset of the actual road network that is supported by diesel refueling stations. As the lion share of diesel consumptions are refueled at a small share of diesel refueling stations (**Fig. S4**) (similar uneven distributions on fuel sales at gasoline station were observed in (Melaina and Bremson 2006)), our model does not lose much by focusing on the refueling demands of long-haul trucks.

Fig. S3 shows the distributions of capacity factors of LNG refueling stations at different shares of natural gas trucks. Because we cap the capacity factor to 40% in the model, all refueling stations have capacity factors below 40% as expected. What is more interesting, though, is that with the increase in the share of natural gas trucks in the long-haul truck fleet, the distributions of capacity factors increase as well. When the share of natural gas trucks is 15%, most refueling stations already operate at a capacity factor higher than 20%, exceeding the break-even capacity factor calculated for the one-refueling-station case (see the Section V below).

We find that most high-demand refueling stations are located at highway intersections. For instance, assuming a vehicle range of 300 miles, the 10 largest demands sites are at intersections, including #24 (Des Moines, IA), #54 (Toledo, OH), #26 (Oklahoma City, OK), #45 (Chicago, IL), #46 (Indianapolis, IN), #34 (Peru and LaSalle, IL), #38 (Memphis, TN), #48 (Nashville, TN), and #90 (Dallas, TX). Because we modeled ring highways and assumed multiple intersections near several metropolitan areas, only two such intersections are among the 10 largest refueling demands. But when all nearby intersections are combined together, these metropolitan areas (such as Dallas, Chicago, San Antonio, and Atlanta) have very large truck flows.

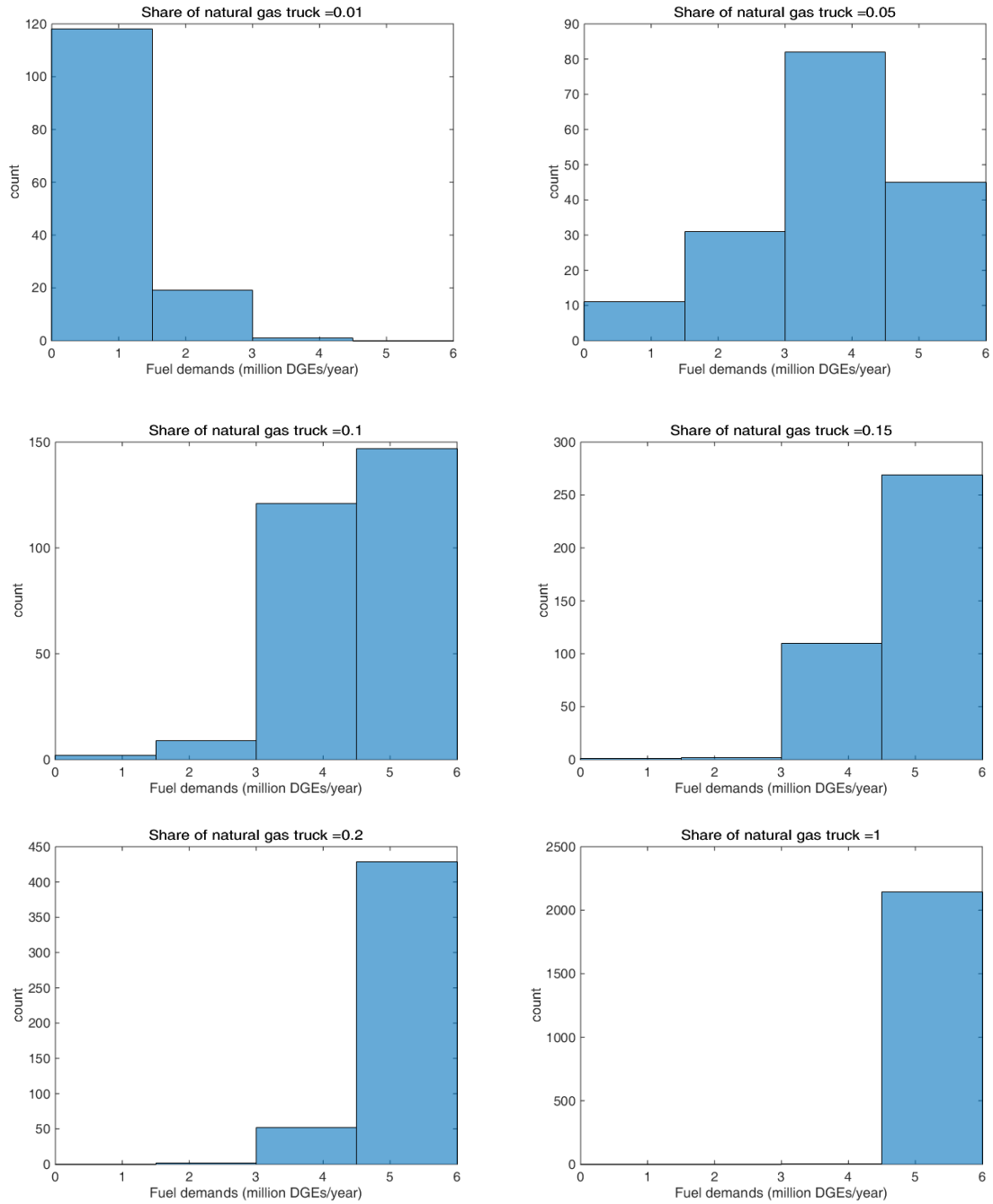


Fig. S2. Distributions of refueling demands faced by LNG refueling stations when the share of LNG trucks in the long-haul truck fleet is 1% (top left), 5% (top right), 10% (middle left), 15% (middle right), 20% (bottom left), and 100% (bottom right).

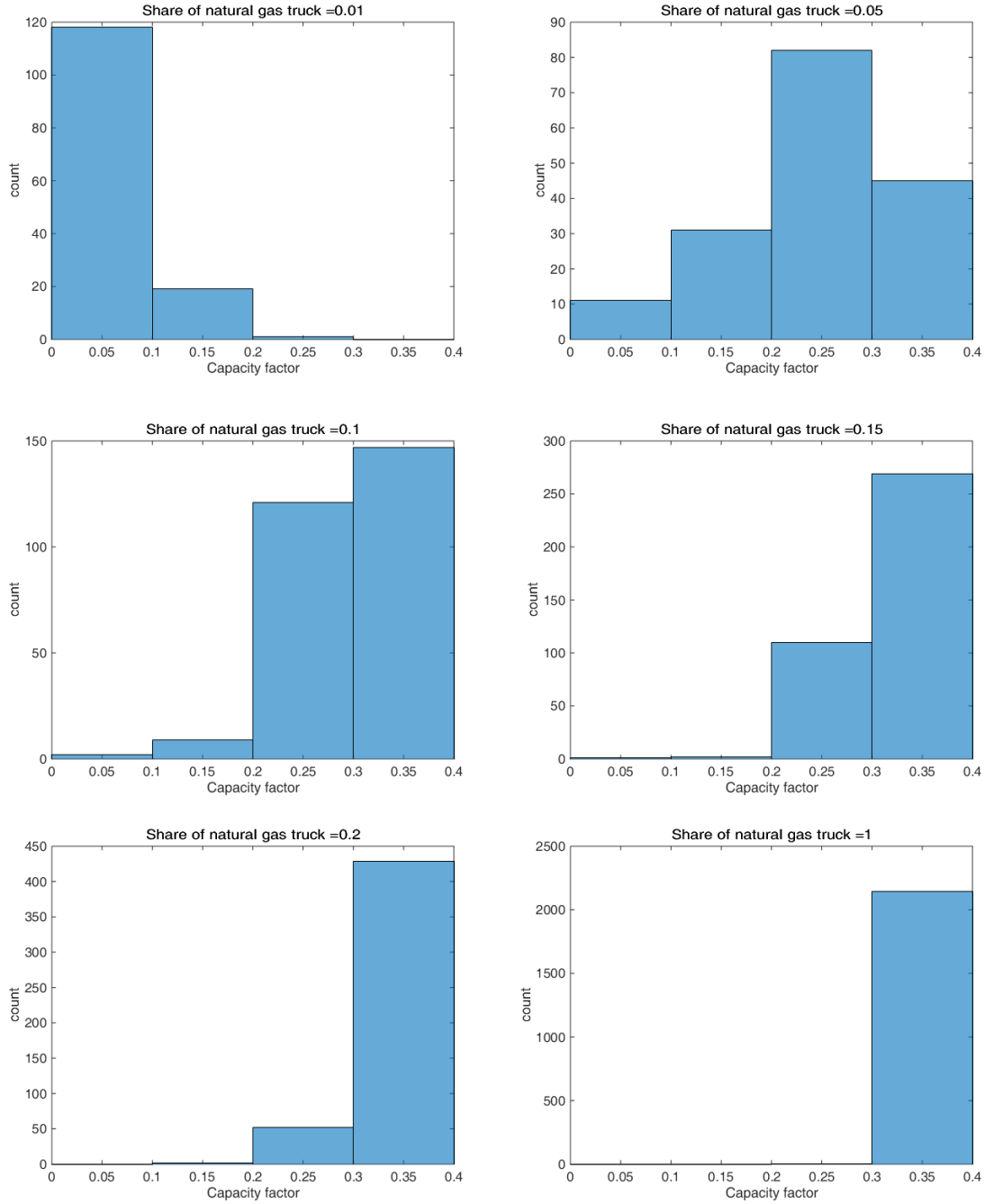


Fig. S3. Distributions of capacity factors of LNG refueling stations when the share of LNG trucks in the long-haul truck fleet is 1% (top left), 5% (top right), 10% (middle left), 15% (middle right), 20% (bottom left), and 100% (bottom right).

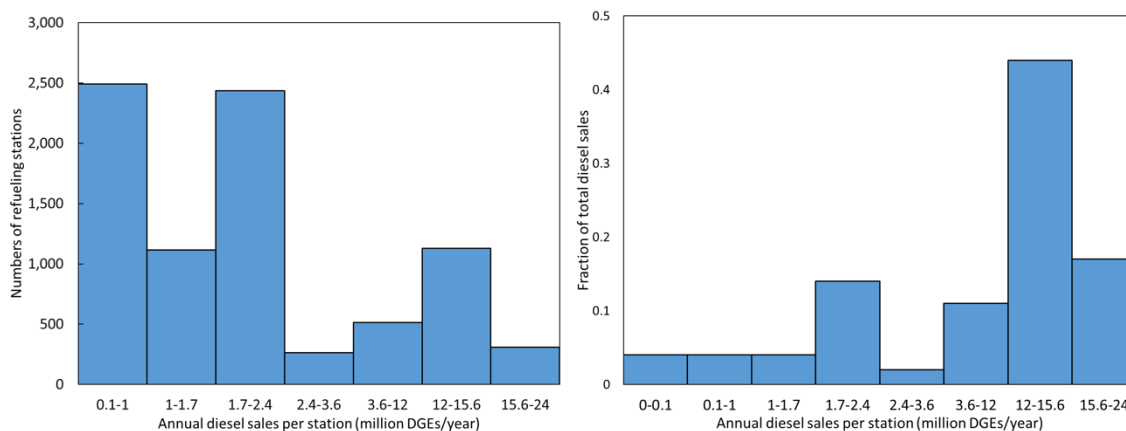


Fig. S4. Distributions of diesel refueling stations and diesel sales from an industrial survey.

The figures are drawn based on data from (TIAX LLC 2012a). Only existing diesel refueling stations with annual sales larger than 0.1 million DGEs are included. The diesel refueling stations surveyed are not always along highways.

III. Comparison of LNG, CNG, and diesel fuel prices

Fig. S5 compares the historical price trends of LNG, CNG, and diesel fuels. The diesel price was taken directly from (U.S. Energy Information Administration (EIA) 2017). LNG and CNG fuel prices are reconstructed as a total of the cost components discussed in **Table S3** because U.S. Energy Information Administration (EIA) does not have records until recently. The “land use and other fixed cost” was calibrated by comparing our estimations with the average LNG and CNG fuel prices in 2017 reported by (U.S. Department of Energy (DOE) 2017). Here we do not consider government subsidies such as tax credits. Furthermore, and we are unable to estimate regional fuel prices due to data limitations.

Fig. S5 shows that the cost differential between diesel and LNG and the cost differential between diesel and CNG have large variabilities over the last decade. The cost savings can be as large as \$1.5/DGE and as low as -\$1.8/DGE for LNG. CNG fuel saw similar range of cost savings, from -\$1.6/DGE to \$1.8/DGE. While CNG and LNG prices were pretty stable for the past two decades, there was significant volatility in diesel price. CNG is cheaper than LNG because it is easier and less energy intensive to produce CNG than LNG (U.S. Department of Energy (DOE) 2017; U.S. National Petroleum Council (NPC) 2012).

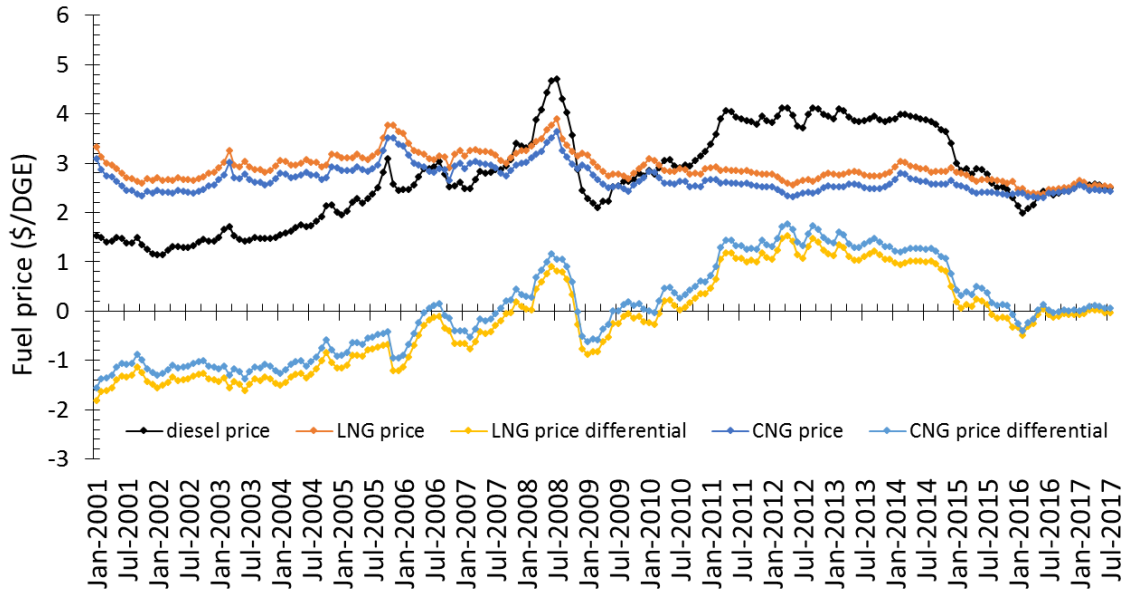


Fig. S5. U.S. average diesel price, LNG price, CNG price, LNG price differential, and CNG price differential in 2001-2017. The price differential between diesel and LNG (or CNG) is defined as diesel fuel price minus LNG (CNG) fuel price.

Table S3. Assumptions and references for cost components used to reconstruct LNG and CNG retail prices for transportation markets.

Cost component	LNG	CNG	Reference
Energy/Feedstock cost	Natural gas industrial price from U.S. EIA		(U.S. NPC 2012)
Utilization access fee	\$0.04/GGE*	\$0.1/GGE	
Liquefaction	\$0.50/GGE	Do not apply	
LNG delivery	\$0.16/GGE		
Refueling station variable cost (operation & maintenance)	\$0.28/GGE	\$0.36/GGE	
Profit margin (to pay for refueling station equipment)	\$0.05/DGE	\$0.1/DGE	This study's assumptions
Land use, and other fixed cost	\$0.60/DGE	\$1.1/DGE	This study's calculation
Federal tax	\$0.413/DGE before 2016, \$0.243/DGE since 2016	\$0.183/CGE	U.S. EIA

Note: * 1 gasoline gallon equivalent (GGE) equals 114,300 Btu and 1 diesel gallon equivalent (DGE) equals 128,700 BTU (https://www.eia.gov/energyexplained/index.cfm?page=about_btu).

IV. Summary of LNG and CNG refueling station assumptions in literature

We performed a literature review of LNG and CNG refueling station assumptions. The findings are presented in **Table S4** and **Table S5**. We find that there are large variations in capital cost and capacity assumptions of LNG and CNG refueling stations. These refueling station assumptions are influenced by a number of design goals (e.g. station size and redundancy) and design variables (e.g. refueling rate and on-site storage size). Furthermore, there are ambiguities in the scope of these variables. The capital cost usually include equipment cost but may or may not include construction cost (or labor cost), land cost, etc. The capacity can either be nameplate capacity (i.e. maximum capacity based on refueling rate) or actual capacity (where a maximum capacity factor is assumed). What is worse, the existing studies usually do not report these important details, which make it hard to compare across studies.

As a result, we based our assumptions on the most recent and most detailed studies – for LNG refueling stations, we assume a \$2.5 million equipment cost for an actual capacity of 6 million DGEs/year (where the nameplate capacity is 15 million DGEs/year calculated based on the refueling rate), based on (Myers et al. 2012). For CNG refueling stations, we assume a \$3.35 million equipment cost for an actual capacity of 4.2 million DGEs/year (where the nameplate capacity is 10.5 million DGEs/year calculated based on the refueling rate), based on (Gladstein Neandross & Associates (GNA) 2012). We performed theoretical and empirical sensitivity analysis on these variables in Section V and Section VIII in this Appendix.

Table S4. A summary of LNG refueling station assumptions from recent literature.

Reference	(TIAX LLC 2012b)				(Myers et al. 2012)		(NPC (2012))
Description	Base station	with additional storage	Clean Energy		Base station	PA Turnpike Commission White Paper	Base station
Nameplate capacity (million DGEs/year)	3.2	6.4	4*	20*	15**	N/A ***	4.9
Actual capacity (million DGEs/year)	2.1	5.3			N/A	N/A	3.9
Capital cost (\$million)	0.77	1.34	2.25	7.5	1.8-3.95****	2-2.5	1.75
Equipment cost	included						
Installation cost	N/A	N/A	N/A	N/A	Included	N/A	likely included
Utilization factor	67%	83%	N/A	N/A	N/A	N/A	80%
Technical detail	Aggregate numbers		Aggregate numbers		Aggregate numbers with schematic layout	Aggregate numbers	Aggregate numbers

* The authors cannot confirm whether these capacities are nameplate capacity or actual capacity. ** Naive calculation based on the average refueling rate. *** N/A represents Not Available. **** These are construction cost estimates to build the LNG refueling station at existing service plazas along Pennsylvania Turnpike (I76).

Table S5. A summary of CNG fast-fill refueling station assumptions from recent literature.

Reference	(TIAX LLC 2012b)	(TIAX 2012)	(Gladstein Neandross & Associates (GNA) 2012)	(Myers et al. 2012)	(NPC (2012))
Nameplate capacity (million DGEs/year)	2.2	N/A	10.6*	N/A	1.25
Actual capacity (million DGEs/year)	1	1.83	N/A	N/A	1
Capital cost (\$million)	1**	1.0	N/A	2.8-3.4	1.5
Equipment cost	included	0.65	3.1-3.6	included	included
Installation cost	N/A	0.35	1.9-2.1	N/A	likely included
Utilization factor	45%	N/A	N/A	N/A	80%
Technical detail	Aggregate numbers	Full equipment break-down		Aggregate numbers (citing PA Turnpike Commission White Paper)	Aggregate numbers

* Naive calculation based on the average refueling rate. ** The authors do not know if installation costs are included.

V. Economic analysis of a one-refueling-station system

It is worthwhile to examine the economic performance of a one-refueling-station system as it provides some insights to understand how and why the capacities, capital investments, and net profits of the national refueling infrastructure are impacted by technical assumptions (practical maximum capacity of the refueling station) and economic assumptions (profit margin per unit fuel sold, refueling station capital cost, discount rate, and lifetime).

When there is only one refueling station, the engineering economic model in the main text (Equations (6)-(8)) has the following form,

$$\begin{aligned}
 & \text{Net profit} \\
 & = -\text{capital cost} + \text{annuity factor}_{\text{lifetime, discount rate}} \times \text{fuel sales} \times \text{profit margin} \quad (\text{S1}) \\
 & = -\text{capital cost} + \frac{1 - (1 + \text{discount rate})^{-\text{lifetime}}}{\text{discount rate}} \times \text{fuel sales} \times \text{profit margin}
 \end{aligned}$$

In essence, fuel sales and the four economic variables determine the net profit of a refueling station. To understand the trade-offs between these variables, we set the net profit to zero and solved the resulting boundary equation. We found the get following formula,

$$\text{fuel sales} = \frac{\text{capital cost}}{\text{profit margin}} \times \frac{\text{discount rate}}{1 - (1 + \text{discount rate})^{-\text{lifetime}}} \quad (\text{S2})$$

This formula shows that there is a linear relationship between the refueling station capital cost and the profit margin per unit fuel sold. If the capital cost of a refueling station increases, an investor would want to increase the profit margin if everything else remains unchanged. On the other hand, fuel sales and refueling station capital cost are proportional at the boundary condition. Intuitively, this means that a large-scale refueling station and two half-sized and half-cost refueling stations have the same economic performance if the refueling demand remains the same.

When the economic variables are fixed, we can calculate the break-even refueling demands for a LNG and a CNG refueling station using the Equation S2, as shown in **Table S6** and **Table S7**. The break-even capacity factor can be calculated by dividing the break-even refueling demands and the theoretical maximum capacity (15 million DGEs/year for the LNG refueling station, and 10.5 million DGEs/year for the CNG refueling station). With the baseline economic assumptions, the break-even capacity factor for a LNG refueling station is 31%, but under the “best” and

“worst” cases, the break-even capacity factors are 2% and 509%. (It is interesting to observe that a CNG refueling station finds similar break-even capacity factors to a LNG refueling station.) These numbers have important relevance when we consider the capacity factors of actual refueling stations. Experts suggest that most existing gasoline and diesel refueling stations have capacity factors around 15-30%. A capacity factor of 509% suggests that the investors can never get positive returns for the “worst” scenario. On the other hand, facing the “best” scenario, even a refueling station with low truck flows can get positive returns. In the main text, we assume a practical maximum capacity of 6 million DGEs/year, which is 40% utilization rate. The economic scenarios that have break-even capacity factors higher than 40% would lead to negative returns even without running the full infrastructure refueling model.

The break-even truck annual mileage was calculated by multiplying the break-even refueling demand and the average fuel economy of LNG or CNG trucks. In the refueling model, we assume that the refueling stations are located less than the truck range. In other words, the refueling stations at most will serve the refueling demands within a truck range. Here, assuming a 300-mile truck range, we find that the break-even LNG truck flow has to be large than 737 trucks/day for the refueling station to see positive profits. The break-even CNG truck flow is 459 trucks/day because we assumed a higher profit margin for CNG than for LNG.

It is interesting to compare these break-even numbers with the actual weighted-average truck flows of the studied network, which is 6,500 trucks/day for year 2012 and 11,325 trucks/day for year 2045. According to our analysis, if a hypothetical refueling station can refuel all trucks in the studied highway, then the break-even share of LNG trucks in the truck fleet is 11.3%, which is quite close to the break-even share of LNG trucks calculated using the refueling infrastructure model (12.4%, at a vehicle range of 300 miles). Several reasons lead to the difference: (1) there is significant variance in truck flows across corridors; (2) the distribution of refueling stations in the highway network is not spatially uniform; and (3) the two-dimensional connection of highways means that multiple refueling stations collectively refuel trucks in multiple connected corridors. Nevertheless, the break-even truck flow estimated here a single-station case can be used to provide a preliminary screening of refueling station locations.

Finally, the above discussions indicate that the refueling infrastructure is more likely to achieve positive return when the highway truck flows increase assuming all other factors remain unchanged. This is exactly the case when we study the refueling infrastructure model on the

projected truck flows in 2045 which are 74% higher than those in 2012. In other words, under the same set of economic assumptions, the break-even share of natural gas trucks in the total fleet can be 74% lower when the 2045 data is used instead of the 2012 data.

Table S6. Break-even refueling demands for one LNG refueling station.

Scenario description	Economic assumptions				Break-even estimates				
	capital cost (million \$)	discount rate	lifetime (year)	profit margin (\$/DGE)	refueling demand (million DGEs/year)	capacity factor	truck mileage (million km/year or million miles/year)*	truck flow (#/day) for a 480 km (300 mile) coverage	percentage of weighted-average truck flow in 2012**
Baseline scenario	2.5	0.07	20	0.05	4.7	31%	27	737	11%
Low profit margin	2.5	0.07	20	0.01	23.6	157%	135	3,685	57%
High profit margin	2.5	0.07	20	0.1	2.4	16%	13	369	6%
Low capital cost	0.5	0.07	20	0.05	0.9	6%	5	147	2%
High capital cost	4.5	0.07	20	0.05	8.5	57%	48	1,327	20%
Low discount rate	2.5	0.03	20	0.05	3.4	22%	19	525	8%
High discount rate	2.5	0.11	20	0.05	6.3	42%	36	981	15%
Low life time	2.5	0.07	10	0.05	7.1	47%	41	1,112	17%
High lifetime	2.5	0.07	30	0.05	4.0	27%	23	629	10%
Best scenario	0.5	0.03	30	0.1	0.3	2%	1	40	1%
Worst scenario	4.5	0.11	10	0.01	76.4	509%	436	11,933	184%

* We calculate the break-even LNG truck flows here assuming the fuel economy of a LNG long-haul truck is 5.7 mile/DGE. ** The weighted-average truck flow in our selected highway network is 6,500 trucks/day in 2012.

Table S7. Break-even refueling demands for one CNG refueling station.

Scenario description	Economic assumptions				Break-even estimates				
	capital cost (million \$)	discount rate	lifetime (year)	profit margin (\$/DGE)	refueling demand (million DGEs/year)	capacity factor	truck mileage (million km/year or million miles/year)*	truck flow (#/day) for a 480 km (300 mile) coverage	percentage of weighted-average truck flow in 2012**
Baseline scenario	3.35	0.07	20	0.1	3.2	30%	17	459	7%
Low profit margin	3.35	0.07	20	0.02	15.8	150%	84	2,296	35%
High profit margin	3.35	0.07	20	0.2	1.6	15%	8	230	4%
Low capital cost	1.35	0.07	20	0.1	1.3	12%	7	185	3%
High capital cost	5.35	0.07	20	0.1	5.1	48%	27	733	11%
Low discount rate	3.35	0.03	20	0.1	2.3	21%	12	327	5%
High discount rate	3.35	0.11	20	0.1	4.2	40%	22	611	9%
Low life time	3.35	0.07	10	0.1	4.8	45%	25	693	11%
High lifetime	3.35	0.07	30	0.1	2.7	26%	14	392	6%
Best scenario	1.35	0.03	30	0.2	0.3	3%	2	50	1%
Worst scenario	5.35	0.11	10	0.02	45.4	432%	241	6,596	101%

* Note we calculate the break-even CNG truck flows here assuming the fuel economy of a CNG long-haul truck is 5.3 mile/DGE. ** The weighted-average truck flow in our selected highway network is 6,500 trucks/day in 2012.

VI. Economic analysis of a one-truck fleet

Here we provide the details for the economic analysis of natural gas trucks in the main text. The lifetime cost (NPV) of the diesel, LNG, and CNG trucks can be calculated according to Equation (S3). To simplify calculation, we assume the two trucks have the same annual vehicle miles and the same lifetime.

$$\begin{aligned}
 & \textit{lifetime cost}_{truck} \\
 &= \textit{capital cost}_{truck} + \frac{1 - (1 + \textit{discount rate})^{-\textit{lifetime}}}{\textit{discount rate}} \times \textit{fuel consumptions}_{truck} \times \textit{fuel cost} \quad (S3) \\
 &= \textit{capital cost}_{truck} + \frac{1 - (1 + \textit{discount rate})^{-\textit{lifetime}}}{\textit{discount rate}} \times \frac{\textit{truck distance per year}}{\textit{fuel economy}_{truck}} \times \textit{fuel cost}
 \end{aligned}$$

At the boundary condition, the lifetime costs of diesel and LNG (or CNG) trucks should equal, so we find the boundary condition (S4).

$$\begin{aligned}
 & \Delta \textit{capital cost}_{LNG \textit{ or } CNG \textit{ truck}} \\
 &= \frac{1 - (1 + \textit{discount rate})^{-\textit{lifetime}}}{\textit{discount rate}} \times \left[\frac{\textit{truck distance per year}}{\textit{fuel economy}_{diesel \textit{ truck}}} \times \textit{fuel cost}_{diesel} - \frac{\textit{truck distance per year}}{\textit{fuel economy}_{LNG \textit{ or } CNG \textit{ truck}}} \times \textit{fuel cost}_{LNG \textit{ or } CNG} \right] \quad (S4)
 \end{aligned}$$

Essentially, the boundary condition describes that the truck cost premium of LNG (or CNG) trucks have to be paid for by fuel cost savings so that the LNG (or CNG) trucks are equally attractive as diesel trucks. Here, we are more interested the fuel cost difference between diesel and LNG (or CNG), so we derive the following boundary condition for LNG cost given the fuel economy estimates of LNG and diesel trucks, discount rate, and lifetime of trucks.

$$\begin{aligned}
 & \Delta \textit{LNG (or CNG) price} \\
 &= \textit{diesel price} - \textit{LNG (or CNG) price} \\
 &= \left(1 - \frac{\textit{fuel economy}_{LNG \textit{ or } CNG \textit{ truck}}}{\textit{fuel economy}_{diesel \textit{ truck}}} \right) \times \textit{diesel price} - \frac{\textit{discount rate} \times \Delta \textit{capital cost}_{LNG \textit{ (or) CNG \textit{ truck}}}}{1 - (1 + \textit{discount rate})^{-\textit{lifetime}}} \times \frac{\textit{fuel economy}_{LNG \textit{ (or) CNG \textit{ truck}}}}{\textit{truck distance per year}} \quad (S5)
 \end{aligned}$$

To calculate the break-even fuel price differentials, we use the truck cost premium of LNG and CNG trucks in Table 1 in the main text. According to (Tong et al. 2015), long-haul trucks travel 120,000 miles and the typical lifetime is 4 years. Here we do not consider the resale values of the trucks as we assume they are the same for the two types of trucks. We also use the same discount

rate (7%) as in the main text. The resulting break-even cost differentials for CNG and LNG as a function of diesel fuel cost are shown in **Figure 7** in the main text.

VII. Capital investment on natural gas trucks and refueling stations

In **Fig. S6**, we compare the incremental capital investment on natural gas trucks and refueling stations relative to diesel trucks and refueling stations. For trucks, the incremental investment is calculated as the multiplication of the number of long-haul trucks and the incremental cost of a LNG (or CNG) truck over a comparative diesel truck (**Table 1** in the main text). For refueling stations, we assume diesel refueling stations are already built and we ignore existing natural gas refueling stations for the reasons discussed in the main text. As a result, we assume all investment on the natural gas refueling stations are incremental investment.

We find that for a given share of natural gas trucks in the long-haul truck fleet, the incremental investment on natural gas trucks is an order of magnitude larger than those on natural gas refueling stations except for very low shares of natural gas trucks (<5%). While CNG refueling stations require slightly higher investment than LNG refueling stations, the investment on CNG trucks is much lower than LNG trucks. Furthermore, we find that the truck range assumption has significant impacts on the investment of the natural gas trucks but has negligible impacts on infrastructure investment. Due to the scope of our study, we do not estimate the incremental capital investment needed on the liquefaction infrastructure (for LNG) and natural gas systems (in particular, transmission and distribution pipelines). Some estimates on these infrastructure are available in (U.S. National Petroleum Council (NPC) 2012).

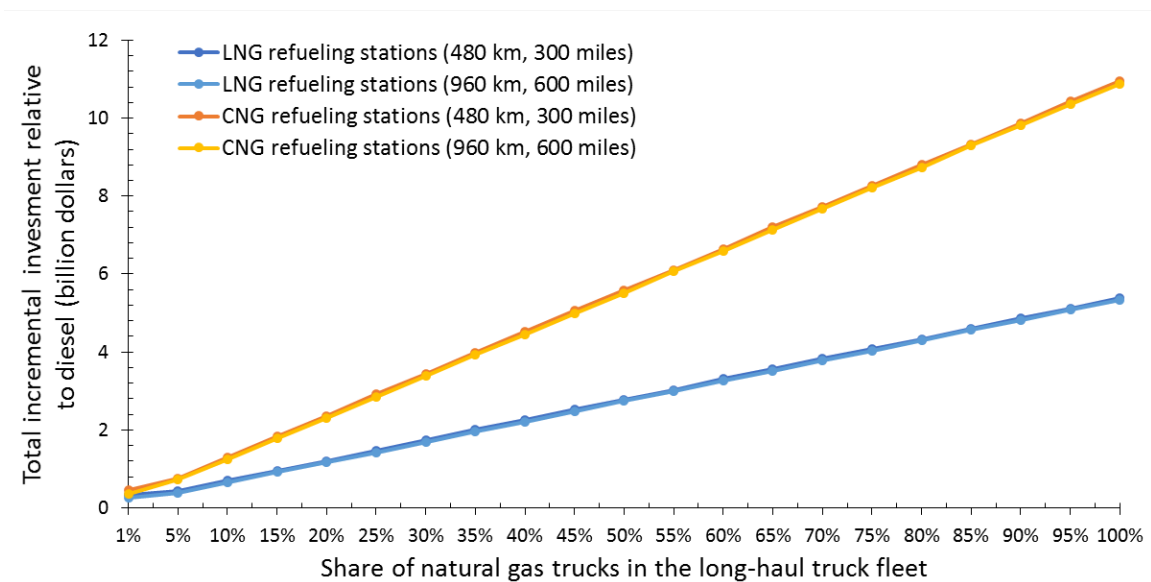
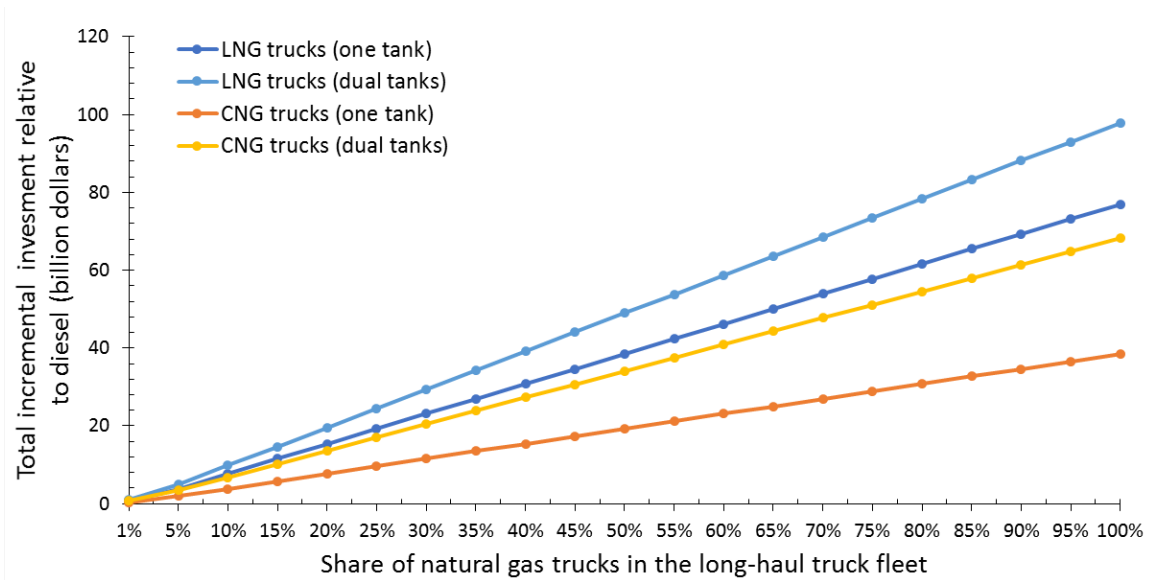


Fig. S6. Total incremental investment on natural gas trucks (top) and refueling stations (bottom) relative to diesel trucks and diesel refueling stations as a function of the share of natural gas trucks in the long-haul truck fleet. Here we assume diesel refueling stations are already built so all investment on natural gas refueling stations is incremental. The range of CNG and LNG trucks are about 480 km (300 miles) (with one tank) and 960 km (600 miles) (with dual tanks).

VIII. Additional numerical results for the LNG refueling infrastructure

In this section, we provide additional numerical results on the economic analysis of the LNG refueling infrastructure discussed in the main text. We present results for 11 economic scenarios defined in **Table S8**. These 11 scenarios include one baseline scenario used in the main text, 8 scenarios where one variable is changed to the boundary values of the assumed range, and 2 scenarios where all variables are at their boundaries to form the “best” and “worst” scenarios.

Table S9 and **Table S10** present the economic results of the national and regional refueling infrastructure using the truck flow data in 2012. These numerical results are complementary to **Figure 5** and **Figure 6** in the main text.

Table S11 and **Table S12** present the economic results of the national and regional refueling infrastructure using the truck flow data in 2045. These results provide an alternative snapshot of the refueling infrastructure in the future.

Table S13 and **Table S14** present the economic results of the national refueling infrastructure using alternative assumptions on the standardized refueling station. **Table S13** assumes that the practical maximum capacity is reduced by half to force the refueling stations have similar low capacity factors ($\leq 22.5\%$) with the existing diesel refueling stations. **Table S14** considers a small-scale refueling station whose capital cost and the practical maximum capacity are reduced by half. The motivation is to see how the discrete size of the refueling capacity impacts the economic performance of the refueling infrastructure.

Table S8. Economic assumptions for the LNG refueling infrastructure.

Index	Description	capital cost (million \$)	profit margin (\$/DGE)	discount rate	lifetime (year)
1	Baseline scenario	2.5	0.05	0.07	20
2	Low profit margin	2.5	0.01	0.07	20
3	High profit margin	2.5	0.1	0.07	20
4	Low capital cost	0.5	0.05	0.07	20
5	High capital cost	4.5	0.05	0.07	20
6	Low discount rate	2.5	0.05	0.03	20
7	High discount rate	2.5	0.05	0.11	20
8	Low life time	2.5	0.05	0.07	10
9	High lifetime	2.5	0.05	0.07	30
10	Best scenario	0.5	0.1	0.03	30
11	Worst scenario	4.5	0.01	0.11	10

Table S9. Net profit and capital investment for the national LNG refueling infrastructure in 2012 under different combinations of vehicle range assumptions, shares of natural gas trucks in the total fleet, and economic assumptions.

Scenario	320 km (200 miles)						480 km (300 miles)						960 km (600 miles)					
	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%
Net profit (million \$)																		
#1	-364	-152	-64	-3	78	123	-279	-92	-36	37	115	186	-196	-62	4	75	158	224
#2	-417	-416	-593	-797	-980	-1,199	-332	-356	-565	-757	-943	-1,137	-249	-326	-525	-719	-900	-1,099
#3	-298	179	598	989	1,401	1,777	-213	239	625	1,029	1,438	1,839	-130	269	666	1,067	1,481	1,878
#4	-20	234	516	793	1,074	1,347	-3	246	522	801	1,081	1,360	14	252	530	809	1,090	1,368
#5	-708	-538	-644	-799	-918	-1,101	-555	-430	-594	-727	-851	-988	-406	-376	-522	-659	-774	-920
#6	-337	-18	204	398	613	792	-252	42	231	438	650	855	-170	72	272	476	693	893
#7	-380	-234	-228	-249	-251	-287	-295	-174	-200	-209	-213	-225	-213	-144	-160	-172	-170	-187
#8	-386	-263	-287	-337	-368	-434	-301	-203	-259	-297	-331	-371	-219	-173	-219	-260	-288	-334
#9	-353	-95	50	167	304	407	-268	-35	77	207	342	469	-185	-5	117	245	385	507
#10	159	1,127	2,302	3,472	4,646	5,812	176	1,139	2,308	3,480	4,653	5,825	192	1,145	2,316	3,488	4,663	5,834
#11	-767	-832	-1,231	-1,681	-2,094	-2,570	-614	-724	-1,182	-1,609	-2,026	-2,458	-465	-670	-1,110	-1,541	-1,950	-2,390
Capital investment (million \$)																		
#1	430	483	725	995	1,245	1,530	345	423	698	955	1,208	1,468	263	393	658	918	1,165	1,430
#2	430	483	725	995	1,245	1,530	345	423	698	955	1,208	1,468	263	393	658	918	1,165	1,430
#3	430	483	725	995	1,245	1,530	345	423	698	955	1,208	1,468	263	393	658	918	1,165	1,430
#4	86	97	145	199	249	306	69	85	140	191	242	294	53	79	132	184	233	286
#5	774	869	1,305	1,791	2,241	2,754	621	761	1,256	1,719	2,174	2,642	473	707	1,184	1,652	2,097	2,574
#6	430	483	725	995	1,245	1,530	345	423	698	955	1,208	1,468	263	393	658	918	1,165	1,430
#7	430	483	725	995	1,245	1,530	345	423	698	955	1,208	1,468	263	393	658	918	1,165	1,430
#8	430	483	725	995	1,245	1,530	345	423	698	955	1,208	1,468	263	393	658	918	1,165	1,430
#9	430	483	725	995	1,245	1,530	345	423	698	955	1,208	1,468	263	393	658	918	1,165	1,430
#10	86	97	145	199	249	306	69	85	140	191	242	294	53	79	132	184	233	286
#11	774	869	1,305	1,791	2,241	2,754	621	761	1,256	1,719	2,174	2,642	473	707	1,184	1,652	2,097	2,574

Table S10. Net profit and capital investment for the regional (California and Texas) LNG refueling infrastructure in 2012 under different combinations of vehicle range assumptions, shares of natural gas trucks in the total fleet, and economic assumptions.

Scenario	320 km (200 miles)						480 km (300 miles)						960 km (600 miles)					
	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%
Net profit (million \$)																		
#1	-55	-29	-21	-6	0	3	-45	-22	-14	-6	7	15	-37	-19	-6	-1	12	15
#2	-61	-60	-82	-97	-122	-149	-51	-52	-75	-97	-115	-137	-43	-50	-67	-92	-110	-137
#3	-47	9	55	108	152	193	-37	16	62	108	159	205	-30	19	70	113	164	206
#4	-5	25	57	90	122	153	-3	26	58	90	123	155	-1	27	60	91	124	155
#5	-105	-83	-99	-102	-122	-147	-87	-70	-86	-102	-109	-125	-73	-65	-72	-93	-100	-125
#6	-52	-14	9	40	61	80	-42	-7	17	40	69	92	-34	-4	24	45	74	92
#7	-57	-39	-40	-34	-38	-45	-47	-31	-33	-34	-31	-32	-39	-29	-25	-29	-26	-32
#8	-57	-42	-47	-44	-52	-61	-47	-35	-40	-44	-44	-49	-40	-32	-32	-39	-39	-49
#9	-54	-23	-8	14	26	35	-44	-15	-1	14	33	48	-36	-13	7	19	38	48
#10	16	127	262	398	533	666	18	129	263	398	534	668	19	129	265	400	535	669
#11	-112	-117	-167	-203	-258	-316	-94	-104	-154	-203	-244	-294	-80	-99	-140	-194	-235	-294
Capital investment (million \$)																		
#1	63	68	98	120	153	188	53	60	90	120	145	175	45	58	83	115	140	175
#2	63	68	98	120	153	188	53	60	90	120	145	175	45	58	83	115	140	175
#3	63	68	98	120	153	188	53	60	90	120	145	175	45	58	83	115	140	175
#4	13	14	20	24	31	38	11	12	18	24	29	35	9	12	17	23	28	35
#5	113	122	176	216	275	338	95	108	162	216	261	315	81	104	149	207	252	315
#6	63	68	98	120	153	188	53	60	90	120	145	175	45	58	83	115	140	175
#7	63	68	98	120	153	188	53	60	90	120	145	175	45	58	83	115	140	175
#8	63	68	98	120	153	188	53	60	90	120	145	175	45	58	83	115	140	175
#9	63	68	98	120	153	188	53	60	90	120	145	175	45	58	83	115	140	175
#10	13	14	20	24	31	38	11	12	18	24	29	35	9	12	17	23	28	35
#11	113	122	176	216	275	338	95	108	162	216	261	315	81	104	149	207	252	315

Table S11. Net profit and capital investment for the national LNG refueling infrastructure in 2045 under different combinations of vehicle range assumptions, shares of natural gas trucks in the total fleet, and economic assumptions.

Scenario	320 km (200 miles)						480 km (300 miles)						960 km (600 miles)					
	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%
Net Profit (million \$)																		
#1	-315	-71	35	164	292	401	-230	-49	80	204	330	451	-150	-14	115	234	378	479
#2	-407	-532	-887	-1,219	-1,552	-1,904	-322	-510	-842	-1,179	-1,514	-1,854	-242	-475	-807	-1,149	-1,466	-1,826
#3	-200	505	1,187	1,892	2,597	3,282	-114	528	1,233	1,933	2,635	3,333	-34	563	1,268	1,963	2,683	3,361
#4	29	447	929	1,416	1,902	2,385	46	451	938	1,424	1,910	2,395	62	458	945	1,430	1,920	2,401
#5	-659	-589	-859	-1,088	-1,318	-1,583	-506	-549	-778	-1,016	-1,250	-1,493	-362	-486	-715	-962	-1,164	-1,443
#6	-268	162	501	863	1,224	1,566	-183	184	546	903	1,262	1,616	-103	219	581	933	1,310	1,644
#7	-343	-214	-251	-266	-280	-314	-258	-192	-206	-226	-242	-264	-178	-157	-171	-195	-195	-236
#8	-354	-265	-353	-419	-484	-570	-269	-243	-308	-379	-447	-520	-189	-208	-273	-349	-399	-492
#9	-295	27	232	460	687	895	-210	50	277	500	725	945	-130	85	313	530	773	973
#10	340	2,003	4,041	6,084	8,126	10,165	357	2,007	4,050	6,092	8,134	10,176	374	2,015	4,058	6,099	8,145	10,183
#11	-761	-1,101	-1,883	-2,625	-3,366	-4,144	-608	-1,061	-1,802	-2,553	-3,299	-4,054	-464	-998	-1,739	-2,499	-3,213	-4,004
Capital investment (million \$)																		
#1	430	648	1,118	1,565	2,013	2,480	345	625	1,073	1,525	1,975	2,430	265	590	1,038	1,495	1,928	2,403
#2	430	648	1,118	1,565	2,013	2,480	345	625	1,073	1,525	1,975	2,430	265	590	1,038	1,495	1,928	2,403
#3	430	648	1,118	1,565	2,013	2,480	345	625	1,073	1,525	1,975	2,430	265	590	1,038	1,495	1,928	2,403
#4	86	130	224	313	403	496	69	125	215	305	395	486	53	118	208	299	386	481
#5	774	1,166	2,012	2,817	3,623	4,464	621	1,125	1,931	2,745	3,555	4,374	477	1,062	1,868	2,691	3,470	4,325
#6	430	648	1,118	1,565	2,013	2,480	345	625	1,073	1,525	1,975	2,430	265	590	1,038	1,495	1,928	2,403
#7	430	648	1,118	1,565	2,013	2,480	345	625	1,073	1,525	1,975	2,430	265	590	1,038	1,495	1,928	2,403
#8	430	648	1,118	1,565	2,013	2,480	345	625	1,073	1,525	1,975	2,430	265	590	1,038	1,495	1,928	2,403
#9	430	648	1,118	1,565	2,013	2,480	345	625	1,073	1,525	1,975	2,430	265	590	1,038	1,495	1,928	2,403
#10	86	130	224	313	403	496	69	125	215	305	395	486	53	118	208	299	386	481
#11	774	1,166	2,012	2,817	3,623	4,464	621	1,125	1,931	2,745	3,555	4,374	477	1,062	1,868	2,691	3,470	4,325

Table S12. Net profit and capital investment for the regional (California and Texas) LNG refueling infrastructure in 2045 under different combinations of vehicle range assumptions, shares of natural gas trucks in the total fleet, and economic assumptions.

Scenario	320 km (200 miles)						480 km (300 miles)						480 km (600 miles)					
	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%
Net profit (million \$)																		
#1	-50	-16	-4	8	27	39	-40	-13	1	13	29	43	-32	-16	3	13	34	49
#2	-60	-67	-107	-146	-179	-218	-50	-65	-102	-141	-176	-213	-42	-67	-99	-141	-171	-208
#3	-37	48	124	200	284	360	-27	51	129	205	286	364	-19	48	132	205	291	370
#4	0	48	102	156	211	265	2	49	103	157	211	265	4	48	103	157	212	267
#5	-100	-80	-110	-140	-157	-187	-82	-75	-101	-131	-153	-179	-68	-80	-97	-131	-144	-169
#6	-44	10	48	86	131	168	-34	13	53	90	133	173	-27	10	55	91	138	179
#7	-53	-32	-36	-40	-37	-41	-43	-29	-31	-35	-34	-36	-35	-32	-28	-35	-29	-31
#8	-54	-37	-47	-57	-60	-70	-44	-35	-42	-52	-57	-65	-36	-37	-40	-52	-52	-60
#9	-47	-5	18	41	71	94	-37	-2	23	46	73	98	-30	-5	25	46	78	104
#10	35	222	449	676	904	1,132	37	222	450	677	905	1,132	39	222	450	677	906	1,134
#11	-111	-137	-224	-312	-385	-473	-93	-132	-215	-303	-381	-464	-80	-137	-211	-303	-372	-455
Capital investment (million \$)																		
#1	63	80	133	185	230	283	53	78	128	180	228	278	45	80	125	180	223	273
#2	63	80	133	185	230	283	53	78	128	180	228	278	45	80	125	180	223	273
#3	63	80	133	185	230	283	53	78	128	180	228	278	45	80	125	180	223	273
#4	13	16	27	37	46	57	11	16	26	36	46	56	9	16	25	36	45	55
#5	113	144	239	333	414	509	95	140	230	324	410	500	81	144	225	324	401	491
#6	63	80	133	185	230	283	53	78	128	180	228	278	45	80	125	180	223	273
#7	63	80	133	185	230	283	53	78	128	180	228	278	45	80	125	180	223	273
#8	63	80	133	185	230	283	53	78	128	180	228	278	45	80	125	180	223	273
#9	63	80	133	185	230	283	53	78	128	180	228	278	45	80	125	180	223	273
#10	13	16	27	37	46	57	11	16	26	36	46	56	9	16	25	36	45	55
#11	113	144	239	333	414	509	95	140	230	324	410	500	81	144	225	324	401	491

Table S13. Net profit and capital investment for the national LNG refueling infrastructure in 2012 under different combinations of vehicle range assumptions, shares of natural gas trucks in the total fleet, and economic assumptions. Here we assume the refueling station costs \$2.5 million but has a practical maximum capacity of 3 million DGEs/year (same cost but 50% less capacity limit than those assumed in the main text).

Scenario	320 km (200 miles)						480 km (300 miles)						960 km (600 miles)					
	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%
Net profit (million \$)																		
#1	-364	-394	-584	-785	-972	-1,174	-281	-367	-546	-750	-927	-1,127	-201	-327	-503	-705	-892	-1,089
#2	-417	-659	-1,113	-1,579	-2,030	-2,497	-334	-631	-1,075	-1,544	-1,985	-2,449	-254	-591	-1,033	-1,499	-1,950	-2,412
#3	-298	-64	78	207	351	479	-215	-36	115	242	396	527	-135	4	158	287	431	565
#4	-20	186	412	637	864	1,088	-3	191	420	644	873	1,097	13	199	429	653	880	-20
#5	-708	-974	-1,580	-2,207	-2,808	-3,436	-559	-925	-1,512	-2,144	-2,727	-3,351	-415	-853	-1,435	-2,063	-2,664	-708
#6	-337	-261	-316	-384	-437	-506	-255	-233	-279	-349	-392	-458	-175	-193	-236	-304	-357	-420
#7	-380	-476	-748	-1,032	-1,301	-1,585	-298	-449	-710	-997	-1,256	-1,537	-218	-409	-668	-952	-1,220	-1,499
#8	-386	-506	-807	-1,120	-1,418	-1,731	-304	-478	-769	-1,085	-1,373	-1,684	-224	-438	-726	-1,040	-1,338	-1,646
#9	-353	-338	-470	-615	-746	-891	-270	-310	-433	-580	-701	-843	-190	-270	-390	-535	-665	-805
#10	159	1,079	2,198	3,315	4,436	5,553	175	1,084	2,206	3,323	4,445	5,562	191	1,092	2,215	3,332	4,453	5,571
#11	-767	-1,268	-2,167	-3,089	-3,984	-4,906	-618	-1,219	-2,100	-3,026	-3,903	-4,820	-474	-1,147	-2,023	-2,945	-3,840	-4,753
Capital investment (million \$)																		
#1	430	725	1,245	1,778	2,295	2,828	348	698	1,208	1,743	2,250	2,780	268	658	1,165	1,698	2,215	2,743
#2	430	725	1,245	1,778	2,295	2,828	348	698	1,208	1,743	2,250	2,780	268	658	1,165	1,698	2,215	2,743
#3	430	725	1,245	1,778	2,295	2,828	348	698	1,208	1,743	2,250	2,780	268	658	1,165	1,698	2,215	2,743
#4	86	145	249	356	459	566	70	140	242	349	450	556	54	132	233	340	443	86
#5	774	1,305	2,241	3,200	4,131	5,090	626	1,256	2,174	3,137	4,050	5,004	482	1,184	2,097	3,056	3,987	774
#6	430	725	1,245	1,778	2,295	2,828	348	698	1,208	1,743	2,250	2,780	268	658	1,165	1,698	2,215	2,743
#7	430	725	1,245	1,778	2,295	2,828	348	698	1,208	1,743	2,250	2,780	268	658	1,165	1,698	2,215	2,743
#8	430	725	1,245	1,778	2,295	2,828	348	698	1,208	1,743	2,250	2,780	268	658	1,165	1,698	2,215	2,743
#9	430	725	1,245	1,778	2,295	2,828	348	698	1,208	1,743	2,250	2,780	268	658	1,165	1,698	2,215	2,743
#10	86	145	249	356	459	566	70	140	242	349	450	556	54	132	233	340	443	549
#11	774	1,305	2,241	3,200	4,131	5,090	626	1,256	2,174	3,137	4,050	5,004	482	1,184	2,097	3,056	3,987	4,937

Table S14. Net profit and capital investment for the national LNG refueling infrastructure in 2012 under different combinations of vehicle range assumptions, shares of natural gas trucks in the total fleet, and economic assumptions. Here we assume the refueling station costs \$1.25 million but has a practical maximum capacity of 3 million DGEs/year (50% less cost and 50% capacity limit than those assumed in the main text).

Scenario	320 km (200 miles)						480 km (300 miles)						960 km (600 miles)					
	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%
Net profit (million \$)																		
#1	-149	-32	39	103	175	240	-108	-18	58	121	198	263	-68	2	79	144	216	283
#2	-202	-296	-490	-690	-883	-1,083	-161	-283	-471	-673	-860	-1,059	-121	-263	-450	-650	-843	-1,040
#3	-83	299	700	1,095	1,498	1,893	-41	313	719	1,113	1,521	1,917	-1	333	741	1,136	1,539	1,936
#4	23	258	537	814	1,093	1,371	31	261	541	818	1,098	1,375	39	265	545	823	1,102	1,380
#5	-321	-322	-459	-608	-743	-891	-247	-297	-425	-576	-702	-849	-175	-261	-387	-535	-670	-814
#6	-122	102	306	504	710	908	-81	116	325	522	733	932	-41	136	347	545	751	951
#7	-165	-114	-125	-143	-153	-171	-124	-100	-107	-126	-131	-147	-84	-80	-85	-103	-113	-128
#8	-171	-143	-184	-231	-271	-318	-130	-130	-165	-214	-248	-294	-90	-109	-144	-191	-230	-275
#9	-138	25	152	273	402	523	-96	39	171	291	424	547	-56	59	192	314	442	566
#10	202	1,151	2,323	3,493	4,665	5,835	210	1,154	2,327	3,497	4,670	5,840	218	1,158	2,331	3,502	4,674	5,845
#11	-380	-616	-1,047	-1,489	-1,918	-2,361	-305	-591	-1,013	-1,458	-1,878	-2,318	-233	-555	-975	-1,417	-1,846	-2,284
Capital investment (million \$)																		
#1	215	363	623	889	1,148	1,414	174	349	604	871	1,125	1,390	134	329	583	849	1,108	1,371
#2	215	363	623	889	1,148	1,414	174	349	604	871	1,125	1,390	134	329	583	849	1,108	1,371
#3	215	363	623	889	1,148	1,414	174	349	604	871	1,125	1,390	134	329	583	849	1,108	1,371
#4	43	73	125	178	230	283	35	70	121	174	225	278	27	66	117	170	222	274
#5	387	653	1,121	1,600	2,066	2,545	313	628	1,087	1,568	2,025	2,502	241	592	1,049	1,528	1,994	2,468
#6	215	363	623	889	1,148	1,414	174	349	604	871	1,125	1,390	134	329	583	849	1,108	1,371
#7	215	363	623	889	1,148	1,414	174	349	604	871	1,125	1,390	134	329	583	849	1,108	1,371
#8	215	363	623	889	1,148	1,414	174	349	604	871	1,125	1,390	134	329	583	849	1,108	1,371
#9	215	363	623	889	1,148	1,414	174	349	604	871	1,125	1,390	134	329	583	849	1,108	1,371
#10	43	73	125	178	230	283	35	70	121	174	225	278	27	66	117	170	222	274
#11	387	653	1,121	1,600	2,066	2,545	313	628	1,087	1,568	2,025	2,502	241	592	1,049	1,528	1,994	2,468

IX. Additional numerical results for the CNG refueling infrastructure

We present the economic results for the CNG refueling infrastructure in this section. There are two sets of economic assumptions, where one has the same profit margin assumption as the LNG cases (Table S15), and the other one has a more optimistic profit margin assumptions (

Table S16).

Table S17, Table S18, Table S19, and Table S20 correspond to the more pessimistic economic assumptions (Table S15) for the national and regional infrastructure in years 2012 and 2045.

Table S21, Table S22, Table S23, and Table S24 correspond to the more pessimistic economic assumptions (Table S16) for the national and regional infrastructure in years 2012 and 2045.

Table S15. Economic assumptions for the CNG refueling infrastructure.

Index	Description	capital cost (million \$)	profit margin (\$/DGE)	discount rate	lifetime (year)
1	Baseline scenario	3.35	0.05	0.07	20
2	Low profit margin	3.35	0.01	0.07	20
3	High profit margin	3.35	0.1	0.07	20
4	Low capital cost	1.35	0.05	0.07	20
5	High capital cost	5.35	0.05	0.07	20
6	Low discount rate	3.35	0.05	0.03	20
7	High discount rate	3.35	0.05	0.11	20
8	Low life time	3.35	0.05	0.07	10
9	High lifetime	3.35	0.05	0.07	30
10	Best scenario	1.35	0.1	0.03	30
11	Worst scenario	5.35	0.01	0.11	10

Table S16. Alternative economic assumptions for the CNG refueling infrastructure.

Index	Description	capital cost (million \$)	profit margin (\$/DGE)	discount rate	lifetime (year)
1	Baseline scenario	3.35	0.1	0.07	20
2	Low profit margin	3.35	0.02	0.07	20
3	High profit margin	3.35	0.2	0.07	20
4	Low capital cost	1.35	0.1	0.07	20
5	High capital cost	5.35	0.1	0.07	20
6	Low discount rate	3.35	0.1	0.03	20
7	High discount rate	3.35	0.1	0.11	20
8	Low life time	3.35	0.1	0.07	10
9	High lifetime	3.35	0.1	0.07	30

10	Best scenario	1.35	0.2	0.03	30
11	Worst scenario	5.35	0.02	0.11	10

Table S17. Net profit and capital investment for the national CNG refueling infrastructure in 2012 under different combinations of vehicle range assumptions, shares of natural gas trucks in the total fleet, and economic assumptions in Table S15.

Scenario	320 km (200 miles)						480 km (300 miles)						960 km (600 miles)					
	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%
Net profit (million \$)																		
#1	-505	-448	-639	-822	-1,003	-1,203	-391	-405	-585	-779	-942	-1,136	-284	-361	-541	-722	-882	-1,076
#2	-562	-733	-1,208	-1,676	-2,141	-2,626	-448	-689	-1,154	-1,632	-2,081	-2,559	-341	-646	-1,111	-1,575	-2,020	-2,498
#3	-434	-93	73	244	420	575	-320	-49	126	288	480	642	-213	-5	170	345	541	703
#4	-161	32	167	306	445	577	-115	49	189	323	470	604	-72	67	207	346	494	628
#5	-849	-928	-1,445	-1,950	-2,451	-2,983	-667	-859	-1,359	-1,881	-2,354	-2,876	-496	-789	-1,289	-1,790	-2,258	-2,780
#6	-476	-305	-351	-391	-428	-484	-362	-261	-298	-347	-367	-417	-255	-217	-254	-290	-307	-356
#7	-523	-537	-815	-1,087	-1,356	-1,645	-409	-493	-762	-1,044	-1,296	-1,578	-302	-450	-718	-987	-1,235	-1,517
#8	-529	-568	-878	-1,182	-1,482	-1,803	-415	-525	-825	-1,138	-1,422	-1,736	-308	-481	-781	-1,081	-1,361	-1,675
#9	-493	-387	-517	-640	-759	-899	-379	-344	-463	-596	-699	-832	-272	-300	-420	-539	-638	-771
#10	31	992	2,088	3,187	4,287	5,378	77	1,010	2,110	3,204	4,311	5,406	120	1,027	2,128	3,228	4,336	5,431
#11	-912	-1,244	-2,077	-2,899	-3,715	-4,564	-730	-1,175	-1,991	-2,829	-3,619	-4,457	-559	-1,105	-1,922	-2,738	-3,523	-4,360
Capital investment (million \$)																		
#1	576	804	1,350	1,889	2,425	2,982	462	760	1,296	1,846	2,365	2,915	355	717	1,253	1,789	2,305	2,854
#2	576	804	1,350	1,889	2,425	2,982	462	760	1,296	1,846	2,365	2,915	355	717	1,253	1,789	2,305	2,854
#3	576	804	1,350	1,889	2,425	2,982	462	760	1,296	1,846	2,365	2,915	355	717	1,253	1,789	2,305	2,854
#4	232	324	544	761	977	1,202	186	306	522	744	953	1,175	143	289	505	721	929	1,150
#5	920	1,284	2,156	3,017	3,873	4,762	738	1,214	2,070	2,948	3,777	4,655	567	1,145	2,001	2,857	3,681	4,558
#6	576	804	1,350	1,889	2,425	2,982	462	760	1,296	1,846	2,365	2,915	355	717	1,253	1,789	2,305	2,854
#7	576	804	1,350	1,889	2,425	2,982	462	760	1,296	1,846	2,365	2,915	355	717	1,253	1,789	2,305	2,854
#8	576	804	1,350	1,889	2,425	2,982	462	760	1,296	1,846	2,365	2,915	355	717	1,253	1,789	2,305	2,854
#9	576	804	1,350	1,889	2,425	2,982	462	760	1,296	1,846	2,365	2,915	355	717	1,253	1,789	2,305	2,854
#10	232	324	544	761	977	1,202	186	306	522	744	953	1,175	143	289	505	721	929	1,150
#11	920	1,284	2,156	3,017	3,873	4,762	738	1,214	2,070	2,948	3,777	4,655	567	1,145	2,001	2,857	3,681	4,558

Table S18. Net profit and capital investment for the national CNG refueling infrastructure in 2045 under different combinations of vehicle range assumptions, shares of natural gas trucks in the total fleet, and economic assumptions in Table S15.

Scenario	320 km (200 miles)						480 km (300 miles)						960 km (600 miles)					
	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%
Net profit (million \$)																		
#1	-452	-603	-915	-1,226	-1,531	-1,873	-355	-543	-844	-1,179	-1,471	-1,809	-255	-479	-800	-1,122	-1,437	-1,762
#2	-551	-1,099	-1,906	-2,714	-3,514	-4,352	-454	-1,039	-1,836	-2,667	-3,454	-4,288	-354	-975	-1,792	-2,610	-3,420	-4,241
#3	-328	17	325	633	948	1,226	-231	77	395	680	1,008	1,290	-131	141	439	738	1,043	1,338
#4	-108	127	371	616	863	1,095	-69	151	400	635	887	1,121	-29	177	418	658	901	1,140
#5	-796	-1,333	-2,201	-3,068	-3,925	-4,841	-641	-1,237	-2,088	-2,993	-3,829	-4,739	-481	-1,135	-2,018	-2,902	-3,775	-4,664
#6	-402	-352	-414	-475	-529	-620	-305	-292	-343	-427	-468	-556	-204	-228	-299	-370	-434	-509
#7	-483	-757	-1,222	-1,688	-2,147	-2,642	-386	-697	-1,152	-1,641	-2,086	-2,578	-285	-633	-1,108	-1,584	-2,052	-2,531
#8	-494	-812	-1,332	-1,853	-2,367	-2,917	-397	-752	-1,262	-1,806	-2,306	-2,853	-296	-688	-1,218	-1,749	-2,272	-2,806
#9	-431	-497	-702	-908	-1,106	-1,342	-334	-437	-632	-861	-1,046	-1,278	-233	-373	-588	-803	-1,012	-1,231
#10	226	1,800	3,718	5,636	7,556	9,462	266	1,825	3,747	5,655	7,581	9,488	306	1,851	3,765	5,679	7,596	9,509
#11	-906	-1,884	-3,302	-4,721	-6,128	-7,595	-751	-1,788	-3,190	-4,646	-6,032	-7,493	-591	-1,686	-3,120	-4,555	-5,978	-7,418
Capital investment (million \$)																		
#1	576	1,223	2,154	3,085	4,010	4,971	479	1,162	2,084	3,038	3,950	4,908	379	1,099	2,040	2,982	3,916	4,861
#2	576	1,223	2,154	3,085	4,010	4,971	479	1,162	2,084	3,038	3,950	4,908	379	1,099	2,040	2,982	3,916	4,861
#3	576	1,223	2,154	3,085	4,010	4,971	479	1,162	2,084	3,038	3,950	4,908	379	1,099	2,040	2,982	3,916	4,861
#4	232	493	868	1,243	1,616	2,003	193	468	840	1,224	1,592	1,978	153	443	822	1,202	1,578	1,959
#5	920	1,953	3,440	4,927	6,404	7,939	765	1,856	3,328	4,852	6,308	7,838	605	1,755	3,258	4,762	6,254	7,763
#6	576	1,223	2,154	3,085	4,010	4,971	479	1,162	2,084	3,038	3,950	4,908	379	1,099	2,040	2,982	3,916	4,861
#7	576	1,223	2,154	3,085	4,010	4,971	479	1,162	2,084	3,038	3,950	4,908	379	1,099	2,040	2,982	3,916	4,861
#8	576	1,223	2,154	3,085	4,010	4,971	479	1,162	2,084	3,038	3,950	4,908	379	1,099	2,040	2,982	3,916	4,861
#9	576	1,223	2,154	3,085	4,010	4,971	479	1,162	2,084	3,038	3,950	4,908	379	1,099	2,040	2,982	3,916	4,861
#10	232	493	868	1,243	1,616	2,003	193	468	840	1,224	1,592	1,978	153	443	822	1,202	1,578	1,959
#11	920	1,953	3,440	4,927	6,404	7,939	765	1,856	3,328	4,852	6,308	7,838	605	1,755	3,258	4,762	6,254	7,763

Table S19. Net profit and capital investment for the regional (California and Texas) CNG refueling infrastructure in 2012 under different combinations of vehicle range assumptions, shares of natural gas trucks in the total fleet, and economic assumptions in Table S15.

Scenario	320 km (200 miles)						480 km (300 miles)						960 km (600 miles)					
	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%
Net profit (million \$)																		
#1	-76	-63	-82	-102	-128	-147	-62	-63	-82	-105	-121	-137	-52	-63	-76	-102	-114	-134
#2	-82	-96	-148	-200	-259	-311	-69	-96	-148	-203	-252	-301	-59	-96	-141	-200	-245	-297
#3	-67	-22	0	21	36	57	-54	-22	-1	18	42	67	-44	-22	6	21	49	71
#4	-26	-1	16	32	46	63	-20	-1	16	31	49	67	-16	-1	18	32	52	68
#5	-126	-125	-180	-236	-302	-357	-104	-125	-180	-241	-291	-341	-88	-125	-170	-236	-280	-336
#6	-72	-46	-49	-52	-62	-64	-59	-46	-49	-56	-55	-55	-49	-46	-42	-52	-48	-51
#7	-78	-73	-103	-132	-168	-198	-64	-73	-103	-136	-162	-188	-54	-73	-96	-132	-155	-185
#8	-78	-77	-110	-143	-183	-216	-65	-77	-110	-146	-176	-206	-55	-77	-103	-143	-169	-203
#9	-74	-56	-68	-81	-100	-112	-61	-56	-68	-84	-93	-102	-51	-56	-62	-81	-86	-99
#10	-3	110	237	364	488	615	2	109	236	362	491	619	6	110	239	364	494	621
#11	-133	-161	-253	-345	-447	-539	-111	-161	-253	-350	-437	-523	-95	-161	-242	-345	-426	-518
Capital investment (million \$)																		
#1	84	104	164	224	291	352	70	104	164	228	285	342	60	104	157	224	278	338
#2	84	104	164	224	291	352	70	104	164	228	285	342	60	104	157	224	278	338
#3	84	104	164	224	291	352	70	104	164	228	285	342	60	104	157	224	278	338
#4	34	42	66	90	117	142	28	42	66	92	115	138	24	42	63	90	112	136
#5	134	166	262	358	465	562	112	166	262	364	455	546	96	166	251	358	444	540
#6	84	104	164	224	291	352	70	104	164	228	285	342	60	104	157	224	278	338
#7	84	104	164	224	291	352	70	104	164	228	285	342	60	104	157	224	278	338
#8	84	104	164	224	291	352	70	104	164	228	285	342	60	104	157	224	278	338
#9	84	104	164	224	291	352	70	104	164	228	285	342	60	104	157	224	278	338
#10	34	42	66	90	117	142	28	42	66	92	115	138	24	42	63	90	112	136
#11	134	166	262	358	465	562	112	166	262	364	455	546	96	166	251	358	444	540

Table S20. Net profit and capital investment for the regional (California and Texas) CNG refueling infrastructure in 2045 under different combinations of vehicle range assumptions, shares of natural gas trucks in the total fleet, and economic assumptions in Table S15.

Scenario	320 km (200 miles)						480 km (300 miles)						960 km (600 miles)					
	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%
Net profit (million \$)																		
#1	-70	-88	-120	-151	-189	-211	-57	-78	-103	-141	-173	-204	-46	-75	-106	-131	-173	-204
#2	-81	-144	-230	-317	-410	-487	-68	-134	-214	-307	-394	-480	-58	-130	-217	-297	-394	-480
#3	-56	-19	18	56	87	135	-43	-9	35	66	103	141	-33	-6	32	76	104	141
#4	-20	6	34	63	89	121	-15	10	41	67	95	124	-10	11	40	71	95	124
#5	-120	-182	-274	-365	-467	-543	-99	-166	-247	-349	-441	-532	-82	-161	-252	-333	-441	-532
#6	-64	-60	-64	-67	-78	-71	-51	-50	-47	-58	-61	-65	-41	-47	-51	-47	-61	-64
#7	-73	-106	-154	-203	-258	-297	-60	-96	-137	-193	-241	-290	-50	-92	-141	-183	-241	-290
#8	-75	-112	-166	-221	-283	-327	-61	-102	-150	-211	-266	-321	-51	-98	-153	-201	-266	-320
#9	-68	-77	-96	-116	-142	-152	-54	-67	-79	-106	-125	-145	-44	-63	-83	-96	-125	-145
#10	17	192	407	622	835	1,054	23	196	414	626	841	1,056	27	198	413	630	842	1,057
#11	-132	-244	-397	-549	-713	-850	-111	-228	-370	-533	-686	-839	-95	-222	-375	-517	-686	-839
Capital investment (million \$)																		
#1	84	157	258	358	466	556	70	147	241	348	449	549	60	144	245	338	449	549
#2	84	157	258	358	466	556	70	147	241	348	449	549	60	144	245	338	449	549
#3	84	157	258	358	466	556	70	147	241	348	449	549	60	144	245	338	449	549
#4	34	63	104	144	188	224	28	59	97	140	181	221	24	58	99	136	181	221
#5	134	251	412	572	744	888	112	235	385	556	717	877	96	230	391	540	717	877
#6	84	157	258	358	466	556	70	147	241	348	449	549	60	144	245	338	449	549
#7	84	157	258	358	466	556	70	147	241	348	449	549	60	144	245	338	449	549
#8	84	157	258	358	466	556	70	147	241	348	449	549	60	144	245	338	449	549
#9	84	157	258	358	466	556	70	147	241	348	449	549	60	144	245	338	449	549
#10	34	63	104	144	188	224	28	59	97	140	181	221	24	58	99	136	181	221
#11	134	251	412	572	744	888	112	235	385	556	717	877	96	230	391	540	717	877

Table S21. Net profit and capital investment for the national CNG refueling infrastructure in 2012 under different combinations of vehicle range assumptions, shares of natural gas trucks in the total fleet, and economic assumptions in Table S16.

Scenario	320 km (200 miles)						480 km (300 miles)						960 km (600 miles)					
	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%
Net profit (million \$)																		
#1	-434	-93	73	244	420	575	-320	-49	126	288	480	642	-213	-5	170	345	541	703
#2	-548	-662	-1,066	-1,463	-1,856	-2,270	-434	-618	-1,012	-1,419	-1,796	-2,203	-327	-575	-968	-1,362	-1,736	-2,143
#3	-292	619	1,495	2,378	3,265	4,131	-178	662	1,549	2,422	3,325	4,199	-71	706	1,593	2,480	3,387	4,260
#4	-90	387	879	1,372	1,868	2,355	-44	405	900	1,390	1,892	2,382	-1	423	918	1,413	1,917	2,407
#5	-778	-573	-733	-884	-1,028	-1,205	-596	-503	-648	-814	-932	-1,098	-425	-433	-578	-723	-835	-1,001
#6	-376	195	648	1,107	1,570	2,013	-263	238	701	1,151	1,631	2,080	-155	282	745	1,208	1,692	2,141
#7	-469	-269	-281	-285	-287	-308	-355	-226	-227	-242	-226	-241	-248	-182	-183	-185	-166	-180
#8	-482	-332	-407	-475	-539	-624	-368	-289	-353	-431	-479	-557	-261	-245	-310	-374	-418	-496
#9	-410	29	316	610	907	1,184	-296	73	370	654	968	1,251	-188	116	414	711	1,029	1,313
#10	294	2,308	4,720	7,135	9,551	11,958	340	2,326	4,742	7,152	9,575	11,986	383	2,344	4,760	7,177	9,602	12,013
#11	-904	-1,205	-1,998	-2,780	-3,557	-4,366	-722	-1,135	-1,912	-2,711	-3,461	-4,259	-551	-1,066	-1,843	-2,620	-3,364	-4,163
Capital investment (million \$)																		
#1	576	804	1,350	1,889	2,425	2,982	462	760	1,296	1,846	2,365	2,915	355	717	1,253	1,789	2,305	2,854
#2	576	804	1,350	1,889	2,425	2,982	462	760	1,296	1,846	2,365	2,915	355	717	1,253	1,789	2,305	2,854
#3	576	804	1,350	1,889	2,425	2,982	462	760	1,296	1,846	2,365	2,915	355	717	1,253	1,789	2,305	2,854
#4	232	324	544	761	977	1,202	186	306	522	744	953	1,175	143	289	505	721	929	1,150
#5	920	1,284	2,156	3,017	3,873	4,762	738	1,214	2,070	2,948	3,777	4,655	567	1,145	2,001	2,857	3,681	4,558
#6	576	804	1,350	1,889	2,425	2,982	462	760	1,296	1,846	2,365	2,915	355	717	1,253	1,789	2,305	2,854
#7	576	804	1,350	1,889	2,425	2,982	462	760	1,296	1,846	2,365	2,915	355	717	1,253	1,789	2,305	2,854
#8	576	804	1,350	1,889	2,425	2,982	462	760	1,296	1,846	2,365	2,915	355	717	1,253	1,789	2,305	2,854
#9	576	804	1,350	1,889	2,425	2,982	462	760	1,296	1,846	2,365	2,915	355	717	1,253	1,789	2,305	2,854
#10	232	324	544	761	977	1,202	186	306	522	744	953	1,175	143	289	505	721	929	1,150
#11	920	1,284	2,156	3,017	3,873	4,762	738	1,214	2,070	2,948	3,777	4,655	567	1,145	2,001	2,857	3,681	4,558

Table S22. Net profit and capital investment for the national CNG refueling infrastructure in 2045 under different combinations of vehicle range assumptions, shares of natural gas trucks in the total fleet, and economic assumptions in Table S16.

Scenario	320 km (200 miles)						480 km (300 miles)						960 km (600 miles)					
	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%
Net profit (million \$)																		
#1	-328	17	325	633	948	1,226	-231	77	395	680	1,008	1,290	-131	141	439	738	1,043	1,338
#2	-527	-975	-1,658	-2,342	-3,018	-3,732	-429	-915	-1,588	-2,295	-2,958	-3,668	-329	-851	-1,544	-2,238	-2,924	-3,621
#3	-80	1,256	2,804	4,351	5,905	7,423	17	1,317	2,874	4,398	5,966	7,487	117	1,381	2,919	4,457	6,001	7,536
#4	16	747	1,611	2,475	3,342	4,194	55	771	1,639	2,494	3,366	4,220	95	797	1,657	2,518	3,381	4,240
#5	-672	-713	-961	-1,209	-1,446	-1,742	-517	-617	-849	-1,134	-1,350	-1,640	-357	-515	-779	-1,042	-1,295	-1,564
#6	-228	518	1,327	2,136	2,952	3,731	-131	578	1,398	2,184	3,013	3,796	-30	642	1,442	2,241	3,047	3,844
#7	-390	-291	-291	-290	-283	-313	-293	-231	-220	-243	-223	-249	-192	-167	-176	-186	-189	-202
#8	-412	-401	-511	-620	-723	-863	-315	-341	-440	-573	-663	-799	-214	-277	-396	-516	-629	-751
#9	-286	229	749	1,270	1,797	2,287	-189	289	820	1,317	1,858	2,351	-88	353	864	1,375	1,892	2,399
#10	685	4,093	8,304	12,515	16,729	20,928	724	4,118	8,333	12,535	16,754	20,955	765	4,144	8,352	12,560	16,770	20,977
#11	-893	-1,815	-3,164	-4,514	-5,853	-7,250	-737	-1,719	-3,052	-4,439	-5,756	-7,149	-577	-1,617	-2,982	-4,348	-5,703	-7,074
Capital investment (million \$)																		
#1	576	1,223	2,154	3,085	4,010	4,971	479	1,162	2,084	3,038	3,950	4,908	379	1,099	2,040	2,982	3,916	4,861
#2	576	1,223	2,154	3,085	4,010	4,971	479	1,162	2,084	3,038	3,950	4,908	379	1,099	2,040	2,982	3,916	4,861
#3	576	1,223	2,154	3,085	4,010	4,971	479	1,162	2,084	3,038	3,950	4,908	379	1,099	2,040	2,982	3,916	4,861
#4	232	493	868	1,243	1,616	2,003	193	468	840	1,224	1,592	1,978	153	443	822	1,202	1,578	1,959
#5	920	1,953	3,440	4,927	6,404	7,939	765	1,856	3,328	4,852	6,308	7,838	605	1,755	3,258	4,762	6,254	7,763
#6	576	1,223	2,154	3,085	4,010	4,971	479	1,162	2,084	3,038	3,950	4,908	379	1,099	2,040	2,982	3,916	4,861
#7	576	1,223	2,154	3,085	4,010	4,971	479	1,162	2,084	3,038	3,950	4,908	379	1,099	2,040	2,982	3,916	4,861
#8	576	1,223	2,154	3,085	4,010	4,971	479	1,162	2,084	3,038	3,950	4,908	379	1,099	2,040	2,982	3,916	4,861
#9	576	1,223	2,154	3,085	4,010	4,971	479	1,162	2,084	3,038	3,950	4,908	379	1,099	2,040	2,982	3,916	4,861
#10	232	493	868	1,243	1,616	2,003	193	468	840	1,224	1,592	1,978	153	443	822	1,202	1,578	1,959
#11	920	1,953	3,440	4,927	6,404	7,939	765	1,856	3,328	4,852	6,308	7,838	605	1,755	3,258	4,762	6,254	7,763

Table S23. Net profit and capital investment for the regional (California and Texas) CNG refueling infrastructure in 2012 under different combinations of vehicle range assumptions, shares of natural gas trucks in the total fleet, and economic assumptions in Table S16.

Scenario	320 km (200 miles)						480 km (300 miles)						960 km (600 miles)					
	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%
Net profit (million \$)																		
#1	-67	-22	0	21	36	57	-54	-22	-1	18	42	67	-44	-22	6	21	49	71
#2	-80	-87	-131	-175	-226	-270	-67	-87	-131	-179	-219	-260	-57	-87	-125	-175	-213	-256
#3	-51	60	163	267	363	467	-38	60	163	263	370	476	-28	60	170	267	377	480
#4	-17	40	98	155	210	267	-12	40	97	154	212	271	-8	40	100	155	215	273
#5	-117	-84	-98	-113	-138	-153	-96	-84	-99	-118	-128	-137	-80	-84	-88	-113	-117	-131
#6	-61	11	66	120	168	223	-47	11	66	117	175	233	-37	11	72	120	182	237
#7	-71	-42	-41	-40	-45	-44	-58	-42	-41	-43	-39	-34	-48	-42	-34	-40	-32	-31
#8	-73	-50	-56	-62	-74	-80	-60	-50	-56	-65	-68	-71	-49	-50	-49	-62	-61	-67
#9	-65	-8	28	63	92	127	-51	-8	27	60	98	137	-41	-8	34	63	106	141
#10	27	261	539	818	1,094	1,372	32	261	539	816	1,096	1,375	36	261	542	818	1,100	1,378
#11	-132	-157	-244	-331	-429	-516	-111	-157	-244	-337	-418	-500	-94	-157	-233	-331	-408	-495
Capital investment (million \$)																		
#1	84	104	164	224	291	352	70	104	164	228	285	342	60	104	157	224	278	338
#2	84	104	164	224	291	352	70	104	164	228	285	342	60	104	157	224	278	338
#3	84	104	164	224	291	352	70	104	164	228	285	342	60	104	157	224	278	338
#4	34	42	66	90	117	142	28	42	66	92	115	138	24	42	63	90	112	136
#5	134	166	262	358	465	562	112	166	262	364	455	546	96	166	251	358	444	540
#6	84	104	164	224	291	352	70	104	164	228	285	342	60	104	157	224	278	338
#7	84	104	164	224	291	352	70	104	164	228	285	342	60	104	157	224	278	338
#8	84	104	164	224	291	352	70	104	164	228	285	342	60	104	157	224	278	338
#9	84	104	164	224	291	352	70	104	164	228	285	342	60	104	157	224	278	338
#10	34	42	66	90	117	142	28	42	66	92	115	138	24	42	63	90	112	136
#11	134	166	262	358	465	562	112	166	262	364	455	546	96	166	251	358	444	540

Table S24. Net profit and capital investment for the regional (California and Texas) CNG refueling infrastructure in 2045 under different combinations of vehicle range assumptions, shares of natural gas trucks in the total fleet, and economic assumptions in Table S16.

Scenario	320 km (200 miles)						480 km (300 miles)						960 km (600 miles)					
	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%	1%	5%	10%	15%	20%	25%
Net profit (million \$)																		
#1	-56	-19	18	56	87	135	-43	-9	35	66	103	141	-33	-6	32	76	104	141
#2	-78	-130	-203	-276	-355	-418	-65	-120	-186	-266	-338	-411	-55	-116	-189	-255	-338	-411
#3	-29	119	295	470	639	825	-15	129	311	480	656	831	-5	132	308	491	656	832
#4	-6	75	172	270	365	467	-1	79	179	274	371	469	3	80	178	278	372	469
#5	-106	-113	-136	-158	-191	-197	-85	-97	-109	-142	-165	-187	-69	-92	-114	-126	-164	-187
#6	-45	37	130	223	310	414	-32	46	147	233	327	420	-21	50	143	244	327	421
#7	-63	-54	-50	-47	-50	-37	-50	-44	-34	-37	-34	-30	-40	-40	-37	-27	-33	-30
#8	-65	-66	-75	-84	-99	-98	-52	-56	-58	-74	-83	-92	-42	-52	-61	-64	-83	-91
#9	-51	4	66	127	181	253	-38	14	82	137	198	259	-28	18	79	147	198	260
#10	68	448	918	1,389	1,857	2,331	74	451	925	1,392	1,863	2,333	78	453	924	1,397	1,864	2,335
#11	-131	-236	-381	-526	-682	-811	-109	-220	-354	-510	-655	-801	-93	-215	-360	-494	-655	-801
Capital investment (million \$)																		
#1	84	157	258	358	466	556	70	147	241	348	449	549	60	144	245	338	449	549
#2	84	157	258	358	466	556	70	147	241	348	449	549	60	144	245	338	449	549
#3	84	157	258	358	466	556	70	147	241	348	449	549	60	144	245	338	449	549
#4	34	63	104	144	188	224	28	59	97	140	181	221	24	58	99	136	181	221
#5	134	251	412	572	744	888	112	235	385	556	717	877	96	230	391	540	717	877
#6	84	157	258	358	466	556	70	147	241	348	449	549	60	144	245	338	449	549
#7	84	157	258	358	466	556	70	147	241	348	449	549	60	144	245	338	449	549
#8	84	157	258	358	466	556	70	147	241	348	449	549	60	144	245	338	449	549
#9	84	157	258	358	466	556	70	147	241	348	449	549	60	144	245	338	449	549
#10	34	63	104	144	188	224	28	59	97	140	181	221	24	58	99	136	181	221
#11	134	251	412	572	744	888	112	235	385	556	717	877	96	230	391	540	717	877

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END OF APENDIX S1

Appendix S1 is also available online in the ASCE Library: www.ascelibrary.org



About the Fuels Institute

The Fuels Institute, founded by NACS in 2013, is a 501(c)(4) non-profit research-oriented think tank dedicated to evaluating the market issues related to vehicles and the fuels that power them. By bringing together diverse stakeholders of the transportation and fuels markets, the Institute helps to identify opportunities and challenges associated with new technologies and to facilitate industry coordination to help ensure that consumers derive the greatest benefit.

The Fuels Institute commissions and publishes comprehensive, fact-based research projects that address the interests of the affected stakeholders.

Such publications will help to inform both business owners considering long-term investment decisions and policymakers considering legislation and regulations affecting the market. Research is independent and unbiased, designed to answer questions, not advocate a specific outcome. Participants in the Fuels Institute are dedicated to promoting facts and providing decision makers with the most credible information possible, so that the market can deliver the best in vehicle and fueling options to the consumer.

For more about the Fuels Institute, visit fuelsinstitute.org

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The Fuels Institute was founded in 2013 by NACS, the international association that advances convenience and fuel retailing. Through recurring financial contributions and daily operational support, NACS helps the Fuels Institute to invest in and carry out its work to foster collaboration among the various stakeholders with interests in the transportation energy market and to promote a comprehensive and objective evaluation of issues affecting that market and its customers both today and in the future. NACS was founded August 14, 1961, as the National Association of Convenience Stores, and represents more than 2,100 retail and 1,600 supplier company members.

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FUELS INSTITUTE STAFF

JOHN EICHBERGER

Executive Director

jeichberger@fuelsinstitute.org

AMANDA APPELBAUM

Director, Research

aappelbaum@fuelsinstitute.org

DONOVAN WOODS

Director, Operations

dwoods@fuelsinstitute.org

Fuels Institute

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(703) 518-7970
FUELSINSTITUTE.ORG
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1600 DUKE STREET
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ALEXANDRIA, VA 22314