Methods in Transportation Econometrics and Statistics (Master)

Winter semester 2024/25, Solutions to Tutorial No. 13

Solution to Problem 13.1: Life-cycle assessment (LCA) of internal combustion and battery-electric vehicles

(a) The life-cycle inventory of the gasoline vehicle (internal combustion vehicle, ICV) defined as

$$\vec{y}^s = \begin{pmatrix} \text{kg steel} \\ \text{kg aluminum} \\ \text{kg plastic} \\ \text{kg rubber} \\ \text{kg starter batteries} \\ \text{l gasoline} \end{pmatrix}:$$

is given by

$$\vec{y}^s = \vec{y}_{\text{prod}} + \vec{y}_{\text{driving}} + \vec{y}_{\text{recycl}} = \begin{pmatrix} 900 \\ 100 \\ 100 \\ 30+20 \\ 12 \\ 0 \end{pmatrix} + \begin{pmatrix} 100 \\ 0 \\ 0 \\ 3*4*5 \\ 24 \\ 200\,000*0.06 \end{pmatrix} + \begin{pmatrix} -180 \\ -40 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 820 \\ 60 \\ 100 \\ 110 \\ 36 \\ 12\,000 \end{pmatrix}$$

(b) Total emissions via the Life-cycle inventory of the materials and the first line of the given emission-factor matrix (in kg CO_2):

$$\begin{aligned} e_1^{\text{ICV}} &= \sum_{j=1}^{6} C_{1j} y_j^s \\ &= (4*820 + 30*60 + 2*100 + 2*110 + 20*36 + (2.39+0.4)*12\,000)\,\text{kg} \\ &= 39\,700\,\text{kg } CO_2. \end{aligned}$$

The contribution 0.4 kg/l of the last emission factor denotes the "well-to-tank" (w2t) emissions in kg CO_2 per liter of gasoline available at the gas station. This includes all the emissions during crude-oil extraction, transport to the refineries, the refining process (making gasoline out of crude oil), and the transport to the gas stations.

For the pure CO_2 emission by the material (including wear&tear and recycling), we have

$$e_1^{\text{mat,ICV}} = \sum_{j=1}^{5} C_{1j} y_j^s = 6\,220\,\text{kg } CO_2.$$

The overall driving emissions are

$$e_1^{\text{driving,ICV}} = e_1^{\text{ICV}} - e_1^{\text{mat,ICV}} = 33\,480\,\text{kg}$$

Comparing the material emissions during production and repair with the direct and indirect driving emissions, we observe that the driving emissions during the lifetime are about five times (!) that of production & repair. Per km, we have

- Direct driving emissions: $C_{16}^{\text{T2W}} * 6\,\text{liters/km} = 143.4\,\text{g/km}$
- Driving emissions including the gasoline supply chain: $C_{16}^{\text{W2W}} * 6\,\text{liters/km} = 167.4\,\text{g/km}$
- Including everything (material+driving emissions per km): $e_1^{\text{ICV}}/L = 198.5\,\text{g/km}$

(c) After $L^* = 100\,000\,\text{km}$ we have,

- Without political action: old vehicles at their ends of lifetime plus, per old vehicle, a total emission of

$$C_{\text{noAction}} = L^*\ 0.10\,\text{liters/km} * C_{16}^{\text{W2W}} = 27\,900\,\text{kg}$$

- With political action: replaced vehicles at half of their lifetime plus, per vehicle, a total emission of

$$C_{\text{Action}} = L^*\ 0.05\,\text{l/km} * C_{16}^{\text{W2W}} + e_1^{\text{mat}} = 20\,170\,\text{kg}$$

So, without action, one has already emitted more CO_2 *and* need to replace the old vehicles, right now, while, with action, the emission per vehicle is more than 7 500 kg less *and* the replaced cars can run another 100 000 km before replacement. Thus, under the above assumption, the action "wreck & replace semi-old cars" will definitely save emissions!

(d) The LC inventory of the BEV is similar to that of the ICV with the first four items identical, the 5'th item (starter batteries → low-voltage batteries) factor 2/3, new item driving battery and needed kWh instead of liter gasoline:

$$(\vec{y}^{s})_{\text{el}} == \begin{pmatrix} 820\,\text{kg steel} \\ 60\,\text{kg aluminum} \\ 100\,\text{kg plastic} \\ 110\,\text{kg rubber} \\ 24\,\text{kg low} - \text{voltage batteries} \\ 400\,\text{kg driving batteries} \\ 0.2\,\text{kWh/km} * 200\,000\,\text{km} = 40\,000\,\text{kWh} \end{pmatrix}.$$

The emissions during production and material replacements are

$$e_1^{\text{BEV,mat}} = \sum_{j=1} 65 C_{1j} y_j^{\text{s,el}} = (4{*}82+30{*}60+2{*}100+2{*}110+20{*}24+20{*}600)\,\text{kg} = 13\,980\,\text{kg}$$

and that during driving

$$e_1^{\text{BEV,driving}} = C_{17} y_7^{\text{s,el}} = 0.38\,\text{kg/kWh} * 40\,000\,\text{kWh} = 13\,200\,\text{kg}$$

resulting in a total LCA emission of

$$e_1^{\text{BEV}} = 27\,180\,\text{kg},$$

which is about 30 % less than that of the ICV (39 700 kg).

(e) In the scenarios (i) and (ii), only $e_1^{\text{BEV,driving}} = C_{17} y_7^{\text{s,el}}$ changes, in (iii) the inventory y_6^s is reduced by a factor 0.5:

(i) China mix:

$$\begin{aligned} C_{17} &= 1.00\,\text{kg/kWh}, \\ e_1^{\text{BEV,driving}} &= C_{17} y_7^{\text{s,el}} = 40\,000\,\text{kg}, \\ e_1^{\text{BEV}} &= e_1^{\text{BEV,driving}} + e_1^{\text{BEV,mat}} = 53\,980\,\text{kg} \end{aligned}$$

(ii) Norway-Sweden mix:

$$\begin{aligned} C_{17} &= 0.05\,\text{kg/kWh}, \\ e_1^{\text{BEV,driving}} &= C_{17} y_7^{\text{s,el}} = 2\,000\,\text{kg}, \\ e_1^{\text{BEV}} &= e_1^{\text{BEV,driving}} + e_1^{\text{BEV,mat}} = 15\,980\,\text{kg} \end{aligned}$$

(iii) DE mix and two Li-batteries needed during the lifetime:

$$e_1^{\text{BEV}} = e_1^{\text{BEV,(f)}} + 400 * 20\,\text{kg} = 35\,180\,\text{kg}$$

The question whether a BEV saves CO_2 emissions or not, depends crucially on the energy mix of the power plants for electricity production. The mass of the batteries (proportional to the range) and the question if a replacement is necessary during lifetime or not are also critical factors.

(f) This question relates to four numbers:

- Net CO_2emissions to make, service and recycle the ICV and the BEV:

$$\begin{aligned} e_1^{\text{mat,ICV}} &= 6\,220\,\text{kg}, \\ e_1^{\text{mat,BEV}} &= 13\,980\,\text{kg} \end{aligned}$$

- Total direct and indirect CO_2emissions per km driving:

$$\begin{aligned} e_1^{\text{drive,ICV}} &= C_{16}^{\text{w2w}} * 0.06\,\text{liters/km} = 0.1674\,\text{kg/km}, \\ e_1^{\text{drive,BEV}} &= C_{17}^{\text{DE}} * 0.2\,\text{kWh/km} = 0.66\,\text{kg/km} \end{aligned}$$

The driving emissions are the same as the material emissions if

$$e_1^{\text{mat}} = e_1^{\text{drive}} x \quad \Rightarrow \quad x_= = \frac{e_1^{\text{mat}}}{e_1^{\text{drive}}},$$

so

- ICV: $x_= = 37\,200\,\mathrm{km}$
- BEV, DE mix: $x_= = 211\,800\,\mathrm{km}$

The critical distance x_c above which the BEV outperforms the ICV (in terms of less CO_2) is given by the condition of equal distance-dependent total emissions:

$$e_1^{\mathrm{ICV}} = e_1^{\mathrm{mat,ICV}} + e_1^{\mathrm{drive,ICV}} x = e_1^{\mathrm{BEV}} = e_1^{\mathrm{mat,BEV}} + e_1^{\mathrm{drive,BEV}} x$$

hence

$$x_c = \frac{e_1^{\mathrm{mat,BEV}} - e_1^{\mathrm{mat,ICV}}}{e_1^{\mathrm{drive,ICV}} - e_1^{\mathrm{drive,BEV}}} = 76\,500\,\mathrm{km}$$

So, the BEV needs to drive quite a distance before the increased materials emissions are compensated for by the lower driving emissions.