Sustainability assessment of alternative fuels for freight transport: methodological approach and case study for liquefied natural gas

Jose Luis Osorio-Tejada, Eva Llera-Sastresa and Sabina Scarpellini

CIRCE- Centre of Research for Energy Resources and Consumption, University of Zaragoza, Spain, jlosorio@unizar.es

Abstract:
This paper introduces a model that allows to analyse strategies towards the introduction of alternative fuels in the urban and interurban road freight transport from the integration of several perspectives (technology, infrastructures, binding legislation and market development) what configures the so-called "transport system". An impact assessment framework that applies a multi-criteria analysis (MCA) methodology to assess the simultaneous impact on the environment, economic development and social welfare throughout the life cycle of the transport systems is also designed and specifications for the estimation of the corresponding indicators are presented. Even though this methodology aims to estimate the potential sustainability in its broadest conception of any low carbon technologies for road transport, it is applied to the deployment of liquefied natural gas in Spain as a case study. Different scenarios are taken into account and weighting factors matrix for MCA are consequently generated based on stakeholders’ perspectives.

Keywords:
Liquefied natural gas, Freight transport, Alternative fuel, Sustainability, MCA.

1. Introduction

Although the corporate environmental responsibility and the sustainable development are in discussion since the 80’s [1], companies in the transport sector had not been concerned about taking initiatives to streamline operations bearing into account the environmental impact. Main reasons are that the regulations derived from the Kyoto Protocol [2] against climate change were only focused on reducing emissions of greenhouse gases (GHG) in the industrial and energy sectors, which were included in the Emissions Trading Scheme (ETS) in the Directive 2003/87/CE [3].

The growth in the share of freight transport by road, which carries 75.4% of tons-kilometer (tkm) inside the EU [4], is a concern that increasingly takes more importance. Transport sector in the EU released 24.4% of total GHG in 2013 [5], where road mode contributed 94.6% of the total of these emissions [6]. Although regulations such as the European air pollution standards (Euro I-VI) [7], set limits on vehicle emissions of carbon monoxide (CO), volatile organic compounds (VOCs), nitrogen oxides (NOx) and particulate matter (PM), regulation to control the emissions of carbon dioxide (CO₂) in heavy duty vehicles (HDV) has not been established.

However, since the inclusion in 2009 of diffuse sectors in the ETS and consequently the transport sector [8], calculation and reporting of GHG in freight transport companies has been promoted. This scenario has also encouraged companies to adopt strategies to differentiate themselves from their competitors by producing low contribution to the carbon footprint of the transported products, saving fuel and therefore getting a sustainable freight transport subsector, at least environmentally.

Due to the CO₂ emissions in vehicles depend on the amount of fuel consumed, the progress made by manufacturers to increase energy efficiency in HDV, such as aerodynamic body, lightweight materials, low viscosity lubricants or inflated auto tires, could reduce the amount of such emissions. However, the efforts to meet the European air quality standards requirements by modifying engines
and installing devices for the after-treatment of exhaust gases, as exhaust gas recirculation valves and particulate filters to reduce NOx emissions and PM respectively, have affected the fuel efficiency [9–11]. In addition to improving the performance of these processes, the most appropriate measure to reduce the environmental impact of trucks is by using less polluting alternative fuels, which do not need excessive treatments.

For decision-making, legislators and local governments, as well as by companies’ managers and users of freight transport need to have reliable information to estimate the short-, medium- and long-term impacts of one or more low emission strategies in the sector. It is essential to assess the impact of these strategies, not only in environmental but also in socio-economic terms. Sometimes, making progress in reducing GHG emissions, can also lead to social problems, which often are not taken into account when a specific emissions reduction strategy is proposed, giving rise to possible collateral damage after its implantation. For instance the Green Paper on security of energy supply in the European Union [12], projected replace 20% of conventional fuels used in road transport by 2020 in order to mitigate environmental pollution and dependence on oil in the transport sector. It was expected that biofuels were participating at least 6% of the fuels used in road transport in 2010 [13]. However, it was reported that by this year biofuels only shared 4.4% of energy consumption in road transport [14], mainly as a result of some socioeconomic problems generated in Europe and in developing countries which produce these fuels, such as the increase in food prices and the land use competition. For that reason, the European Commission recommended to encourage the introduction of different alternative fuels based on the maturity of the technologies for each application, such as electricity, Compressed Natural Gas (CNG) and hydrogen for urban use vehicles and Liquefied Natural Gas (LNG) for long haul transport.

In Europe, public institutions and transport companies have encouraged to make carbon footprint reports and carry out inventories of energy consumption and emissions of road vehicle fleet. A large number of initiatives, methodologies, databases and commercial tools have been developed. By 2011 these initiatives amounted a total of 102 according to the report of COFRET project [15]. Currently, most of the available initiatives work based on the European standard EN-16258:2012 Methodology for calculation and declaration of energy consumption and GHG emissions in transport services (transport freight and passenger). This standard limits the reporting to the Well-to-Wheels (WTW) analysis, which includes only the fuel life cycle, due to the vehicle use phase is responsible for over 80% of GHG released throughout the transport system (vehicles, infrastructure and fuels) in its life cycle [16,17]. Therefore, the WTW analysis leaves out the impact of vehicle and infrastructure construction, because these factors are considered minor or little weight in the total GHG emissions. Nevertheless, taking into account other emissions, the contribution of vehicles and infrastructure in the life cycle emissions is noteworthy. For example, PM emissions associated to road construction phase are three times higher than those emitted during production and use of road transport fuels [18]. Similarly, if the economic and social impacts were measured, these factors could represent a much greater weight, which should not be neglected.

For this reason, as the introduction of alternative fuels in the transport sector generates consequences in different factors of the transport system, it is important for decision-making purposes to have a model that integrates the three pillars of sustainability analyzing the economic, environmental and social impacts for each one of factors (Vehicles, Infrastructure and Fuels).

In this paper, a simplified model based on Multi-Criteria Analysis (MCA) for assessing the sustainability of alternative fuels in urban and interurban transportation systems is presented. Section 2 introduces the theoretical framework of the MCA models for the evaluation of alternatives taking into account different criteria and stakeholders to establish the advantages of using this type of methodology for decision-making in the transport systems. The model is presented in Section 3, describing each step to carry out a correct selection based on a sustainability index. In Section 4, the case study to the introduction of LNG combustion technology in a private
fleets for road freight transport in Spain is described. Subsequently the results and discussions are presented and finally the study's conclusions are set.

2. Multi-criteria analysis in the transport sector

In practice, both private companies and public administrations usually apply financial, profitability and Cost-Benefits analysis for decision-making in the transport sector [19]. These techniques assess different alternatives in monetary terms of economic aspects and some social and environmental aspects represented in external costs such as air pollution, noise and accidents. However, monetizing many of these variables requires great expertise, time and training to carry out these studies properly, besides many other variables or indicators that are very difficult to compare by these methods.

The difficulties for decision-makers when handling large number of indicators can be avoided with simpler and more transparent methods such as the MCA tools, which allow the classification of the indicators according impact categories or criteria groups as well as the integration of the stakeholders interests offering a solution in terms of scores, rankings and relative weighting [20].

There are different MCA methods that can be applied in the transport sector, among the most popular are [20]: Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), REGIME, ELECTRE family, Multi Attribute Utility approach, and ADAM type. The MCA method selection depends on several factors such as the objectives, scope, expected accuracy level, the stakeholders involved, the availability of information, number of indicators, among others. A MCA method that incorporates significantly the views of the stakeholders as part of the decision-making group is the AHP developed by T. Saaty [21]. This method allows building a hierarchical tree and weighting each indicator by pairwise comparison between criteria and indicators through a matrix, getting a consistent and coherent management of both quantitative and qualitative data.

Models for decision-making based on MCA have been considered by several authors to evaluate alternatives in the transport sector [20,22] and specifically for freight transport [23–25]. These authors have used MCA for basically cost modeling of the supply chain, analyzing alternatives for different transport modes and intermodal terminals, as well as the internalization of external costs of intermodal transport, taking into account different stakeholders.

In transport sector, specifically for the assessment of biofuel sustainability, several authors have used MCA models in order to hybridize the social and economic criteria with life-cycle assessments (LCA) [26–30]. L. Elghali et al. [31] integrated socio-economic aspects in decision-making from a LCA, in the sense of involving perceptions of people through group interviews for each environmental impact category identified in a LCA for 6 different processes for road maintenance.

3. Sustainability assessment model in freight transport

The proposed MCA model aims to provide a basic and simplified guide for decision-makers to assess the sustainability of the introduction of technologies for the use of alternative fuels in trucks fleets. The model lets decision-makers take into account the comprehensive view of customers, employees and owners in an analytic hierarchy evaluation process.

Because of the model is focused on private transportation companies, a detailed guide is developed; which includes the steps for qualitative assessment of the selected sub-criteria for the environmental, social and economic criteria. The model requires including sub-criteria related to market aspects into the economic criterion to assess indicators such as the reliability of the technology, supply security and legal issues. The guide consists of the following five steps, as seen in Fig. 1:
1) Selection of alternatives and establishment of items by factor
2) Establishment of three sub-criteria and indicators, by criterion
3) Pairwise comparison of alternatives by sub-criteria
4) Weighting of criteria for evaluating scenarios
5) Selection of the most sustainable alternative

Fig. 1. Sustainable freight transport assessment model

3.1 - Alternatives selection and the establishment of items by factor

After establishing the scope and objectives of the evaluation process, alternatives \((q = 1, 2 \ldots n)\) and items \((j_{qf})\) for every factor, i.e., Vehicles \((V)\), Infrastructure \((I)\) and Fuels \((F)\), which have an impact on economic \((EC)\), environmental \((EN)\) and social \((S)\) aspects, are identified through an initial market analysis.

Items must be identified based on the preliminary selection of two alternatives, i.e. the traditional \((q = 1)\) and the new alternative \((q = 2)\). All needed items to operate with an alternative fuel have to be classified in the respective factor. For example, if to operate with electricity \((q = 2)\) is available only the electric truck with lead batteries, it would be an item of the vehicles factor \((i.e., j_{2V} = 1)\). Furthermore, if to recharge the trucks is possible at an own station to be built inside the company facilities or at third parties’ charging stations located in different points in the city, both options would be items of the infrastructure factor \((i.e., j_{2I} = 2)\). Subsequently, the kind of fuel identified for both options would be the same electricity from the city’s energy mix \((i.e., j_{2F} = 1)\).

To begin the analysis, it is important to ensure that for each alternative, at least one item in one of the three factors of the transport system is identified \((\forall f \in q, j_{qf} \neq 0)\). Besides, each factor cannot have more than one item \((\forall f \in q, j_{qf} \geq 0)\). Therefore, if there are two or more items in one of the factors, the additional item must be converted to a new alternative \((j_{qf} > 1 \rightarrow q = n + j_{qf} - 1 \rightarrow j_{qf} = 1)\), hence each new alternative will have only one item in the respective factor. In this sense, for the previous example would now be three alternatives: the traditional diesel truck \((q = 1)\), the electric truck charged at own station \((q = 2)\) and the electric truck charged at third parties’ stations \((q = 3)\).

It should be notice that for the selection of alternatives, appropriate information available on the market is needed, as far it interacts to aspects related to technological development and legislation. This information has been defined in some studies as technological criterion, where the main...
indicator has been the efficiency, followed by reliability and maturity of the technology [32]. However, technological aspects must be evaluated in parallel with the legal aspects and market trends. Those aspects should be analyzed from not only information providers but also successful cases in the same sector and studies with sufficient scientific rigor to provide accurate and consistent results. Some technological aspects are: safety and performance; warranty and after-sales service; guaranteed supply and price stability of spare parts, supplies and fuel; staff training requirement; and availability of refueling stations. Whereas some legislation aspects are: incentives for investment in technology; compliance with air quality standards, noise and safety; permitting and/or special licenses for the free circulation; specific regulations in cities and areas for restricted access due to noise, fuel type, weight or dimensions; analysis of the expected or likely restrictive regulation in the sector, and tax benefits.

3.2 - Establishment of three sub-criteria and indicators, by criterion

For the establishment of a sub-criterion \( (k_c) \) and the corresponding indicator \( (i_k) \) for the social, economic and environmental criteria, they should be at least three sub-criteria based on the different interests of the stakeholders for each criterion. All this to assure inclusion in the economic criterion, besides the financial sub-criterion, other sub-criteria related to reliability of technology and legal aspects involved in the expected performance of the investment over lifetime.

In this regard, the three recommended sub-criteria for the economic criterion would be reliability investment and operating costs and legislation. For environmental and social criteria, the three sub-criteria to choose may vary depending on the interests of the company and stakeholders. Among the most commonly used sub-criteria for environmental criterion are GHG and air pollutants emissions, land use and noise, while for the social criterion they would be job creation, social benefits or social acceptability [32]. In addition, for each sub-criterion a valid indicator must be chosen to compare the results between the selected alternatives, e.g., square meters would be an indicator to land used for refueling stations and decibels would be an indicator to the noise from engines.

3.3 - Pairwise comparison of alternatives by sub-criterion

Pairwise Comparison Matrices (PCM) for each sub-criterion to compare the alternatives in each factor are developed. The Global Priority Vector to each alternative by criterion-factor will be obtained based on the Saaty AHP guidelines [21]:

a. For each sub-criterion, PCM are performed, establishing a rating of relative importance among the alternatives considered. The rating is established from the following scale:

1 = equally preferred
3 = moderately preferred
5 = strongly preferred
7 = very strongly preferred
9 = extremely preferred

Pair values can be assigned and a reciprocal rating \((1/3, 1/5 \ldots)\) when the second alternative is preferred over the first one. A number 1 is assigned to an alternative comparison with itself.

b. Develop a Normalized Comparison Matrix (NCM) dividing each number in a column of the MCP by the sum total of the column for each sub-criterion.

c. Develop the Priority Vector (PV) to each sub-criterion by calculating the average of each row of the NCM. This average per row vector represents the priority of the alternative with respect to the considered sub-criterion.
d. The consistency of the views used in the PCM can be determined through the Consistency Ratio (CR). A CR less than 0.10 is considered acceptable. When the CR is greater than 0.10, opinions and judgments should be reconsidered.

e. After completing the above points for each one of the sub-criteria, the results obtained at point c are summarized in a Priority Matrix (MP), listing alternatives by row and sub-criteria by column.

f. Construction of the Sub-criteria Pairwise Comparison Matrix (SPCM), the NCM and the PV to the sub-criteria comparison. These matrices and sub-criteria PV are developed similarly to what was done for the alternatives comparison in points a, b and c.

g. Develop the Global Priority Vector of alternatives for each criterion ($Y_{cf}$) multiplying the sub-criteria PV obtained in the previous step by the MP of alternatives from the point e.

\[
Y_{cf} = \begin{bmatrix} y_{c1f} \\ y_{c2f} \\ \vdots \\ y_{cnf} \end{bmatrix},
\]

where:

c = EC, EN, S.

f = V, I, F.

q = 1, 2... n.

3.4 – Weighting of criteria for evaluating scenarios

Weights for each criterion ($W_c$) to establish different scenarios based on the interests of stakeholders are made. The baseline scenario would be constructed considering equal importance to each of the three criteria ($W_{EC}=1/3$, $W_{EN}=1/3$, $W_{S}=1/3$); while scenario 1 would be made based on the interests of the decision-maker team. This team commonly is composed of strategy planners, the head of maintenance department, a member of the board of directors, the general manager and employee representative of the company, but also could be involved in a representative of the community or local government.

Additional scenarios where the weighting depend on the opinion of certain stakeholder or the same decision-maker team based on different market expectations or potential changes in legislation are established, in order to know the best alternatives that they should choose for a given scenario.

3.5 - Selection of the most sustainable alternative

From the Global Priority Vectors of alternatives for each criterion ($Y_{qf}$) obtained at the end of section 3.3 and weightings from section 3.4, the sustainability index is obtained for each alternative ($SI_q$) in certain scenario, where the highest value would be the most sustainable alternative:

\[
SI_q = \left[ W_{EC} \left( y_{ECV,q} + y_{ECI,q} + y_{ECF,q} \right) + W_{EN} \left( y_{ENV,q} + y_{ENI,q} + y_{ENF,q} \right) + W_{S} \left( y_{SV,q} + y_{SL,q} + y_{SF,q} \right) \right] / 3,
\]

\[
\sum_{q=1}^{n} SI_q = 1.
\]
4. Case Study: LNG sustainability assessment for a Spanish road freight company

The objective of the company is to purchase a new truck (tractor unit) for transporting goods. It is expected that the vehicle can travel on average 1 000 km (round-trip) from to the base plant in Zaragoza, with or without refueling in the available stations on their routes. The model seeks to evaluate sustainable cleaner alternative technologies, primarily to a lower contribution to the carbon footprint of the transported products.

The European Commission [14] recommended, through the communication _Clean Power for Transport: A European alternative fuels strategy_, the following alternative fuels for long haul transport: Liquefied Petroleum Gas (LPG), LNG and biofuels. Although for biofuels, only the promotion was recommended when advanced biofuels become commercially available on a large scale, because the first and second generation biofuels in addition to generating socioeconomic problems mentioned recently, biodiesel from and rapeseed or palm oil could generate equal to or greater GHG than fossil fuels considering the Indirect Land Use Change [33].

Currently, as using biodiesel does not require large investments for the company due to its compatibility with conventional diesel engines, the decision of using it is more a macroeconomic issue, in which their introduction would depend on the development of advanced biodiesel technologies as obtained from algae, which have not reached an economically viable production [11]. While in the case of LPG, no European manufacturer offers medium and heavy vehicles with this system, nor is developing, because this fuel does not offer advantages in performance, emissions or prices versus NG [34].

For the above mention, the alternative fuel to diesel oil for long haul transport would be LNG. Additionally, there are many key facts for the motivation of adopting the LNG technology for freight transport. A recent study suggested that the LNG use in HDV has a potential for reducing the environmental impact and noise in cities, in addition to the maturity of technology and energy resource availability, and the clear interest of the EU of supporting the LNG introduction [35]. In addition to the Directive 2014/94/EU on the deployment of alternative fuels infrastructure [36], which set goals to the construction of LNG refueling stations each 400 km, there are other motivations such as the relative LNG low fuel prices, the restrictions to diesel trucks in some urban areas due to local air pollution and noise issues, and taxation benefits. However, while the enough infrastructures are developed, the gap between LNG and diesel prices stabilizes and the legislation for taxation benefits is established, the uncertainty remains for freight transport companies to adopt this new technology.

There are companies that offer kits to convert conventional diesel to dual fuel engines to operate with 95% LNG and 5% diesel, or manufacturers that offer new trucks with 100% dedicated LNG spark ignition engines directly from the factory. For this case study, because the intention is to buy new units for the long distances fleet, two alternatives were selected: to purchase a dedicated LNG 330-horsepower tractor unit and a diesel one equivalent, both domestically manufactured with Euro VI certification, which meet the technical and legal requirements for driving on European roads.

Therefore, items involved in the transportation system would be the new tractor units, refueling stations and fuels, Table 1. Although refueling stations would be built and managed by third parties, they must be taken into account due to their indispensability for the operation of vehicles. Roads and other infrastructure such as parking slots would be the same for both types of trucks.
downs in the economic with a perception on although these overruns is related with the roadside breakdowns, although there is a social emissions respectively. The technician together with the Mean Time To Repair (MTTR) and the waiting time for a skilled maintenance training cost. Fuels Infra Vehicles Factors Table 3. Ratings to the PCM between LNG and diesel alternatives by sub-criteria and factor

Factors | Initial and maintenance costs | Reliability | Legislation | GHG | Air pollutants | Noise | Employment | Social benefits | Social acceptability
---|---|---|---|---|---|---|---|---|---
Vehicles | 1/5 | 1/3 | 5 | 1 | 1 | 9 | 1 | 1 | 3
Infrastructure | 1 | 1/9 | 3 | 1 | 1 | 1 | 3 | 1 | 1
Fuels | 9 | 1 | 3 | 1 | 9 | 1 | 3 | 1 | 3

The LNG alternative had low ratings in the economic sub-criteria because of the truck incremental cost around 30% over the conventional diesel truck [37] and maintenance costs due to the extra training and potential roadside breakdowns [38], although these overruns might be compensated with lower fuel expenses [37,39]. The lowest rating is related with the roadside breakdowns, together with the Mean Time To Repair (MTTR) and the waiting time for a skilled maintenance technician with the spare parts [38,40]. Also, the limited number of refueling stations [41] restricts the Vehicle Routing Problem (VRP), principally for international routes.

The other sub-criteria had positive rating due to LNG engines reduce 70% and 97% of the NOx and PM emissions, respectively [42,43]; and around 50% of the engine noise [44–46]. While GHG emissions have not shown significant reductions in any of the factors [35]. In the social sub-criteria, social acceptability had the greatest rating due to the negative perceptions for diesel combustion, although there is a unjustified fear associated with a perception on the danger of NG vehicles and

| Table 1. Items by factor to each alternative |
|---|---|---|
| Factors | LNG | Diesel |
| Vehicle Infrastructure Fuels | LNG tractor unit LNG refueling station LNG | Diesel tractor unit Diesel refueling station Diesel oil |

Considering the interests of the company, its workers and local community, the selected sub-criteria and their respective indicators is described in Table 2.

| Table 2. Sub-criteria and indicators by criteria to each factor |
|---|---|---|---|---|
| Criteria | Sub-criteria | Indicators by factor |
| Economic | Initial and maintenance costs | €/year | - | €/100 km |
| Reliability | non-productive days/year | Availability | Availability |
| Legislation | Restrictions and benefits | Restrictions | Tax benefits |
| Environment | GHG emissions | gCO2 eq/km | gCO2 eq/km | gCO2 eq/km |
| Air pollutants (NOx and PM emissions) | g/km (each one) | g/km (each one) | g/km (each one) |
| Noise | Decibels | Decibels | - |
| Social | Employment | Direct and indirect jobs | Indirect jobs | Indirect jobs |
| Social benefits | Social benefits | Social benefits | Social benefits |
| Social acceptability | Favorability index | Favorability index | Favorability index |

*considering the life cycle impacts and the emissions per km because both trucks transport the same weight.

*considering also the availability and price stability to over the years.

* social benefits such as royalties, income increase and health benefits.

For some of the chosen sub-criteria, indicators contain qualitative data that might not be very accurate given the lack of information for a particular factor. In addition, because of the inexperienced market for LNG technology, most of the information was obtained from demonstration studies and experimentation performed by different manufactures in other countries. These considerations were taken into account when comparing the importance of specific sub-criterion against another, reducing its weight in the final assessment.

In this way, a summary of the process described in the point a of section 3.3 is shown in Table 3. Each cell of this table is an assigned rating of relative importance to the LNG alternative versus the diesel alternative for each sub-criterion and each involved factor.

Table 3. Ratings to the PCM between LNG and diesel alternatives by sub-criteria and factor

<table>
<thead>
<tr>
<th>Factors</th>
<th>Initial and maintenance costs</th>
<th>Reliability</th>
<th>Legislation</th>
<th>GHG</th>
<th>Air pollutants</th>
<th>Noise</th>
<th>Employment</th>
<th>Social benefits</th>
<th>Social acceptability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicles</td>
<td>1/5</td>
<td>1/3</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>1</td>
<td>1/9</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Fuels</td>
<td>9</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>9</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

For some of the chosen sub-criteria, indicators contain qualitative data that might not be very accurate given the lack of information for a particular factor. In addition, because of the inexperienced market for LNG technology, most of the information was obtained from demonstration studies and experimentation performed by different manufactures in other countries. These considerations were taken into account when comparing the importance of specific sub-criterion against another, reducing its weight in the final assessment.
refueling stations [37]. In the case of infrastructure new jobs in the construction of refueling stations would be generated as well as in the LNG distribution [37].

After performing the previous rating, considering also weights of each sub-criterion through the SPCM construction, the following Global Priority Vectors for each criterion were obtained ($Y_q$):

### Table 4. Global Priority Vectors for each criterion and factor

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Factors</th>
<th>Global priority vector</th>
<th>Alternative 1 (LNG)</th>
<th>Alternative 2 (Diesel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>Vehicles</td>
<td>0.30</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Infrastructure</td>
<td>0.36</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuels</td>
<td>0.71</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>Environment</td>
<td>Vehicles</td>
<td>0.60</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Infrastructure</td>
<td>0.50</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuels</td>
<td>0.54</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>Social</td>
<td>Vehicles</td>
<td>0.57</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Infrastructure</td>
<td>0.66</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuels</td>
<td>0.77</td>
<td>0.23</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 shows the scores for each alternative according to the impact on each factor to certain criterion. A particularity of these results is that the environmental criterion did not give better scores due to the good rating in air pollution and noise sub-criteria. This because the GHG emission was considered the most important sub-criterion in the environmental criterion for the company objectives, thus, the air pollution sub-criterion had a very low weight. Also due to both trucks meet the requirements of the Euro VI standard was not important to give it a higher rate.

Continuing the process to get the consolidated results, the weighting according to the scenarios in Table 5 was considered. The scenarios reflect the different interests of stakeholders. For instance, if the decision were in hands of the government (which targets the environmental and social benefits) the scenario weighting could be described as the second one, while the scenario 1 reflects the interests of the private sector.

### Table 5. Weighted scenarios by criteria

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Economic</th>
<th>Environment</th>
<th>Social</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>1</td>
<td>0.50</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>3</td>
<td>0.80</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>0.50</td>
<td>0.50</td>
<td>0</td>
</tr>
</tbody>
</table>

Sustainability indices were obtained for each alternative ($S_{i,q}$) in each scenario, where the highest value for scenario 1 would be the most sustainable alternative for the decision-maker team.

### Table 6. Sustainability indices by scenario

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>LNG</th>
<th>Alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.56</td>
<td>0.44</td>
</tr>
<tr>
<td>1</td>
<td>0.53</td>
<td>0.47</td>
</tr>
<tr>
<td>2</td>
<td>0.61</td>
<td>0.39</td>
</tr>
<tr>
<td>3</td>
<td>0.48</td>
<td>0.52</td>
</tr>
<tr>
<td>4</td>
<td>0.50</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Although the results in Table 6 mildly indicate that the best alternative for both the baseline and decision-maker scenarios is the LNG alternative, this alternative gains ground whenever the weight on the economic criterion is decreased as in scenario 2. Whereas, if a weight of 80% in scenario 3 to
economic criterion is given, the diesel alternative would take a little more strength. This loss of preference to the LNG alternative was mainly due to the reliability sub-criterion, which was considered one of the most important in the economic criterion. For that reason, if the reliability for the technology and the availability of refueling stations were improved, the LNG trucks would be a better option.

5. Conclusions

Decision-making related to energy resources has been a complex process for its significant economic, environmental and social impacts, requiring the use of quantitative and qualitative indicators for the selection of alternatives that meet the requirements of different stakeholders. This is where MCA-based models have been useful to guide and solve decision problems in the public and private sector.

Because of the interest of private companies to introduce the use of alternative fuels in their fleets for urban and interurban transport, a methodology for assessing the sustainability of these alternatives taking into account the factors involved in the transport system was developed. The methodology presented in this paper integrates, from selection of alternatives; the factors involved in the transport system (vehicles, infrastructure and fuels), ensuring an assessment in the broad sense of sustainability; considering the economic, environmental and social criteria. Furthermore, this methodology allows involving views and interests of decision-makers to prepare different scenarios.

The application of the proposed methodology for the introduction of LNG in road freight transport as case study allowed observing by weighted scenarios for different criteria, consistency in the results, mainly due to the use of three sub-criteria for each evaluated criterion. Based on these results, it could be argued that this model can eliminate uncertainties and dilemmas generated in decision-making when interests of certain stakeholder set wrongly the criteria weights, which could tip the favorability toward a different alternative. This consistency could ensure the success of the alternative in the long term in a dynamic environment, as is the market for alternative fuels for transport, influenced by variables related to oil trade, socio-political interests or changes in community perceptions.

Nomenclature

- $i$: indicator
- $j$: item
- $k$: sub-criterion
- $SI$: sustainability index for a specific alternative
- $W$: weight for each criterion
- $y$: value for a specific alternative, criterion and factor in the Global Priority Vector

Subscripts and superscripts

- $c$: criterion
  - $EC$: economics criterion
  - $EN$: environmental criterion
- $f$: factor
- $F$: fuel factor
- $I$: infrastructure factor
- $q$: alternative
- $S$: social criterion
References


[26] von Dodderer CCC, Kleynhans TE. Determining the most sustainable lignocellulosic bioenergy system following a case study approach. Biomass and Bioenergy 2014;70:273–86. doi:10.1016/j.biombioe.2014.08.014.


