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Overview of strategies for reducing CO_2 emissions during the use phase of passenger cars

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Abstract

Road transport largely dominates the transportation demand and energy consumption. Passenger light-duty vehicles (passenger cars and light trucks) are responsible for almost half of the energy consumption of road transport. This energy is mainly supplied by fuels produced using oil resources, increasingly difficult and expensive to exploit. The use of these fuels also generates greenhouse gases, mainly carbon dioxide. This paper analyzes and compares strategies from different domains – the vehicle, the driver and the environment – for reducing carbon dioxide emissions from the use phase of passenger cars. This analysis is based on a general litterature review primarily focused on strategies applicable to OECD countries. A framework for classifying these strategies and the interactions between measures coming from different domains is proposed. The results highlight the possibilities of integration between domains that remain unexplored and that could bring significant gains in terms of emissions reductions.

Keywords: CO_2 emissions; transportation; energy; passenger cars.

Résumé

Le transport routier est le principal consommateur d'énergie du secteur des transports, et en domine également la demande. Les véhicules légers (voitures particulières et véhicules utilitaires) sont responsables de la moitié de la consommation énergétique du transport routier. Cette énergie provient de carburants produits à partir de ressources pétrolières, de plus en plus difficiles et chères à exploiter. En outre, l'utilisation de ces carburants émet des gaz à effet de serre, principalement du dioxyde de carbone. Cet article compare des stratégies issues de différents domaines – le véhicule, le conducteur et l'environnement – pour réduire les émissions de dioxyde de carbone produites par l'usage des voitures particulières. Cette analyse est basée sur une revue générale de la littérature centrée sur les stratégies applicables aux pays de l'OCDE. Une classification de ces stratégies et de leurs interactions est proposée. Les résultats mettent en évidence les possibilités d'interactions entre mesures qui proviendraient de domaines différents et qui pourraient apporter des réductions d'émissions non-négligeables.

Mots-clé: Émissions de CO_2 ; transport ; énergie ; voitures particulières.

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1. Introduction

Fossil fuels are the main energy source for transportation (IPCC, 2007). Considering the expected growth in transportation demand, mainly in developing countries (IEA, 2012b), this oil dependency represents an issue for sustainable transportation: oil production may reach a peak and the combustion of fossil fuels generates emissions of carbon dioxide (CO_2), a greenhouse gas (GHG) that contributes to the global warming phenomena (IPCC, 2007).

More than three quarters of the transportation energy is consumed by road transport (IEA, 2012a). In the OECD countries, light-duty vehicles (passenger cars and light trucks) account for approximately 70% of the motorised passenger travel, measured in passenger-km per year (IEA, 2012b). Therefore, strategies aiming at reducing the GHG emissions produced by passenger cars represent a step towards sustainable transportation. These emissions are generated during each phase of passenger cars lifecycle: production, use and end-of-life (Leduc et al., 2010). The infrastructures used for road transport have also GHG emissions associated with their construction, maintenance and use (Vandanjon et al., 2012).

For conventional internal combustion engine (ICE) vehicles, almost 80% of energy consumption and GHG emissions comes from the well-to-wheel (WTW) phases: one sixth for the fuel production phase, also called *well-to-tank* (WTT) phase and the remaining for the fuel consumption in the vehicle, also called *tank-to-wheels* (TTW) phase. The other 20% of the energy consumption and emissions are generated in the other life cycle phases, production and end-of-life (Leduc et al., 2010, Ma et al., 2012). The importance of the TTW phase for GHG emissions of conventional ICE vehicles has stimulated the research on strategies for reducing these TTW emissions.

According to a literature review by Schwanen et al. (2011), many published studies consider the effect of emissions reduction strategies focusing on different elements of transport systems simultaneously (Kromer et al., 2010, Leduc et al., 2010). However, the evaluation of the benefits that a combination of strategies could provide on the on-road fleet is less explored in literature. For example, numerous studies evaluate the effect of more stringent speed limits on roads (e.g. Madireddy et al., 2011, Baldasano, 2010). Nevetherless, these studies do not evaluate the effects of these new speed limits on new vehicle characteristics and on vehicle choice.

The aim of this paper is to analyze strategies proposed in literature for reducing CO_2 emissions from passenger cars during the use phase of their life cycle. We expand the existing literature reviews on the subject by comparing the emissions reduction potential of strategies related to the Driver, Vehicle and Environment domains and of the interactions between these strategies. Although the application of the strategies presented depends on public policy aspects (reglementations, regional roadmaps), our aim is to present a review focused on technical and behavourial measures. This analysis can help policymakers, automobile manufacturers, and infrastructure managers to choose among different options to reduce energy consumption from transportation. The reminder of this paper is organized as follows: section 2 presents the methodology applied for structuring the literature review and the analysis, section 3 details the literature review, section 4 presents a discussion of these results and section 5 concludes the paper and draws up the perspectives.

2. Methodology

2.1. Data sources

The literature review was based on articles available on the *ScienceDirect* and *Springer* journals database. Technical sources such as the SAE (Society of Automotive Engineers) journals and reports from organisms as the International Energy Agency (IEA), the European Commission or the US National Research Council, or research organizations such as TNO (Netherlands) were also considered. Although this paper data sources do not constitute the whole literature on the subject of strategies for reducing CO_2 emissions from passenger cars, the variety of sources (scientific publications, agencies and research group reports) provides a cross-sectional view of the field.

2.2. Definition of the domains of the strategies for emissions reduction

The system formed by the driver, the vehicle and the environment, is called the Driver-Vehicle-Environment (DVE) system. This term come from road safety research (Enke, 1979) and summarizes the elements acting during the use phase of vehicles and also the interactions between these elements. The environment includes the infrastructure in which the vehicles are driven, the traffic conditions, the land planning, the weather conditions, and other external elements, such as regulations, and taxes. The strategies for reducing CO_2 emissions during the use phase of passenger cars were classified according to the domain targeted by the strategy: (i) the driver, for measures that reduces emissions by influencing driver behavior or decisions, (ii) the vehicle, for strategies aiming at improving vehicle systems; (iii) the environment, for measures that mitigate emissions by changing environmental conditions.

During the use phase of vehicles, energy consumption, which is related to the emissions generated, can be estimated considering vehicle dynamics: the vehicle must produce a tractive force at the wheels in order to overcome the different resistances to movement and to provide energy for other vehicle systems. The components of the required tractive force are aerodynamic drag and rolling resistance forces, inertial acceleration and grade-climbing forces, the last three being proportional to the vehicle mass (Burgess & Choi, 2003). These authors also propose that other forces such as the cornering losses at the tyres, can be taken into account as a component of tractive force. The total energy consumption calculated using these tractive forces allow the identification of the roles of each domain of the DVE system. The driver acts mainly upon the vehicle speed and inertial acceleration. The vehicle design influences the aerodynamic drag, the rolling resistance (tyres), the vehicle mass, the efficiency of the energy conversion and the other systems consumption. The environment influences the rolling resistance, by means of road surface conditions and also the vehicle speed, by traffic, weather and road geometry. We classified the strategies proposed in literature into one of these three domains based on these roles and on the parameters targeted by the strategies.

Two other aspects influencing energy consumption are the GHG emissions produced by the energy source and the distances travelled by the vehicles. Although economic and policy instruments constitute one element of the DVE system, a comprehensive literature review on the effects of these instruments on the emissions reduction is beyond the scope of this paper.

2.3. Comparisons of emissions reduction potentials

The present literature review aims at comparing different emissions reduction potentials during the use phase of cars obtained by applying different strategies presented in literature. Performing these comparisons can be a complex task as each study has its own methodology and assumptions: different time frames, different baseline vehicle models, and can involve real-life experimentation data or normalized driving cycles. This limitation was circumvented by considering the magnitude of emissions reductions gains achieved with these strategies. Moreover, the well-to-tank phase of the vehicle lifecycle shoud also be considered for a more complete evaluation of the potential of emissions reduction.

3. Literature Review

In this literature review the emissions reduction potential for conventional ICEs using fossil fuels such as gasoline or diesel, are considered as being roughly proportional to the fuel consumption reduction potential. Another term that can also be found in the literature is the improvement of fuel economy. Fuel consumption is the inverse of fuel economy, and changes in the fuel consumption are not exactly equivalent to changes in fuel economy: a 50% reduction in fuel consumption equals a 100% increase in fuel economy (NRC, 2011).

3.1. Strategies influencing the driver

In the driver domain of the DVE system, defined in section 2.2, achieving emissions reduction during the use phase of passenger cars implies changes on driver behaviour, mainly on its driving style, which is directly related to the fuel consumption. The driver behaviour can also be related to the decisions drivers make for using or buying vehicles. Michon (1985) and Boer & Hoedemaeker (1998) propose a description of driver behaviour using three hierarchical levels:

- *Strategic* or navigation level; in which the driver defines the general planning stages of a trip. It involves route choice, modal choice and evaluation of potential risks.

- *Tactical* or guidance or manoeuvre level, consisting of all manoeuvres planning including speed, acceleration, lane choice and behaviour at junctions.
- *Operational level*, often called control level, in which the driver controls all vehicle inputs such as the gas, brake and clutch pedals but also the steering wheel.

One of the strategies proposed for reducing the emissions based on changes on driver behavior is *eco-driving*. In this strategy, the driver adapts these three hierarchical levels in order to achieve lower fuel consumption. According to Barkenbus (2010), eco-driving implies following several rules: do not drive too fast, do not accelerate too quickly, shift gears sooner to keep engine speed lower, maintain steady speeds, anticipate traffic flow when accelerating and slowing down and keep the vehicle in good maintenance. The main recent studies on this topic show that eco-driving could allow about 5% to 20% fuels savings during the use phase of cars. A widespread adoption of eco-driving is slowed by the required driver-training needs. While some countries have already introduced eco-driving requirements in the initial training, most of professional driving teachers still prefer to concentrate on road safety. Nevertheless, several companies proposing eco-trainings have been created.

Actually, the driver can hardly change its operational level as it is a matter of reaction time and physiological characteristics. Advanced Driver Assistance Systems (ADAS) can help drivers dealing with this aspect. Historically, the main aim of ADAS was the optimization of safety and comfort while driving. The fuel savings and consequently the CO_2 emissions reduction aspects were not considered as a primary objective of these systems, and little is known about the combined effects of such systems. One of the first attempts of introducing fuel efficient driving strategies in the already existing safety-related ADAS were the speed regulation systems. These systems can be used for fuel saving by reducing vehicle speed or maintaining a steady speed. A recent large scale field operational test in Europe provided some evidence on the environmental impacts of these systems (downloadable documents are available at the EuroFOT project website - http://www.eurofot-ip.eu). For the Speed Limiter and the Cruise Control which are activated on demand by the driver, respectively 0.26% and 0.71% of fuel consumption reduction could be achieved (results combining direct effects and usage rate). Automatic Cruise Control could induce a 1.37% reduction. Other alternative is Intelligent Speed Adaptation (ISA), for which large scale field studies highlighted the absence of significant effects on fuel consumption (Saint Pierre & Ehrlich, 2008; Carsten et al., 2008).

A simple acceleration advisory tool has also lead to disappointing results (Larsson & Ericsson, 2009). It is worth mentioning that instant fuel gauge is now very common and did not succeed in transforming every single driver into an eco-driver. Designing new types of devices focused on fuel efficiency, often called Ecological Driving Assistance Systems (EDAS), seems to be a more promising approach as many automakers are developing their own monitoring devices. The two main challenges for effective EDAS are first to help the driver to learn fuel savings driving tips, and then to maintain efficiency over time once training is complete (Beusen et al., 2009). The currently running European project EcoDriver (http://www.ecodriver-project.eu) focus on building both embedded and nomadic systems for teaching the driver to save fuel and helping maintaining his driving efficiency. Results from the large field tests of this project will provide evidence on the effects of these systems.

The above described measures reduce fuel consumption by improving driver behavior after vehicle purchase, and the potential emissions reduction refers to the use phase. Sivak & Schoettle (2012) consider vehicle selection (class, model, and configuration) and vehicle maintenance as other strategic decisions contributing for reducing fuel consumption. The driver can also opt to reduce driving distances (by car sharing/ better use of public transportation networks, etc.).

3.2. Strategies based on vehicle system improvements

As explained at the methodology section, the *energy conversion* in the engine influences the total energy consumption. For conventional ICEs, from 100% of fuel energy that enters the engine, it is estimated that only 10 to 20 % is used for providing the required tractive force in standard testing cycles (Atabani et al., 2011). Improving this energy conversion efficiency by acting on the powertrain or by recovering energy losses are strategies for reducing fuel consumption and GHG emissions.

Powertrain improvements include strategies such as: implementing valve-timing systems, variable compression ratios, improved thermal management, reducing engine friction losses or engine downsizing with turbocharging.

The fuel economy improvements for this last strategy were estimated between 17% and 10% (IEA, 2012a) with a "strong downsizing" for gasoline and diesel engines, respectively. NRC (2011) considered slightly lower achievable fuel consumption reductions for downsizing: 2 to 6% for gasoline engines with direct injection, and 3 to 5% for diesel engines. The potential of the other measures to reduce fuel consumption was inferior to 10% (NRC, 2011; IEA,2012a; TNO et al., 2011). The observed differences between diesel fueled and gasoline fueled engines, are due to the superior fuel efficiency of compression ignition engines (Schipper, 2011). Diesel engines for passenger cars are popular in Europe, although their lower fuel consumption is offset by differences in vehicle use, vehicle choice and other factors detailed by Schipper (2011) and also by other pollutants emissions, such as particulates. Reducing *transmission losses* include strategies such as increasing the number of ratios (e.g. using continuously variable transmission, CVT). The fuel consumption reduction potential for transmission improvements ranges from 3 to 8% for gasoline engines and from 2 to 5% for diesel (NRC, 2011; TNO et al., 2011).

Besides modifying the conventional engines, hybridizations allow better energy conversion since the electric motor can be used for optimizing the efficiency of the ICE: allowing the adjustment of the ICE torque and speed to their best efficiency operating points and can recover some energy losses such as braking losses. For the different hybrid types, fuel consumption savings were estimated as: 6% and 1% for gasoline and diesel engines respectively for the stop/start system (NRC, 2011), 20-30% for mild hybrids (Chan, 2007; TNO et al., 2011), 30-50% for full hybrids (Chan, 2007; TNO et al., 2011; NRC, 2011) and 50% or more for plug-in hybrids (Atabani et al., 2011). The type of driving conditions can influence these percentages, as hybrids have characteristics that allow greater savings on lower speed conditions (Fonseca et al., 2011).

Another strategy belonging to the vehicle domain is the adoption of *alternative energy sources* produced using renewable energy sources or with lower fossil fuel content. Electricity, hydrogen or biofuels are examples of these alternative sources. Full electric vehicles generate zero CO_2 emissions from the energy use in the vehicle, but the energy-mix used to produce the electricity can have high impacts on the well-to-tank CO_2 emissions. Electricity can be produced using renewable and less CO_2 emitting sources of energy, but there are still some limitations that refrain the more widespread adoptions of the electric vehicles: high cost, shorter driving ranges, longer refueling times, infrastructure investments (Romm, 2006; Chan, 2007). For hydrogen, there are two possibilities. It can be used in ICEs subject to modifications (Pourkhesalian et al., 2010) or in fuel cells to generate electricity, in the so-called Fuel Cell Vehicles (FCV). The FCV option is currently under development by vehicles manufacturers and the high initial costs and the production and distribution of hydrogen are the main limiting factors for its development: Romm (2006) estimated that the market penetration of this technology would be less than 5% in 2030. Biofuels can be produced using a wide variety of vegetable oils and biomass. The use of these fuels in ICEs requires minor changes, and have the advantage of having their CO_2 emissions during the combustion being absorbed by the photosynthesis process of plants and thus considered globally as zero. However, direct and indirect land-use changes and competition with food agriculture can offset these environmental gains. It is worth noting that in the European Union for example, the legislation is incentivating biofuels with reduced indirect land use change emissions and no longer supports biofuels from food crops.

Vehicle-design related parameters such as vehicle mass, frontal area, drag and rolling resistance coefficients represent loads that, if reduced, can diminish the total tractive force required. Moreover, reducing the consumption of accessories such as air conditioning, could also reduce the energy needs. The tyres rolling resistance can be reduced by acting in one (or all) of the following vehicle-dependent aspects: tyre pressure (increasing inflation of tyres reduces flattening and thus reduces rolling resistance), tyre materials and design (contributing to less friction between tyres and roads). The range of the achievable fuel economy reduction by the combination of low resistance tyres and tyre pressure monitoring systems was estimated as 3 to 5% (IEA, 2012a). The aerodynamic drag can be reduced by acting upon the frontal area, the aerodynamic drag coefficient (related to vehicle streamlining) or by reducing the vehicle velocity. Considering the two first vehicle-related parameters, Burgess & Choi (2003) estimated that decreasing the frontal area or the aerodynamic drag coefficient by 10% could reduce the vehicle total energy demand by 2%. Fontaras & Samaras (2010) obtained using simulations on the NEDC cycle a reduction in the CO_2 emissions ranging from 1.2 to 2.4% with 10% of combined reduction of frontal area and aerodynamic drag coefficient.

Vehicle weight is the most significant parameter affecting vehicle energy consumption from vehicle loads (Burgess & Choi, 2003). The results obtained by Fontaras & Samaras (2010) for an NEDC cycle, showed that a 10% reduction in vehicle mass could allow CO_2 emissions reduction ranging from 2.7 to 3.6%. These reductions may be achieved by the use of lightweight materials, for example. However, making assumptions over the

possible gains coming from reducing vehicle mass without considering the effects that the reduced mass could have on the powertrain can be misleading since lower vehicle weight can also be used for improving the powertrain efficiency (by downsizing, for example) (Cheah & Heywood, 2011). Other vehicle loads include energy used for lighting (up to 0.5% fuel consumption savings) and air-conditioning systems (3 to 4% fuel consumption savings), according to IEA (2012a).

The strategies encompassing the vehicle system improvements are the subject of many regulation measures in different regions of the world (Atabani et al., 2011). In Europe, for example, since the 1990s automotive manufacturers signed voluntary agreements to promote the reduction of CO_2 emissions from cars during their use phase. The regulation 443/2009 set CO_2 emission performance standards and emissions objectives that must be achieved by cars manufacturers. In 2015 for example, the objective for all new cars is to achieve an average of 130 gCO_2/km, and 95 gCO_2/km. is the target for 2020. This regulation includes penalties for manufacturers not reaching the targets and gives credits for manufacturers producing innovations allowing emissions reduction, called "eco-innovations", and for those producing extremely low emissions (below 50 gCO_2/km) (European Union, 2009).

3.3. Strategies encompassing the environmental conditions

Road design and characteristics directly influence energy consumption of vehicles traveling on it: the slopes incidence and grade strongly impact fuel consumption, especially above thresholds where it is necessary to brake on a following downhill (Coiret et al., 2012, Tsang et al., 2011). The level of sinuosity on an itinerary, or curve rate comparing to straight sections, has an influence on both the vehicle braking and on developed lateral forces (Burgess & Choi, 2003). The choice of materials and the road conditions are also relevant parameters (Chupin et al., 2010, Hu et al., 2012). Infrastructure parameters have more importance for energy demand than it is usually suspected, particularly because fuel consumption tests do not take into account road characteristics such as wind, hills and corners. This aspect is highlighted in the study of two UK commuter routes by Burgess & Choi (2003): the magnitude of fuel consumption is 2 to 3 times superior to those obtained in the European extra urban test cycle, this difference being largely due to infrastructure parameters.

Chupin et al. (2010) evaluated the influence of road infrastructure deformations on vehicle energy demand. The results revealed that no more that 1% of engine power output is dissipated by the viscous response of pavements. Road surface effects on rolling resistance have been studied experimentally using coastdown tests by Hammarstrom et al. (2009). These tests rely on deceleration measurements and have the advantage of estimating contact forces while avoiding uncertainties caused by engine and used fuel. It has been estimated that at 15 m/s, the rolling resistance increased by 19% for changes in road roughness from 1 to 10, and by 46% for changes of mean profile depth from 0.3 to 3. Higher impacts are found for higher speeds and these results are in the intervals of a comparable literature survey (Sandberg, 1997).

As mentioned in Section 2.2, the strategies involving the reduction of distances travelled can be associated with environmental strategies, such as pricing and taxes, car-sharing schemes, and better land-use and traffic congestion reduction (DeCicco & Mark, 1998, DeVlieger et al., 2000, Monzon et al., 2012). According to IPCC (2007), the set of strategies that should be applied depend on the country and its growth dynamics and the synergistic impacts of these strategies can be significant. At last, life cycle analysis (LCA) of a road shows that energies involved for alternative constructions must be considered when comparing energy needed for the use phase of these alternative designs (Vandanjon et al., 2012). The LCA-based MIPS method (material input per service unit – Saari et al., 2007) adds an indicator for measuring the material consumption in relation to the service they provide. For example, MIPS value for abiotic resources depletion is much lower for a motorway (1.19 kg/person-km) than for a connecting road (3.21 kg/person-km), mostly because of variations in the use phase (traffic).

3.4. Interactions between the DVE domains

Some strategies involving interactions between the three domains were identified in litterature. In the vehicles domain, the interactions between the reduction of load factors and the vehicle energy conversion improvements are vastly explored in order to optimize fuel consumption (Cheah & Heywood, 2011). However, new technologies such as hybrids may represent an increase in vehicle weight, diminishing the overall fuel

consumption benefits (Reynolds & Kandlikar, 2007). Besides obvious interactions such as those between road slope and vehicle mass, vehicle and environment strategies interactions have a positive effect in emissions reduction, as shown in studies on the integration of vehicle-infrastructure communication and hybrid vehicles (He et al., 2012). There are other domains related to fuel consumption, such as road safety (Esposito et al., 2011). Some of the strategies proposed for reducing fuel consumption can also contribute to enhance safety, and multiple variable assessments can be useful for evaluating these combined effects.

4. Analysis and Discussion

In this article, different strategies for reducing CO_2 emissions from the use phase of passenger cars were assessed and the potential for interactions of strategies coming from different domains was analysed. Regarding the potential for emissions reductions, strategies related to the vehicle domain have received great interest in literature, presenting emissions reduction potentials of more than 50% compared to conventional vehicles, by means of alternative powertrains such as hybrid vehicles. The strategies related to the drivers domain have also an important potential of 20% savings for the eco-driving strategy. For those belonging to the environment domain the benefits are more difficult to quantify since environmental strategies cover very distinct fields such as road characteristics or transport policy.

As mentioned in Section 2.3, quantitative comparisons between the potentials coming from the three different domains are not straightforward, and would not be accurate. However, the different strategies can be compared considering: The *difficulty* in the application of the strategies as highlighted in the literature review for strategies such as electric and fuel cell vehicles, the strategy *extent* and the possibilities of *combinations* with other strategies for enhancing their individual potentials, also stressed by the literature review:

- *Difficulty in the application:* Three aspects are important for evaluating this difficulty: the technical constraints, the customers acceptance and the required efforts from policy measures.
  The magnitude of these difficulties for strategies in the vehicle domain can be illustrated by the fuel cell vehicles strategy. While this technology shows great potential for reducing fuel consumption and emissions (if hydrogen is produced using renewable and low-carbon emitting resources), its development is constrained by difficulties associated, according to Romm (2006), with the need of developing a refuelling infrastructure and the high vehicle cost.

- *Strategy extent:* some strategies affect only new vehicles that enter the market, while other strategies affect the whole vehicle fleet or drivers. The emissions reduction potential is different for each case. For example, if eco-driving (10% average reduction potential) is applied by all drivers, the cumulative fuel consumption of the vehicle fleet over the next 15 years (2015-2030) will be reduced by 10%. However, a strategy such as the development of plug-in hybrids (up to 50% emissions savings potential), is subject to market uptake constraints. Assuming that PHEV may constitute 10% of new vehicle sales in 2030, the cumulative fuel consumption over the whole vehicle fleet for the next 15 years will be reduced by less than 1%. This difference stresses the importance of considering the impacts of strategies over the entire vehicle fleet and over time: The benefits of applying simple measures over the whole vehicle fleet may be superior to those achieved with the development of new technologies depending on the market uptake.

- *Combination of strategies:* the literature review reveals that the combination of strategies from different domains can have at least three effects: A positive effect, when the combination allows a greater fuel consumption reduction than the application of the individual strategies, as shown in the case of combination of strategies inside the vehicle domain, when a reduction of a load factors such as weight allow the resizing of other components and more emissions benefits; a neutral effect, when the combination do not allow greater gains and a negative effect, when the combination may offset the fuel consumption benefit. The effects of the combination can be illustrated by the following example: if three strategies such as eco-driving (10% emissions reduction), engine downsizing (10% emissions reduction) and the reduction vehicle travel (5% emissions reduction – estimated) were combined, the total fuel consumption reduction would achieve 30%. The same 30% can also be obtained with technological improvements such as hybrid vehicles, which are dependent on costs and customers acceptance for achieving the required market penetration.

Considering these aspects, we propose a framework for classifying the strategies for reducing the emissions from passenger cars use phase considering the following elements: the domain targeted by the strategy, the difficulty and efficiency of the strategy and the possibility of combination between strategies (Table 1). The analysis of this framework must take into account the hypothesis made for its construction:

- Other dimensions could be added for the difficulty evaluation, such as the costs (for clients, for manufacturers, for the government);
- The differences between on-road and on-cycle emissions measures, mainly for those not quantifiable in standard testing cycles, which also influence the efficiency aspect;
- The calculations of the benefits obtained by the application of a strategy over the whole vehicle fleet require a deeper analysis of the fleet evolution dynamics and the construction of scenarios;
- The effective quantification of the positive / neutral / negative effects of the combination of strategies will mainly depend on simulations and real-life experiments to be validated, considering that unexpected factors may also influence the results.

Table 1. Framework for evaluating strategies for emissions reduction

Aspects	
Domain targeted by the strategy	Driver / Vehicle / Environment
Difficult of the strategy	Regarding customers / policy measures / technical constraints
Efficiency of the strategy	Emissions reduction potential (on-road/ on-cycle) & extent of the strategy (new fleet/ whole vehicle fleet)
Combination with other strategies	Positive/ negative/ neutral effect

5. Conclusions and further work

This literature review presented strategies related to the reduction of passenger cars use phase emissions. These strategies highlighted elements that should be included in the analysis of strategies for reducing emissions: the domain targeted by the strategy, the difficulty, the efficiency and the potential of combination with other strategies. This framework allows a better understanding of the scope and expected potentials of strategies, including the expected effects over the whole vehicle fleet. The comparison between measures coming from different domains revealed that the technical improvements of vehicles can lead to important reductions, but elaborating sustainable reductions allowing the effective mitigation of the climate change phenomena will require deeper integration between measures from the three DVE domains and the application of measures over the whole vehicle fleet.

Further work should include a deeper study on the effects of integrating measures coming from different domains, using simulations and models accounting for the influences of the driver, vehicle and environment on emissions. These effects should be evaluated at a global level over the OECD vehicle fleet with the elaboration of prospective scenarios which should also include the cost-effectiveness of the strategies combination. Such a general approach generally produces imprecise results and more local cost-benefit analysis could be more pertinent. Further works will then be focused on European Union (EU) countries scenarios, and the potential of the strategies specific to the EU region, such as eco-innovations and emissions standards, will be evaluated.

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