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Energy and fleet modelling within the TRIMODE integrated transport model framework for Europe

Pelopidas Siskos[a*], Pantelis Capros[a], Georgios Zazias[a], Davide Fiorello[b], Klaus Noekel[c]

[a]*E3MLab, 9 Iroon Polytechniou Str., Athens 15773, Greece*
[b]*TRT Trasporti e Territorio, Via Rutilia 10/8, 20144 Milano, Italy*
[c]*PTV Group,Haid-und-Neu-Strasse 15, 76131 Karlsruhe, Germany*

Abstract

This paper presents the Energy and Fleet module of the TRIMODE (TRansport Integrated MODel for Europe) model framework which serves to project mobility, energy consumption and emissions up to 2050 in the EU countries. TRIMODE features a modular structure which includes a network-based transport model that simulates passenger and freight transport activity, a dedicated energy and fleet model and a computable general equilibrium model. TRIMODE formulates such individual models within a common interrelated complex modelling framework. This paper presents the energy and fleet model of TRIMODE and focuses, in particular, on the novel model developments that benefit from the direct linkages with the passenger and network models and enhance the energy consumption and emissions calculation methodology. Illustrative examples demonstrate new model formulations.

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Keywords: Energy consumption and emission modeling; transport economics; transport modeling

1. Introduction

The transport sector is responsible for approximately a quarter of energy related GHG emissions in the EU and presents the strongest inflexibility in reducing emissions from fuel combustion. Deep emission reduction in the transport sector is necessary, though, in order to limit the increase of global temperature (well) below 2ºC, compared to pre-industrial levels as agreed by the majority of Head of States during the discussions of the COP21 meeting in

* Corresponding author. Pelopidas Siskos. Tel. +30-2107723630; E-mail address: siskos@e3mlab.eu, pelsiskos@gmail.com

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Paris, November 2015. The use of modelling tools serves to provide policy makers with quantitative information on how the envisaged targets may become a reality.

The TRIMODE (TRansport Integrated MODel for Europe) transport model framework serves to project mobility, energy consumption and emissions for the horizon up to 2050 in the EU countries. TRIMODE features a modular structure which includes a network-based transport model that simulates passenger and freight transport activity, a dedicated Energy/Fleet model and a computable general equilibrium (CGE) economy model. TRIMODE represents the newest addition to the transport models that are used by the European Commission. Despite the fact that the individual models that comprise TRIMODE are based on proven and existing methods, they have been designed afresh, extended with new enhancements and are being formulated within a common framework. TRIMODE will be completed in 2019.

This paper focuses on the new model developments on the energy and the fleet modelling aspects of TRIMODE, especially drawing from the direct linkages with the passenger and network models. The main purpose of the Energy/Fleet model is to estimate the evolution and the annual operation (e.g. energy consumption and emissions, costs, etc.) of the fleet of vehicles throughout the projection period. The Energy/Fleet model of TRIMODE is largely based on the PRIMES-TREMOVE transport model, developed by E3MLab of National Technical University of Athens. The paper is structured as follows: Section 2 presents a brief presentation of the TRIMODE integrated modelling system and describes the role of the Energy/Fleet model within this structure. Section 3 presents the basic formulation of the Energy/Fleet model. The section is focused on the novel model developments which improve the energy consumption and emissions calculation methodology. Illustrative examples are demonstrated. Section 4 concludes the paper.

2. The TRIMODE integrated transport model

The TRIMODE model solves a market equilibrium problem for the transport sector through the interaction of the transport, the Energy/Fleet and the economy models. The TRIMODE economy model is a fully fledged CGE macroeconomic and regional model, ensuring completeness of all macroeconomic, demographic and industrial mechanisms so as to ensure consistent closed loop interaction between transport, infrastructure, vehicle fleet, energy, emissions and the economy. The economy model estimates the zonal demographic, economic activities and change of bilateral trade in a particular year for all zones of the model. The estimation is made first at the national level and is then regionalised at NUTS-3 level; it serves to generate the demand for passenger and freight transport.

The transport model estimates demand for the passenger and freight transport activity. It includes three main elements: a passenger demand model, a freight demand model and a network model. The passenger model deals with generation, distribution and modal split of trips considering the whole mobility, from local trips to long distance journey, and therefore all relevant modes available, from walking to air services. The freight model simulates the spatial pattern of freight movements generated by intra-regional trade, taking explicitly into account the role of logistics and distribution channels, and the choice between alternative modes including intermodal chains. The network model takes passenger and freight demand as well as unit costs from the economy and energy model and assigns the vehicle movements to the paths and links of their respective modal networks. From resulting levels of service of each mode user costs are skimmed and fed back into the demand and economy models. Transport activity is sent to the energy model for a detailed estimation of emissions and consumption.

Equilibrium is established through the iterations of the entire TRIMODE model and the exchange of variables (i.e. levels of transport activity and changes in unit cost of transport, Fig. 1) between the models. The Energy/Fleet model determines the supply required to accommodate the demand of transport activity in terms of stock of vehicles of different types: cars, trucks, buses, vessels, etc.

2.1. Role of the Energy/Fleet Model within TRIMODE

The Energy/Fleet model computes energy consumption in the transport sector by fuel type; greenhouse gas emissions; pollutant emissions and external costs. The model estimates the evolution and the operation of the fleet of vehicles throughout the projection period. The model estimates the amount of new vehicles, vessels and aircrafts, the size and composition of the fleet for all transport modes, as well as the operation in terms of annual usage.

The Energy/Fleet model solves a non-linear optimisation problem with constraints. The model determines the optimum investments in terms of new vehicles, as well as the optimal operation of the vehicle fleet, by performing cost minimization. The optimization problem follows a 5-year dynamic forward looking approach. Stock-flow relationships are employed to model the evolution of the vehicle fleet throughout the projection period. The estimation of the total amount of new cars and their split into different technology categories and types is a variable of the model and is obtained as part of the optimization process. The annual vehicle operation by technology type and its allocation over the stylized trips categories is another variable of the optimization process.

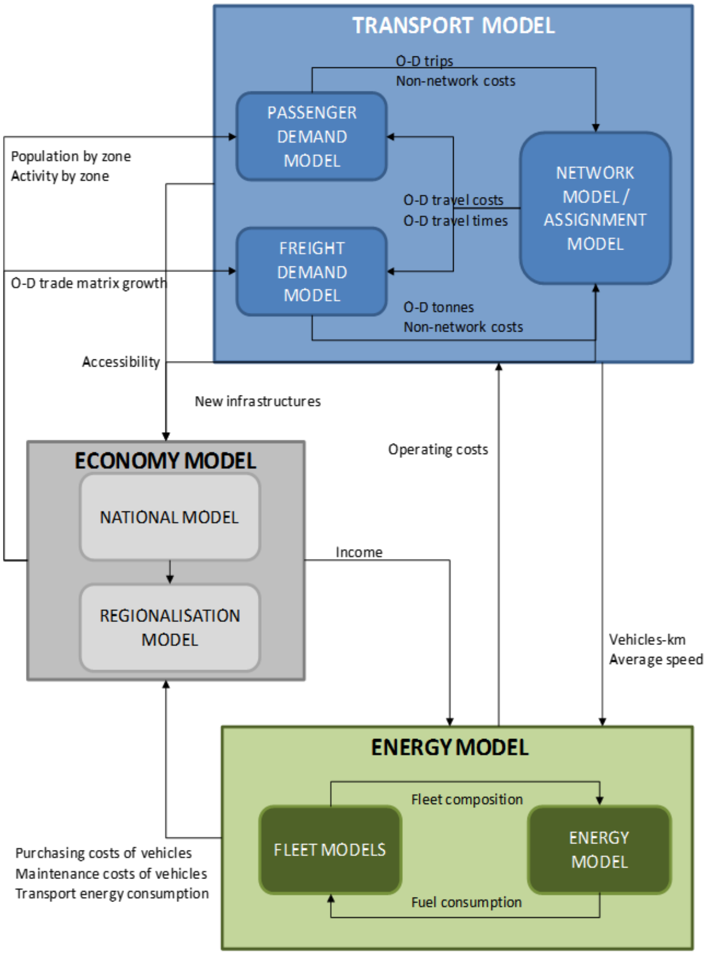


Fig. 1. Overview of the TRIMODE integrated modelling system

The Energy/Fleet model also calculates the operating costs (fuel costs) for all transport modes. The evolution of the fleet over the years yields changes in the average costs related to the purchasing of vehicles (e.g. more capital-intensive but more fuel efficient vehicle technologies). The changes in the unit costs of these two components (fuel costs and purchasing costs) are fed to the passenger demand and network models to establish a closed-loop system.

In the following section, we present the novel model developments of the Energy/Fleet model of TRIMODE which, thanks to the enhanced links with the passenger and network models, improve the simulation processes of the energy and fleet modelling compared to standard practices.

3. Enhanced links between the Energy/Fleet model and the passenger transport and network models

The private passenger transportation implementation in the Energy/Fleet model has been designed to reflect to a certain extent the segmentation of the detailed transport models of TRIMODE. Transport activity is segmented by geographical area (i.e. metropolitan, dense urban, other urban, inter-urban areas), by type of link (urban links, motorways, major and minor roads), trip purpose, household income category and speed bands. The links established improve the processes related to the expansion of the vehicle fleet (dynamically formulated through the years), the retirement (scrapping of older equipment) and the operation of the fleet (in particular, specific fuel consumption and emissions calculation).

Table 1. Segmentation of passenger transport demand in the Energy model.

Geographical area	Type of link	Household income Group	Trip purpose
Metropolitan Area Dense Urban Area Other Urban Area Inter-Urban Area	Urban Links Motorways Major Roads Minor Roads	High Low/Medium	Commuting Business Non-business

3.1. Procedures related to Fleet modelling

The choice of technology (and fuel type) when purchasing a new vehicle is represented in the model as a discrete choice model following a nested formulation, as presented in Siskos et al. (2015). The decision is segmented into Internal Combustion Engine conventional types, battery-based electric cars and fuel cell cars. The next level distinguishes between conventional, hybrid and plug-in hybrids. Each of these car types is further disaggregated in technology types, regarding efficiency for conventional cars, range for electric cars, etc. A Weibull functional form is used to determine the frequency of choice of a certain car type k (alias kk) which is expressed as the share $Shveh$ of vehicle type k in total sales of new cars (Castillo et al., 2008; Mattsson et al., 2014):

$$Shveh_{k,t} = \frac{w_{k,t} \cdot Cwb_{k,t}{}^{\gamma}}{\sum_{kk} w_{kk,t} \cdot Cwb_{kk,t}{}^{\gamma}} \tag{1}$$

The coefficient γ controls the degree of substitution among alternative options. The parameters w (with values between 0 and 1) are indexes which reflect the relative maturity and market share of options depending on market diffusion and availability of technologies. In Eq. 1, Cwb is a unit cost index (€/vehicle-km) of option k in year t inclusive of purchasing costs, expressed in equivalent annuity costs, fixed, variable and hidden costs such as range anxiety depending on car performance and availability of refuelling/recharging infrastructure. Eq. 2 presents the part of fixed cost elements $fc_{i,k}$, the annuity payment for the purchasing price of vehicles $I_{i,k}$ and variable costs $vc_{i,k}$. The cost index is transformed into a unit cost indicator by dividing with the overall annual mileage $Mlg_{i,k,t}$ of the alternative vehicle option.

$$Cwb_{i,k,t} = \frac{fc_{i,k} + I_{i,k} \cdot \dfrac{\delta_{i,k}\left(1+\delta_{i,k}\right)^{n_i}}{\left(1+\delta_{i,k}\right)^{n_i} - 1}}{Mlg_{i,k,t}} + vc_{i,k} \tag{2}$$

Regarding the purchases of transport equipment, the term I denotes the purchasing price of the vehicle, which is different by vehicle type. Purchasing costs are transformed into annual payments over the economic lifetime of the investment denoted as n using a certain discount rate δ.

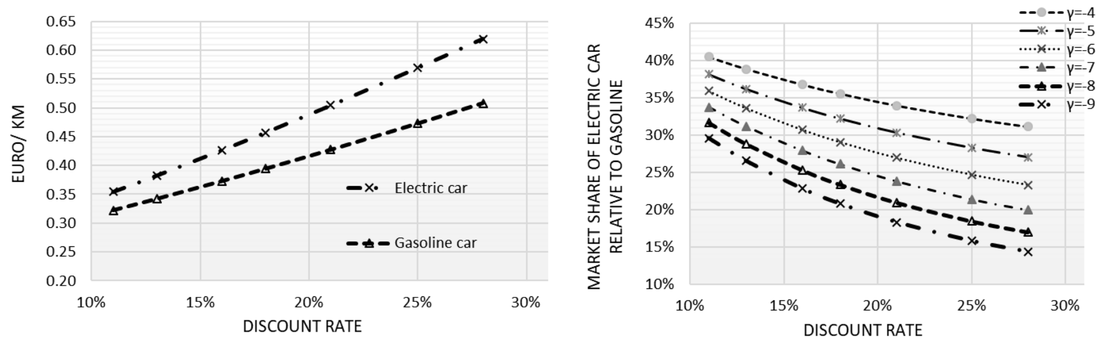
Improved simulation of decision making processes related to the purchasing and retirement of vehicle by household income category

Naturally, the standard practice is to assume a representative household and use a single value of the discount rate. In TRIMODE, the decision makers for private transport modes are split into High and Medium/Low Income categories. The passenger activity by income segment reflects behavioural patterns of each segment that are relevant for the purchase of new transport equipment. Low income categories, for instance, exhibit a more risk averse behavior and have limited access to capital funds. This is reflected in the modelling via higher subjective discount rates which tend to undervalue more capital intensive, yet more efficient, vehicle technologies. Discount rates can vary significantly as a function of the household income. The Energy/Fleet model associates different discount rates for each income category instead of using a single discount rate. Thus, the model is able to track down the market uptake of the different vehicle powertrains by household income category, capture potential inertia effects and provide relevant policy insight.

Table 2. Technologies considered for the fleet of passenger cars

Category	Type	Technology
	Gasoline	Conventional, Euro classes
	Bio-ethanol	Blended Bio-ethanol, E85 FFV
	Hybrid gasoline	Euro classes
	Plug-in hybrid gasoline	Plug-in hybrid technology
	Diesel	Conventional, Euro classes
Small/Lower-medium/Upper-medium/Large	Bio-diesel	Blended biodiesel
	Synthetic fuels	Synthetic fuels
	Hybrid diesel	Euro classes
	Plug-in hybrid diesel	Plug-in hybrid technology
	LPG	Conventional, Euro classes
	CNG	Euro classes
	Battery electric	Battery electric technology (Electric range classes between 140-500 km)
	Hydrogen	Hydrogen fuel cells

We present an illustrative example of the impact of the discount rates on the calculation of the cost index (Eq. 1) and market shares (Eq. 2) of an electric and a gasoline car. High Income households are associated with low discount rates, while the opposite holds true for low income households. The relative performance of an electric car compared to a gasoline one is expected to deteriorate, in terms of unit costs, as the discount rate increases. For a discount rate of 11%, the unit cost of an electric car is 0.35€/km vs 0.32€/km for a gasoline car (Fig. 2). For a discount rate of 25%, the cost of the electric car worsens compared to the gasoline car (0.57€/km vs 0.47€/km). The relative cost performance of the options matters in discrete choice modelling (Eq. 1). This affects the market shares of electric cars, which are found to increase for low discount rates (i.e. high Income households) compared to high ones (for a spectrum of values of γ).



Notes: Authors' calculations based on Eq. 1 and Eq. 2. Illustrative assumptions: Purchasing cost of gasoline and electric car 20500€ and 29200€, respectively. Average annual mileage of 15000km. Annual fuel costs of 1350€ and 360€, for the gasoline and the electric car, respectively. An economic lifetime of 10 years was assumed. No fixed costs are considered; w=1

Fig. 2. Illustration of the impact of the discount rates over the cost index and market share formulation in new vehicle choice considerations

The vehicle fleet model within the energy model tracks technology vintages and formulates the dynamics of vehicle stock turnover by combining scrapping and new registrations. The surviving stock of vehicles $stock$ in time period t is calculated as the probability that a vehicle will still be in use after a years from its first registration; T_i reflects lifetime.

$$stock_{i,a,t} = exp\left[-\left(\frac{a+F_i}{T_i}\right)^{F_i}\right] \cdot stock_{i,a-5,t-1} \tag{3}$$

The retirement functions for privately-owned vehicles differentiate by assuming different lifetime factors T_i for the vehicles. Lower income households, ceteris paribus, tend to retain their transport equipment for longer time compared to high income ones; yet, income is not the sole criterion for determining the replacement time of the equipment. Higher values of T_i are assumed for low/medium household income categories. This results in slower vehicle turnover cycles for this income segment compared to the high income one (see Fig. 3 using Eq. 3); a case of a single household is also presented. The combination of the modified vehicle turnover cycles and the varying discount rates is expected to differentiate the vehicle fleet evolution (especially the penetration of new clean technologies) for the two different household income categories. This is particularly important for scenarios assessing transport decarbonisation in 2050.

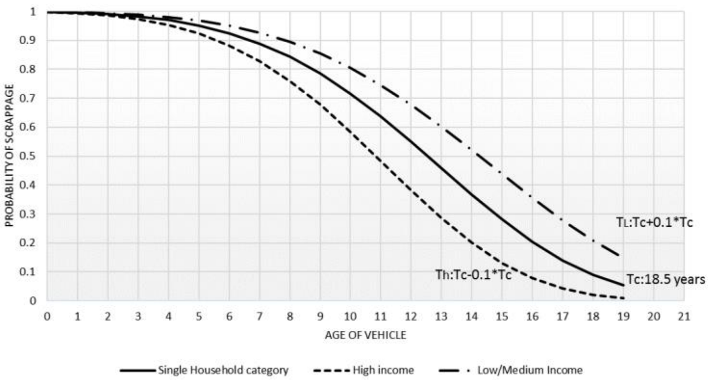


Fig. 3. Illustration of vehicle retirement functions, by household income category, as a probability of their age

3.2. Procedures related to modelling energy consumption

The passenger transport and the network models provide the transport activity by transport mode, geographical area, link type and speed band to the Energy/Fleet model (as shown in Table 1). The detailed disaggregation of transport activity allows to calculate, in a bottom-up approach, the energy consumption and emissions compared to practices using single average specific fuel consumption factors. For road transport models, specific fuel consumption differs by mode, technology, trip area; it is determined endogenously by the energy model and calculated based on the COPERT V methodology (Ntziachristos and Samaras, 2000). Eq. 4 shows the real world energy consumption by vehicle type, fuel, age and trip ψ. Annual vehicle mileage and specific fuel consumption are denoted as M and sfc, respectively.

$$energy_{i,k,\psi,\alpha} = stock_{i,k,\psi,\alpha} * M_{i,k,\psi,\alpha} * sfc_{i,k,\psi,\alpha} \quad (4)$$

The COPERT methodology enables calculation of the specific fuel consumption of road vehicles as a function of their speed, which is determined by the passenger, freight and network models. Parameters a, β, ε, ζ and θ, draw from COPERT and differ for each vehicle type, technology, and trip area; U is the respective average speed. Generally, low travel speed leads to higher specific fuel consumption.

$$sfc_{i,k,\psi} = a_{i,k,\psi} + \beta_{i,k,\psi} \cdot U_{i,\psi} + \varepsilon_{i,k,\psi} \cdot {U_{i,\psi}}^2 + \zeta_{i,k,\psi} \cdot {U_{i,\psi}}^{\theta_{i,k,\psi}} \quad (5)$$

Implementation of travelling speed profiles for road transport modes: An enhanced calculation of specific fuel consumption of road transport vehicles

The calculation of the specific fuel consumption could be calculated based on a single value of the speed of the vehicle, using Eq. 5 for each geographical area and link type. Test laboratories indicate that specific energy consumption and pollutant emission factors largely depend on the vehicle speed and present strong non-linear profiles, especially at vehicle speeds towards the lower and upper ends (see Fig. 4, the specific fuel consumption of a small gasoline car for different speed bins and some provisional distribution of the activity of the car into the speed categories).

For the purposes of the TRIMODE model, we did not assume a single speed value for the calculation of the specific energy consumption. From the connection with the passenger and network model, the activity by transport mode is disaggregated into speed bins: 0-10 km/h, 10-20 km/h, 20-40 km/h, 40-70 km/h, 70-90 km/h, 90-120 km/h and >120 km/h. The Energy/Fleet model calculates the energy consumption of road vehicles within each speed band, in contrast with the case of using a single average value for the speed by geographical area and link type.

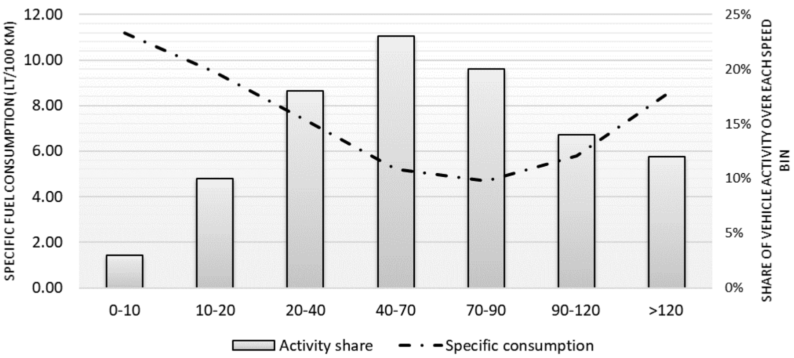


Fig. 4. Illustration of the specific fuel consumption of a small gasoline car for different speed profile (left axis) and distribution of its mileage (right axis) over the speed bins (provisional data); speed bins υ_{υ} (km/hr); average speed (km/hr): $\sum_{\upsilon} VKM(i,\psi,\upsilon)/\sum_{\upsilon}\left({VKM(i,\psi,\upsilon)}/{\upsilon_{\upsilon}}\right)$

The average specific fuel consumption is calculated as the weighted average of the specific fuel consumption by speed band and the share of transport activity within each band. Let us denote each speed band as υ and the activity by transport mode VKM for each speed band. The averaging over the speed classes yields from Eq. 6, using Eq. 5 to derive specific fuel consumption by each speed band. The average specific fuel consumption of the car of the example of Fig. 4 according to the new methodology would be in the order of 6.6 lt/100km. Contrastingly, the average speed, based on the distribution of the activity of the car of the example would be 36 km/hr (see formulation in Fig. 4). This yields a comparable specific fuel consumption of 6.7 lt/100km.

$$sfc_{i,k,\psi} = \frac{\sum_{\upsilon}\left(sfc_{i,k,\psi,\upsilon} * VKM(i,\psi,\upsilon)\right)}{\sum_{\upsilon} VKM(i,\psi,\upsilon)} \tag{6}$$

The example presented in this paper is based on provisional data on the distribution of the car mileage over the speed bins. Let us see, now, how the new formulation behaves if congestion levels increase, using the assumptions of Fig 4 as a starting point. The new bottom-up methodology, aims to reflect congestion effects more accurately. This becomes particularly relevant when considering the developments of new transport infrastructure in a scenario. In that case, the feedback from the network model would show an increase in the shares of activity over higher travelling speeds, which would result in more optimal fuel use; hence, lower energy consumption. On the other hand, an increase in travel demand from cars with the network capacity unchanged would increase congestion.

We present an illustrative example of the impact of increased congestion on the average specific fuel consumption, based on the new and the standard method. In the example provided in Fig. 5, we assume two cases: (i) slight and (ii) heavy congestion. For the two cases of congestion, we assume that the activity share of the car in the low speed bins progressively increases. The change in the specific fuel consumption based on the new approach is 2.5% and 8.3% in the case of slight and heavy congestion, respectively compared to our starting point. The standard method would result in average speeds of 32 km/hr and 25 km/hr, in the slight and heavy congestion cases, respectively (based on the formulation as in Fig. 4). The resulting change in specific fuel consumption is in the order of 5.6% and 20.8% in the two congestion cases (Fig. 5a). There is evidence that the two methods diverge. We cannot assert, though, that the conventional approach consistently overestimates the change in the specific energy consumption compared to the new approach, when congestion levels increase; more research is needed to this respect.

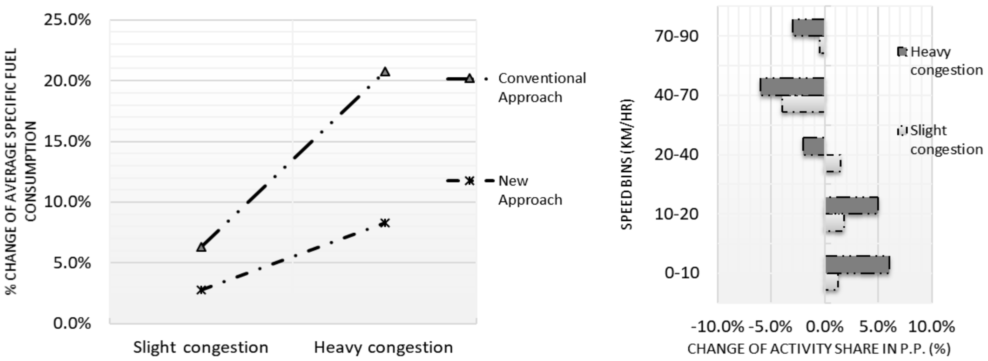


Fig. 5. (a) % change of the average specific fuel consumption of a small gasoline car under slight and heavy congestion conditions; (b) assumed change of activity mileage distribution over the speed bins for the two congestion conditions relative to the base distribution (Fig.4)

4. Conclusions

This paper presented the newly developed Energy/Fleet model which is part of the TRIMODE (TRansport Integrated MODel for Europe). TRIMODE is an integrated transport model which projects passenger and freight mobility, energy consumption and emissions up to 2050. The Energy/Fleet model is interlinked with a network-based transport model that simulates passenger and freight transport activity and a computable general equilibrium economy model.

This paper presented the novel model developments of TRIMODE, relative to standard practices, as regards the energy and fleet modelling literature. The new model mechanisms aim to reflect in a more refined manner decision making processes as regards new vehicle purchasing and old vehicle retirement choices, by distinguishing consumers into two income categories. A more refined calculation of the specific energy consumption using a histogram of distribution of transport activity by speed band, as fed by the network model, has been employed. The new bottom-up calculation aims to sufficiently simulate changes in the fuel consumption of road vehicles, when congestion levels differentiate. Our method scopes to remove discrepancy that is associated with the non-linearity profile of specific energy consumption of conventional vehicles at very low speeds and adequately simulate changes from new infrastructure developments.

When the TRIMODE model is completed, in 2019, the suite of modelling tools available at the European Commission will be enriched by a new model for policy analysis.

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