MIT Climate & Sustainability Consortium

Where can companies pool resources to lower the barriers to decarbonizing transportation?

Appendix to the MCSC Parallel Session Pre-read

Event Date: November 16, 2023

Appendix: Estimating infrastructure savings from pooled investment

The theory underlying the pooled infrastructure analysis, presented in Section 3.2 of the pre-read, is constructed in several steps.

Step 1: Wait time for fully occupied chargers

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

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

Fig. A1: Truck arrives at a truck stop with all chargers in use.

We'll make the simplifying assumption that the truck charging process follows Poisson statistics (i.e. the probability of an individual charger freeing up is independent both of when the charger freed up and 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:

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

Where T_c 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:

$$P_C(t) = \begin{cases} \left(1 - \frac{t}{T_{ch}}\right)^C & \text{for } t \leq T_{ch} \\ 0 & \text{for } t > T_{ch} \end{cases} \tag{2}$$

The average wait time is given by:

$$\mu_C = \int_0^{T_{ch}} t\, P_C(t) dt \tag{3}$$

Fig. A2 shows μ_C as a function of C, with T_{ch}=4h.

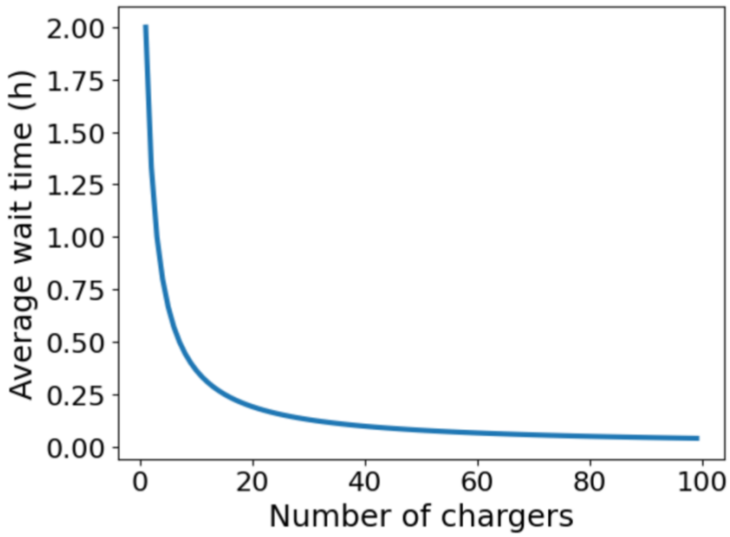


Fig. A2: Variation of average wait time μ_C as a function of number of chargers C for a charging time T_{ch}=4h.

Step 2: Wait time for chargers with a queue

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

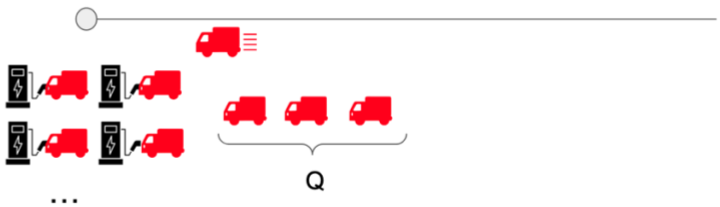


Fig. A3: Truck arrives at truck stop with all chargers in use, and a queue of length Q trucks waiting to charge.

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

If there's one truck in the queue (Q=1), the newly arrived truck will need to wait for a period μ_C 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:

$$\mu_C(Q = 1) = \mu_C(Q = 0) + \int_{\mu_C(Q=0)}^{T_{ch}} tP_{C-1}(t)dt \quad (4)$$

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:

$$\mu_C(Q) = \sum_{i=1}^{Q} \left[\mu(i-1) + \int_{\mu(i-1)}^{4\text{h}} tP_{C-i}(t)dt\right] \qquad \text{for } Q \leq C \quad (5)$$

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

$$\mu_C(Q) = \text{F} \times T_{ch} + \mu_C(R) \qquad \text{for } Q > C \quad (6)$$

Fig. A4 shows the $\mu_C(Q)$ as a function of the queue length Q for a range of charger numbers C, assuming $T_{ch} = 4h$.

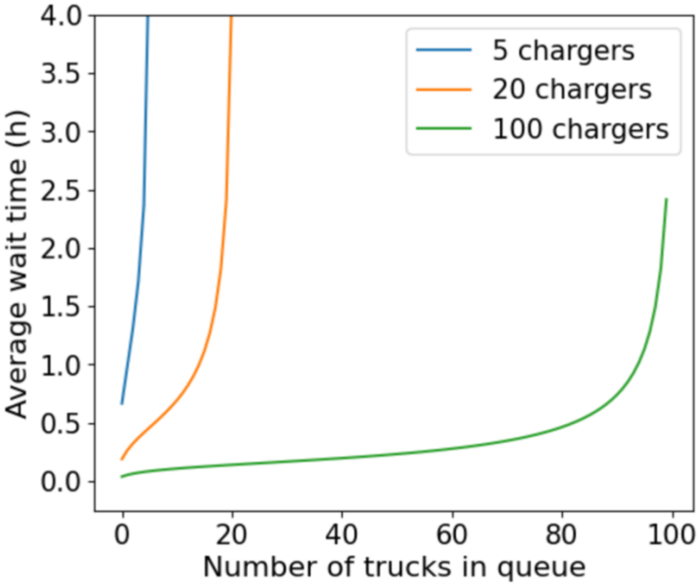


Fig. A4: Average wait time $\mu_C(Q)$ for a newly arrived truck to start charging, as a function of the number Q of trucks in the queue, shown for several options for the number C of chargers at the truck stop.

Step 3: Average wait time for chargers

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

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

Assuming that truck arrivals follow Poisson statistics (i.e. 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:

$$P(X) = \binom{N-1}{X} \left(\frac{T_{ch}}{24\text{h}}\right)^{X} \left(\frac{24\text{h} - T_{ch}}{24\text{h}}\right)^{N-1-X} \quad (7)$$

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:

$$Q(\text{X, C}) = \begin{cases} X - C & for\ X > C \\ 0 & for\ X \leq C \end{cases} \quad (8)$$

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

$$t_{\text{wait}}(N, C) = \sum_{X=C}^{N} P(\mathrm{X}) \cdot \mu_C(X - C) \quad (9)$$

Fig. A5 shows $t_{\text{wait}}(N, C)$ for various choices of N and C.

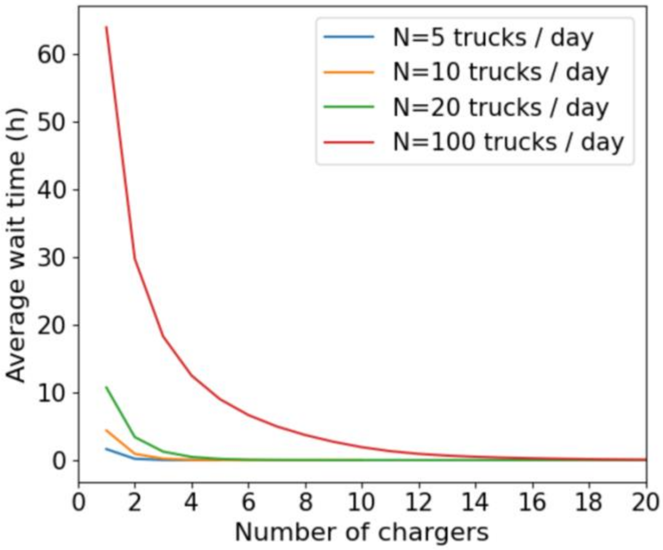


Fig. A5: Average time $t_{\text{wait}}(N, C)$ for a charger to free up, for a truck arriving randomly at a station with C chargers that receives on average N trucks stopping to charge per day.

Step 4: Minimum charger-to-truck ratio to keep wait time for chargers below a given threshold

Now, let's apply a constraint that the average wait time be below some maximum threshold $t_{\text{wait, max}}$.

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

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_{cand}, $t_{\text{wait}}(N, C_{\text{cand}})$ is evaluated using Eq. 9. Using this method, we identify the minimum value C_{min} such that $t_{\text{wait}}(N, C_{\text{min}}) < t_{\text{wait, max}}$. The minimum charger-to-truck ratio r_{min} is then evaluated as:

Fig. A6 shows r_{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 In general, the minimum charger-to-truck ratio drops quickly as the number of daily truck charges increases up to a certain point (in this case ~20 charges/day), beyond which the

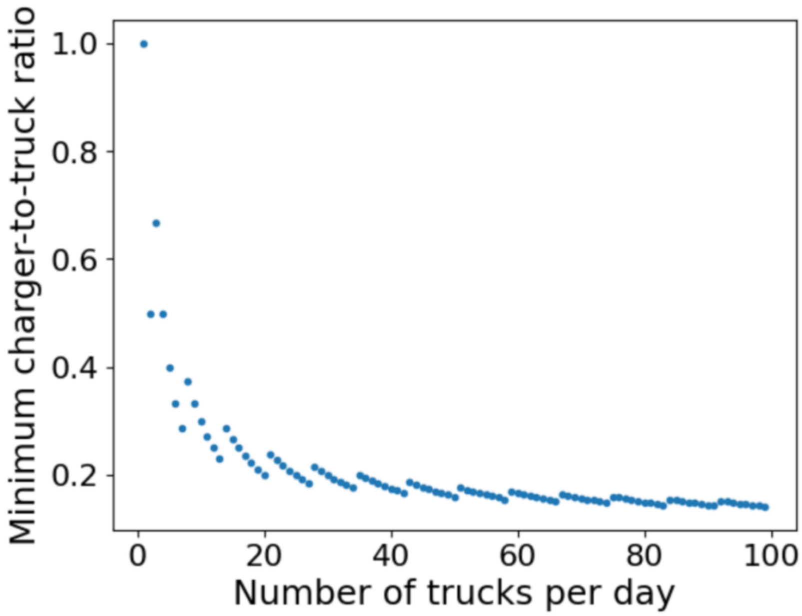


Fig. A6: Minimum charger-to-truck ratio r_{min} as a function of the number N of trucks stopping to charge at the station per day, assuming a charging time T_{ch} of 4h and a maximum allowable average wait time $t_{\text{wait, max}}$ of 30 minutes.

Step 5: Application to the U.S. highway network

The DOT maintains a database of truck stop locations in the U.S. Assuming that 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.

Fig. A7 compares the truck stop network before and after this random selection.

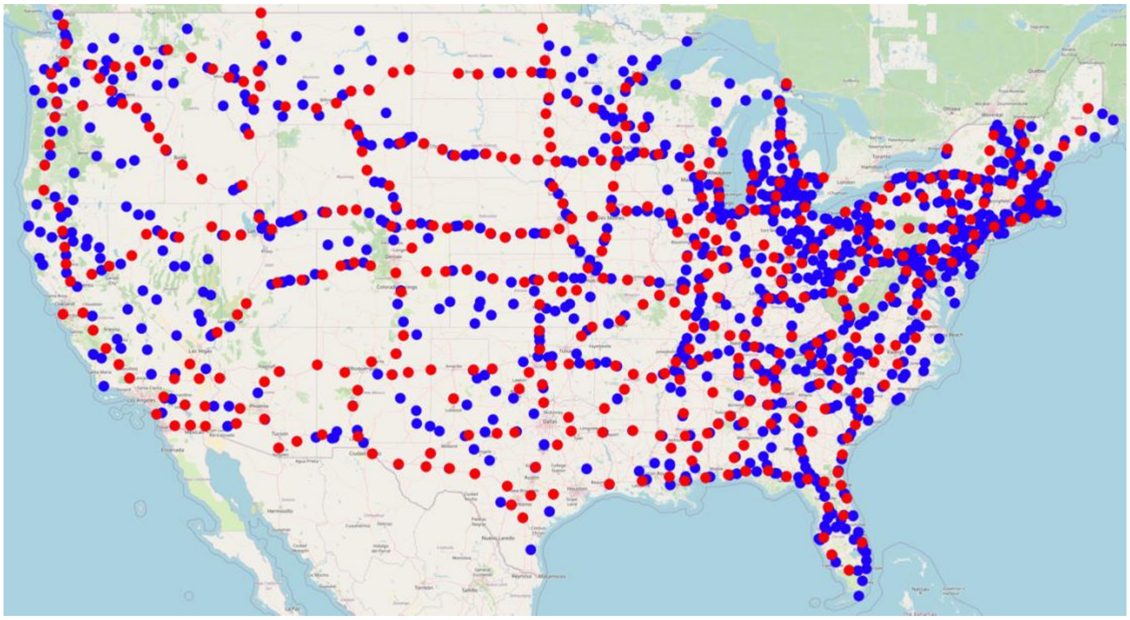


Fig. A7: U.S. truck stop network before (blue) and after (red) randomly selecting stops separated by 100 miles on average and at least 50 miles.

Question: Consider a hypothetical scenario in which all 2022 U.S. truck trips are carried out with BEV trucks. For a BEV truck 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?

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_{pass} of trucks passing each truck stop per day is then evaluated based on the nearest interstate highway link.

Fig. A8 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.

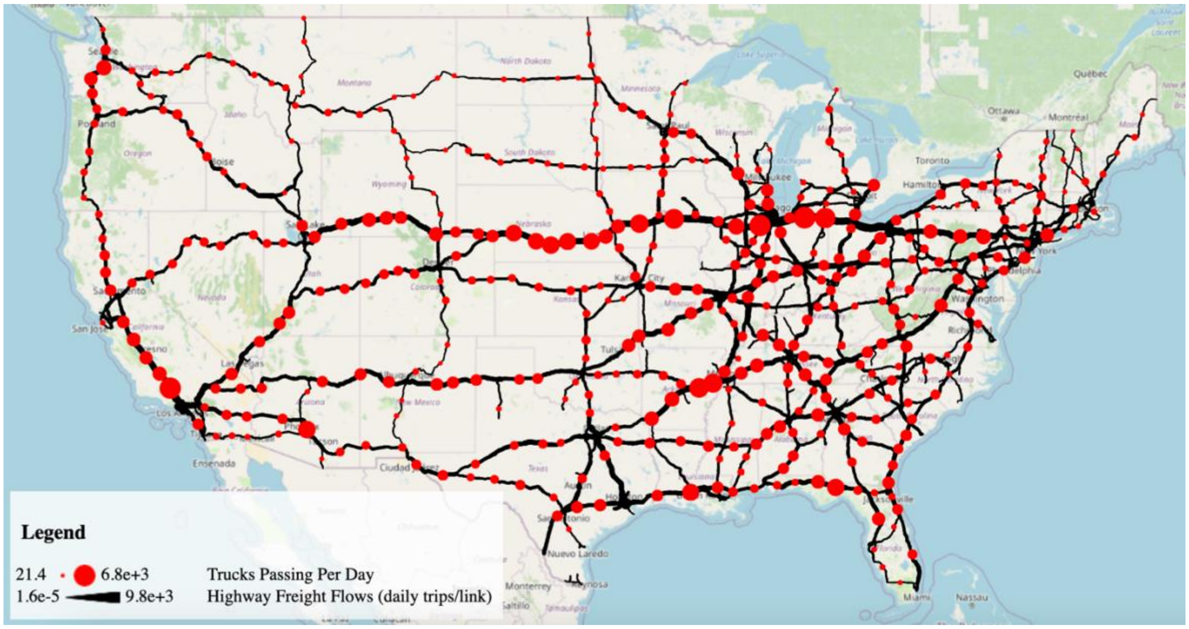


Fig. A8: Number of trucks passing each selected truck stop per day

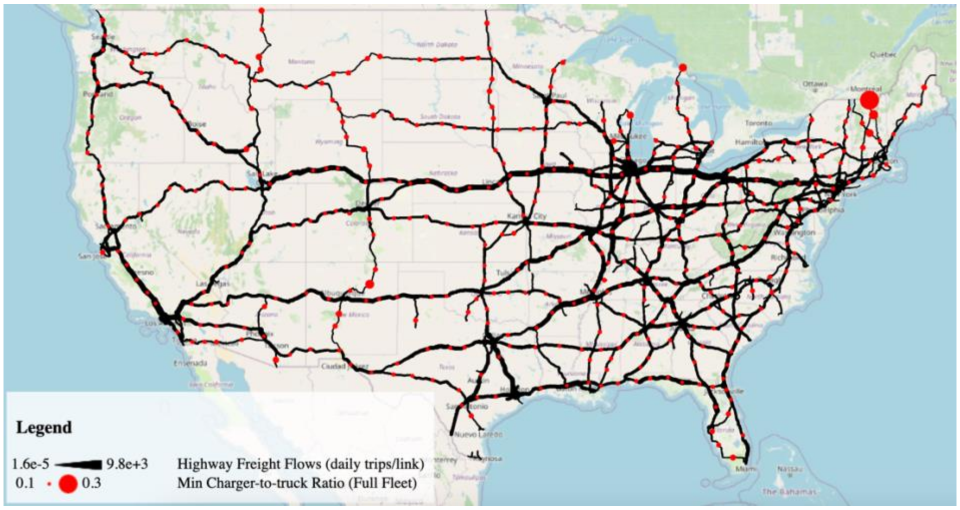
Assuming that trucks will only stop when their battery is nearly depleted, the number N of trucks stopping to charge per day at each station is then estimated from the truck's range R as follows:

$$N = N_{\text{pass}} \left(\frac{\text{floor}(R)}{100 \text{ miles}} \right) \tag{10}$$

Using the obtained N for each truck stop, we follow the procedure in steps 1-4 to evaluate the minimum charger-to-truck ratio. The results are illustrated in Fig. A9 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

Fig. A9: Results of applying the analysis outlined in steps 1-4 to randomly selected truck stops along the U.S. interstate network.

Step 6: Estimating savings from pooled vs. separate investment and usage of charging infrastructure

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 fleets is divided equally into two sub-fleets (representing two separate carrier companies) that purchase and utilize charging infrastructure separately.

Thus, we now have two possible scenarios:

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?

To assess the potential infrastructure savings, we repeat the analysis in step 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:

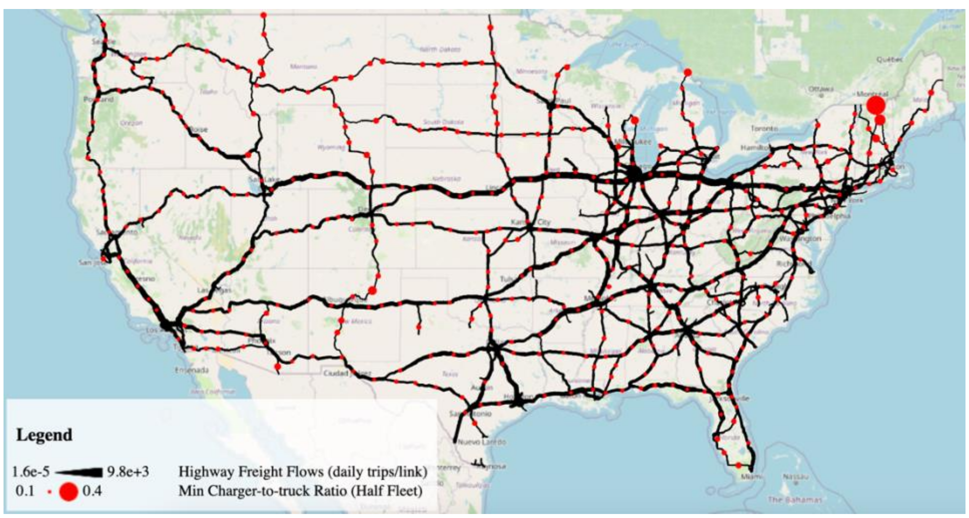
$$\% \text{ Infrastructure Savings} = \left(1 \frac{C_N/N}{C_{N/2}/(N/2)}\right) \times 100\% \qquad (11)$$

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

Fig. A10 illustrates the results of applying steps 1-4 in the half fleet scenario with the default parameters, and Fig. A11 visualizes the % infrastructure savings of pooled investment, evaluated with Eq. 11.

a) Truck charges per day

b) Minimum required chargers



c) Minimum charger-to-truck ratio

Fig. A10: Results of applying the analysis outlined in steps 1-4 to randomly selected truck stops along the U.S. interstate network in the half fleet scenario.

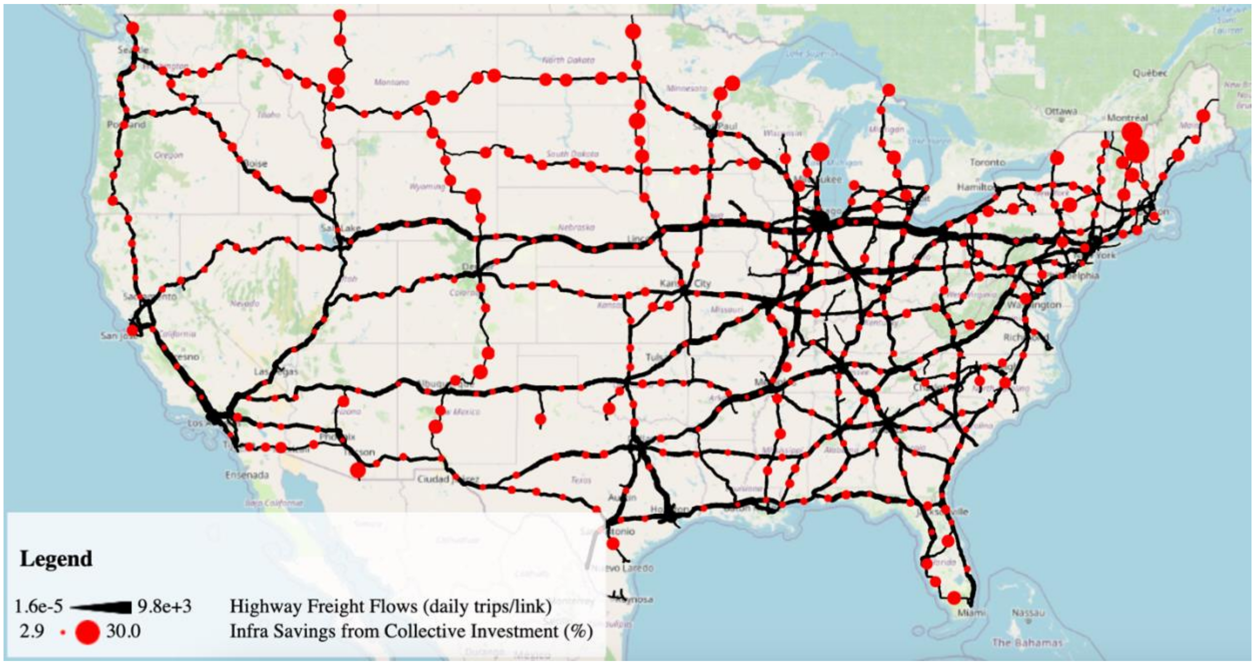


Fig. A11: Evaluated % infrastructure savings from pooled investment in the full fleet scenario, relative to separate investments and usage in the half fleet scenario.