DIGITAL SYSTEMS
SYSTEMS ENGINEERING

Reconciliation of Electric Road System (ERS) Utilization Estimations from Two Seemingly Conflicting Reports

Jakob Rogstadius

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Summary

Data have been published stating that of all heavy trucks (>16 ton) that drive at least 5 days per year on the main Swedish road network (Malmö-Göteborg-Stockholm), only 15% drive more than 50% of their annual mileage on this road network [1]. Intuitively, this gives the impression that charging infrastructure placed on the main road network cannot contribute greatly to electrification of heavy trucks.

Meanwhile, route-based simulation of charging preferences on the Swedish road network has concluded that if Electric Road Systems (ERS) infrastructure is deployed on the main Swedish road network, >95% of heavy traffic on this road network would have sufficient financial incentive to becomes users of the ERS charging infrastructure [2].

This notebook explains how the data from [1] aligns with the findings in [2], namely that the vast majority of heavy traffic on the main Swedish road network would have an incentive to use ERS, if such infrastructure was deployed. This is done by:

1. converting the data in [1] from ratio of trucks into ratio of traffic, which was not done in [1];
2. taking battery charging from ERS into account, which was not considered in [1];
3. considering what happens when ERS is built also outside Sweden, which was an assumption in [2] but not in [1].

For transparency and reproducibility, all input-data, calculation steps and code to generate figures are provided as self-contained Python code, to be executed in a Jupyter Notebook.

The scope of this notebook is only to demonstrate that the data in [1] allow for the conclusions in [2]. No claims are made here (or in [1]) regarding the financial (dis)incentives for dynamic charging of vehicles via ERS.

Major Assumptions

While driving on ERS, a heavy truck can draw at least 200 kW of continuous power, split between propulsion and charging. If there are gaps in the infrastructure, the maximum power per vehicle is increased proportionally.

For a truck to have incentive to use ERS, ERS should be capable of delivering at least 40% of its annual energy (>40% of annual distance on the ERS network was assumed in [1], while simulation results in [2] indicated ERS will deliver approximately half of all electrical energy to heavy trucks).

Conclusions

If ERS is installed on (and only on) the Swedish road network joining Malmö, Göteborg and Stockholm, then the data in [1] shows trucks making up over 60% of heavy traffic on this road network would be drawing power from the infrastructure (figure 10).

If ERS is installed on (and only on) major European high-speed roads, including in Sweden, then approximately 95 % of long-haul vehicles would be ERS users. Translated into ratio of traffic, this represents >98% on the same road network, in agreement with the findings in [2].

The mobility patterns in the data from [1] show that trucks in regional operation are well suited for ERS use, due to their high charging potential per driven km (figure 8).

Regarding trucks in regional operation, these were not considered as potential ERS users in [1], as it was assumed their entire charging needs could be met with static depot charging. The analysis in [2] indicates that a combination of night-time charging at depot and day-time charging from ERS would be cost minimizing for operators, as the addition of dynamic day-time dynamic charging allows for economic battery savings.

Sources

[1] Natanaelsson, Kenneth, et al. (2021). *Analysera förutsättningar och planera för en utbyggnad av elvägar*, Trafikverket. Available at https://urn.kb.se/resolve?urn=urn%3Anbn%3Ase%3Atrafikverket%3Adiva-4498

[2] Rogstadius, Jakob (2022). *Interaktionseffekter mellan batterielektriska lastbilar, elvägar och statisk laddinfrastruktur: Resultat från högupplöst simulering av godstransporter på det svenska vägnätet under perioden 2020–2050*, RISE Rapport 2022:110. Available at https://urn.kb.se/resolve?urn=urn%3Anbn%3Ase%3Ari%3Adiva-61185

[3] Lastbilstrafik 2021, Trafikanalys, 2022. Available at https://www.trafa.se/vagtrafik/lastbilstrafik/

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Reconciliation of Electric Road System (ERS) Utilization Estimations from Two Seemingly Conflicting Reports

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1 Summary

Estimations from Two Seemingly Conflicting Reports

Data have been published stating that of all heavy trucks (>16 ton) that drive at least 5 days per year on the main Swedish road network (Malmö-Göteborg-Stockholm), only 15% drive more than 50% of their annual mileage on this road network [1]. Intuitively, this gives the impression that charging infrastructure placed on the main road network cannot contribute greatly to electrification of heavy trucks.

Meanwhile, route-based simulation of charging preferences on the Swedish road network has concluded that if Electric Road Systems (ERS) infrastructure is deployed on the main Swedish road network, >95% of heavy traffic on this road network would have sufficient financial incentive to becomes users of the ERS charging infrastructure [2].

This notebook explains how the data from [1] aligns with the findings in [2], namely that the vast majority of heavy traffic on the main Swedish road network would have an incentive to use ERS, if such infrastructure was deployed. This is done by:

- converting the data in [1] from *ratio of trucks* into *ratio of traffic*, which was not done in [1];
- taking battery charging from ERS into account, which was not considered in [1];
- considering what happens when ERS is built also outside Sweden, which was an assumption in [2] but not in [1].

The scope of this notebook is only to demonstrate that the data in [1] allow for the conclusions in [2]. No claims are made here (or in [1]) regarding the financial (dis)incentives for dynamic charging of vehicles via ERS.

1.1 Major assumptions

- While driving on ERS, a heavy truck can draw at least 200 kW of continuous power, split between propulsion and charging. If there are gaps in the infrastructure, the maximum power per vehicle is increased proportionally.
- For a truck to have incentive to use ERS, ERS should be capable of delivering at least 40% of its annual energy (>40% of annual distance on the ERS network was assumed in [1], while simulation results in [2] indicated ERS will deliver approximately half of all electrical energy to heavy trucks).

1.2 Conclusions

- If ERS is installed on (and only on) the Swedish road network joining Malmö, Göteborg and Stockholm, then the data in [1] shows trucks making up over **60% of heavy traffic** on this road network would be drawing power from the infrastructure (figure 10).
- If ERS is installed on (and only on) major European high-speed roads, including in Sweden, then approximately **95 % of long-haul vehicles** would be ERS users. Translated into ratio of traffic, this represents >**98%** on the same road network, in agreement with the findings in [2].
- The mobility patterns in the data from [1] show that trucks in **regional operation** are well suited for ERS use, due to their high charging potential per driven km (figure 8).

Regarding trucks in regional operation, these were not considered as potential ERS users in [1], as it was assumed their entire charging needs could be met with static depot charging. The analysis in [2] indicates that a combination of night-time charging at depot and day-time charging from ERS would be cost minimizing for operators, as the addition of dynamic day-time dynamic charging allows for economic battery savings.

1.3 Sources

[1] *Analysera förutsättningar och planera för en utbyggnad av elvägar*, Trafikverket, 2021.

[2] *Interaktionseffekter mellan batterielektriska lastbilar, elvägar och statisk laddinfrastruktur: Resultat från högupplöst simulering av godstransporter på det svenska vägnätet under perioden 2020–2050*, RISE Rapport 2022:110.

[3] *Lastbilstrafik 2021*, Trafikanalys, 2022.

2 Load road network utilization data

From page 45 in [1]: *Road network 2* has been defined as a road network consisting of the following roads: - E6 between Trelleborg and Strömstad (470 km) - E4 between Helsingborg and Stockholm (560 km) - Rv40 between Gothenburg and Jönköping (150 km) - E20 between Gothenburg and Stockholm (480 km) - E18 between Arboga and Stockholm (160 km) - Rv50 between Hallsberg and Mjölby (100 km) - Rv51 between Örebro and Norrköping (115 km)

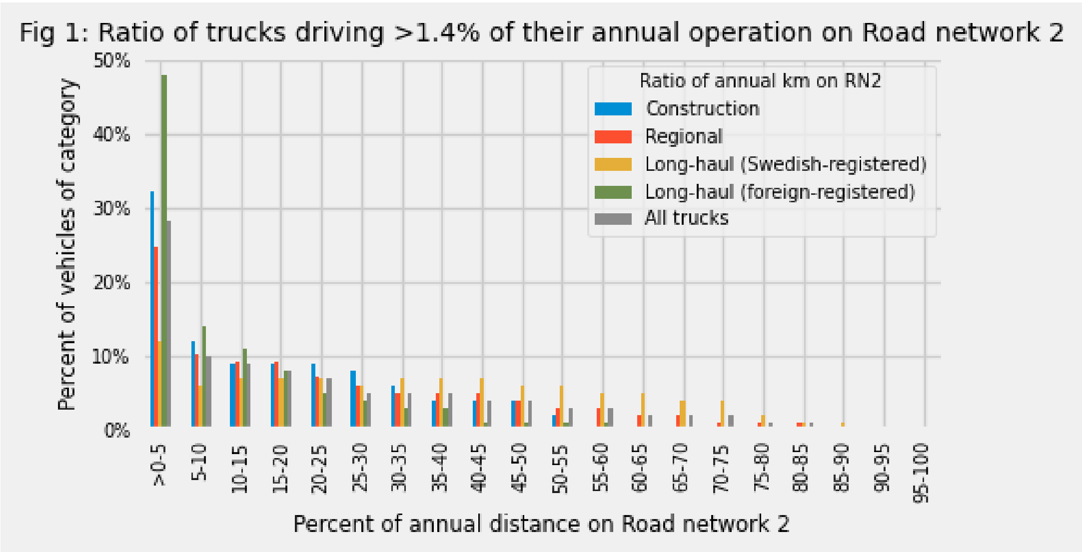
The traffic dataset used in [1] consists of a small table of aggregated totals, stating how many percent of the total vehicle population that drive a given percentage of their total annual distance on *Road network 2*. The dataset does not seem to be accessible anywhere online, but was shared by Trafikverket on request via email.

[1]:
```python
import pandas as pd
import numpy as np
from io import StringIO
import matplotlib.pyplot as plt
import matplotlib.ticker as mtick
import matplotlib_inline
matplotlib_inline.backend_inline.set_matplotlib_formats()
plt.style.use('fivethirtyeight')
plt.rc('font', size=7)
```

[80]:
```python
# Percent of vehicles in each group that drive X % of their annual distance␣
↪on "Road Network 2"
```

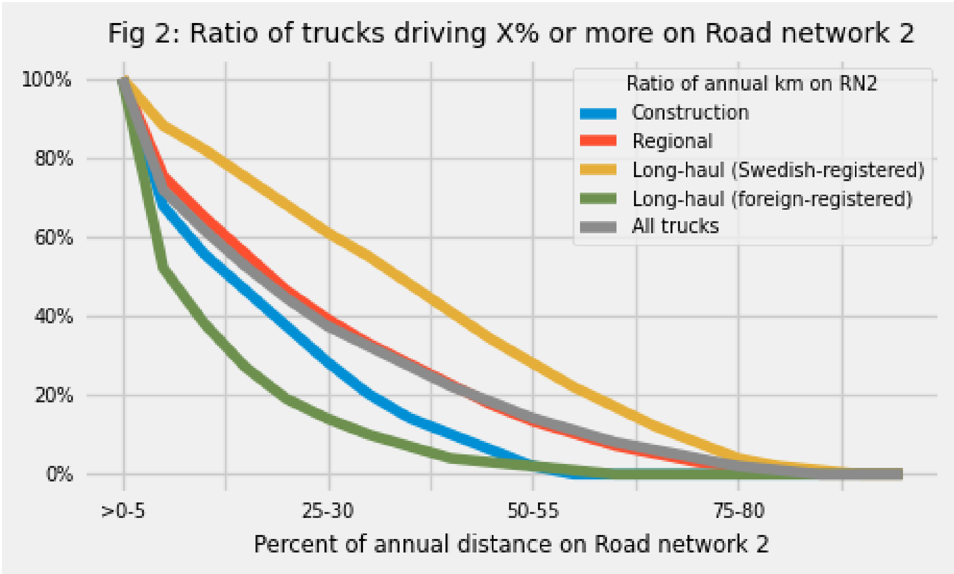
```
# The population is all vehicles that "have operated at least five days␣
↪within one year in Sweden".

tmp = '''Ratio of annual km on RN2,>0-5,5-10,10-15,15-20,20-25,25-30,30-35,␣
↪35-40,40-45,45-50,50-55,55-60,60-65,65-70,70-75,75-80,80-85,85-90,90-95,95-100
Construction,.32,.12,.09,.09,.09,.08,.06,.04,.04,.04,.02,.00,.00,.00,.00,.00,.
↪00,.00,.00,.00
Regional,.24,.10,.09,.09,.07,.06,.05,.05,.05,.04,.03,.03,.02,.02,.01,.01,.01,.
↪00,.00,.00
Long-haul (Swedish-registered),.12,.06,.07,.07,.07,.06,.07,.07,.07,.06,.06,.
↪05,.05,.04,.04,.02,.01,.01,.00,.00
Long-haul (foreign-registered),.48,.14,.11,.08,.05,.04,.03,.03,.01,.01,.01,.
↪01,.00,.00,.00,.00,.00,.00,.00,.00
All trucks,.28,.10,.09,.08,.07,.05,.05,.05,.04,.04,.03,.03,.02,.02,.02,.01,.
↪01,.00,.00,.00'''

raw_road_use_data = pd.read_csv(StringIO(tmp)).set_index("Ratio of annual km␣
↪on RN2").T
raw_road_use_data = raw_road_use_data / raw_road_use_data.sum() # normalize,␣
↪since they don't all add up to exatly 100%
raw_road_use_data.index.name = "Ratio of annual km on RN2"
grps_excl_all = raw_road_use_data.columns[raw_road_use_data.columns != 'All␣
↪trucks']
```

[3]:
```
# Reproduce figure 21 from Trafikverket's report
ax = raw_road_use_data.plot(kind='bar', figsize=(5,3))
ax.set_title("Fig 1: Ratio of trucks driving >1.4% of their annual operation␣
↪on Road network 2")
ax.set_xlabel('Percent of annual distance on Road network 2')
ax.set_ylabel('Percent of vehicles of category')
ax.yaxis.set_major_formatter(mtick.PercentFormatter(1))
plt.tight_layout()
```



3 Plot cumulative distributions of road network use, for easier interpretation

[4]:
```
cumulative_road_use_data = 1 - raw_road_use_data.cumsum() + raw_road_use_data
ax = cumulative_road_use_data.plot.line(figsize=(5,3))
ax.set_title("Fig 2: Ratio of trucks driving X% or more on Road network 2")
ax.set_xlabel('Percent of annual distance on Road network 2')
ax.yaxis.set_major_formatter(mtick.PercentFormatter(1))
plt.tight_layout()
```



4 Some assumptions are required to convert from vehicle counts to AADT

Assumption: Foreign long-haul vehicles have a slightly higher fill rate. Assuming this makes the proportions match later.

Assumption: Within each group there is no correlation between the proportion of mileage on the road network and total annual mileage.

Assumption: All foreign traffic takes place on Road network 2

Assumption: Foreign-registered trucks are all 40-ton, while Swedish-registered long-haul includes some 60-ton.

[5]:
```
bin_ratios = np.linspace(0.025, 0.975, num=20)

# Weights include truck and cargo, including distance driven without cargo
# Population counts and annual distance from [1]
# Weights are guesses, based on that part of Swedish-reg long-haul is 60 ton,␣
↪while foreign is all 40 ton
```

```
# The assumed weights are later (only) used to estimate energy consumption␣
↪per km
tmp = '''Group,Vehicle count,km/vehicle-year,Weight (avg)
Construction,18200,39000,28
Regional,17700,58000,18
Long-haul (Swedish-registered),48300,100000,33
Long-haul (foreign-registered),100000,100000,25'''

vehicle_population = pd.read_csv(StringIO(tmp)).set_index("Group")

# This is necessary for the national annual mileage to match national␣
↪statistics.
# Perhaps there are many old trucks registered that drive very little? It␣
↪does not affect the calculations.
vehicle_population['Vehicle count'] *= 0.65

vehicle_population['tonkm/vehicle-year'] = vehicle_population['Weight (avg)']␣
↪* vehicle_population['km/vehicle-year']
vehicle_population['km/year (total)'] = vehicle_population['Vehicle count'] *␣
↪vehicle_population['km/vehicle-year']
vehicle_population['tonkm/year (total)'] = vehicle_population['Vehicle␣
↪count'] * vehicle_population['km/vehicle-year'] *␣
↪vehicle_population['Weight (avg)']

ratio_of_foreign_traffic_in_sweden = (raw_road_use_data['Long-haul␣
↪(foreign-registered)'].T * bin_ratios).sum()
vehicle_population.loc['Long-haul (foreign-registered)', 'km/year (total)']␣
↪*= ratio_of_foreign_traffic_in_sweden
vehicle_population.loc['Long-haul (foreign-registered)', 'tonkm/year␣
↪(total)'] *= ratio_of_foreign_traffic_in_sweden

avg_weight = (vehicle_population['Weight (avg)'] *␣
↪vehicle_population['Vehicle count']).sum() / vehicle_population['Vehicle␣
↪count'].sum()

vehicle_population_incl_all = vehicle_population.copy()
vehicle_population_incl_all.loc['All trucks'] = vehicle_population.sum()
vehicle_population_incl_all.loc['All trucks', 'Weight (avg)'] = avg_weight

vehicle_population_incl_all
```

[5]:

```
                                Vehicle count  km/vehicle-year  Weight (avg)  ␣
↪\
Group
Construction                          11830.0          39000.0     28.000000
Regional                              11505.0          58000.0     18.000000
Long-haul (Swedish-registered)        31395.0         100000.0     33.000000
Long-haul (foreign-registered)        65000.0         100000.0     25.000000
All trucks                           119730.0         297000.0     26.721498
```

```
                                  tonkm/vehicle-year  km/year (total)  \
Group
Construction                               1092000.0     4.613700e+08
Regional                                   1044000.0     6.672900e+08
Long-haul (Swedish-registered)             3300000.0     3.139500e+09
Long-haul (foreign-registered)             2500000.0     7.377500e+08
All trucks                                 7936000.0     5.005910e+09

                                  tonkm/year (total)
Group
Construction                            1.291836e+10
Regional                                1.201122e+10
Long-haul (Swedish-registered)          1.036035e+11
Long-haul (foreign-registered)          1.844375e+10
All trucks                              1.469768e+11
```

Of total traffic with heavy trucks in Sweden, the following ratios are assumed to come from foreign-registered vehicles:

[6]:
```
cols = ['km/year (total)', 'tonkm/year (total)']
vehicle_population[cols] / vehicle_population[cols].sum()
```

[6]:
```
                                km/year (total)  tonkm/year (total)
Group
Construction                           0.092165            0.087894
Regional                               0.133300            0.081722
Long-haul (Swedish-registered)         0.627159            0.704897
Long-haul (foreign-registered)         0.147376            0.125487
```

[7]:
```
number_of_vehicles_per_bin = raw_road_use_data[grps_excl_all] *␣
 ↪vehicle_population['Vehicle count']

annual_km_on_rn2_per_bin = number_of_vehicles_per_bin *␣
 ↪vehicle_population['km/vehicle-year'] * bin_ratios[:, np.newaxis]
annual_km_in_sweden_per_bin = number_of_vehicles_per_bin *␣
 ↪vehicle_population['km/vehicle-year']
annual_km_in_sweden_per_bin['Long-haul (foreign-registered)'] =␣
 ↪annual_km_on_rn2_per_bin['Long-haul (foreign-registered)']

annual_tonkm_on_rn2_per_bin = number_of_vehicles_per_bin *␣
 ↪vehicle_population['tonkm/vehicle-year'] * bin_ratios[:, np.newaxis]
annual_tonkm_in_sweden_per_bin = number_of_vehicles_per_bin *␣
 ↪vehicle_population['tonkm/vehicle-year']
annual_tonkm_in_sweden_per_bin['Long-haul (foreign-registered)'] =␣
 ↪annual_tonkm_on_rn2_per_bin['Long-haul (foreign-registered)']
```

[8]:
```
#annual_tonkm_on_rn2_per_bin.sum() / annual_tonkm_on_rn2_per_bin.sum().sum()
#annual_tonkm_on_rn2_per_bin.sum() / vehicle_population['tonkm/year (total)']
```

4.1 Validation against known statistics

The report from Trafikverket [1] claims on page 35: "*An analysis of the traffic work along major roads shows that approximately 40 percent of the traffic work takes place on the road network that connects Malmö, Gothenburg and Stockholm. In terms of transport work, the figure is probably somewhat higher because very heavy vehicles travel along this road network, perhaps 50 percent.*"

The assumptions made regarding average vehicle weight, annual distance and number of involved vehicle individuals per group of vehicles results in a matching percentage of traffic work, but a lower share of transport work. If the ratio of transport work is to match the assumption made in [1], construction vehicles can be assumed to have an lower mean weight, or long-haul vehicles a higher mean weight.

[9]:
```
print("Km on Road network 2 (vs. assumed 40%): ")
print(round(100 * annual_km_on_rn2_per_bin.sum().sum() /␣
 ↪annual_km_in_sweden_per_bin.sum().sum()), "%")
print("Tonkm on Road network 2 (vs. assumed 50%): ")
print(round(100 * annual_tonkm_on_rn2_per_bin.sum().sum() /␣
 ↪annual_tonkm_in_sweden_per_bin.sum().sum()), "%")
```

```
Km on Road network 2 (vs. assumed 40%):
41 %
Tonkm on Road network 2 (vs. assumed 50%):
41 %
```

According to statistics from Trafikanalys [3], Swedish-registered heavy trucks together drive approximately 3.2e9 km per year. This includes an unknown percentage of distance and work by Swedish-registered trucks abroad.

[10]:
```
construction_and_regional = ['Construction', 'Regional']
long_haul_swedish = ['Long-haul (Swedish-registered)']
cols = ['km/year (total)']
ratio_of_long_haul_km_in_sweden = 0.7
print("Distance within Sweden by Swedish-registered trucks (vs. 3.2e9 km from␣
 ↪[3]):")
vehicle_population.loc[construction_and_regional, cols].sum() \
  + ratio_of_long_haul_km_in_sweden * vehicle_population.
 ↪loc[long_haul_swedish, cols].sum()
```

```
Distance within Sweden by Swedish-registered trucks (vs. 3.2e9 km from [3]):
```

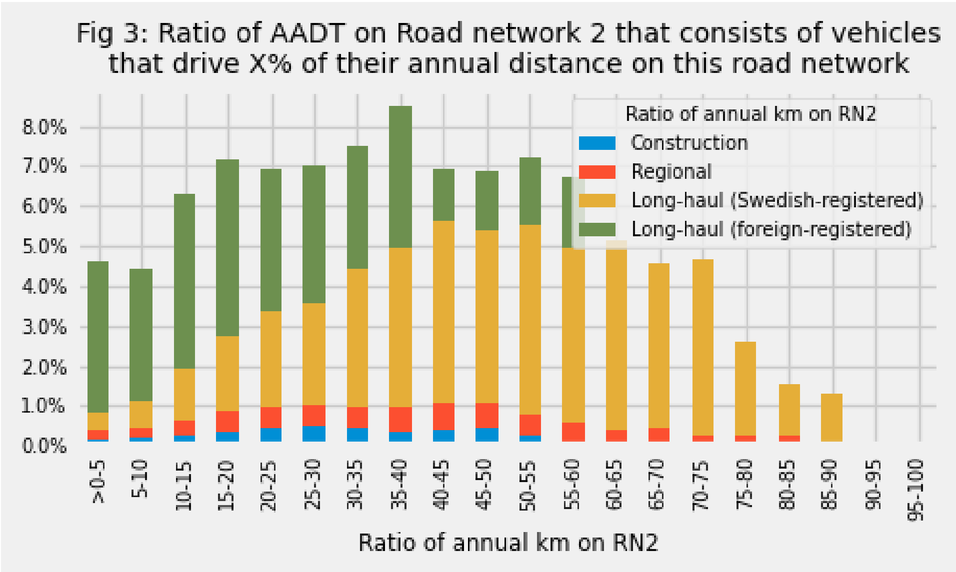
[10]:
```
km/year (total)    3.326310e+09
dtype: float64
```

5 Some vehicles drive on Road network 2 more than others. How many percent of traffic on Road network 2 consists of vehicles with different ratios of their annual km on this road network?

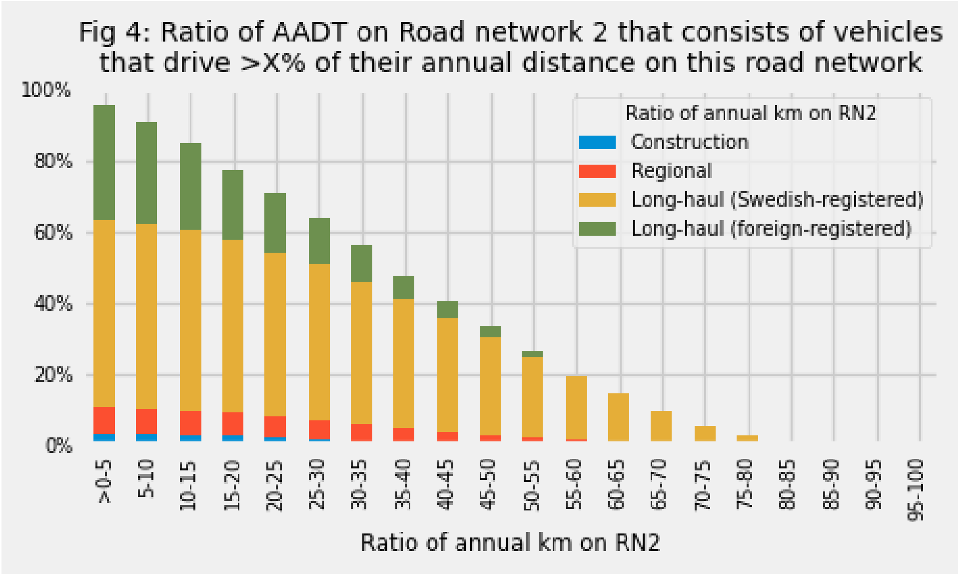
Example: We have a hypothetical road network. Every year on this road network: - 1 vehicle drives 10 000 km; - 1 000 vehicles drive 10 km.

Then vehicles that drive 10 000 km on this road network will make up: - 0.1% of the vehicles - 50% of the traffic (in Average Annual Daily Traffic (AADT), or annual vehicle km)

[11]:
```
# Calculate the contribution to total traffic from each bin of vehicles.

ratio_of_rn2_aadt = annual_km_on_rn2_per_bin / annual_km_on_rn2_per_bin.sum().
↪sum()

ax = ratio_of_rn2_aadt.plot.bar(stacked=True, figsize=(5,3))
ax.yaxis.set_major_formatter(mtick.PercentFormatter(1))
ax.set_title('Fig 3: Ratio of AADT on Road network 2 that consists of␣
↪vehicles\nthat drive X% of their annual distance on this road network')
plt.tight_layout()
```



[12]:
```
# Plot the cumulative distribution

ratio_of_rn2_aadt_reverse_cumulative = ratio_of_rn2_aadt.sum() -␣
↪ratio_of_rn2_aadt.cumsum()

ax = ratio_of_rn2_aadt_reverse_cumulative.plot.bar(stacked=True,␣
↪figsize=(5,3))
ax.yaxis.set_major_formatter(mtick.PercentFormatter(1))
ax.set_title('Fig 4: Ratio of AADT on Road network 2 that consists of␣
↪vehicles\nthat drive >X% of their annual distance on this road network')
plt.tight_layout()
```



6 How much energy can be delivered from ERS given X% of total annual distance on the ERS network?

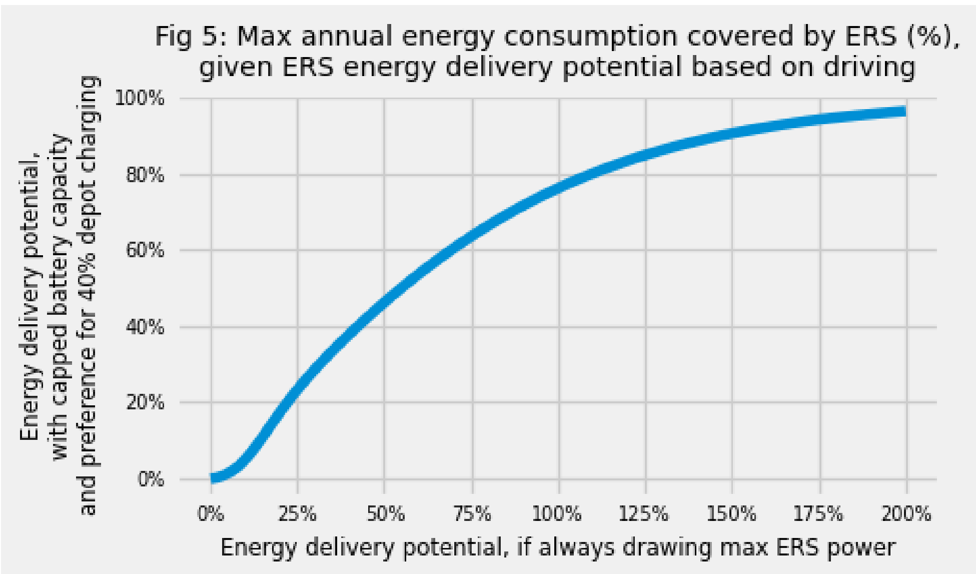
For this, we need to consider: - Vehicles on ERS can charge their battery, which means ERS has greater energy potential than only the propulsion energy spent on the ERS network itself; - Continuous driving and charging on ERS results in a full battery, capping how much charging can take place; - According to simulations in [2], access to ERS reduces the TCO-optimal battery capacity; - Night charging remains attractive even with ERS, but is capped by battery capacity. In [2], this led to approximately 60% of total energy supplied via ERS and 40% via static night charging, for the entire vehicle population; - No vehicle can ever draw more energy from ERS than the total annual energy consumption;

Without simulation of network effects, we cannot accurately quantify these factors. They are approximated with the transfer function below, imitating emergent behavior from such system simulations.

Note: Foreign-registered long-haul trucks are assumed in [1] (page 35) to drive their entire distance **within** Sweden on Road network 2. It follows that the remaining annual distance is driven on roads outside of Sweden, of which some may be ERS-equipped. Presumably, some percent of the annual distance of Swedish-registered long-haul trucks would also be on roads outside of Sweden. If the same assumption is made for them, this traffic abroad would be entirely on ERS equipped roads (if ERS is deployed abroad). **So far, we assume that ERS is built only in Sweden**.

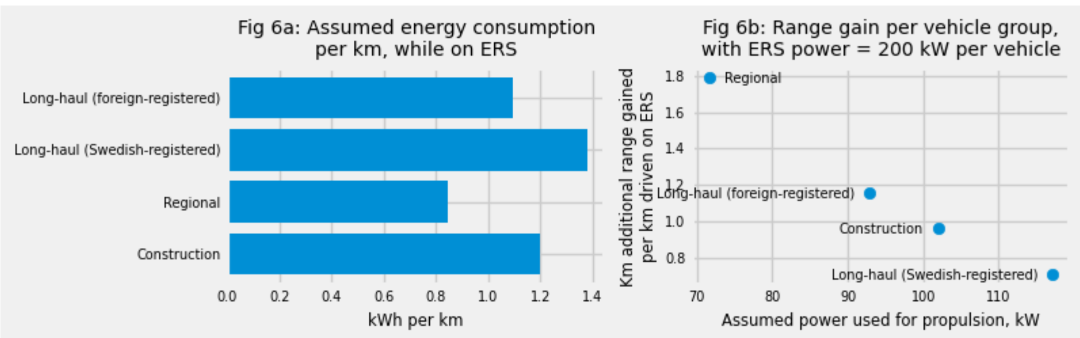
[13]:
```
# Transfer function from [this is how much energy ERS could deliver if the␣
↪battery was never full] to [this is how much energy ERS could realistically␣
↪deliver].

def clamp(x, a, b):
  if x < a:
    return a
  elif x > b:
```

```
    return b
  else:
    return x

def smootherstep(edge0, edge1, x):
  x = clamp((x - edge0) / (edge1 - edge0), 0.0, 1.0)
  return x * x * x * (x * (x * 6 - 15) + 10)

def asymptote(x, max):
  b = x / max
  a = 2 / (1 + np.exp(-2*b)) - 1
  c = 1 / (1 + np.exp(-20*b+2))
  return max * a * c

# This value should be set to <1 if we assume that even vehicles that drive␣
 ↪almost exclusively on ERS will want to charge elsewhere, for instance␣
 ↪because we believe ERS charging will be expensive.
max_ers_charging_ratio = 1

x = np.linspace(0, 2, num=100)
y = asymptote(x, 1)

fig, ax = plt.subplots(figsize=(5,3))
ax.plot(x,y)
ax.set_title("Fig 5: Max annual energy consumption covered by ERS (%),\ngiven␣
 ↪ERS energy delivery potential based on driving")
ax.set_xlabel('Energy delivery potential, if always drawing max ERS power')
ax.set_ylabel('Energy delivery potential,\nwith capped battery capacity\nand␣
 ↪preference for 40% depot charging')
ax.xaxis.set_major_formatter(mtick.PercentFormatter(1))
ax.yaxis.set_major_formatter(mtick.PercentFormatter(1))
plt.tight_layout()
```



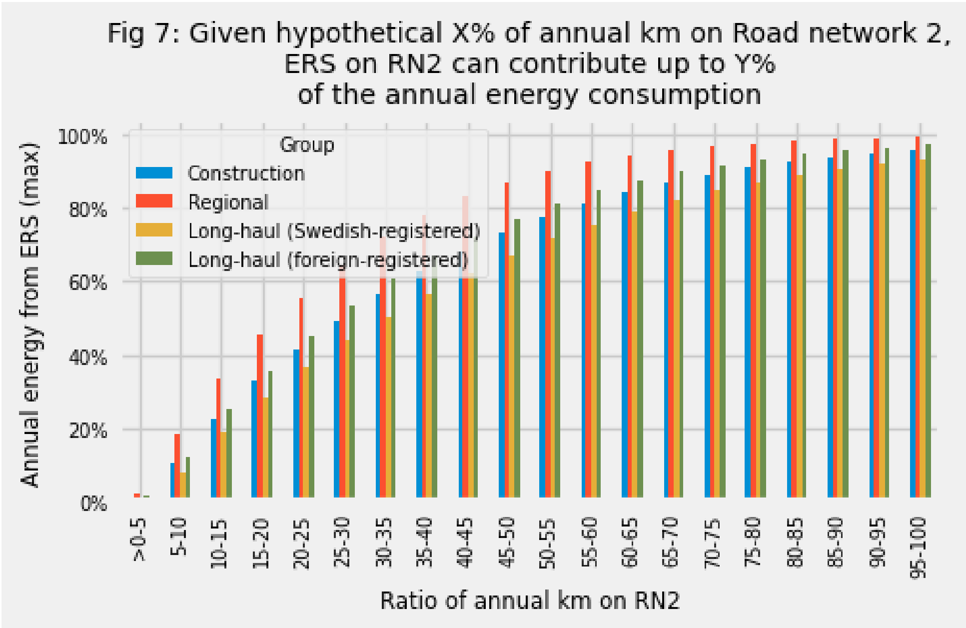
Use the assumed vehicle masses above to estimate the energy consumption of the different vehicle groups. With a fixed power per vehicle from the ERS, the range multiplier differs for vehicles with different energy consumption.

[14]:
```
ers_kmph = 85
ers_max_kW_per_vehicle = 200
kWh_per_km = 0.2 + vehicle_population['Weight (avg)'] / 28
driving_kW_on_ers = ers_kmph * kWh_per_km
ers_range_multiplier = pd.DataFrame(ers_max_kW_per_vehicle /
 ↪driving_kW_on_ers)

fig, ax = plt.subplots(1, 2, figsize=(8,2.5))

ax[0].barh(y=[0, 1, 2, 3], width=kWh_per_km)
ax[0].set_yticks([0, 1, 2, 3], labels=grps_excl_all)
ax[0].set_title("Fig 6a: Assumed energy consumption\nper km, while on ERS")
ax[0].set_xlabel("kWh per km")

ax[1].scatter(driving_kW_on_ers, ers_range_multiplier - 1)
ax[1].set_xlabel("Assumed power used for propulsion, kW")
ax[1].set_ylabel("Km additional range gained\nper km driven on ERS")
ax[1].set_title("Fig 6b: Range gain per vehicle group,\nwith ERS power = " +
 ↪str(ers_max_kW_per_vehicle) + " kW per vehicle")

for i, label in enumerate(grps_excl_all):
  r = (label == 'Regional')
  x = driving_kW_on_ers[label] + 2 * (1 if r else -1)
  y = ers_range_multiplier.loc[label] - 1.03
  align = 'left' if r else 'right'
  ax[1].annotate(label, (x, y), horizontalalignment=align)

plt.tight_layout()
```



[15]:
```
ers_charging_potential = pd.DataFrame(asymptote(np.outer(bin_ratios,
 ↪ers_range_multiplier), max_ers_charging_ratio),
 ↪columns=ers_range_multiplier.index, index=raw_road_use_data.index)
ers_charging_potential.index.name = raw_road_use_data.index.name
```

```
ax = ers_charging_potential.plot.bar(figsize=(5,3.3))
ax.yaxis.set_major_formatter(mtick.PercentFormatter(1))
ax.set_title('Fig 7: Given hypothetical X% of annual km on Road network␣
↪2,\nERS on RN2 can contribute up to Y%\nof the annual energy consumption')
ax.set_ylabel('Annual energy from ERS (max)')
plt.tight_layout()
```



[16]:
```
# Calculate the maximum share of the national energy consumption by heavy␣
↪trucks that can be delivered by ERS
print("If users require that ERS on Road network 2 delivers >40% of the␣
↪truck's energy")
energy_ratio_from_ers = (ers_charging_potential>=0.4) * np.linspace(0.025, 0.
↪975, 20)[np.newaxis].T
print((annual_tonkm_in_sweden_per_bin * energy_ratio_from_ers).sum().sum() /␣
↪annual_tonkm_in_sweden_per_bin.sum().sum())

print("If all trucks on Road network 2 use ERS there")
energy_ratio_from_ers = (ers_charging_potential>=0) * np.linspace(0.025, 0.
↪975, 20)[np.newaxis].T
print((annual_tonkm_in_sweden_per_bin * energy_ratio_from_ers).sum().sum() /␣
↪annual_tonkm_in_sweden_per_bin.sum().sum())
```

```
If users require that ERS on Road network 2 delivers >40% of the truck's energy
0.2678731786337563
If all trucks on Road network 2 use ERS there
0.3108678240064236
```

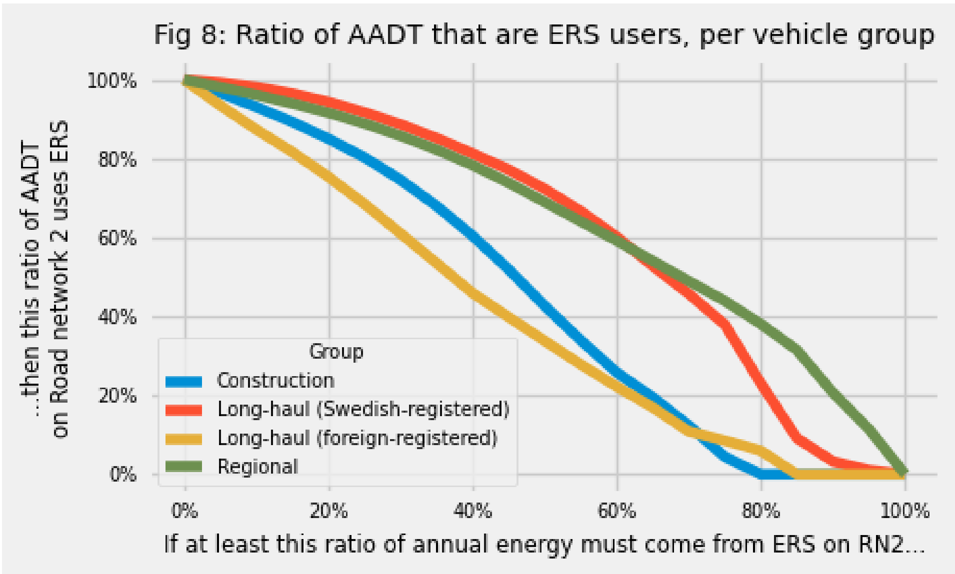
7 What ratio of the traffic on Road network 2 would use ERS, if it is deployed?

We combine the range multipliers and the transfer function that caps total energy gained from ERS, to estimate the distribution of "ERS attractiveness" to the traffic on Road network 2.

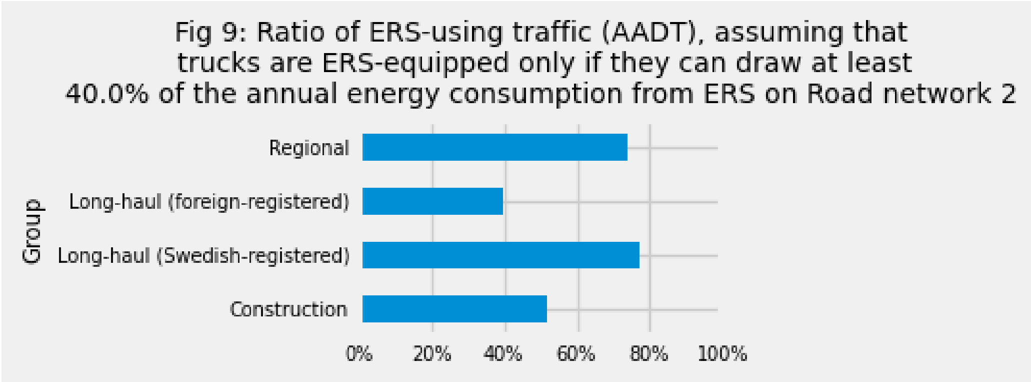
[17]:
```
# Construct a table with [ratio of annual energy] x [vehicle group] -> [ratio␣
↪of vehicle group that can get this much of annual energy from ERS]

ers_charging_potential_flat = ers_charging_potential \
                                .melt(ignore_index=False) \
                                .reset_index() \
                                .rename(columns={'index': raw_road_use_data.
↪index.name, 'value': 'ERS charging potential'}) \
                                .set_index([raw_road_use_data.index.
↪name,'Group'])

ratio_of_aadt_per_bin = annual_km_on_rn2_per_bin / annual_km_on_rn2_per_bin.
↪sum()
ratio_of_aadt_per_bin.index.name = raw_road_use_data.index.name
ratio_of_aadt_per_bin.columns.name = 'Group'

ratio_of_aadt_per_bin_flat = ratio_of_aadt_per_bin \
                                .melt(ignore_index=False, value_name='Ratio of␣
↪RN2 AADT') \
                                .reset_index() \
                                .set_index([raw_road_use_data.index.name,␣
↪'Group'])

ers_charging_potential_flat = ers_charging_potential_flat.
↪merge(ratio_of_aadt_per_bin_flat, left_index=True, right_index=True)

ers_charging_potential_flat['ERS charging potential bin'] =␣
↪(ers_charging_potential_flat['ERS charging potential'] * 20).apply(np.
↪floor) / 20

ers_charging_potential_binned = ers_charging_potential_flat \
                                .reset_index() \
                                .groupby(['Group', 'ERS charging potential␣
↪bin']) \
                                .agg({'Ratio of RN2 AADT': 'sum'}) \
                                .reset_index() \
                                .pivot(columns='Group', index='ERS charging␣
↪potential bin', values='Ratio of RN2 AADT')
ers_charging_potential_binned.loc[1] = np.array([0,0,0,0])
```

One way to assess who will be using ERS infrastructure is to put a threshold on the minimum ratio of the annual energy that this infrastructure should be capable of delivering. For a TCO-based calculation, see [2].

[18]:
```
ers_charging_potential_binned_interpolated = ers_charging_potential_binned.
 ↪interpolate() / ers_charging_potential_binned.interpolate().sum()
ers_charging_potential_binned_interpolated_reverse_cumsum = 1 -␣
 ↪ers_charging_potential_binned_interpolated.cumsum() +␣
 ↪ers_charging_potential_binned_interpolated

ax = ers_charging_potential_binned_interpolated_reverse_cumsum.plot.
 ↪line(figsize=(5,3))
ax.xaxis.set_major_formatter(mtick.PercentFormatter(1))
ax.yaxis.set_major_formatter(mtick.PercentFormatter(1))
ax.set_title("Fig 8: Ratio of AADT that are ERS users, per vehicle group")
ax.set_xlabel("If at least this ratio of annual energy must come from ERS on␣
 ↪RN2...")
ax.set_ylabel("...then this ratio of AADT\non Road network 2 uses ERS")
plt.tight_layout()
```

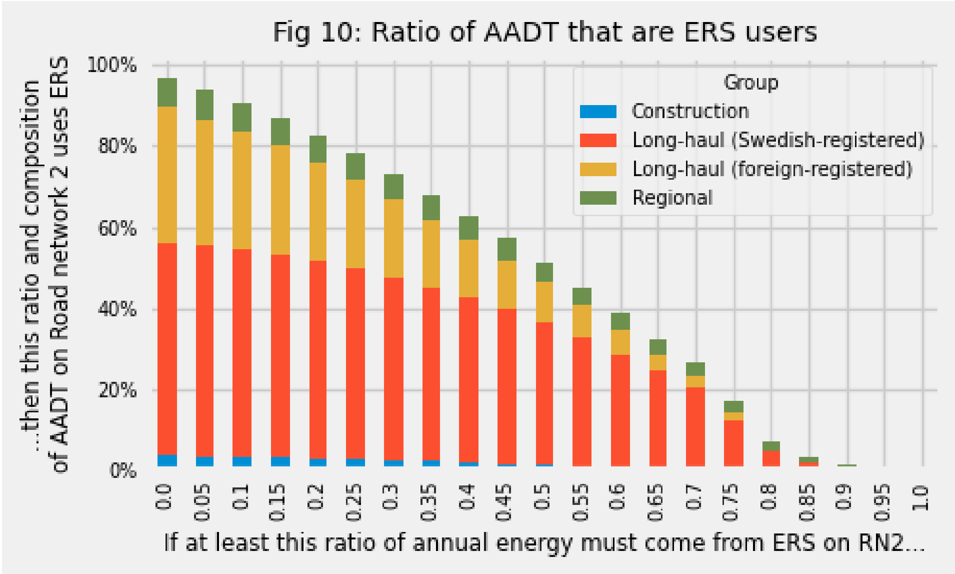


[19]:
```
# Same data as in the figure above, but for a single threshold value

minimum_energy_ratio_to_become_ers_user = 0.4

mask = ers_charging_potential_binned_interpolated.index >␣
 ↪minimum_energy_ratio_to_become_ers_user
ax = ers_charging_potential_binned_interpolated[mask].sum().plot.
 ↪barh(figsize=(4,2))
ax.xaxis.set_major_formatter(mtick.PercentFormatter(1))
ax.set_xlim(0,1)
ax.set_title("Fig 9: Ratio of ERS-using traffic (AADT), assuming that\n␣
 ↪trucks are ERS-equipped only if they can draw at least\n" +␣
 ↪str(minimum_energy_ratio_to_become_ers_user * 100) + "% of the annual␣
 ↪energy consumption from ERS on Road network 2")
plt.tight_layout()
```



Based on simulations in [2], even with ERS in place, around 40% of total energy is expected to be delived by other types of charging infrastructure. This varies depending on ERS coverage along different routes.

[20]:
```
x = (ers_charging_potential_binned_interpolated *␣
 ↪ratio_of_rn2_aadt[grps_excl_all].sum())
ers_charging_potential_binned_interpolated_rev_cumsum =␣
 ↪(ratio_of_rn2_aadt[grps_excl_all].sum() - x.cumsum())
ax = ers_charging_potential_binned_interpolated_rev_cumsum.plot.
 ↪bar(stacked=True, figsize=(5,3))
#ax.xaxis.set_major_formatter(mtick.PercentFormatter(1))  # This breaks. Bug?
ax.yaxis.set_major_formatter(mtick.PercentFormatter(1))
ax.set_title("Fig 10: Ratio of AADT that are ERS users")
ax.set_xlabel("If at least this ratio of annual energy must come from ERS on␣
 ↪RN2...")
ax.set_ylabel("...then this ratio and composition\nof AADT on Road network 2␣
 ↪uses ERS")
plt.tight_layout()

ers_using_aadt_with_ers_on_rn2 =␣
 ↪ers_charging_potential_binned_interpolated_rev_cumsum.
 ↪sum(axis=1)[minimum_energy_ratio_to_become_ers_user]
```



According to figure 10, a bit over 60% of traffic on Road network 2 meets the criteria of being able to draw 40% of the annual energy from ERS, with the assumed ERS power of 200 kW per vehicle.

8 What if we assume ERS in Sweden is part of a European ERS network?

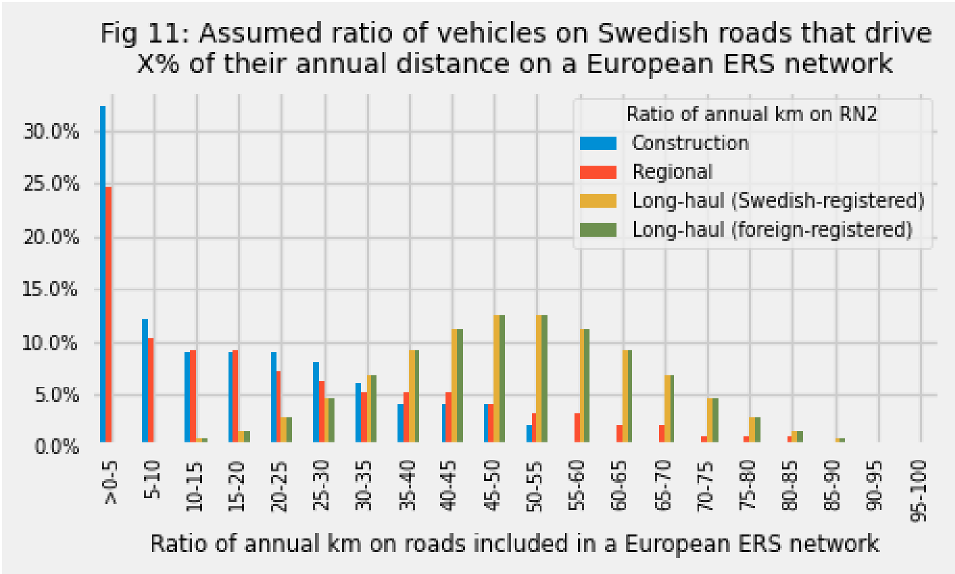
The dataset describing ratio of a vehicle's annual distance that is driven on Road network 2 makes no distinction between if this other driving takes place inside or outside Sweden. This means that for some trucks, the remainder of the annual distance will be driven on minor roads inside Sweden, while some trucks will be driving primarily on roads abroad that could be ERS equipped.

The following should be approximately true: - a large percentage (maybe 30%-70%?) of annual distance travelled by long-haul trucks takes place on motorways, both in Sweden and abroad; - long-haul trucks that drive very little on the Swedish motorway network are more likely to A) drive a lot abroad, than B) drive primarily on minor roads in Sweden; - regional and construction traffic is 100% domestic.

These assumptions are quantified in figure 11.

[21]:
```
normal = np.exp(-20 * (bin_ratios - 0.5)**2)
normal = normal / normal.sum()
tent_use_data = raw_road_use_data[grps_excl_all].copy()
tent_use_data.index.name = 'Ratio of annual km on roads included in a␣
↪European ERS network'
tent_use_data['Long-haul (Swedish-registered)'] = normal
tent_use_data['Long-haul (foreign-registered)'] = normal

tent_use_data_rev_cumsum = 1 - tent_use_data.cumsum() + tent_use_data
ax = tent_use_data.plot.bar(figsize=(5,3))
ax.yaxis.set_major_formatter(mtick.PercentFormatter(1))
```

```
ax.set_title("Fig 11: Assumed ratio of vehicles on Swedish roads that␣
↪drive\nX% of their annual distance on a European ERS network")
plt.tight_layout()
```



[79]:
```
min_ers_energy_ratio = 0.4
veh_grps_with_enough_km_on_eu_ers = (ers_charging_potential >=␣
↪min_ers_energy_ratio)
share_of_veh_pop = (tent_use_data * veh_grps_with_enough_km_on_eu_ers).sum()
share_of_veh_pop

# No data is available to map from ratio of vehicle population to ratio of
# traffic on RN2. Although a dataframe with a relevant-sounding name exists,
# the index dimension in this dataframe is not the same as in "tent_use_data".
```

[79]:
```
Ratio of annual km on RN2
Construction                      0.373737
Regional                          0.556701
Long-haul (Swedish-registered)    0.944496
Long-haul (foreign-registered)    0.972337
dtype: float64
```

According to the assumed distribution in figure 11 above, 95% of long-haul trucks drive 20-25% of their annual distance on roads likely to be included in a future European ERS network. According to figure 7, a long-haul truck that drives 25% of its annual distance on ERS can get up to 40% of its annual energy consumption supplied from ERS. If 40% of annual energy is the threshold for ERS participation, then around 95% of long-haul trucks would use ERS if ERS in Sweden is part of a European network. This ratio of trucks should be translated into ratio of traffic, which we lack information to do. However, the share of the vehicle population is so high the remaining non-ERS-using trucks (of all four categories) drive almost entirely outside of the ERS network. At least 98% of the traffic on Road network 2 are expected to be ERS users if a European ERS network is built.

If the minimum share of energy from ERS is increased to 60% (above some simulation results in [2]), we are still expecting ERS use from 74% of Swedish long-haul trucks, 90% of foreign-registered and 40% of trucks in regional operation. As a share of traffic, this is still very high, probably near 90%.

This analysis has not considered whether ERS charging is a cost-attractive alternative, in competition with several other forms of charging. TCO-minimizing behavior is studied in [2], which concludes that night-time depot charging is the cheapest alternative when energy prices are lowest at night, and also that ERS enables cost-saving reductions in battery capacity per truck, resulting in that less than a full day's worth of energy can be charged during night. This converges to an approximately even share of night-time energy from the depot and day-time energy from ERS, with a bias towards ERS charging for long-haul traffic and a bias towards depot charging for regional traffic.