Energy Transition for Sustainable Transportation System: Graphical Approach

Yee Van Fan, Jiří Jaromír Klemeš
Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno, University of Technology - VUT Brno, Technická 2896/2, 616 00 Brno, Czech Republic

Abstract
Transportation is one of the significant contributors of GHG and air pollutants, from both the tank to well and well to wheel cycle. This study aims to introduce a graphical approach to mapping the circumstances where the energy transition offers a lower emission. The proposed method is demonstrated by a case study of the EU condition (EU-28, Latvia and Sweden). Assessed energy sources to power transportation are electricity, compressed natural gas, liquefied natural gas, diesel and biodiesel. This approach facilitates the transport mode selection (road, rail, sea) and the understanding of how electricity mix or renewable energies influence the energy transition. The environmental oriented approach can be improved in a future study by integrating the economic perspective.

Keywords: Energy Transition, GHG, Graphical Approach, Air pollutants, Transportation

1. Introduction
A considerable effort has been introduced to minimise the negative impacts of the transportation sector. This includes optimisation of transportation infrastructure including public transport, carpool, traffic management. This should also include the enhancement of fuels and engine efficiency as well as introducing alternative energy sources. Energy transition and modal shift are one of the measures that have received high research attention. Among the strategies to mitigate the emission from transport, electric vehicles have been in relatively fast advancement and started to gain visible share in the market. An electric car has been branded as a vehicle with zero emissions. However, it apparently could not be a full zero emissions when the whole life cycle (well to wheel) has been evaluated. The power generation emitted GHG and air pollutants. This is especially in the present case as the power supply has been produced from the energy mix where fossil fuel is still dominant. WRI [1] suggested that electrification to create low carbon emissions cities is only valid to the country with the carbon intensity of less than 600 tCO2eq/GWh. The feasibility of energy transition needs to be assessed by considering the different factors (e.g. availability, maturity, demand and the policy of a country).

There has been a number of studies on assessing the energy transition and transport selection. The considered scope and criteria differ from one another. Relatively few studies include non-GHG emissions and/or consider more than two transportation modes in a single study. Fan et al. [2] show that the transport mode with the lowest GHG emission is not necessarily the best solution when considering more air pollutants. Most of the proposed decision models use mathematical optimisation. Studies based on a graphical approach for decision making is comparatively few. One such study proposes an iso-emission map [3]. Jonkeren et al. [4] propose a shift-share components tool to visualise how changes in freight transport mode affect CO2 emissions. A graphical transportation decision tool has been presented by How et al. [5] using weight/volume of materials to be transported and travelling distance as the two axes. However, their plot only compares two alternatives at a time, focusing on vehicle capacity constraints and CO2 emission. Bigazzi [6] highlights the bias of comparing the transportation options by average emission factors rather than the marginal emissions. To summarise, graphical-based decision-making tools primarily use the perspective of GHG emissions. It deserves more development to consider additional and marginal emissions. This study aims to propose a novel graphical approach to identify the transportation mode with lower emissions and the relevance of energy transition.

2. Method
The graphical tool consists of R (distance ratio of the compared transportation mode) as the y-axis, L (Load) as the x-axis. The plotted lines on the graph represent the “break-even” conditions where two transportation modes emit the same amount of emissions.
The total emissions released \( (E_{tot}) \) is determined using Eq(1). Eq(1) is formulated based on the idea that emissions from a vehicle are linearly proportional to its total weight (body weight of empty vehicle + load). Most transport emissions factors are reported for a fully loaded vehicle on a per t of transport freight. As a result, the first term \( (n \cdot e_{empty} \cdot D) \) in Eq(1) relates to the energy or emissions due to the bodyweight and the second term \( (L \cdot e_{load} \cdot D) \) determines the emissions due to the weight of the load.

\[
E_{tot} = (n \cdot e_{empty} + L \cdot e_{load}) \cdot D \quad \text{where} \quad n = \text{Roundup} \left( \frac{L}{w_{max}} \right) \quad \text{and} \quad n \in \mathbb{Z} \tag{1}
\]

Where \( e_{empty} \) is the specific emission of an empty transport vehicle fleet (t/km); \( e_{load} \) is the marginal specific emission of a transport vehicle fleet per t of transport load (g/tkm); \( n \) is the required number of transport vehicles; \( D \) is the total transport distance that each vehicle has to travel (km), and \( L \) is the total transport load across all vehicles (t). Both \( e_{empty} \) and \( e_{load} \) are determined by Eq(2) and Eq(3).

\[
e_{empty} = E_{full} \left( w_{max}/w_{empty} \right) \tag{2}
\]

\[
e_{load} = E_{full} \left( w_{max}/w_{full} \right) \tag{3}
\]

Where \( w_{max} \) is the maximum load that one vehicle can transport (t), \( w_{empty} \) is the weight of an empty vehicle (t), and \( w_{full} \) is the weight of a full vehicle (t). Emission factors, \( E_{full} \), which have the units of MJ/t-km (or g/t-km), noting t (in the denominator) is a ton of transport load (excludes the empty vehicle weight) and a transport distance in km.

To identify the point where the generating emission of two transportation modes \( (i \text{ and } j) \) are the same, i.e. \( E_{tot,i} = E_{tot,j} \), the following equation has been obtained for the ratio \( R \), which is \( D/D_i \), for a constant \( L \).

\[
R = \frac{D_i}{D_j} = \frac{n_j \cdot e_{empty,j} + L \cdot e_{load,j}}{n_i \cdot e_{empty,i} + L \cdot e_{load,i}} \tag{4}
\]

The plot \( E_{tot,j} = E_{tot,j} \) can only capture and compare a single dimension, e.g., one type of emission. Total environmental burden, \( T_{env}(€) \), as in Eq(5), is introduced to account for the emissions of both GHG and air pollutants by summing the cost/pric equation contribution of each emission/pollutant, \( k \).

\[
T_{env} = \sum_{i} (E_{tot}(k) \cdot c_{env}(k)) \tag{5}
\]

Where \( c_{env} \) is the environmental price coefficient of the emission type (e.g., CO\(_2\)eq, SO\(_2\), NO\(_x\) and PM) in €/t. \( T_{env,i} \) is equal to \( T_{env,j} \) in identifying the border where the environmental price is the same.

3. Case Study

The evaluated transportation modes to demonstrate suggested graphical approach are a lorry, train, and general cargo. Table 1 shows the specification of the transports. The lorry runs by different energy sources are assessed, and the emissions are presented in Table 2. In this study, the environmental price is assigned based on the value reported in [7]. Three scenarios (Latvia, Sweden, EU-28) are illustrated to show the impact of the electricity mix. The carbon emissions intensities are 1,168 gCO\(_2\)eq/kWh (Latvia), 47 g CO\(_2\)eq/kWh (Sweden) and 447 g CO\(_2\)eq/kWh (EU-28) [8]. To construct a break even line on the graphical tool, L is varied from 1 to 100,000 t. A log scale is applied to the axis. The identified border divides the space and suggests that under a given amount of load (L) to be transported and the known distance ratio of two routes (R), which transportation mode would have lower emission.

### Table 1 Specification of Transportation Mode [9]

<table>
<thead>
<tr>
<th>Transport Mode</th>
<th>Maximum capacity (t), ( w_{max} )</th>
<th>Weight of fully loaded vehicle (t), ( w_{full} )</th>
<th>Weight of empty vehicle (t), ( w_{empty} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lorry</td>
<td>13</td>
<td>28</td>
<td>15</td>
</tr>
<tr>
<td>Train</td>
<td>70</td>
<td>988</td>
<td>918</td>
</tr>
<tr>
<td>General Cargo</td>
<td>7,339</td>
<td>10,000</td>
<td>2,661</td>
</tr>
</tbody>
</table>

### Table 2 Emissions of different transport type [9], Carbon emission intensity based on [8]

<table>
<thead>
<tr>
<th>Transport type</th>
<th>Emission factors (EF(_{full}), g/tkm)</th>
<th>GHG</th>
<th>NO(_x)</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Lorry</td>
<td>27.8929</td>
<td>0.1750</td>
<td>0.0010</td>
<td></td>
</tr>
<tr>
<td>Biodiesel Lorry</td>
<td>6.1364</td>
<td>0.2222</td>
<td>0.0025</td>
<td></td>
</tr>
<tr>
<td>LNG(^a) Lorry</td>
<td>24.2668</td>
<td>0.0228</td>
<td>0.0007</td>
<td></td>
</tr>
<tr>
<td>CNG(^a) Lorry</td>
<td>22.5932</td>
<td>0.0003</td>
<td>0.0158</td>
<td></td>
</tr>
<tr>
<td>Electric Train</td>
<td>20.1150(^b)</td>
<td>0.0170</td>
<td>0.0010</td>
<td></td>
</tr>
<tr>
<td></td>
<td>52.5600(^c)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.1150(^c)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric Lorry</td>
<td>17.3833(^d)</td>
<td>0.0210</td>
<td>0.0010</td>
<td></td>
</tr>
<tr>
<td></td>
<td>45.4222(^e)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.8278(^e)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General Cargo</td>
<td>21</td>
<td>0.3600</td>
<td>0.0090</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)EU-28 average. \(^b\)Latvia. \(^c\)Sweden. \(^d\)Liquefied compressed gas. \(^e\)Compressed natural gas

4. Results and Discussion

The plotted lines in Figure 1a show the comparison of different transport alternatives as listed in Table 2. For example, the blue line (CNG lorry vs Electric Train), it suggests the area above the line is for electric train and the area below for CNG lorry. Figure 1b shows the simplification mapping for Latvia by reserving the
dominant/decisive line. At $R=1$ (distance to travel by lorry and train is equivalent), biodiesel lorry is the best from the view of GHG (Figure 1b) and CNG lorry (Figure 2) by Total Environmental Burden under all the assessed load (1-100,000 t).

A contradict observation is obtained in Figure 3 and 4. In Sweden, lorry run by electricity is the best from both GHG and Total Environmental Burden perspective. Sweden has a cleaner electricity mix than in Latvia. The electric train is the preferable option in Sweden with the increasing load. This is not in the case of Latvia which dominant by biodiesel and CNG at $R=1$.

In EU 28 (Figure 5), at $R=1$, biodiesel is the option with the lowest GHG emission. However, CNG is the best option when considering the Total Environmental Burden (Figure 6). This contradiction remark again emphasised the possible bias of considering only GHG emission in decision making. By referring to Figure 6(b), the Electric Lorry vs Electric Train line is very close to CNG. Electrification generally contributes to a lower Total Environmental Burden in the EU, especially for a country which has a carbon intensity of lower average (447 g CO$_2$eq/kWh).

**Figure 1** Graphical tool based on GHG-Latvia (a) Original (b) Simplify. $R =$ distance ratio of the compared transportation mode). L= Load

**Figure 2** Graphical tool based on Total Environmental Burden-Latvia

**Figure 3** Graphical tool based on GHG-Sweden

**Figure 4** Graphical tool based on Total Environmental Burden-Sweden
expected to ease the selection process. R is established in a way to prevent the model from restricted to the origin-destination pairs considered. Biodiesel lorry is found to be the best low GHG option for Latvia at R=1 (distance to travel by lorry and train is equivalent), regardless of the load. In Sweden, the electric lorry is the best from both GHG and Total Environment Burden perspective while the electric train is preferable with increasing load. In the EU-28, biodiesel is the option with the lowest GHG emission and CNG when considering the Total Environmental Burden. The importance of including air pollutants emission in transports decision making is highlighted.

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**Reference**