MIT Climate & Sustainability Consortium

# Thought experiment to explore potential savings from pooled charging infrastructure investment

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## 1 Summary

A thought experiment is designed to explore potential savings associated with economies of scale when pooling truck charging infrastructure investments along the U.S. interstate network. It leverages truck stop location and freight flow datasets maintained by the U.S. Department of Transportation (DOT), and considers a scenario in which all truck trips carried out in 2022 are electrified. A simplifying assumption is made that all charging takes place at truck stops.

### 1.1 Investment Scenarios Considered

Truck stop locations from the DOT Bureau of Transportation Statistics located within the U.S. interstate highway network are randomly selected to be provisioned with charging infrastructure. Selected truck stops are required to be separated by 100 miles on average and at minimum 50 miles. Two simplified scenarios are considered for infrastructure investment and usage:

**Full Fleet (pooled investment):** The entire electrified U.S. trucking fleet shares investment and utilization in charging infrastructure at the selected truck stops.

**Half Fleet (separate investment):** The electrified U.S. trucking fleet is equally divided into two sub-fleets (representing two distinct carriers), which invest and utilize charging infrastructure separately at the selected truck stops.

### 1.2 Method to evaluate infrastructure savings

A constraint is applied to cap the maximum average time that any given truck must wait for a charger to free up upon arriving at a station. Freight flow data is then used to estimate the number of chargers needed at each truck stop subject to this maximum wait time constraint.

Infrastructure savings from pooled investment are evaluated at each truck stop based on the reduction in charger-to-truck ratio needed in the full fleet scenario relative to the half fleet scenario:

$$\% \text{ Infrastructure Savings} = \left(1 - \frac{C_N/N}{C_{N/2}/(N/2)}\right) \times 100\% \qquad (1)$$

where N is the average number of trucks expected to stop and charge at the truck stop per day, and $C_N$ is the number of chargers needed at the stop to keep average wait times below the allowable maximum.

## 2 Results

The results of the thought experiment are visualized with an interactive web tool available on the MCSC DataHub, as demoed in this video. The demo allows the user to vary the following parameters in the analysis:

- Truck range (250 miles by default)
- Average charging time (4h by default)
- Cap on average wait time for a charger to become available (30 minutes by default)

Estimated infrastructure savings from pooled investment, shown in Figure 2.1 with the default parameters, vary from 3-30%, depending on the typical volume of trucks passing the station (represented in Figure 2.1 by the width of the nearest highway link). In general, regions with lower truck flow volumes can expect larger potential savings from pooled infrastructure investment, because they have more potential for efficiency gains from increased usage.

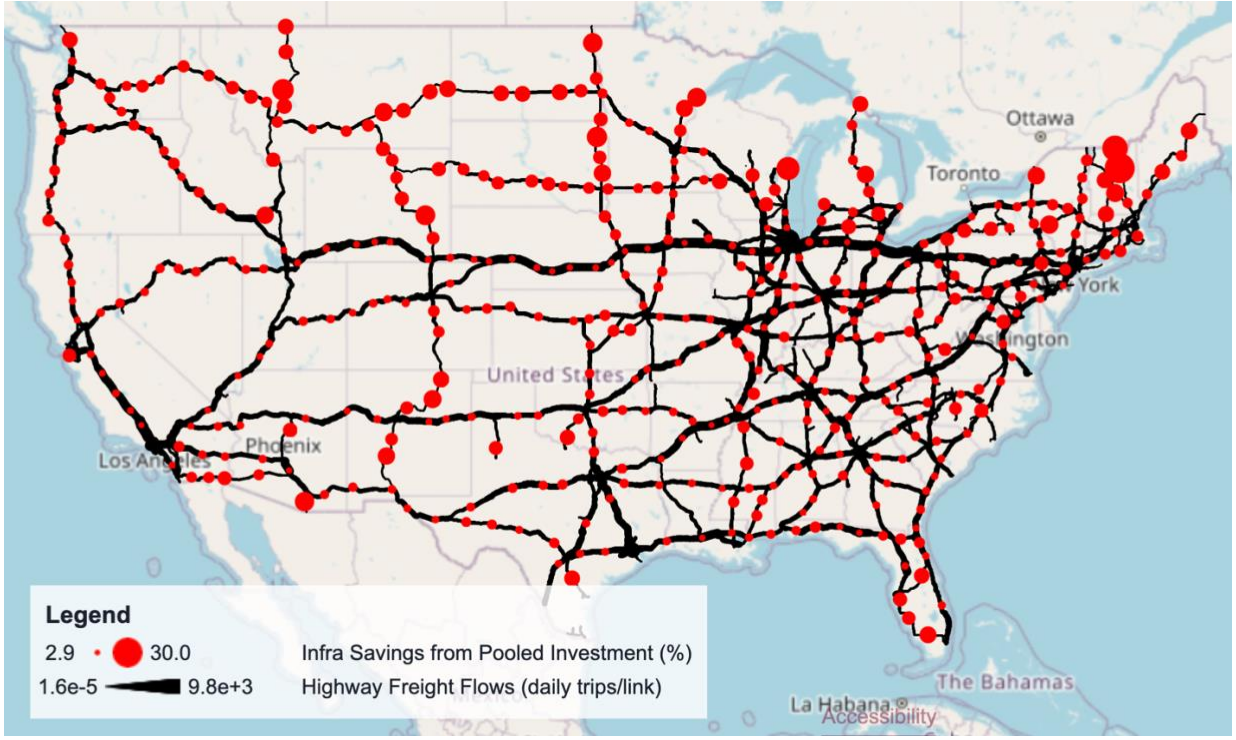



Figure 2.1: Theoretical infrastructure savings from the pooled investment scenario relative to the separate investment scenario.

# 3 Key Takeaways

While it lacks the nuance of a detailed network analysis, this thought experiment highlights two important points:

1) Appreciable savings from pooled infrastructure investment are possible in principle, even at the level the entire U.S. trucking fleet.

2) Benefits of pooled investments are expected to be most pronounced early in the transition when fleet sizes are small, and in regions with relatively low freight flow density.

# 4 Methodology

The methodology underlying the thought experiment is constructed in several steps. Each step is framed as a scenario with an associated question, and builds upon prior steps by adding increasing detail and sophistication.

## 4.1 Wait time for fully occupied chargers

### Scenario

First, consider a single truck stop equipped with C chargers. An EV truck pulls up to the truck stop, but all the chargers are in use.

Figure 4.1: Truck arrives at a truck stop with all chargers in use

### Question

On average, how long will the truck need to wait for a charger to free up as a function of C?

### Approach

We'll make the simplifying assumption that, upon a truck arriving at a station, chargers free up according to Poisson statistics (i.e. the probability of an individual charger freeing up is independent both of when other chargers free up and of when the truck arrived at the station).

Under this assumption, the probability p(t) that a given charger frees up over an infinitesimal time period follows a uniform distribution.

Therefore, the cumulative probability P(t) that a given charger is still in use after a time t is given by:

$$P(t) = \begin{cases} 1 - \frac{t}{T_{ch}} & \text{for } t \leq T_{ch} \\ 0 & \text{for } t > T_{ch} \end{cases} \quad (2)$$

Where $T_{ch}$ is the average time needed for the trucks to charge. Given that there are C chargers at the stop, the probability $P_C(t)$ that the truck is still waiting for a charger after time $t$ is given by:

$$P_C(t) = \begin{cases} \left(1 - \frac{t}{T_{ch}}\right)^C & \text{for } t \leq T_{ch} \\ 0 & \text{for } t > T_{ch} \end{cases} \quad (3)$$

The average wait time is given by:

$$\mu_C = \int_0^{T_{ch}} t\, P_C(t) dt \quad (4)$$

Figure 4.2 shows $\mu_C$ as a function of C, with $T_{ch}$=4h.

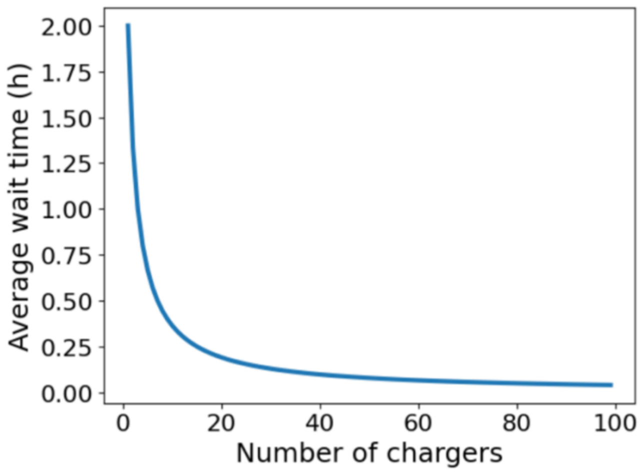



Figure 4.2: Average wait time $\mu_C$ as a function of number of chargers C for a charging time $T_{ch}$=4h

## Key Finding

Average wait time varies inversely with the number of chargers.

## 4.2 Wait time for chargers with a queue

### Scenario

Suppose now that, upon arrival, there's a queue of Q other trucks waiting to charge.

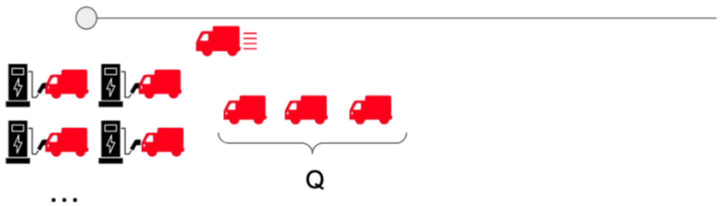



Figure 4.3: Truck arrives at truck stop with all chargers in use, and with a queue of length Q trucks waiting to charge

### Question

How does the average wait time vary as a function of C and Q?

### Approach

If there's one truck in the queue (Q=1), the newly arrived truck will need to wait for a period $\mu_C$ (from Equation 4) on average for the truck ahead to start charging. Once a charger frees up, the truck ahead will begin charging, and there will be C-1 chargers left available to free up before the charging period $T_{ch}$ has passed since the truck arrived (note: once $T_{ch}$ has passed, all remaining C-1 chargers will necessarily have freed up).

The average wait time $\mu_C(Q = 1)$ with one truck in the queue is thus given by:

$$\mu_C(Q = 1) = \mu_C(Q = 0) + \int_{\mu_C(Q=0)}^{T_{ch}} tP_{C-1}(t)dt \tag{5}$$

We can now generalize this to any queue length Q, as follows.

If the queue length is smaller than or equal to the number of available chargers ($Q \leq C$), then:

$$\mu_C(Q) = \sum_{i=1}^{Q} \left[\mu(i-1) + \int_{\mu(i-1)}^{4\text{h}} tP_{C-i}(t)dt\right] \qquad \text{for } Q \leq C \tag{6}$$

If the queue length exceeds the number of available chargers ($Q > C$), then the newly arrived truck will necessarily need to wait for the $C \times \text{floor}(Q/C)$ trucks in front to complete a full charge. For the $R = Q - C \times \text{floor}(Q/C)$ trucks remaining in the queue after the first $C \times \text{floor}(Q/C)$ complete their full charge, the wait time will be given by $\mu_C(R)$.

Therefore, letting $F = \text{floor}(Q/C)$:

$$\mu_C(Q) = \text{F} \times T_{ch} + \mu_C(R) \qquad \text{for } Q > C \tag{7}$$

Figure 4.4 shows $\mu_C(Q)$ as a function of the queue length Q for a range of charger numbers C, assuming $T_{ch} = 4h$.

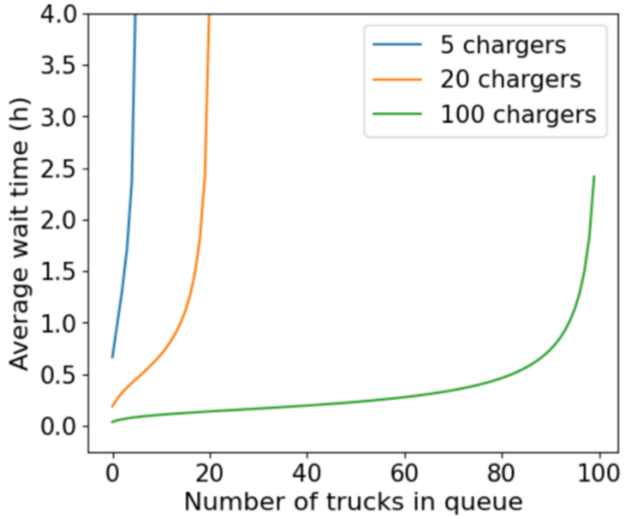



Figure 4.4: Average wait time $\mu_C(Q)$ for a newly arrived truck to start charging as a function of the number $Q$ of trucks in the queue, for several options for the number C of chargers at the truck stop

**Key Finding**

Average wait time increases rapidly as the number Q of trucks in the queue approaches the number C of available chargers.

In the following sections, we suppose that N trucks stop to charge at a given truck stop per day on average, and evaluate:

1) The average wait time at a given truck stop equipped with C chargers (Section 4.3), and
2) The minimum ratio of chargers installed to N daily truck stops ("charger-to-truck ratio") needed to keep wait times below a given threshold (Section 4.4).

In Sections 4.5 and 4.6, we apply the methodology developed up to Section 4.4 to randomly selected truck stops in the U.S. interstate network that see a range of daily truck stop rates N, for a hypothetical scenario in which all U.S. truck flows are electrified.

## 4.3 Average wait time for chargers

### Scenario

Consider a truck stop along a highway interstate equipped with C chargers. Suppose that N trucks stop to charge at the truck stop per day on average. Assume trucks take an average time $T_{ch}$ to charge at the station.

### Question

For a truck arriving at the station at random, what is the average time that it will wait for a charger?

### Approach

Assuming the likelihood of a given truck arriving is independent of truck arrivals preceding it, the probability that there will be X other trucks charging at the station is given by the following binomial distribution:

$$P(X) = \binom{N-1}{X}\left(\frac{T_{ch}}{24\text{h}}\right)^{X}\left(\frac{24\text{h} - T_{ch}}{24\text{h}}\right)^{N-1-X} \tag{8}$$

where it's assumed that the charging time $T_{ch}$ is in hours.

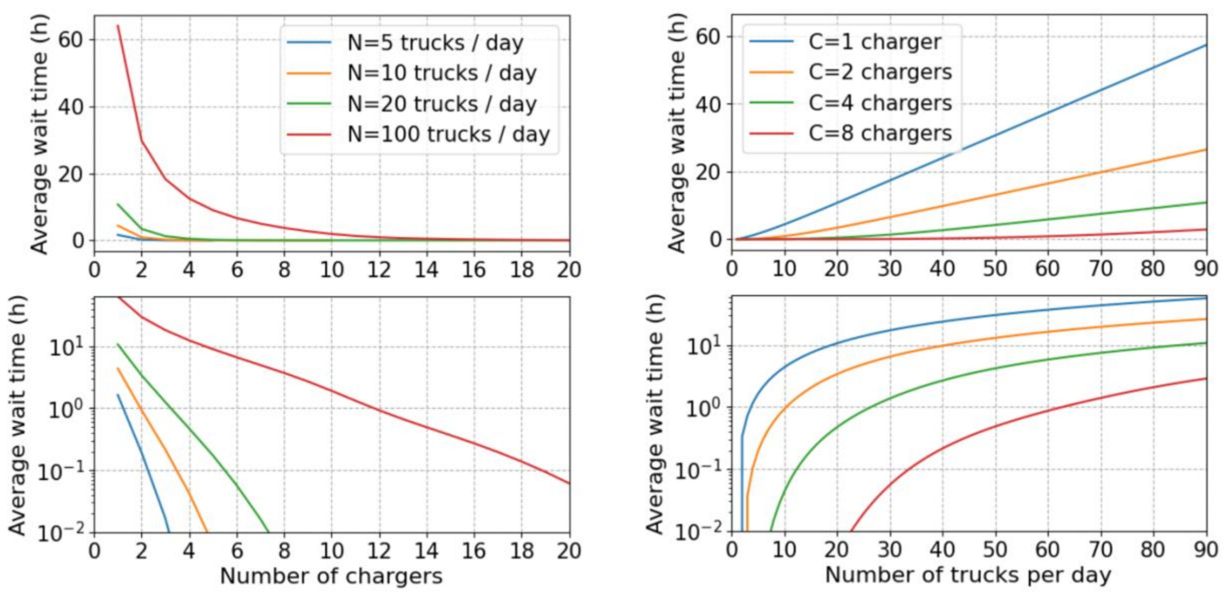
For a given number X of other trucks charging when the truck arrives, there will be a queue of length:

$$Q(\text{X}, \text{C}) = \begin{cases} X - C & \text{for } X > C \\ 0 & \text{for } X \leq C \end{cases} \tag{9}$$

The average wait time $t_{\text{wait}}(N, C)$ is thus given by:

$$t_{\text{wait}}(N, C) = \sum_{X=C}^{N} P(\text{X}) \cdot \mu_C(X - C) \tag{10}$$

Figure 4.5 shows $t_{\text{wait}}(N, C)$ for various choices of N and C.




a) As a function of number C of chargers

b) As a function of number N of trucks per day

Figure 4.5: Average time $t_{\text{wait}}(N, C)$ for a charger to free up, for a truck arriving at a station with C chargers that receives on average N daily truck stops. Top row: linear y-axis. Bottom: log-scale y-axis.

## Key Finding

Average wait time increases with the number N of trucks stopping to charge per day, but can be reduced to a negligible level provided sufficient chargers are installed.

### 4.4 Minimum charger-to-truck ratio to keep wait time for chargers below a threshold

#### Scenario

We now apply a constraint that the average wait time be below some threshold $t_{\text{wait, max}}$.

#### Question

Given N trucks stopping to charge at the stop per day, what is the minimum charger-to-truck ratio needed to satisfy this constraint?

#### Approach

To answer this, consider candidate values for the number $C$ of chargers at the station ranging from 1 to N. For each candidate value $C_{\text{cand}}$, $t_{\text{wait}}(N, C_{\text{cand}})$ is evaluated using Equation 10. Using this method, we identify the minimum value $C_{\text{min}}$ such that $t_{\text{wait}}(N, C_{\text{min}}) < t_{\text{wait, max}}$. The minimum charger-to-truck ratio $r_{\text{min}}$ is then evaluated as: $r_{\text{min}} = \frac{C_{\text{min}}}{N}$.

Figure 4.6 shows $r_{\text{min}}$ as a function of the number of trucks stopping to charge per day, for $T_{ch} = 4\text{h}$ and $t_{\text{wait, max}} = 30$ minutes.

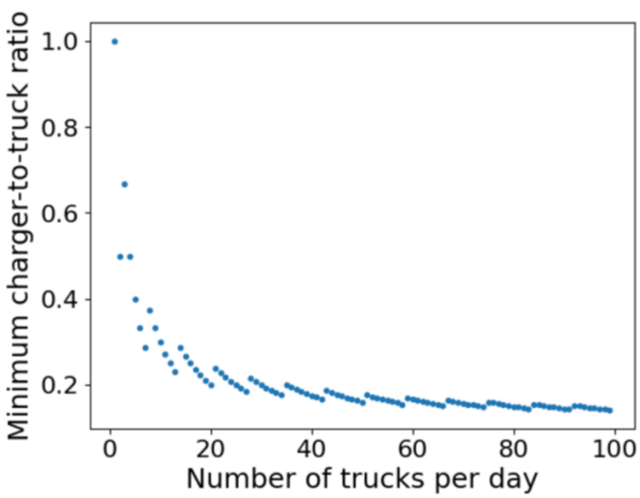



Figure 4.6: Minimum charger-to-truck ratio $r_{\text{min}}$ as a function of the number N of trucks stopping to charge at the station per day, assuming a charging time $T_{ch}$ of 4h and a maximum allowable average wait time $t_{\text{wait, max}}$ of 30 minutes.

**Key Finding**

The minimum charger-to-truck ratio $r_{\text{min}}$ varies inversely with daily truck charges N, with minor discontinuities arising from integer increments to the number C of chargers.

## 4.5 Application to the U.S. highway network

### Background

The DOT maintains a database of truck stop locations in the U.S. Assuming trucks have a range of 100 miles or more, we randomly select truck stops from this database to equip with charging infrastructure. The truck stops are required to be along the U.S. interstate network. Adjacent stops are required to be separated by 100 miles on average, and at least 50 miles.

Figure 4.7 compares the truck stop network before and after this random selection.

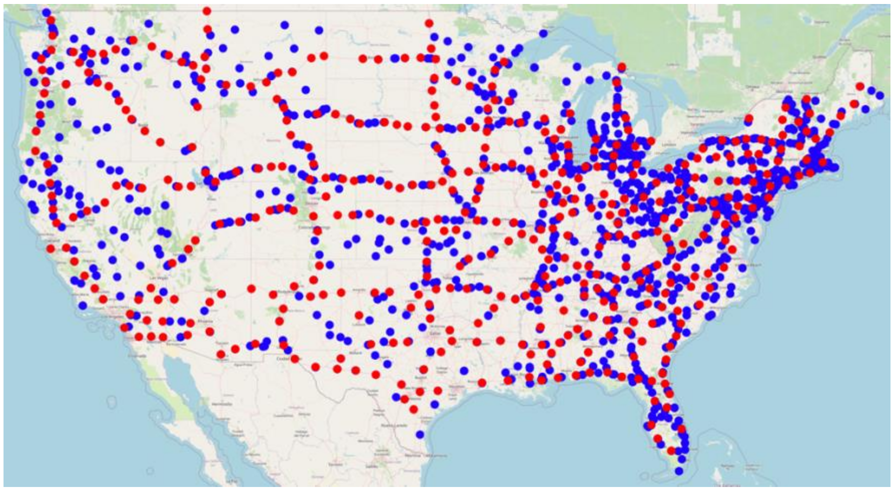


Figure 4.7: U.S. truck stop network before (blue) and after (red) randomly selecting stops separated by 100 miles on average and at least 50 miles

### Scenario

Consider a hypothetical scenario in which all 2022 U.S. truck trips are carried out with battery electric trucks (BETs).

### Question

For a BET arriving at a station at random, what is the minimum charger-to-truck ratio needed to ensure that the average wait time for chargers stays below 30 minutes?

### Approach

First, the randomly selected truck stops are overlaid on the highway interstate network. For each link of the interstate network, the number of trucks passing over the link per day is quantified using data from the DOT's Freight Analysis Framework. The number $N_{\text{pass}}$ of trucks passing each truck stop per day is then evaluated based on the nearest interstate highway link.

Figure 4.8 shows the selected truck stops overlaid on the highway interstate network, where the width of each link in the interstate network is proportional to the number of daily truck trips over it. Similarly, the size of each truck stop is proportional to the number of daily truck trips passing over the nearest interstate highway link.

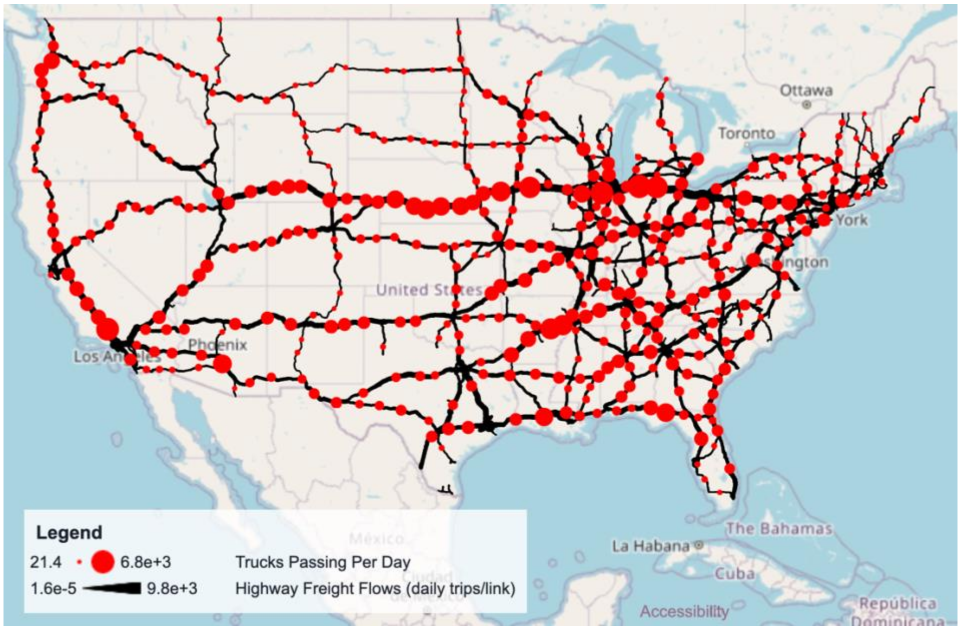


Figure 4.8: Number of trucks passing each selected truck stop per day

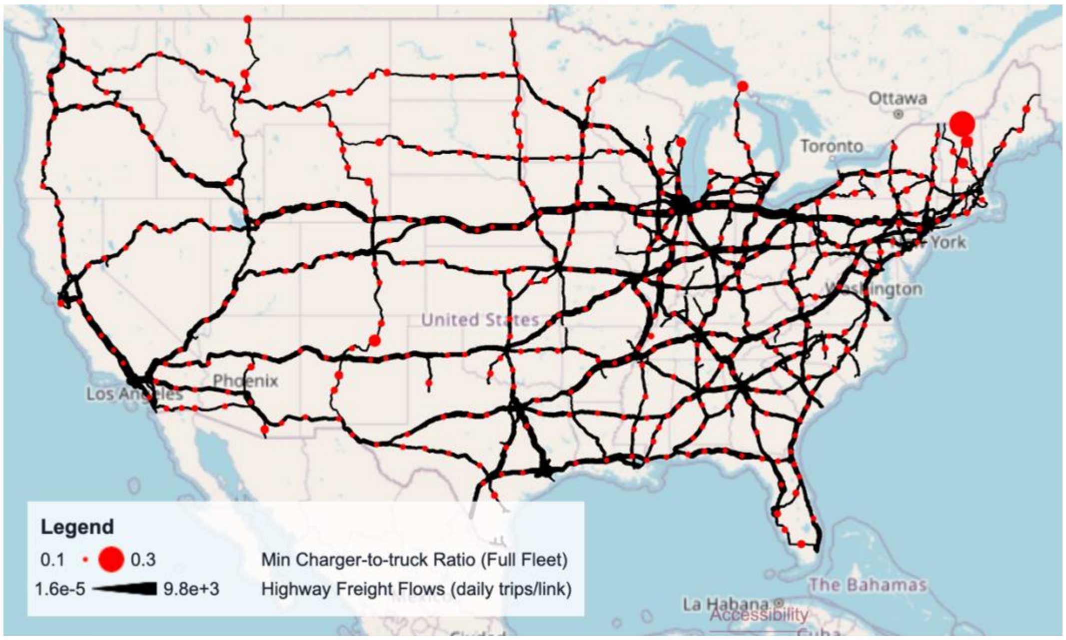
Assuming trucks will only stop when their battery is nearly depleted, the number N of trucks stopping to charge per day at each station is then estimated from the truck's range $R$ as follows:

$$N = N_{\text{pass}} \left( \frac{100 \text{ miles}}{R} \right) \tag{11}$$

Using the obtained N for each truck stop, we follow the procedure in steps 3.1-3.4 to evaluate the minimum charger-to-truck ratio. The results are illustrated in Figure 4.9 for the default parameters ($R = 250$ miles, $T_{ch} = 4$h and $t_{\text{wait, max}} = 30$ minutes).


a) Truck charges per day


b) Minimum required chargers




c) Minimum charger-to-truck ratio

Figure 4.9: Results of applying the analysis outlined in steps 3.1-3.4 to randomly selected truck stops along the U.S. interstate network.

## Key Finding

Minimum charger-to-truck ratios vary from 0.1 to 0.3 over the U.S. interstate system, and are typically higher in areas with relatively low truck flows.

## 4.6 Estimating savings from pooled vs. separate investment and usage of charging infrastructure

### Scenario

The above step assumed that all charging infrastructure is shared among the entire electrified trucking fleet. To evaluate potential savings from pooled infrastructure investments, consider an alternative scenario in which the U.S. trucking fleet is divided equally into two sub-fleets that purchase and utilize charging infrastructure separately.

Thus, we now have two possible infrastructure investment strategies:

**Full Fleet (pooled investment):** The entire electrified U.S. trucking fleet shares investment and utilization in charging infrastructure at the selected truck stops.

**Half Fleet (separate investment):** The electrified U.S. trucking fleet is equally divided into two sub-fleets (representing two distinct carriers), which invest and utilize charging infrastructure separately at the selected truck stops.

### Question

At each truck stop, what are the potential infrastructure savings per truck from the pooled investment scenario (full fleet) compared with the separate investment (half fleet) scenario?

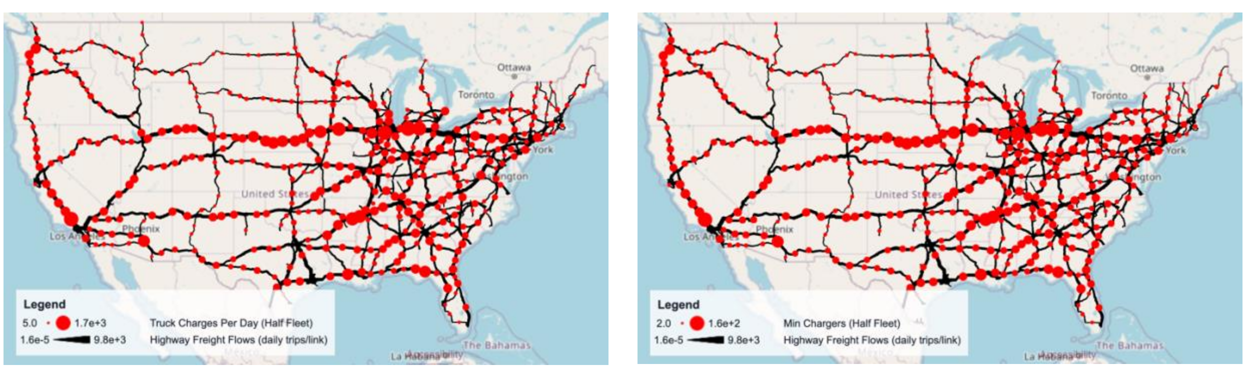
### Approach

To assess the potential infrastructure savings, we repeat the analysis in step 4.5 for only half the U.S. fleet (half fleet scenario) and compare the resulting increase in the charger-to-truck ratio to evaluate the potential per-truck infrastructure savings:

$$\%\ \text{Infrastructure Savings} = \left(1 \frac{C_N/N}{C_{N/2}/(N/2)}\right) \times 100\% \qquad (12)$$

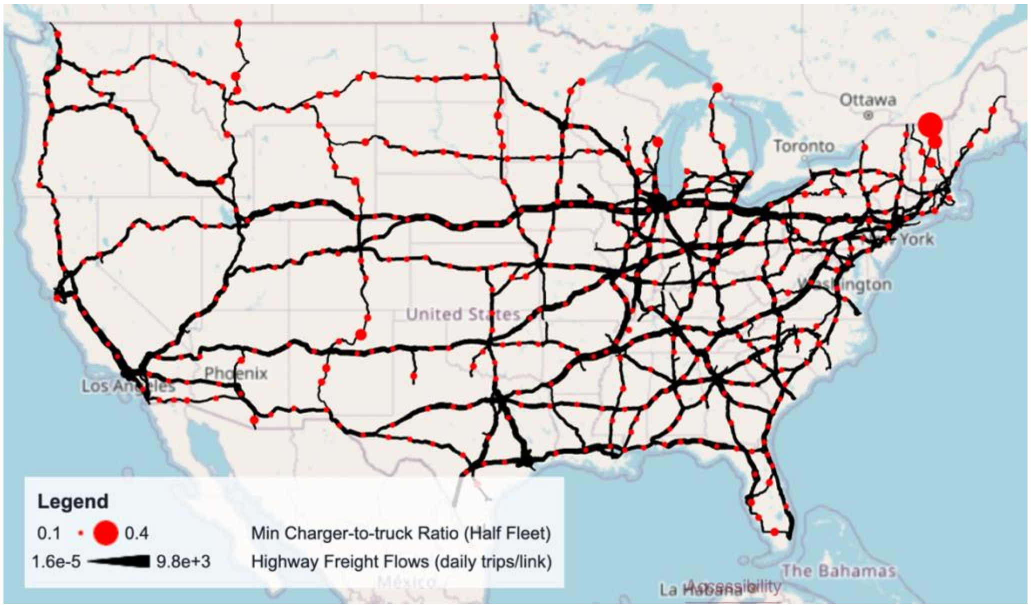
where N (or N/2) is the average number of trucks expected to stop and charge at the truck stop per day in the full fleet (or half fleet) scenario, and $C_N$ (or $C_{N/2}$) is the number of chargers needed at the stop to keep average wait times below the allowable maximum in the full fleet (or half fleet) scenario.

Figure 4.10 illustrates the results of applying steps 3.1-3.4 in the half fleet scenario with the default parameters, and Figure 4.11 visualizes the % infrastructure savings of pooled investment, evaluated with Equation 12.




a) Truck charges per day

b) Minimum required chargers




c) Minimum charger-to-truck ratio

Figure 4.10: Results of applying the analysis outlined in steps 3.1-3.4 to randomly selected truck stops along the U.S. interstate network in the half fleet scenario.

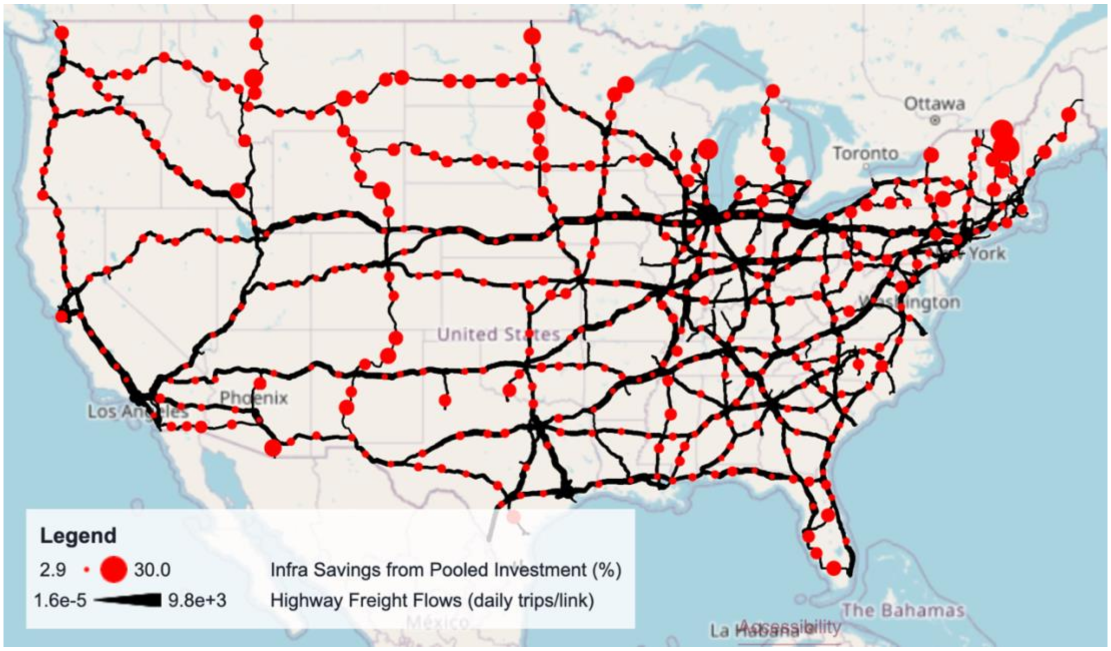



Figure 4.11: Evaluated % infrastructure savings from pooled investment in the full fleet scenario, relative to separate investments and usage in the half fleet scenario.

## Key Finding

Potential savings from pooled infrastructure investment range from 3-30% over the U.S. interstate system, and regions with lower truck flow volumes can expect larger savings.