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Reducing CO_2 emissions of conventional fuel cars by vehicle photovoltaic roofs

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ABSTRACT

The European Union has adopted a range of policies aiming at reducing greenhouse gas emissions from road transport, including setting binding targets for tailpipe CO_2 emissions for new light-duty fleets. The legislative framework for implementing such targets allows taking into account the CO_2 savings from innovative technologies that cannot be adequately quantified by the standard test cycle CO_2 measurement. This paper presents a methodology to define the average productivity of vehicle-mounted photovoltaic roofs and to quantify the resulting CO_2 benefits for conventional combustion engine-powered passenger cars in the European Union. The method relies on the analysis of a large dataset of vehicles activity data, i.e. urban driving patterns acquired with GPS systems, combined with an assessment of the shading effect from physical obstacles and indoor parking. The results show that on average the vehicle photovoltaic roof receives 58% of the available solar radiation in real-world conditions, making it possible to reduce CO_2 emissions from passenger cars in a range from 1% to 3%, assuming a storage capacity of 20% of the 12 V battery dedicated to solar energy. This methodology can be applied to other vehicles types, such as light and heavy-duty, as well as to different powertrain configurations, such as hybrid and full electric.

1. Introduction

The European Union (EU-28) is committed to reduce overall greenhouse gas emissions (GHG) by 20% with respect to the 1990 baseline under the Europe 2020 Strategy (EC, 2010) and the Kyoto Protocol's second period (2013–2020). The transport sector is the second biggest source of GHGs in the EU, with road transport being responsible for more than two thirds of the whole transport emissions (European Commission). To address this issue, a range of policies aiming at decreasing the detrimental atmospheric footprint from transport has been adopted by the EU-28 (EC, 2011a). For example, the in-force type approval EU regulation sets binding tailpipe CO_2 emission targets for new passenger car (M1) and light commercial vehicle (N1) fleets (EC, 2009, 2011b). In 2015, newly registered cars were required to emit no more than an average of 130 g of CO_2 per kilometre (gCO_2/km, in-cycle emissions), expressed as fleet average per large-volume car manufacturer. By 2021, phased in from 2020, the objective for all new cars is 95 g of CO_2 per kilometre (in-cycle emissions). Compared with the 2007 fleet average, the 2015 and 2021 targets represent reductions of about 18% and 40% respectively. N1 fleets are similarly regulated, and they are required meeting an average fleet target of 175 gCO_2/km by 2017 and 147 gCO_2/km by 2020.

The technical procedures to assess the CO_2 performance of cars and vans in Europe are twofold (EU, 2014). First, the well-

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Nomenclature

Abbreviations

GPS	global positioning system
GSM	global system for mobile communications

Latin symbols

B	baseline vehicle CO_2 emissions (gCO_2/km)
C	fraction of time when the vehicle is shadowed by the near obstacle (–)
C_{CO_2}	CO_2 savings as eco-innovation (gCO_2/km)
CF	CO_2 conversion factor of the fuel (gCO_2/l)
CO_2	specific carbon dioxide emissions (gCO_2/km)
d_{car}	mean width of the passenger cars (m)
d_{road}	mean width of the streets (m)
E	eco-innovation vehicle CO_2 emissions (gCO_2/km)
h_{car}	mean height of the passenger cars (m)
h_{obs}	mean height of the physical obstacles (m)
M	mean annual mileage (km/h)
mPp	measured peak power output of the PV panel (W)
N	number of EU member states (–)
P	power (W)
pt	duration of a parking event (h)
rc	number of registered passenger cars (–)
rw	real-world driving conditions (–)
sw	shadowed cars (–)
SCC	solar correction coefficient (–)
SI	solar irradiance (W/m^2)
UF	usage factor (–)
V_{Pe}	fuel consumption to energy content ratio (l/kWh)

Greek symbols

Δ	difference (–)
η	efficiency (%)
θ	lengthwise inclination of the PV roof (°)

Subscripts

Alt	alternator
c	circulating, in motion
h	index for the hours of the day
i	index for the EU member states
indoor	indoor parking
MC	modified testing conditions
p	vehicles parked
PV	photovoltaic roof
PVS	photovoltaic system
STC	standard test conditions
TA	type-approval test conditions
urb	urban area

established laboratory test based on a driving cycle (currently the New European Driving Cycle, NEDC) (UNECE, 2013) provides the CO_2 emissions under reference driving conditions. Because of the limitations of the Type 1 test procedure to evaluate the real-world vehicle emission performance (Meyer and Wessely, 2009; Fontaras and Samaras, 2010; Weiss et al., 2011; Fontaras and Dilara, 2012; Sileghem et al., 2014; Martin et al., 2015), additional procedures under the so called eco-innovation scheme (EC, 2011c, 2014) were launched in 2009 to assess the performance of those technologies whose effects cannot be observed or properly quantified while driving the vehicle under laboratory conditions (i.e. off-cycle CO_2 savings). In addition, incentives are given only to technologies with a market penetration of 3% or less in EU newly registered vehicles in the reference year 2009, with the aim of facilitating their introduction and wide-spread penetration into the market. This includes for example technologies that reduce vehicle CO_2 emissions by increasing the efficiency of auxiliary components, by recovering energy that would normally be wasted or by taking advantage of ambient energy sources.

Applications for eco-innovations can be submitted by either vehicle manufacturers or components suppliers. The application must include the necessary evidence that the eligibility criteria set by the in-force normative are fully met, including a proposal of the methodology for measuring the CO_2 savings based on average EU-28 fleet data (EC, 2011c, 2014; Malfettani et al., 2016). The application is then processed, and, if compliant with the requirements, approved with a European Commission Implementing Decision. After this step, it may be used by manufacturers for certifying the CO_2 savings from eco-innovations as part of the type approval process for new vehicles equipped with that specific solution.

The technologies approved so far, concern the improvement of electrical and mechanical components, and the storage and use of thermal, potential and ambient energy. Examples of these technologies are, among others, efficient exterior lighting, efficient alternators, engine heat storage systems and battery charging photovoltaic (PV) roofs. In the latter case, the technology is intended to provide electric energy for charging and sustaining the low-voltage battery of conventional combustion engine-powered vehicles, thus reducing the mechanical load to the engine caused by the alternator. This leads to a lower fuel consumption and hence to a reduction of the CO_2 emissions. To evaluate the CO_2 emission savings, a specific methodology has been developed in the framework of the eco-innovation scheme (EC, 2015, 2016; Noce et al., 2015), which calls for the evaluation of the effective solar radiation to which the vehicle PV roof is exposed in real-world conditions.

There are a few existing studies which discuss the use of PV roofs in passenger cars (Pisanti, 2014; Giannouli and Yianoulis, 2012; Birnie, 2016). Pisanti (Pisanti, 2014) compared a movable PV roof with solar tracking functions with a fixed horizontal one for hybrid electric vehicles. The energetic analysis is limited to the maximum energy produced by the systems on monthly basis for a city in southern Italy considering the available solar irradiance. A solar energy gain in the range of 30–47% is found for the movable PV roof when compared with the fixed one but no absolute values are reported. Giannouli and Yianoulis (2012) determined the energy production potential of an horizontal PV roof installed on a hybrid electric vehicle. Also in this study the solar energy production was based on solar irradiance availability for one location, in this case in Greece. For a $1.2\,m^2$ solar PV roof, solar cells efficiency of 20% and 15 000 km of annual mileage, an annual saving in the range of 100 L gasoline was found. Birnie (2016) studied the competition