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Methods in Transportation Econometrics and Statistics (Master)

Winter semester 2021/22, Solutions to Tutorial No. 13

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

(a) Life-cycle inventory of the gasoline vehicle (internal combustion vehicle, ICV). The first 5 components are in kg, the last one in liters:

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

(b) Direct driving emissions for a total of $L = 200\,000\,\text{km}$:

$$e_1^{\text{dir,driving}} = 12\,000\,\text{liters} * 2.39\,\text{kgCO}_2/\text{liter} = 28\,680\,\text{kg CO}_2.$$

This coresponds to $143.5\,\text{g CO}_2/\text{km}$.

(c) Indirect emissions via the Life-cycle inventory of the materials+w2t emissions of gasoline (see below) and the emission factors (in kg CO_2):

$$\begin{aligned} e_1^{\text{indir}} &= \sum_{j=1}^{6} C_{1j} y_j^s \\ &= (4*820 + 30*60 + 2*100 + 2*110 + 20*36 + 0.4*12\,000)\,\text{kg} \\ &= 11\,020\,\text{kg CO}_2. \end{aligned}$$

The first five emission factors C_{1j}, $j = 1, \ldots, 5$ are dimensionless since they define the ration kg CO_2 divided by kg of the material in question. The last 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 (without the indirect w2t gasoline emissions but including wear&tear), we have

$$e_1^{\text{mat}} = \sum_{j=1}^{5} C_{1j} y_j = 6\,220\,\text{kg CO}_2.$$

Since also the w2t-emissions of the gasoline production are related to driving rather than production, the overall driving emissions are

$$e_1^{\text{driving}} = e_1^{\text{dir,driving}} + e_1^{\text{indir,driving}} = 28\,680\,\text{kg} + 12\,000\,\text{liters} * 0.4\,\text{kg/liter} = 33\,480\,\text{kg}$$

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.

(d) The total LCA emissions are

$$e_1 = e_1^{\text{dir,driving}} + e_1^{\text{indir}} = e_1^{\text{driving}} + e_1^{\text{mat}} = 39\,700\,\text{kgCO}_2.$$

In order to calculate the total emissions with the LC inventory, one needs to redefine the gasoline emission factor to include both the w2t and the tank-to-wheel (t2w) emissions, i.e., the combustion, resulting in the well-to-wheel (w2w) emission factor

$$\tilde{C}_{16} = C_{16}^{\text{w2t}} + C_{16}^{\text{t2w}} = (0.4 + 2.39)\,\text{kg/l} = 2.79\,\text{kg/l}.$$

With ($\tilde{C}_{1j} = (4, 30, 2, 2, 20, 2.79\,\text{kg/l})$, we obtain the same result as above,

$$e_1^{\text{ICV}} = \sum_{j=1}^{6} \tilde{C}_{1j} y_j^s = 39\,700\,\text{kgCO}_2.$$

(e) 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!

(f) 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

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

and that during driving

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

resulting in a total LCA emission of

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

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

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

(i) China mix:

$$C_{16} = 1.00\,\mathrm{kg/kWh}, \quad e_1^{\mathrm{BEV,driving}} = C_{16} y_6^{\mathrm{s,el}} = 40\,000\,\mathrm{kg}, \quad e_1^{\mathrm{BEV}} = e_1^{\mathrm{BEV,driving}} + e_1^{\mathrm{BEV,prod}} = 57\,500\,\mathrm{k}$$

(ii) Norway-Sweden mix:

$$C_{16} = 0.05\,\mathrm{kg/kWh}, \quad e_1^{\mathrm{BEV,driving}} = C_{16} y_6^{\mathrm{s,el}} = 2\,000\,\mathrm{kg}, \quad e_1^{\mathrm{BEV}} = e_1^{\mathrm{BEV,driving}} + e_1^{\mathrm{BEV,prod}} = 19\,500\,\mathrm{kg}$$

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

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

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

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

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

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

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

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):

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

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.