Methods in Transportation Econometrics and Statistics (Master)

Winter semester 2023/24, 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

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

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.

The driving emissions per kilometer (wtw emissions, i.e., w2t and t2w) are simply[1]

$$e'_{\text{ICV}} = C_{16} * 6\,\text{l/km} = \frac{e_1^{\text{driving,ICV}}}{200\,000\,\text{km}} = 0.167\,\text{kg/km}$$

(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

$$C_{\text{noAction}} = L^*\ 0.10\,\text{l/km} * \tilde{C}_{16} = 27\,900\,\text{kg}$$

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

$$C_{\text{Action}} = L^*\ 0.05\,\text{l/km} * \tilde{C}_{16} + e_1^{\text{indir}} = 24\,970\,\text{kg}$$

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 nearly 3 000 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 and the last one relating to the emissions during the driving phase (though nonlocal, they are emitted neartime during the charging process since electricity cannot be stored at any relevant amount):

$$(\vec{y}^s)_{\text{el}} == \begin{pmatrix} 820\,\text{kg steel} \\ 60\,\text{kg aluminum} \\ 100\,\text{kg plastic} \\ 110\,\text{kg rubber} \\ 600\,\text{kg Li-batteries} \\ 0.2\,\text{kWh/km} * 200\,000\,\text{km} = 40\,000\,\text{kWh} \end{pmatrix}.$$

The emissions during production and material replacements are

$$e_1^{\text{BEV,mat}} = \sum_{j=1}^{5} C_{1j} y_j^{\text{s,el}} = (4*82 + 30*60 + 2*100 + 2*110 + 20*600)\,\text{kg} = 17\,500\,\text{kg}$$

[1]Notice that the EU regulations required a fleet emission of less than 157 g/km, and now become more and more restrictive (95 g/km). Even if one implies that this is only related to the t2w emissions, one sees that these are physically impossible to reach. The same regulation also attributes zero emissions to BEV which is, of course, incorrect as we show here.

and that during driving

$$e_1^{\text{BEV,driving}} = C_{16} y_6^{\text{s,el}} = 0.48\,\text{kg/kWh} * 40\,000\,\text{kWh} = 19\,200\,\text{kg}$$

resulting in a total LCA emission of

$$e_1^{\text{BEV}} = 36\,700\,\text{kg},$$

which is 3 000 kg or less than 10 % less than that of the ICV.

(e) In the scenarios (i) and (ii), only $e_1^{\text{BEV,driving}} = C_{16} y_6^{\text{s,el}}$ changes, in (iii) the inventory Y_5^s is reduced by a factor 0.5:

(i) China mix:

$$\begin{aligned} C_{16} &= 1.00\,\text{kg/kWh}, \\ e_1^{\text{BEV,driving}} &= C_{16} y_6^{\text{s,el}} = 40\,000\,\text{kg}, \\ e_1^{\text{BEV}} &= e_1^{\text{BEV,driving}} + e_1^{\text{BEV,prod}} = 57\,500\,\text{kg} \end{aligned}$$

(ii) Norway-Sweden mix:

$$\begin{aligned} C_{16} &= 0.05\,\text{kg/kWh}, \\ e_1^{\text{BEV,driving}} &= C_{16} y_6^{\text{s,el}} = 2\,000\,\text{kg}, \\ e_1^{\text{BEV}} &= e_1^{\text{BEV,driving}} + e_1^{\text{BEV,prod}} = 19\,500\,\text{kg} \end{aligned}$$

(iii) DE mix and only one Li-battery needed during the lifetime:

$$e_1^{\text{BEV}} = e_1^{\text{BEV,(f)}} - 20 * 300\,\text{kg} = 30\,700\,\text{kg}$$

Comparing the total emissions with that of the ICV (39 700 kg) and the BEV for the DE mix (36 700 kg), we conclude: 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 also influences the balance essentially

(f) Including the w2t emissions (see (d)), we have for the ICV $\tilde{C}_{16} = 2.79\,\text{kg/l}$ and a specific CO_2 emission of

$$e'_{\text{ICV}} = \tilde{C}_{16} * 0.06\,\text{l/km} = 0.1674\,\text{kg/km}$$

(compare this with the specific *direct* driving emissions of $e'_{\text{dir}} = e_{\text{dir, driving}}/L = 0.1435\,\text{g/km}$, see (d)). For the DE mix, the BEV has a (nonlocal) specific driving emission of

$$e'_{\text{BEV}} = C_{16}^{\text{DE mix}} * 0.2\,\text{kWh/km} = 0.096\,\text{kg/km}$$

Furthermore, we have for the pure production and wear&tear but without w2t emissions (which are attributed to the driving emissions) according to (c) and (f):

$$e_1^{\text{mat,ICV}} = 6\,220\,\text{kg}, \quad e_1^{\text{mat,BEV}} = 17\,500\,\text{kg}$$

So, the critical number of driven kilometers to produce the production and wear&tear amount of CO_2 are

- ICV: $x = e_1^{\text{mat,ICV}}/e'_{\text{ICV}} = 65\,800\,\text{km}$
- BEV, DE mix: $x = e_1^{\text{mat,BEV}}/e'_{\text{BEV}} = 182\,300\,\text{km}$

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:

$$e_1^{\text{ICV}} = e_1^{\text{mat,ICV}} + e'_{\text{ICV}}x = e_1^{\text{BEV}} = e_1^{\text{mat,BEV}} + e'_{\text{BEV}}x$$

hence

$$x_c = \frac{e_1^{\text{mat,BEV}} - e_1^{\text{mat,ICV}}}{e'_{\text{ICV}} - e'_{\text{BEV}}} = 158\,000\,\text{km}$$

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