Energy Savings in Light-Duty Vehicles Considering Automotive Materials and Fuel Shift in Developing Countries

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論文内容要旨

Road passenger transportation represents a significant part of the global energy demand in the transportation sector. Most of this energy is supplied by fossil fuels and it is used to power light-duty vehicles (LDVs). In the past, the largest part of the LDV fleet stock was located in developed countries. However, in the future it is expected that the largest increment in global LDV fleet will happen in developing countries. Vehicle ownership, defined as the number of vehicles per inhabitants of a region, increases as income grows. The growth follows an ‘S-shape’ pattern limited by a saturation value that is characteristic of each economy. While vehicle ownership is close to the saturation values in developed countries, in developing countries values are far from saturation values. Therefore, as income increases in developing countries, the number of vehicles will grow.

Current global LDV fleet is mainly composed of steel-intensive, fossil fuel-powered internal combustion engine vehicles (ICEVs). These vehicles offer a good agreement between reliability, range and cost. However, they also generate negative impacts on the society such as greenhouse gas (GHG) emissions, local pollutant emissions and noise. Improving public transportation, optimizing city design, eliminating subsidies for fossil fuels and other measures to reduce mobility demand and promote modal shift are necessary to reduce carbon emissions from transportation. Nevertheless, not all the solution for low-carbon transportation relies on modal shift and mobility demand reduction. It is necessary to deploy advanced vehicles with low-carbon emissions. Two alternatives are zero-emission vehicles (ZEVs) and vehicles using lightweight materials. However, replacing conventional ICEVs with advanced vehicles affects automotive material requirements and it is important to analyze the effect on energy and material flows. In that sense, the goal of this research is to determine the energy savings and CO_2 emissions reductions achievable in the LDV fleet with lightweight automotive materials, electric powertrains and fuel shift in the context of developing countries. Colombia was analyzed as case of study.

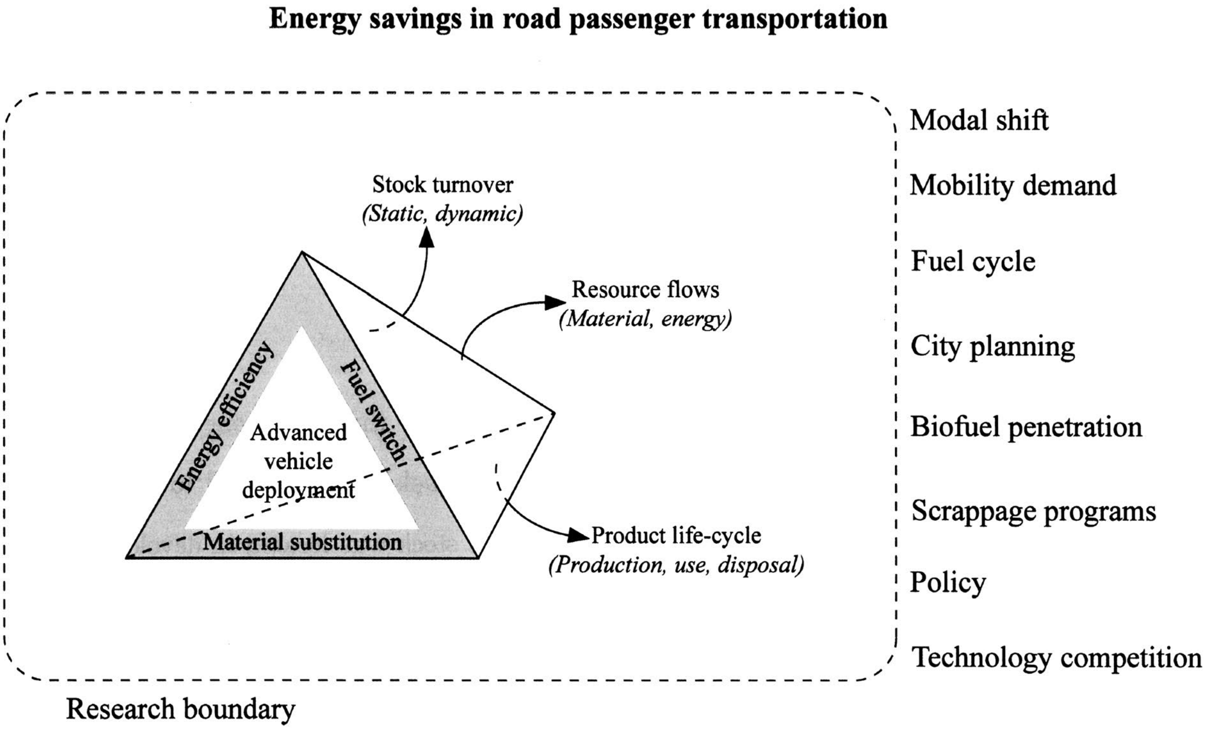

Figure 1. Schematic representation of the research idea.

The research idea is represented in Figure 1. The relevance of this research can be seen from two points of view: Theoretical and practical. From the theoretical point of view this research contributes towards a more integrated assessment of energy systems design considering the links between energy systems and material systems. These links are caused by materials consumption in technologies used to provide energy services. This research contributes to that problem considering material choices in the traditional energy resource – conversion technology/end-use device allocation problem. On a first step, material flows are only accounted for and the energy resource – conversion technology/end-use device allocation problem is solved (chapter 3). Then material choices are included and the problem is solved dynamically excluding the economic dimension (chapter 4). Finally, the economic dimension is included (chapter 5) in what can be called energy-economic-environmental-material model.

The practical contribution of this work is the detailed study of the LDV fleet in the future and the possibilities to reduce road transport CO_2 emissions deploying advanced vehicles, accounting also for the effects that they will have on energy and material flows and vehicle fleet cost. This contributes to a better understanding of the technological options to reduce future energy consumption and CO_2 emissions in the context of developing countries. Compared to previous studies, considering the effect of simultaneous variations in powertrains and automotive materials on energy and material flows, CO_2 emissions and cost in the context of developing countries is a contribution. Previous researches mainly focused on variations in energy flows and CO_2 emissions associated to the use of ZEVs or lightweight vehicles in developed countries; while in the case of material flows, the focus has been on aluminum and steel.

Chapter 3 is a first approach to the interactions between materials and energy systems. It is focused on the problem of energy consumption and CO_2 emissions reduction in aluminum and copper processing. Aluminum is one of the most promising lightweight materials in the short-term, while copper stock in LDVs is significant and shares several similarities with aluminum that justify their joint study. Previous researches have focused on primary aluminum production considering secondary production and semi-fabrication in an aggregate way; this work instead proposes a disaggregate analysis to explore the possibilities for energy savings and CO_2 emissions reduction of fuel switch and energy efficiency improvement in the particular case of Colombia. A static linear programming optimization model was developed using the General Algebraic Modeling System (GAMS) to study the energy system. Results show that energy efficiency can reduce energy use and CO_2 emissions 73% and 72% at negative costs. Further CO_2 emissions reductions, up to 88%, are possible with fuel switching to low-carbon electricity, increasing the costs for the energy system; nevertheless, cost reductions caused by energy efficiency improvement outweigh cost increments of fuel switching. However, the low relative share of the non-ferrous industry in total industrial energy consumption leads to a low real impact on national energy use and CO_2 emissions. Despite of that, the approach developed here can be used in other cities, regions or countries with more significant secondary production and semi-manufacturing of aluminum and copper; and even expanded to secondary production and semi-manufacturing of iron and steel. Additionally, the low-carbon characteristic of Colombian national grid makes efficient electric technologies the best option for aluminum and copper processing, in contrast with the widely accepted conception of efficient natural gas-fired furnaces as the best practice in metal heating processes. The high reliance of the electricity grid on hydropower requires coupling policies on the demand side in the energy-intensive industry with policies in the supply side in power generation, to guarantee in the future the benefits achieved with low-carbon electrification.

Compared to chapter 3, chapter 4 adds another dimension to the energy resource – conversion technology/end-use device allocation problem: Material choices. Material choices are explored in the context of the LDV fleet of developing countries, studying the effect of deploying advanced vehicles using zero-carbon fuel-powered electric powertrains and lightweight materials. Potential energy savings and CO_2 emissions reductions resulting from the successful penetration of battery electric vehicles (BEVs), fuel cell hybrid-electric vehicles (FCHEVs) and lightweight vehicles are studied. A dynamic bottom-up accounting model developed using the Long-Range Energy Alternatives Planning Systems (LEAP) was used to study the Colombian passenger car fleet between 2010 and 2050, under four alternative scenarios: BEV, Light BEV, FCHEV and Light FCHEV scenarios; which consider the successful penetration of BEVs, lightweight BEVs, FCHEVs and lightweight FCHEVs, respectively. Results show that Tank-to-Wheel (TTW) energy consumption and Well-to-Wheel (WTW) and TTW CO_2 emissions can be significantly reduced with the deployment of ZEVs and lightweight vehicles, with powertrain electrification accounting for the largest part of the reductions. However, in the context of a rapidly growing vehicle fleet composed by ICEVs with long service lives, the successful penetration of advanced vehicles in the new vehicle market cannot reduce 2050 energy consumption and CO_2 emissions below the 2010 levels. In that sense, automotive technology improvement alone cannot overcome the effect on energy consumption and CO_2 emissions from increased mobility demand and growing LDV stock and other measures need to be implemented. In the case of material flows, iron and steel remain as the main automotive materials; even if vehicles using lightweight materials are successfully deployed. Aluminum consumption increases in all the cases; while carbon fiber reinforced polymer (FRP) increases in the case of lightweight vehicle penetration and FCHEV deployment. Scenarios considering successful penetration of lightweight vehicles and electric powertrains imply changes not only on energy resources, but also on automotive materials. Combined energy and material flows for the base scenario and the Light BEV scenario in the year 2050 are presented in Figure 2 and 3.

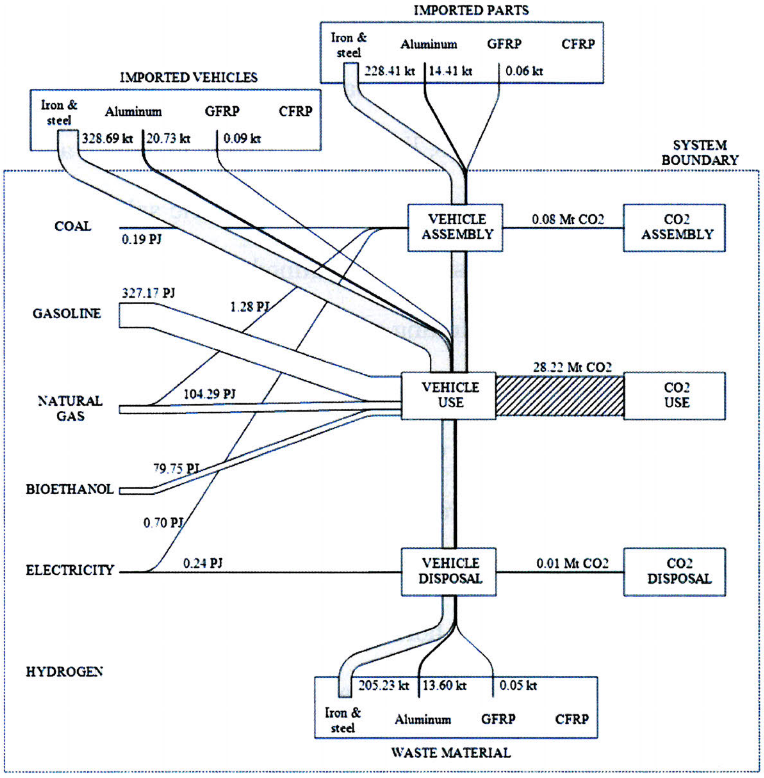

Figure 2. Energy and material flows for the passenger car fleet in the base scenario in 2050.

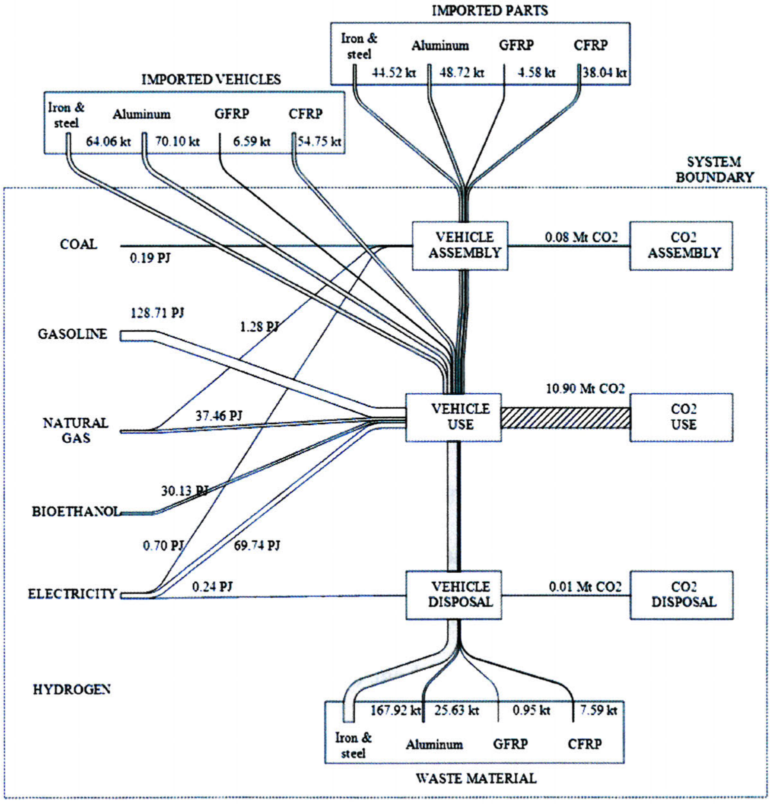

Figure 3. Energy and material flows for the passenger car fleet in the Light BEV scenario in 2050.

In chapter 5, the stock turnover model used in chapter 4 was refined, changing the advanced vehicle diffusion pattern from a linear pattern to an 'S-shape' pattern following a logistic curve. Scenarios were defined in terms of vehicle market share of BEVs, lightweight BEVs, FCHEVs and lightweight FCHEVs, similar to chapter 4. With the improved estimation for advance vehicle sales, the fossil fuel displacement was calculated and the stock turnover mechanism was explained in detail. Additionally, the vehicle fleet total cost of ownership (TCO) was estimated, including energy, capital and operating and maintenance costs. Values found for potential energy savings and CO_2 emissions reductions are similar to the results of chapter 4, showing the robustness of the model. Cost estimations revealed that advanced vehicle deployment reduces energy costs and increases capital costs relative to the base scenario. In the BEV and Light BEV scenarios the net cash flow becomes zero in 2045; while in the FCHEV and Light FCHEV scenarios the net cash flow is larger than zero over the time horizon. The costs of avoided CO_2 range from 600 USD/tonne-CO_2 saved in 2020 to -100 USD/tonne-CO_2 saved in 2050 for BEV and Light BEV scenarios; and from 7,000 USD/tonne-CO_2 saved in 2020 to 800 USD/tonne-CO_2 saved in 2050 for FCHEV and Light FCHEV scenarios.

Finally, in chapter 6 the benefits of including material choices in the energy resource – conversion technology/end-use device allocation problem are discussed; including the possibilities for acting on material flows linked to the energy system. The applicability of the approach considering material choices in energy system design for other sectors was discussed.

In summary, general outcomes from this research show the possibilities for energy consumption and CO_2 emissions reductions that can be achieved improving energy efficiency and switching fuels in the LDV fleet and the secondary production and semi-manufacturing of aluminum and copper. Additionally, deployment of advanced vehicles using electric powertrains and lightweight materials in the national LDV fleet changes the quantity and types of materials required for new vehicles and consequently cumulated in the vehicle fleet stock and released after vehicle retirement. Accounting for material flows in energy systems assessment allows for a better understanding of the effect that low-carbon technology deployment causes in other systems. Main recommendations from this work are:

- Natural gas-fired furnaces are not necessary the best option to reduce CO_2 emissions from non-ferrous metals processing. In the case of low-efficiency technologies and the availability of low-carbon electricity, low-carbon electrification can provide larger energy consumption and CO_2 emissions reductions and still be cost-effective. Therefore, the analysis must be done from a system perspective considering the characteristics of each country/region/city.

- Benefits of low-carbon electrification in the industrial and transportation sector can be lost if low-carbon electricity is not assured over time. In both cases, energy conversion technologies/end-use devices are capital intensive and have long service lives, therefore policies in the supply and demand side must be coupled to ensure the benefits achieved.
- It is necessary to develop policies to promote the efficient use of energy and the shift to renewable energy sources. Considering existing barriers for the penetration of more efficient energy technologies and renewable energy sources, it is necessary to design specific action plans to overcome these barriers. Education about the benefits that can be achieved with more efficient technology use with RD&D projects is fundamental. However, the first step must be the detailed characterization of the energy system.
- The deployment of advanced vehicles in the future will affect the amount and type of materials entering the system that eventually will become sources for secondary material production. It is important to account for the material stock and promote technologies to recycle and reuse it.
- Comparing the simultaneous effect of powertrain electrification and weight reduction in the vehicle fleet, it was found that most of the energy savings and CO_2 emissions reductions are due to shift from internal combustion engine to electric powertrains. However, the use of lightweight materials to reduce the vehicle weight contributes to improve other characteristics of the vehicle, which are important for the successful deployment of electric powertrains. Therefore both measures are complementary.
- Improvements in technology alone cannot outweigh the growth in energy consumption and CO_2 emissions in the future due to the significant increase of vehicle fleet size and the long survival times.

論文審査結果の要旨

持続可能な社会を実現するには、世界のエネルギー総需要の約 50 パーセントに増大見込みの開発途上国を対象にして、省エネルギーを確実に進めることが必須である。なかでも、運輸部門はエネルギー需要の約四分の一を占めるだけでなく、燃料資源が原油に特定されるので、自動車の軽量化とともに、原油以外への燃料シフトが有効な施策となる。本論文は、開発途上国にて利用される自動車を対象として、製造、使用、廃棄に至る一連のライフサイクルの性能評価に基づいて、地域の実情に合致する省エネルギーの提案を目的としている。自動車利用に伴うエネルギーフローとマテリアルフローの両特性を組み合わせて、自動車の省エネルギー効果について経済・環境・エネルギー評価の観点から初めて探求したものであり、全編 7 章から成る。

第 1 章は序論であり、本論文の目的、構成、背景について述べている。

第 2 章では、自動車の一連のライフサイクルを、ガソリン自動車、天然ガス自動車、電気自動車、プラグインハイブリッド自動車の四形式について分析して、2050 年に向けた技術性能向上を考慮した省エネルギー効果を明らかにしている。自動車の運用形態、車種構成の推移、バッテリーの資材構成など、多様な観点から洞察している。

第 3 章では、自動車部材の主要非鉄金属である銅とアルミニウムに焦点を置いて、総費用や二酸化炭素排出量に上限を課した場合に、精錬プロセスを合理的に選択する数理モデルを構築している。線形計画法を用いた解析プログラムを作成して、プロセス性能の評価手法を独自に考案している。

第 4 章では、自動車の軽量化と燃料シフトに伴う省エネルギー効果のポテンシャルを定量的に評価している。自動車の車種構成の推移や燃料価格の変化を考慮して、エネルギー・カーボンフローの各観点から、省エネルギーの進展にきわめて重要な知見を得ている。

第 5 章では、前章の知見に経済的側面を付加して、車両価格、燃料費、維持費を含めたキャッシュフローを示している。二酸化炭素排出量の単位削減費用を算出して、省エネルギーを進める指針をまとめるとともに、技術性能の変遷を含む具体的かつ実効性の高い方策を明示している。

第 6 章では、以上から得られた知見に基づいて、自動車に関わる一連のエネルギー・マテリアルフローを総括して、二酸化炭素排出量削減方策に有用な基本理念を提示している。

第 7 章は、結論である。

以上要するに本論文は、開発途上国の運輸部門の省エネルギーに向けた自動車利用の合理的な形態について、フローとストックの推移を物理・経済的アプローチから初めて明らかにし、自動車利用の最適車種構成と地域社会への省エネルギー効果を明示したもので、熱工学およびエネルギーシステム工学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。