Low carbon road passenger transportation system design using combined energy and materials flows in Colombia

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Abstract

Light-duty vehicles for road passenger transportation are responsible for a substantial amount of energy consumed and constitute a significant stock of materials in any country. Choices on new vehicles affect energy and materials flows depending on the vehicle type preferences. This study examines the impacts of using hybrid vehicles, plug-in hybrid vehicles and fuel cell vehicles together with vehicle lightweighting using high-strength steel, as measures to reduce carbon emissions from light-duty vehicle fleet, considering jointly energy and materials flows. Direct effects of vehicle use and indirect effects linked to vehicle production and disposal were accounted using a model developed in LEAP (Long-range Energy Alternatives Planning System). The model was used to study the evolution of light-duty vehicle fleet in Colombia until 2050 under six scenarios that represent different choices regarding powertrains, fuels and materials for vehicle manufacturing. We found that the use of alternative powertrains contribute to reduce energy demand and CO_2 emissions at a larger extend than vehicle lightweighting, as weight reductions considered here are moderated (under 5%). In terms of vehicles production and disposal, the impact is limited to the increment of waste material from retired vehicles, since new vehicles are imported or assembled in the country using mainly imported components.

Keywords

Road passenger transportation, light-duty vehicles, energy and materials flows modeling

1. Introduction

Transportation sector represents around one third of global energy consumption, form which light-duty vehicles (LDV) for road passenger transportation consume the largest part. Most of these vehicles use the internal combustion engine (ICE) as powertrain and use fossil fuels. At the same time, these vehicles represent a significant materials stock in the economy, mainly constituted by steel, the preferred material for vehicle manufacturing. However, that panorama may change in the future, moving from the traditional configurations mentioned before to less carbon intensive configurations as the result of efforts with different motivations like reducing oil consumption, increasing energy security and reducing GHG emissions. The goal of these configurations is the reduction of fuel consumption while maintaining or increasing safety and comfort for passengers. As these new configurations are available in the market they are included in the LDV fleet, affecting energy and materials flows.

In that sense, the consideration of energy and materials dimensions in vehicle selection to study the evolution of LDV fleet for road passenger transportation can provide better information about the effects of vehicle selection in future status of the system; given that the effects of vehicles choices in the system are not limited to energy and also include supply and availability of materials. This is not the commonly used approach, since conventional decision making is based on final vehicle use. However, its use is becoming more frequent derived from studies using Life Cycle Assessment (LCA), particularly to study the impact of policies for the conversion of the LDV fleet (Cheah and Heywood, 2011; Kim et al., 2004). Other studies also consider the effect on energy consumption of substituting steel with lighter materials, like aluminum and plastics, and the effects of varying materials combinations (Bouwman and Moll, 2000; Kram et al., 2001). These studies show that even though most of the energy consumption and pollutant emissions are related to vehicle use, indirect impacts associated to vehicle production and disposal are also important. Besides, they also give valuable insights about future changes in materials flows caused by vehicle selection.

The objective of this paper is to assess the effect of fuel, powertrain and materials choices in LDV fleet for road passenger transportation on energy, carbon and materials flows; in order to understand better the effect of replacing current fossil fueled ICE vehicle fleet with a future vehicle fleet with lower carbon intensity. Powertrain options considered here, include besides internal combustion engine vehicles (ICEV), hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV) and fuel cell vehicles (FCV). Moderate lightweighting using high-strength steel (HSS) is considered additionally to conventional vehicle. For that purpose, a model in LEAP (Long-range Energy Alternatives Planning System) was developed, which considers the evolution on the vehicle fleet at national level from 2010 to 2050. The model was used to study vehicle fleet evolution in Colombia to illustrate the challenges that developing countries may be facing in the future, due to the increment of the vehicle stocks. The rest of the paper is organized as follows: section 2 describes the methodology; section 3 shows the results and their discussion; and finally conclusions are presented in section 4.

2. Methodology

The effects of both, introducing more efficient powertrains and lighter materials were assessed using a national level dynamic model developed in an accounting framework, LEAP. The model considers materials and energy interactions derived from the life cycle of materials used in the production of automobiles. Future vehicle stocks are modeled using base year stocks distributed by vintage, vehicle sales projections and estimated vehicles survival rates. The modeled system is presented in Figure 1.

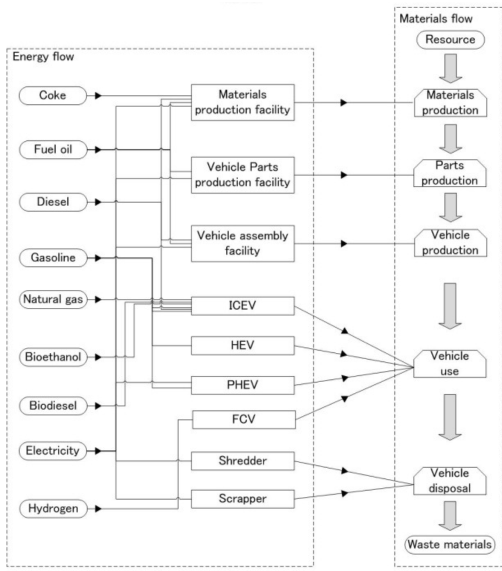

Figure 1 Materials and energy flows in the system

Six powertrains-fuel options were modeled under two vehicle materials configurations, for a total of 12 options that are presented in Table 1. These options represent the future alternatives that buyers will have at the time of purchasing a new vehicle in the future. Conventional materials breakdowns for each type of vehicle were estimated from (Burnham et al., 2006; Cheah et al., 2010). The materials breakdowns for HSS lightweighting options were obtained using the mass reduction factors from Das (2004). Fuel economy (Table 2) for the conventional configurations was obtained from (EPA, 2006, 2010; Gonder et al., 2009) and it was corrected for the HSS body configuration using the fuel consumption correction factors by weight reduction proposed by (Cheah et al., 2010).

Direct energy consumption and CO_2 emissions derived from vehicle use were estimated using 'Transport Analysis'; while indirect energy consumption and CO_2 emissions were estimated using 'Useful Energy Demand Analysis'. For a more detailed explanation about the mathematical formulation of each one of the used methodologies, the reader is referred to LEAP documentation (SEI, 2011).

Table 1 Light-duty vehicle alternatives

Code	Powertrain	Fuel	Vehicle Body Material	Available since
ICVEC	ICEV	E0 - E25	Conventional steel	2010
ICVBC	ICEV	B0 - B20	Conventional steel	2010
ICVNC	ICEV	CNG	Conventional steel	2010
HEVC	HEV	Gasoline	Conventional steel	2015
PHEVC	PHEV	Gasoline/Electricity	Conventional steel	2015
FCVC	FCV	Hydrogen	Conventional steel	2020
ICVEH	ICEV	E0 - E25	High-strength steel	2010
ICVBH	ICEV	B0 - B25	High-strength steel	2010
ICVNH	ICEV	CNG	High-strength steel	2010
HEVH	HEV	Gasoline	High-strength steel	2015
PHEVH	PHEV	Gasoline/Electricity	High-strength steel	2015
FCVH	FCV	Hydrogen	High-strength steel	2020

Table 2 Fuel economy by configuration

Configuration	ICE	ICE	ICE	HEV	PHEV		FCV
	E0-E25[a]	B0-B20[a]	CNG[a]	Gasoline[a]	Gasoline[a]	Electricity[b]	Hydrogen[a]
Car							
Conventional	29.0	29.9	32.3	51.6	55.0	89.0	84.2
HSS	29.9	30.8	33.3	54.9	58.9	87.2	90.0
Light truck							
Conventional	22.2	22.1	23.0	36.1	36.6	128.7	53.8
HSS	22.9	22.9	23.8	38.6	39.2	125.2	58.0

[a] Values in [mpg]

[b] Values in [Wh/mi]

The evolution of the vehicle fleet in Colombia was analyzed using the model under six scenarios. Two scenarios, PHEV and FCV, consider the penetration of more efficient powertrains, HEVs, PHEVs and FCVs, under conventional vehicle body configurations. Additionally, the effect of vehicle lightweighting using HSS for vehicle body manufacturing was introduced for the base scenario, as well as for PHEV and FCV scenarios, to configure three more scenarios: base-HSS, PHEV-HSS and FCV-HSS. Scenarios were defined in terms of target for new sales in 2050 by powertrain, fuel and materials configurations, as it is shown in Table 3. Base scenario represents the continuation of current policies for the promotion of biofuels and natural gas use. PHEV and FCV scenarios represent scenarios intended to reduce CO_2 emissions replacing gasoline fueled ICEVs with alternative powertrains. Base-HSS, HEV-HSS and PHEV-HSS scenarios consider the penetration of vehicles were 5% weight reduction was achieved using HSS. It was assumed that fuel economy of new vehicles in 2050 is 30% better than the values in 2010. Stock distribution of current vehicles in Colombia was obtained from (Mintransporte, 2010). Vehicle sales in 2010 were 153,156 cars and 65,358 light trucks (DANE, 2011); and are assumed to grow at a 5.5% rate. As there was not found data about the survival profile for the vehicle fleet, it was adjusted in LEAP until obtaining a vehicle fleet stock forecasted for Colombia by (Acevedo et al., 2009), using a car ownership model.

Table 3 New vehicle target sales by configuration in 2050

Scenario	Target Powertrain-Fuel						Target vehicle material	
	ICE E25	ICE B20	ICE CNG	HEV	PHEV	FCV	Conventional	HSS
Car								
Base	60	0	30	10	0	0	100	0
Base-HSS	60	0	30	10	0	0	50	50
PHEV	20	0	30	20	30	0	100	0
PHEV-HSS	20	0	0	20	30	0	50	50
FCV	30	0	30	10	0	30	100	0
FCV-HSS	30	0	30	10	0	30	50	50
Light truck								
Base	31	29	30	10	0	0	100	0
Base-HSS	31	29	30	10	0	0	50	50
PHEV	4	16	30	20	30	0	100	0
PHEV-HSS	4	16	30	20	30	0	50	50
FCV	11	19	30	10	0	30	100	0
FCV-HSS	11	19	30	10	0	30	50	50

Values in [%]

3. Results and discussion

Vehicle fleet increases in Colombia from 2.7 million vehicles in 2010 to 17.3 million vehicles in 2050. Under the base scenario this will represent a significant increment of fossil fuels use and CO_2 emissions. This scenario considers the shift from gasoline fueled vehicles to CNG and the increased penetration of biofuels. However, due to the dimension of the vehicle fleet increase, it remains a challenge to look for alternatives to reduce fossil fuels use and CO_2 emissions. The additional five scenarios considered here, go in that direction assessing the impact of changes in the vehicle type choices in energy dimension, through fuel and powertrains, and materials dimension, by means of the vehicle components materials. The panorama of the vehicle fleet in 2050 is presented in Figure 2. As the number of LDVs is considered constant, the changes from one scenario to another are described by the share of each vehicle type in the vehicle stocks. In all the scenarios, energy consumed and CO_2 emitted by the vehicle fleet increases. Replacement of ICE by more efficient powertrains causes a reduction in energy demand that is further improved with vehicle lightweighting.

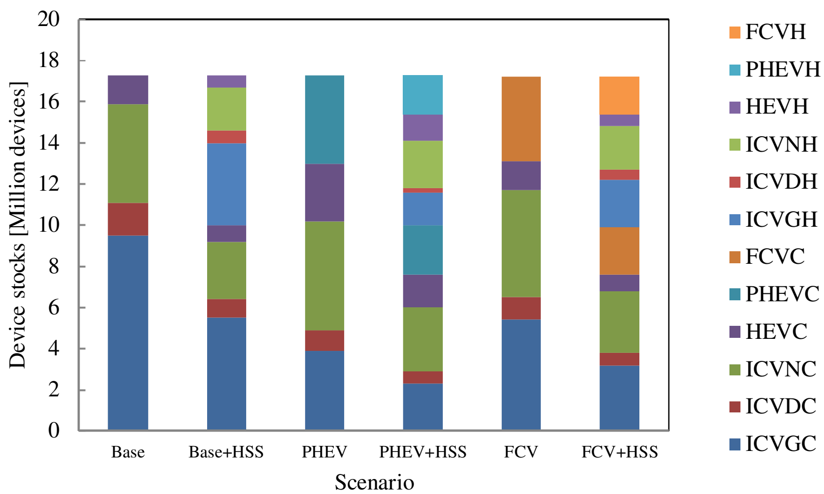

Figure 2 Vehicle fleet distribution in 2050

Energy demand by the vehicle fleet for the year 2050 is presented in Figure 3. Biofuels demand is higher in the base scenario and its lightweighting variation (base-HSS) due to the dominance of the ICE that is fueled with bioethanol and biodiesel blends. Reduction of fossil fuels demand is achieved through the utilization of PHEVs and FCVs. Under the considered assumptions, energy demand in PHEV and PHEV-HSS scenarios are the lowest ones. Increments in electricity use for these two scenarios are not significant compared to fossil fuels and biofuels demand reductions. The effect on vehicle energy consumption of alternative powertrains use is larger than the one achieved with HSS lightweighting. This fact is explained by the conservative lightweighting targets considered. While in this study total weight reduction of HSS configurations compared to conventional configurations is lower than 5%, other studies consider weight reductions over 15% (Cheah and Heywood, 2011; Cheah et al., 2010).

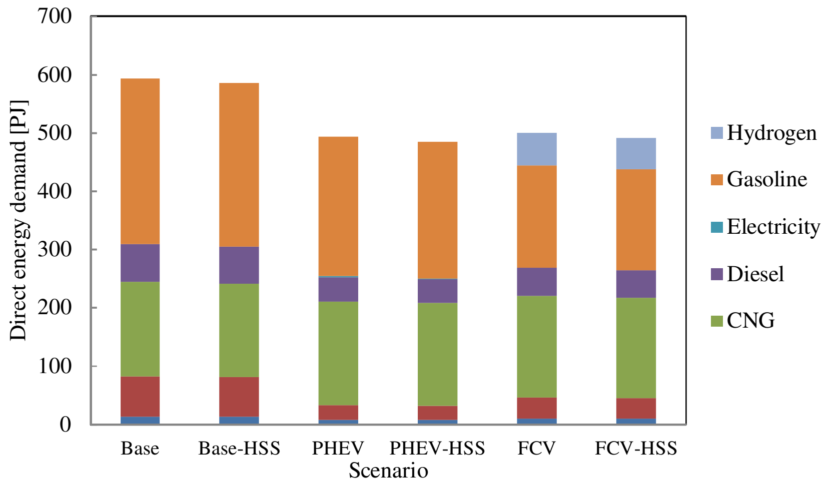

Figure 3 Direct energy demand in 2050

PHEVs and FCVs penetration contribute to CO_2 emissions reductions, as shown in Figure 4. As biofuels are considered carbon neutral, they do not contribute to CO_2 emissions in the system. Even though direct emissions from electricity for PHEVs and hydrogen for FCVs are zero, the emissions related to their production are presented to understand better the impact of shifting to these energy carriers. CO_2 emissions derived from hydrogen production contribute significantly to CO_2 emissions from vehicle use in the FCV and FCV-HSS scenarios. CO_2 emissions derived from hydrogen production are related to the use of electricity and natural gas, since it was assumed here that hydrogen is produced using decentralized natural gas steam reforming. Even though FCVs are introduced in 2020, five years after the introduction of PHEVs and HEVs, differences in energy demand and CO_2 emissions are not significantly different before 2030. The reason is that the increment in vehicle stocks from 2010 and 2030 is much smaller than the increment between 2030 and 2050.

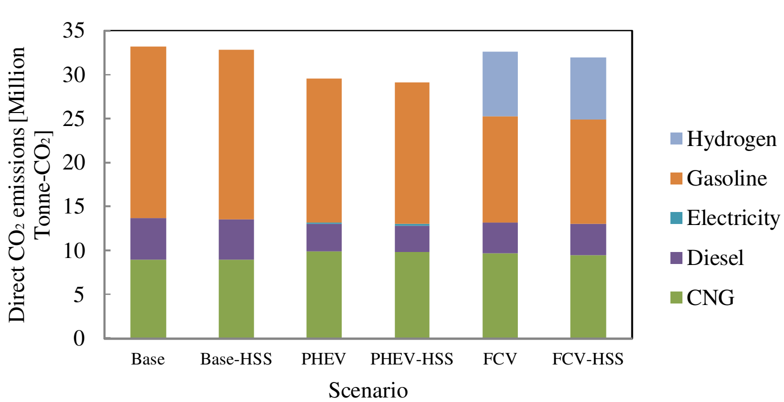

Figure 4 CO_2 emissions from vehicle use in 2050.

Compared to energy demand and CO_2 emissions reductions achieved in the year 2050, when cumulative effects over the time horizon are considered direct energy demand reductions achieved in the FCV-HSS scenario and the PHEV-HSS scenario compared to the base scenario are 9% (966 PJ) and 10% (1,135 PJ) respectively. In both scenarios powertrain and fuel selection account for the largest share, while HSS lightweighting contributes with only 1%, as represented in Figure 5. Again, it must be highlighted that this is due to the conservative assumptions regarding HSS lightweighting. CO_2 emissions are reduced by 3% (14 Million Tonne-CO_2) in FCV-HSS scenario and 7% (46 Million Tonne-CO_2) PHEV-HSS scenario compared to base scenario. The small extend of the changes in energy consumed and CO_2 emitted can be explained examining vehicle stocks in the year 2050 (Figure 2). Despite the penetration of alternative powertrains, ICEV remains as the most used vehicle type, accounting for 68% and 58% of powertrains in vehicle stocks in FCV-HSS and PHEV-HSS scenarios, respectively.

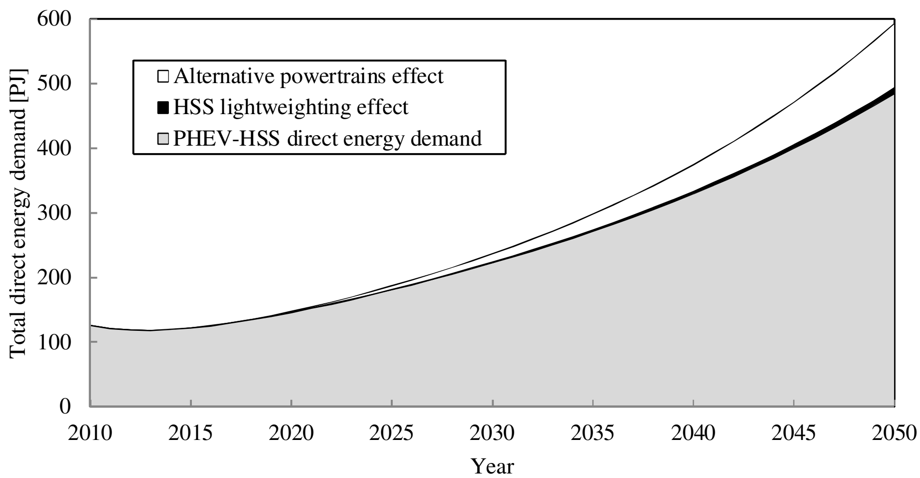

Figure 5 Total energy demand savings under PHEV and PHEV-HSS scenarios

In Colombia, car making industry is mainly composed by vehicle assembly companies that perform painting, welding and joining operations using completely knock down (CKD) components. In that sense, materials and parts fabrication take place outside the country. Material entering the country, like CKD components or imported vehicles, evolves according to the types and amount of vehicles in the country. Penetration of HEVs and PHEVs represent an increment in the materials input to the country due to the higher weight of HEVs and PHEVs. FCVs configuration includes the use of carbon fiber reinforced polymer (Carbon FRP), reducing the use of steel (Figure 6). Waste materials from retired vehicles are determined by materials used in new vehicles sales with a time lag, which is the service life of the vehicles. As the vehicle fleet is growing, the number of retired vehicles is lower than the number of new ones. Therefore, the amount of waste materials is lower than the amount of materials required for new vehicles. The selection of materials that are easy to recycle for LDV fleet and the improvement of recycling processes represent an opportunity for closing the automotive materials cycle and substitute imported vehicle parts by national made components from recycled materials.

Considering that national assembled vehicles represent 41% of total sales in Colombia (Econometría, 2011), estimated energy demand in vehicle assembly and vehicle retirement in 2050 is around 7.5 PJ for all the considered scenarios; equivalent to 1 – 1.5% of total vehicle use energy consumption for that year. This value does not include energy required for secondary materials production from recycled materials. The reason for these small values is that materials production and parts fabrications mainly take place outside the country in the analyzed scenarios. As a result, energy demand in materials life cycle for the vehicle used in Colombia takes place in several locations around the world. In that sense, for the analyzed scenarios the main advantage of including materials flows for the design of the future LDV fleet would be to gather information about flow of waste materials from retired vehicles and the possibility to use them for parts manufacturing through recycling. In the system this will represent a net increase of energy and CO_2 emissions; however in vehicles life cycle this will represent a decrease of energy and CO_2 emissions, as production of materials from recycled materials requires significantly less energy than their production form primary resources.

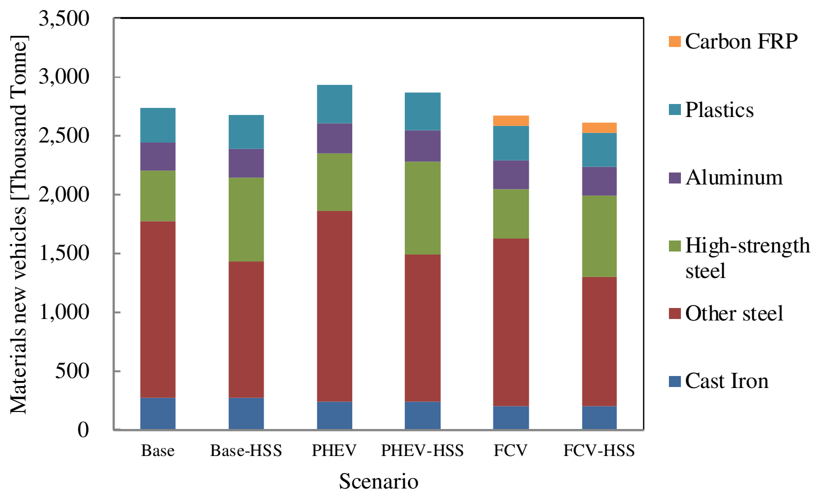

Figure 6 Materials input to the system in new vehicle sales in 2050

The tool developed here can be used to study energy and materials vehicle fleet evolution at a national level for any country. The case of developing countries is particularly interesting due to the expected increment of vehicle fleet caused by the increment in population income. The distribution of energy demand and CO_2 emissions in different places across the world, caused by the distribution of processes related to vehicles life cycle in different location, limits the degrees of freedom to act on energy and materials flows during the vehicle life cycle.

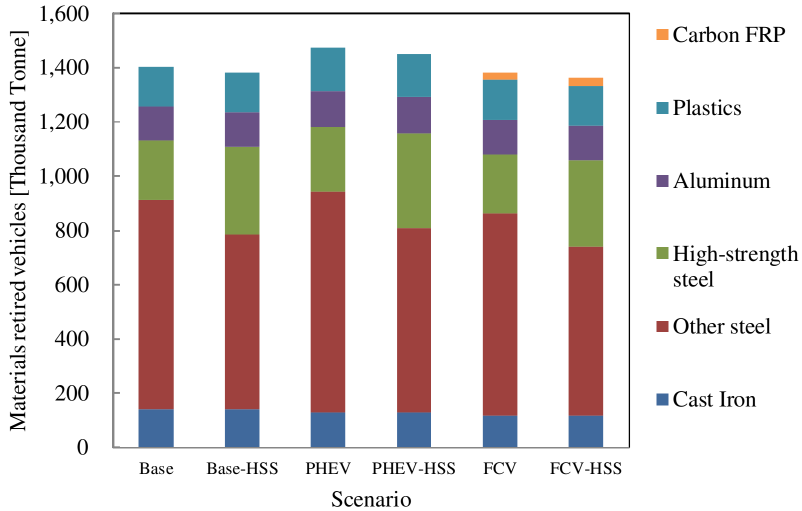

Figure 7 Materials from retired vehicles in 2050

4. Conclusions

Number of vehicles in Colombia, such as in other developing countries, is expected to increase significantly in the future, leading to a larger energy demand as well as the increment of CO_2 emissions. In this paper, alternatives in two dimensions have been considered jointly with the aim of reducing the energy consumption and CO_2 emissions related to vehicle fleet growth in the future: energy dimension, through the selection of fuel and powertrains; and materials dimension, choosing materials for vehicle lightweighting. Under the considered scenarios, energy demand and CO_2 reductions in 2050 can be reduced up to 108 PJ and 4.1 Million Tonne-CO_2 respectively; with more efficient powertrain penetration accounting for the largest part of the reductions.

Changing vehicle configurations affects materials flows and stocks for all materials, since materials breakdown varies from one configuration to another. For the analyzed system the effect of materials change due to vehicle type selection are majorly on vehicle disposal, while vehicle production mainly takes place outside the country. As vehicle stock increases, materials storage in new vehicles and waste materials released from retired vehicles also increase. Materials for new vehicles are mainly imported as CKD parts or vehicles; the result is the net production of materials released when vehicles retire. This fact can suggest the recycle of waste materials to fabricate vehicle parts and partially substitute imported components.

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