# System dynamics modeling for mitigating energy use and CO2 emissions of freight transport in Lebanon

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## Abstract

Lebanon's road transportation sector is one of the most unsustainable in the Middle East region due to the exclusive reliance on conventional engine vehicles for passenger mobility and freight. Previous studies showed that significant reductions in energy use and emissions can be achieved from combining mitigation strategies that improve engine technology for cars and increase the use of public transport. However, these are not sufficient to offset the growth in freight emissions, estimated to account for nearly half of total GHG emissions in 2040. Therefore, this study uses system dynamics modeling to estimate the potential reductions of fuel use and $CO_2$ emissions from cleaner electrified truck technologies, combined with using electric rail for heavy freight transport. Modeling results showed potential reductions of 38% to 49% in 2040 compared to the baseline no-action scenario, depending on the share of electric light duty trucks. This can counter the significant growth trends from freight transport, as needed to transition the entire transportation sector in Lebanon to a more sustainable future.

## Keywords

Freight transport, System dynamics, Mitigation strategies, CO2 emissions, Energy use

## 1. Introduction

Lebanon has one of the most unsustainable transportation systems in the region due to the absence of rail service or an effective bus transportation system. Road transportation in Lebanon is the second largest consumer of energy in the country with over 61% of total energy use and 40% of total oil consumption, and the second biggest emitter of greenhouse gas (GHG) emissions, accounting for over 23% of annual emissions in 2012, in addition to a significant share of air-pollutant emissions (M. Haddad, Mansour, & Stephan, 2015). This is mainly due to a significant increase in the number of conventional engine vehicles on the road, with gasoline and diesel fuels making up 97.9% of total fuel use in the sector (MoE/UNDP/GEF, 2016).

In 2016, Lebanon signed the Paris agreement of the United Nations Framework Convention on Climate Change (UNFCCC) and committed to reduce its total GHG emissions from all sectors of the economy by 15% in 2030 compared to the no-action alternative, or by 30% upon the provision of international financial support (MOE, 2015). To contribute to these reduction targets in the road transport sector, recommended mitigation actions focused on passenger transport since cars and passenger light-duty vehicles accounted for 92.4% of vehicles on the road in 2012 (MOE/UNDP/GEF, 2015). As a result, recommendations consisted of renewing the aging passenger car fleet and providing new roadway infrastructure for passenger transport, as well as rehabilitating the existing informal and limited bus services provided by the private sector.

A previous study (M. G. Haddad, Mansour, & Afif, 2017) assessed the impact of the recommended mitigation options on the energy consumed and the emissions generated in the car passenger transport sector in Lebanon. The study concluded that combining mitigation strategies involving the introduction of fuel-efficient vehicles (FEV) and hybrid-electric vehicles (HEV) in addition to revitalizing the bus transport system by 2040 can reverse growth trends in energy use and emissions, as shown in Figure 1. Specifically, renewing the passenger car fleet through the introduction of FEV and HEV to account for 35% the total vehicle fleet and 10% of new vehicle registrations,

respectively, in 2040, in addition to improving bus services to increase ridership to 45% of passenger-kilometers traveled in 2040 can lead to a combined reduction of 71% in $CO_2$ emissions compared to the baseline.
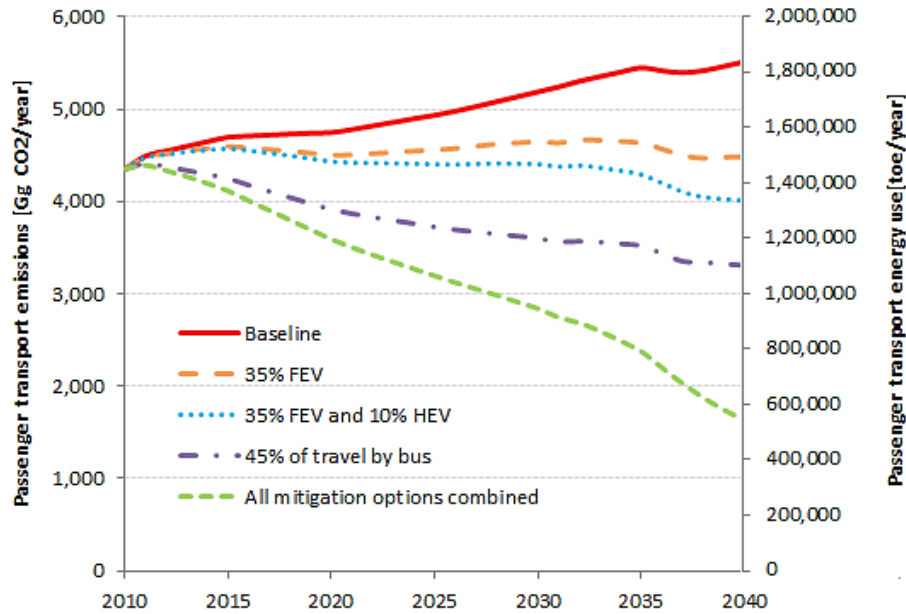


Figure 1. Emission reductions in Lebanon's passenger transport sector under different mitigation option

However, the scope of the previous study was only limited to passenger transport and did not consider the future energy and emissions impacts of freight movement by light duty vehicles and heavy duty trucks. Despite its relatively smaller size, the freight transport sector in 2010 was estimated to consume 30.6% of total transport energy and was responsible for 31.4% of total GHG emissions from road transportation (MOE/UNDP/GEF, 2015).

This makes freight transport a major contributor to the environmental impacts of the road transportation sector in Lebanon, such that freight movement can potentially offset the mitigation of emissions from passenger mobility by motorcycles, private cars, taxis and minivans. This is due to the increase in freight activity as a result of economic growth, as well as the large share of light duty freight vehicles (estimated at 76% of the total fleet of freight vehicles in 2010) which are less energy efficient per tonne-kilometer than larger heavy-duty trucks. In fact, trucks overall are estimated to be the fourth largest contributor to $CO_2$ emissions globally, as shown in Figure 2.
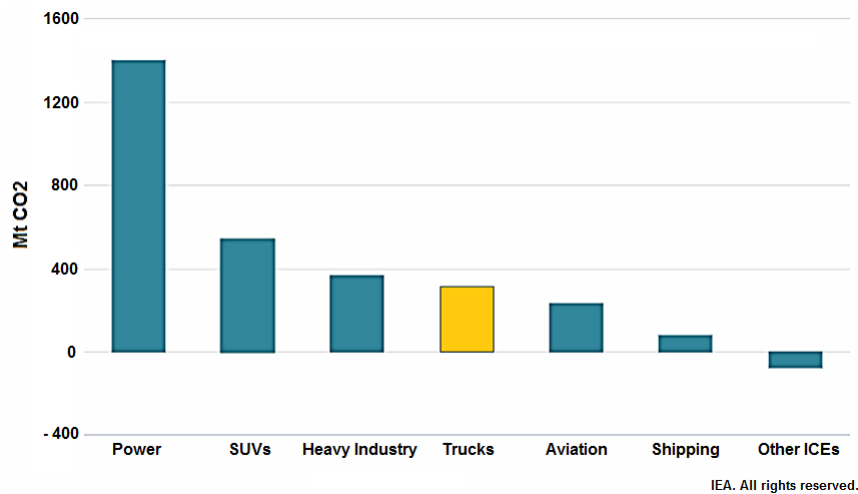
Figure 2. Change in $CO_2$ emissions by energy sector, 2010-18 (Adapted from IEA World Energy Outlook 2019)

Therefore, a more comprehensive assessment that includes freight transport is necessary to determine what mitigation measures are really needed to reduce energy use and emissions from the entire road transportation system. The purpose of this study is then to provide a comprehensive assessment of the energy use and emissions from both the passenger and freight road transportation sectors using a holistic approach. To that end, the study employs the software modeling tool "For Future Inland Transport Systems" (ForFITS), which was developed as a comprehensive assessment tool in the context of a project on climate change mitigation and sustainable transportation by the United Nations Economic Commission for Europe (UNECE), based on the holistic system dynamics modeling approach (UNECE, 2017).

Accordingly, the following section of this paper gives a review of the literature about mitigation studies for the road transportation sector which are based on system dynamics modeling, with a focus on freight transport. Section 3 presents an overview of the ForFITS modeling tool and the local data and assumptions used in the modeling. Sections 4 and 5 present the modeling results for the no-action baseline scenario and the mitigation scenarios, respectively, in terms of their impacts on future energy use and emissions from freight transport. Final recommendations are given in the Conclusion section.

## 2. Review of the Literature

The use of system dynamics modeling in mitigation studies is commonly found in the recent literature, but only a few such studies focus on freight transport. In fact, the majority of mitigation studies focus on passenger road transportation only, for example modeling of energy use and CO2 emissions from urban passenger transport in Beijing (Liu, Ma, Tian, Jia, & Li, 2015), urban passenger traffic in Beijing (Wen & Bai, 2016), inter-city passenger transport in China (Han & Hayashi, 2008), and urban transportation in Taiwan. Only in the latter is freight considered in the modeling, but not in the mitigation strategies, which focus on motorcycles and buses.

Other system dynamics mitigation studies have modeled combined environmental impacts from transportation and other sectors, such as the modeling of pollutant emissions from urban transportation and industry in Tehran (Vafa-Arani, Jahani, Dashti, Heydari, & Moazen, 2014), urban CO2 emissions from cities in Malaysia (Fong, Matsumoto, & Lun, 2009), and urban energy use and CO2 emissions in Beijing (Feng, Chen, & Zhang, 2013). In such studies, the transport sector is considered at a high level of aggregation.

Most studies consider socio-economic factors and policy and financial incentives and disincentives in the technical modeling of transport energy use and emissions. In this respect, system dynamics models allow the incorporation of tangible system components (e.g. vehicle types, modal shares) and intangible ones (e.g. environmental awareness, user preferences) in a way that is easy to visualize, making it possible to represent complex relationships easily. In addition, external policies can be linked to the system for testing their impacts on system behavior over time. Such characteristics are useful for mitigation studies in transportation and make system dynamics an appropriate tool for modeling road transportation and its environmental impacts in a holistic way (Abbas & Bell, 1994).

Of the studies which have focused on freight transport, one study modeled CO2 emission reduction from urban freight transport in Beijing, China (Wang, Fei, Feng, Imura, & Hayashi, 2010) and found that accelerating the development of the railway network and improving the energy efficiency of freight vehicles have the potential of reducing CO2 emissions by up to 30% in 2020 compared to the year 2000. Another study evaluated CO2 emissions from container shipping in a seaport in Qingdao, China (Mamatok, Huang, Jin, & Cheng, 2019) and found that heavy duty vehicles have the biggest share of CO2 emissions, and that the most effective mitigation strategy is to reduce their travel distance in the port so as to quickly shift containers to rail. (Hang & Li, 2010) developed a system dynamics model for evaluating different management policies and regulations to control overweight transportation for the case of Anhui, China, and found that rigid policies for controlling freight volumes can lead to adverse results due to time delays in adjusting to the policy.

It is also noteworthy that the survey of the literature on mitigation studies shows that few studies have been published for the developing world (Aggarwal & Jain, 2016), and only one mitigation study addresses the Middle East region (M. G. Haddad et al., 2017).

## 3. Methodology

The modeling of the energy use and CO2 emissions of freight vehicles under the no-action alternative and the future mitigation actions in the road transportation system in Lebanon was done using the system dynamics approach with the UNECE software tool "ForFITS" (UNECE, 2013). ForFITS takes inputs about the technical aspects of the system (e.g. vehicle types, modal shares, emission factors…) as well as demographic (population), economic (gross domestic product) and social (e.g. environmental awareness, user preferences) data and assumptions to model transport activity and the corresponding energy consumption and $CO_2$ emissions. ForFITS also takes inputs about policy measures (e.g. tax incentives) and assesses their impact on energy consumption and emissions (Andrejszki, Gangonells, Molnar, & Török, 2014).

The types and classes of freight vehicles considered in the modeling are those currently operating in Lebanon, including potential future technologies that are applicable based on available refueling infrastructure, as shown Table 1.

Table 1. Transport modal characteristics considered in the ForFITs model

| Freight Vehicle Type | Vehicle Class | Engine Type | Fuel Type |
|---|---|---|---|
| Light Duty Vehicles (LDV) | Small (2t ≤ mass < 2.3t) Midsize (2.3t ≤ mass < 3.2t) Large (3.2t ≤ mass < 3.5t) | Internal Combustion Engine (ICE) | Gasoline |
| Medium Duty Vehicles (MDV) | Small (3.5t ≤ mass < 7.5t) Large (7.5t ≤ mass < 12t) | ICE | Diesel |
| Heavy Duty Vehicles (HDV) | Small (12t ≤ mass < 26t) Large (mass>26t) | ICE | Diesel |

ForFITS uses the "ASIF" methodology (where *A* is for travel *A*ctivity, *S* is modal *S*hare, *I* is energy *I*ntensity, and *F* is *F*uel carbon content) developed by the International Energy Agency (IEA) for decomposing CO2 emissions from passenger travel or freight. The main ASIF equation shown below estimates total passenger or freight greenhouse gas emissions as a function of travel demand or freight activity, modal structure, modal energy intensities and fuel carbon content (Millard-Ball & Schipper, 2011; Schipper & Marie-Lilliu, 1999):

$$G = A \times S_i \times I_i \times F_{ij} \tag{1}$$

Where $G$ is the carbon emissions from the particular transport sector, $A$ is total travel or freight activity (in vehicle-, passenger- or tonne-kilometers), $S$ is a vector of the modal shares (in shares of vehicle-kilometers by service, mode, vehicle class and powertrain), $I$ is the modal energy intensity of each mode $i$ (the average fuel consumption per vehicle-kilometer by service, mode, vehicle class and powertrain), and $F$ is the total consumption of all fuels $j$ in mode $i$ converted into carbon emissions using standard IPCC coefficients (i.e. well-to-tank and tank-to-wheel emission factors by fuel blend).

Each of these terms is a function of different drivers (income, prices, policies, new technologies, etc.). In particular, the energy intensity $I$ is a function of several factors: first, the technical efficiency of mode $i$, which is the energy consumed per vehicle-kilometer to propel a vehicle a given distance (depending on the motor, drive train, friction and drag, etc.).; second, the vehicle characteristics for each mode $i$ (such as vehicle power and weight); and, third, the load factors (the inverse of capacity utilization for each mode $i$ measured in tonnes per vehicle, or as a dimensionless ratio of actual load to potential load for every km a vehicle moves).

ForFITS is built on top of the system dynamics modeling software "Vensim" (Ventana Systems Inc., 2013) and consists of the technological, environmental and socio-economic subsystems of the transportation system.

Figure 3 illustrates a view of the freight vehicle stock subsystem. Detailed information on the ForFITS model is provided in the user manual (UNECE, 2013).
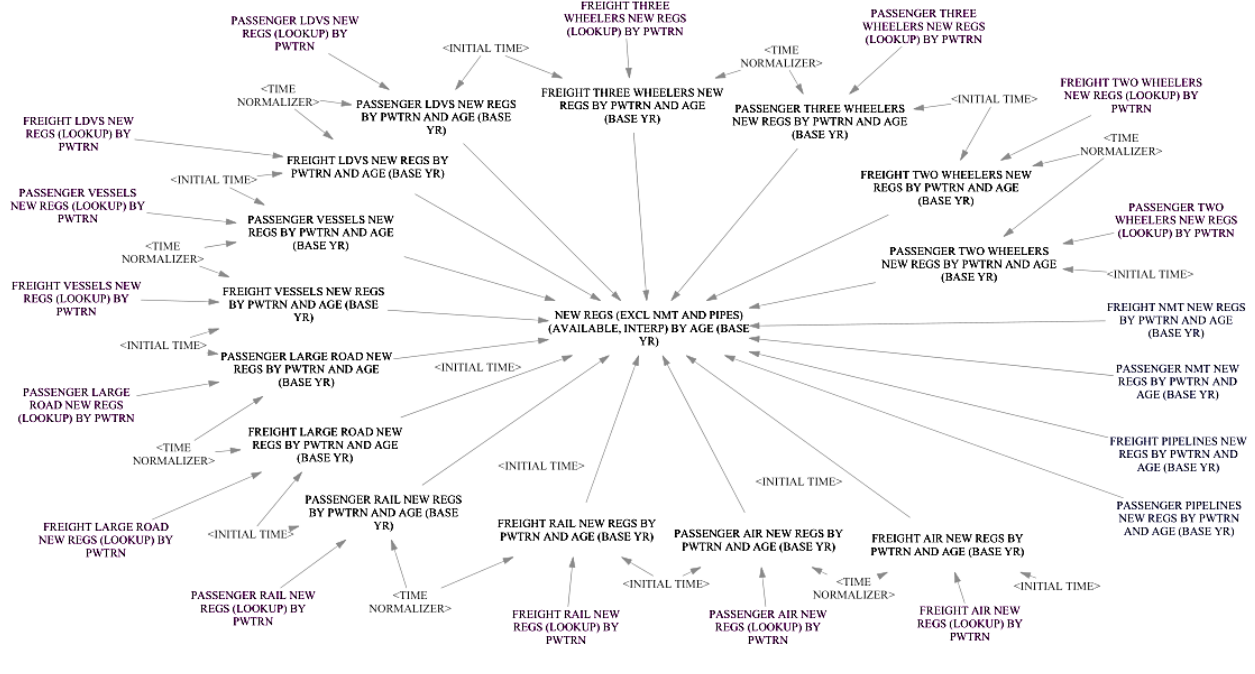
Figure 3. ForFITS Vensim view of the freight vehicle stock subsystem

To ensure comparability of results of this study for freight vehicles with the modeling of the passenger transport system in the previous study by (M. G. Haddad et al., 2017), the same modeling data and assumptions were used for vehicle registrations, fuel consumption, vehicle occupancy, travel distances, emission factors, fuel costs, GDP and population, as detailed in the previous study.

Other assumptions specific to freight transport used in the modeling are listed in Table 2.

Table 2. Main modeling assumptions for the baseline scenario in 2010 with future projections

| Factor | Value | Baseline Projection |
|---|---|---|
| Freight types and transport shares by [LDV, HDV] modes (shares assumed) | Bulk goods: [20%, 55%] Food: [20%, 20%] Manufactured: [20%, 25%] Other goods: [35%, 0%] | Maintained constant |
| Load factor (ForFITS default) | 100% (empty trips are excluded) | Maintained constant |
| Vehicle capacity (ForFITS default) | average value per class | Maintained constant |
| Powertrain shares (actual 2010) | 100% Gasoline ICE for LDV 100% Diesel ICE for HDV | Maintained constant but with improving powertrain efficiencies |
| Trip distances, trip shares and transport shares by [LDV, HDV] modes | Short < 60km: 90% [70%, 30%] Medium < 400km: 10% [0%, 100%] | Maintained constant |
| Fuel prices including tax (USD/lge) *(lge = liter gasoline equivalent)* (actual 2010) | Gasoline: 1.093 Diesel: 0.624 | Growth to 150% by 2040 assumed based on expected increase in fuel taxes and declining petroleum resources |
| $CO_2$ emission factors (tank-to-wheel) (kg $CO_2$/lge) | Gasoline: 2.3207 Diesel: 2.4803 | Maintained constant |

The main data used to describe the detailed characteristics of the transport system in the base year are summarized in Table 3.

Table 3. Characteristics of the road transportation sector in 2010

| Vehicle Class | Vehicle Stock | New vehicle registrations | Annual distance travelled (vehicle-km) | Vehicle load (tonnes/veh) | Vehicle fuel consumption (lge/100 km) |
|---|---|---|---|---|---|
| LDV | 96,236 | 10,303 | 25,000 | 0.5 | 15 |
| MDV | 14,985 | 1,723 | 50,000 | 3 | 18 |
| HDV | 14,985 | 1,724 | 50,000 | 6 | 45 |

The proposed mitigation options in this study are: 1) switching 50% of new registrations in 2040 for heavy duty trucks to the plug-in-hybrid electric powertrain (since this technology is cleaner and more fuel-efficient than diesel without compromising the ability for long-haul HDV operation where electric charging is not always available), and 50% of light duty trucks to the fully electric powertrain (since this technology has zero tailpipe emissions as needed for clean operation of LDV inside cities); 2) switching 20% of heavy freight transport to electric rail (which has zero tank-to-wheel emissions) based on medium-term government plans for reactivating rail services on a portion of the disabled railway network in the country; and, 3) combining both options 1 and 2 together at the same time.

Table 4 summarizes the modeling assumptions for the proposed mitigation options.

Table 4. Assumptions for modeling the mitigation scenarios

| Mitigation option | Share of electric rail freight transport in 2040 | Share of electrified truck powertrains in 2040 | |
|---|---|---|---|
| | | Plug-in Hybrid (PHEV) | Electric (EV) |
| **Option 1:** *Partial switch to electrified truck technologies* | 0% | 50% of new HDV registrations | 50% of new LDV registrations |
| **Option 2:** *Partial switch of heavy freight to electric rail* | 20% | 0% | 0% |
| **Option 3:** *option 1 + option 2 combined* | 20% | 50% of new HDV registrations | 50% of new LDV registrations |

The mitigation options for freight were modeled using local assumptions developed in a similar manner as for the baseline scenario.

## 4. Baseline Results

A baseline scenario for freight transport was modeled separately in ForFITS in order to forecast the growth of freight LDV and HDV vehicle stocks (Figure 4) and travel activity (Figure 5) and their impact on energy use and CO2 emissions (Figure 6) under the no-action business-as-usual conditions.

The freight vehicle stock is projected to almost quadruple in 2040 compared to the base year 2010, while freight transport distances are expected to grow by 3.6 times. This is forecasted to increase energy demand by 2.3 times in 2040 when freight transport is estimated to consume 45.4% of total energy use in road transportation, dictating a similar growth trend in CO2 emissions.
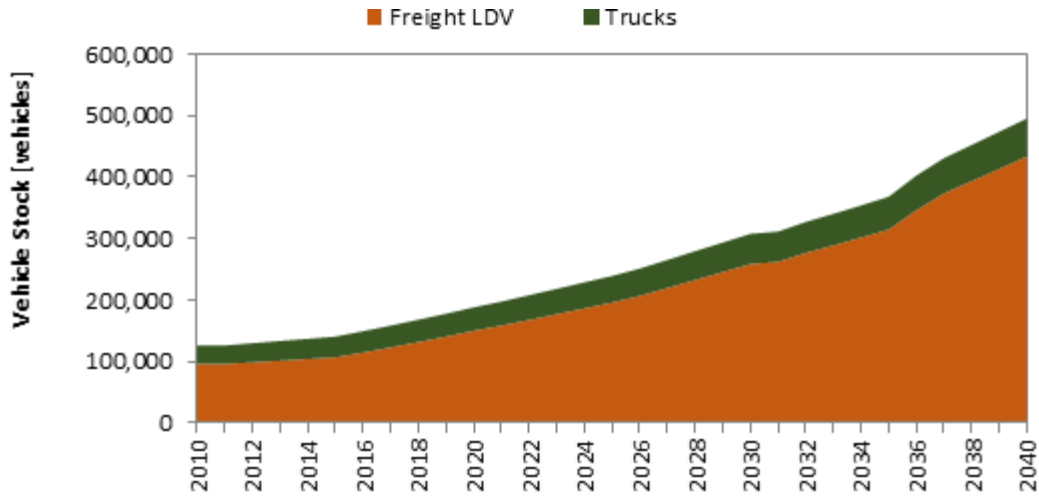
Figure 4. Baseline projection of freight vehicle stock
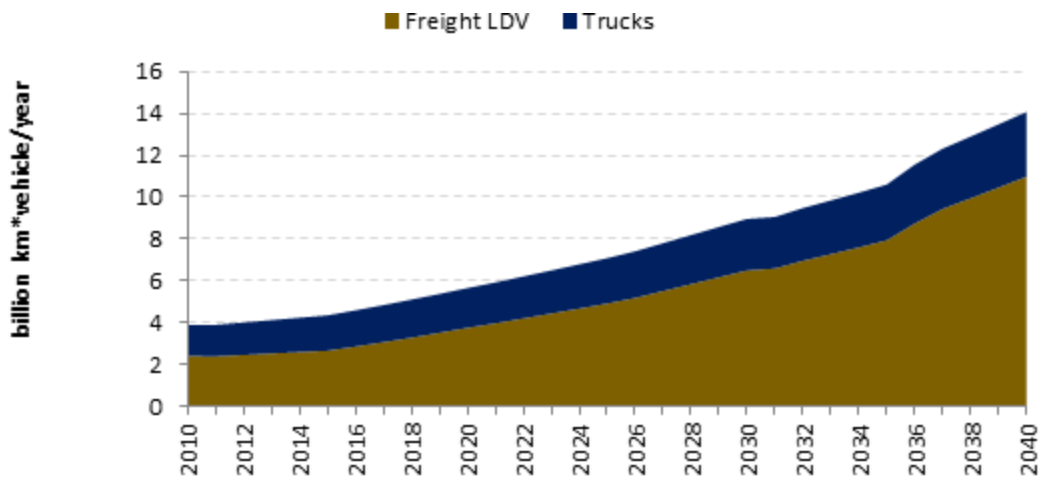


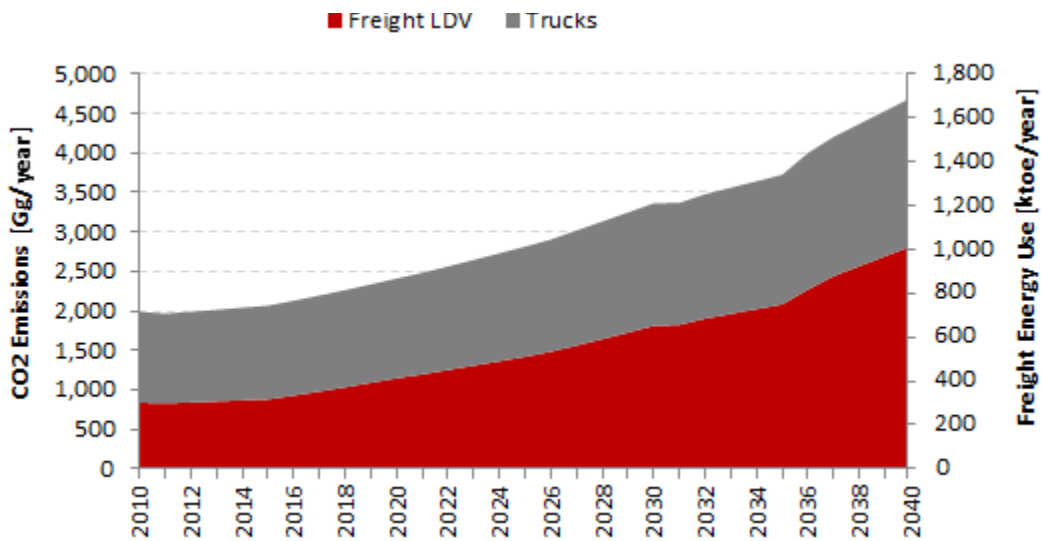Figure 5. Baseline annual estimated freight activity



Figure 6. Baseline projection of freight energy use and CO2 emissions

As the baseline modeling results show, the future growth in CO2 emissions from road freight transport works against Lebanon's INDC commitment to reduce GHG emissions from the transportation sector as a whole, and specifically against the potential reductions from the mitigation interventions underway in passenger transport.

This therefore makes it necessary to explore mitigation actions in freight transport to reduce its significant contribution to CO2 emissions. The modeling results of the proposed mitigation options are presented in the following section and illustrate the potential reductions which are feasible in Lebanon over the long-term.

## 5. Mitigation Results

To allow for a comparison of the benefits of each mitigation option relative to the other scenarios, Figure 7 presents the modeling results of the energy use (in tons of oil equivalent or toe) and $CO_2$ emissions (in Gigagrams or Gg), respectively, of all the considered mitigation scenarios together. The figure also includes the results of the baseline scenario for the purpose of comparing against the no-action conditions.
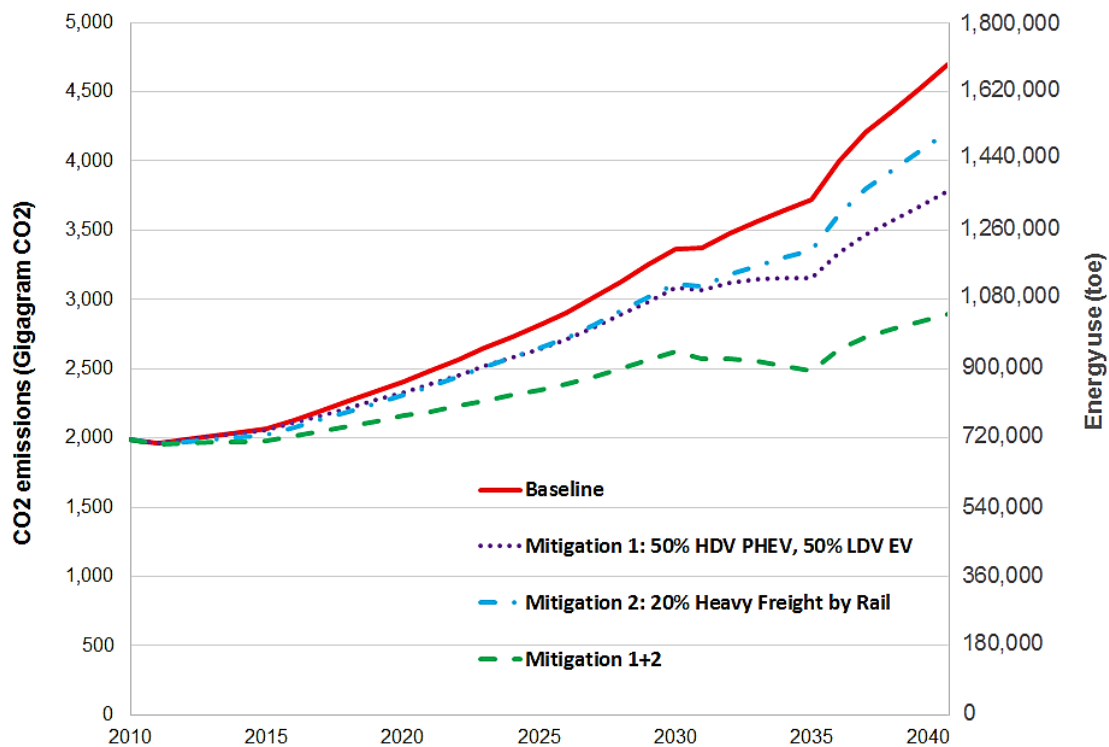


Figure 7. Change in energy use and CO2 emissions under the different scenarios

The first mitigation option of renewing a part of the truck fleet reduces freight transport energy use and CO2 emissions in 2040 by 19% compared to the baseline scenario as a result of the improved fuel economy and the lower tailpipe emissions of the cleaner electrified vehicle technologies.

The second mitigation option of shifting a portion of heavy freight to rail transport results in an additional 10% reduction in 2040 compared to the baseline, due to the elimination of tank-to-wheel emissions of HDV transport for 20% of heavy freight from using zero emission electric rail.

Combining both mitigation options together results in 38% reduction compared to the baseline in 2040, which is 9% higher than the sum of the benefits from each mitigation option alone (i.e. 19% + 10%). This is due to global improvement at the level of the entire freight transport system beyond the mere removal of heavy duty trucks from the road, reducing overall energy use and emissions at the sectoral level (e.g. contributing to the reduction of traffic congestion improves the operating efficiency of remaining trucks on the road).

It can be concluded from the above that combining mitigation options is essential for achieving needed reductions in freight transport. However, the results of the combined benefits from the proposed mitigation options in this study are not enough to control the substantial growth trends of CO2 emissions for the entire road transportation sector.

A sensitivity analysis was therefore conducted to assess the additional reductions from switching to 100% electric LDV in mitigation option 3 (instead of the proposed 50%), and the new results showed a total of 49% reduction in CO2 emissions in 2040. This completely overturns growth trends from freight transport, as needed to contribute to Lebanon's INDC commitment to reduce GHG emissions from the entire transportation sector.

However, this would require an extensive electric charging infrastructure to ensure these vehicles are able to operate effectively without range anxiety. This also requires a clean energy mix to ensure that well-to-tank emissions at the power plant do not offset the benefits achieved from the elimination of on-road tank-to-wheel emissions.

In developing countries where such infrastructure is lacking and financial resources are severely limited, this can be a challenging target. This is why it is essential to start the transition to electric vehicles and freight rail transport early on, and to increase the share of these cleaner freight transport modes over the medium to long-term. Consequently, the adoption of an integrated strategy for the entire road transportation sector, which must include the re-establishment of rail service for freight transport, is necessary to transition the sector to a sustainable future.

## 6. Conclusion

This paper assessed the impact of energy use and CO2 emissions from freight transport in Lebanon using system dynamics modeling. Freight transport is a major contributor to the environmental impacts of road transportation in Lebanon as it constituted 30.6% of total energy use and 31.4% of total GHG emissions in the base year 2010.

The modeling consisted of a baseline no-action scenario and three mitigation options until the year 2040 consisting of: 1) increasing the share of electrified HDV and LDV trucks to reach 50% of new vehicle registrations for each class in 2040; 2) switching 20% of HDV freight to electric rail by 2040; and, 3) combining options 1 and 2 together.

The modeling results showed that in the no-action scenario, significant growth by 45.4% in energy use and CO2 emissions will occur in 2040 compared to 2010 due to the increase in freight vehicles and distances traveled as a consequence of the growth in economic activity. This would offset the benefits that can be achieved in the passenger transport sector where improving vehicle technologies and public transport services has great potential for reducing energy use and emissions.

Increasing the share of plug-in hybrid electric HDV and fully electric LDV trucks resulted in a 19% reduction of energy use and corresponding CO2 emissions by 2040, but is not enough to reverse current growth trends. Increasing the share of rail transport for freight led to an additional 10% reduction of energy use and corresponding emissions by 2040, indicating good potential to help overturn adverse growth trends.

Combining both mitigation options naturally led to the highest savings, with 38% reductions achieved by 2040. A sensitivity analysis showed that switching up new LDV registrations to 100% electric in 2040 can reverse the current unsustainable trends in Lebanon's freight transport sector. This comes at a cost of providing the necessary electric charging infrastructure and clean energy mix to operate these vehicles effectively.

This study also illustrated that a holistic approach is necessary to accurately assess the potential for meeting strategic mitigation targets at the national level, as is advocated by the United Nations call for achieving the Sustainable Development Goals (SDG's) for entire industrial sectors. This approach can be useful for other developing countries in the Middle East region where transport dynamics are similar to those of Lebanon such as the over-reliance on vehicle transport for passengers and freight.

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## Biographies

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**Jad Diab** is an undergraduate student in Mechanical Engineering at the Lebanese American University. His research interests include energy and system dynamics modeling.