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Modeling real-world fuel consumption and carbon dioxide emissions with high resolution for light-duty passenger vehicles in a traffic populated city

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ABSTRACT

Modeling fuel consumption of light-duty passenger vehicles has created substantial concerns due to the uncertainty from real-world operating conditions. Macao is world-renowned for its tourism industry and high population density. An empirical model is developed to estimate real-world fuel consumption and carbon dioxide emissions for gasoline-powered light-duty passenger vehicles in Macao by considering local fleet configuration and operating conditions. Thanks to increasingly stringent fuel consumption limits in vehicle manufacturing countries, estimated type-approval fuel consumption for light-duty passenger vehicles in Macao by model year was reduced from 7.4 L/100 km in 1995 to 5.9 L/100 km in 2012, although a significant upsizing trend has considerably offset potential energy-saving benefit. However, lower driving speed and the air-conditioning usage tend to raise fleet-average fuel consumption and carbon dioxide emission factors, which are estimated to be 10.1 L/100 km and 240 g/km in 2010. Fleet-total fuel consumption and carbon dioxide emissions are modeled through registered vehicle population-based and link-level traffic demand approaches and the results satisfactorily coincide with the historical record of fuel sales in Macao. Temporal and spatial variations in fuel consumption and carbon dioxide emissions from light-duty passenger vehicles further highlight the importance of effective traffic management in congested areas of Macao.

1. Introduction

Recently, the discrepancy between real-world fuel and type-approval fuel consumption (also reported as the road-to-lab gap [1]) for light-duty passenger vehicles (LDPVs) have been identified in Europe [2] and China [3], which is an issue of great concerns regarding transportation energy efficiency. The International Council on Clean Transportation Council indicated that the average road-to-lab discrepancy for European in-use LDPVs rose from less than 10% in 2001 [1] to approximately 40% up to 2015 [2], leading to little to none improvement in real-world fuel consumption since 2010 [1,2]. The discrepancy has highlighted the requirement for more accurate measurement techniques [4]. In addition to overly optimized conditions of the type-approval test procedure [2], traffic congestion and air condition usage may also significantly elevate vehicle fuel consumption [5]. For example, air condition usage may increase fuel consumption for LDPVs by up to 26% [[6]. Similar significant impact of air condition usage on fuel consumption has also been from on urban buses [7]. Therefore, it is essential to model real-world fuel consumption for a traffic populated and tropical city using detailed local data.

This study selects Macao as a case city for modeling real-world

Abbreviations: BAU, business as usual; BEV, battery electric vehicle; CO_2, carbon dioxide; ERP, electronic road pricing; EU, European Union; FES, fuel economy standard; GHG, greenhouse gas; GPS, global positioning system; HEV, hybrid electric vehicle; LDPV, light-duty passenger vehicle; LRT, light rail transit; MLIT, Ministry of Land, Infrastructure, Transport and Tourism of Japan; MY, model year; NEDC, New European Driving Cycle; NO_2, nitrogen dioxide; NOX, nitrogen oxides; PEMS, Portable emission measurement system; VKT, Vehicle kilometres travelled; WTW, well-to-wheel.

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fuel consumption of LDPVs. Macao, one of the two Special Administrative Regions of China, is the most densely populated city in the world approaching 20 thousand people per km^2 by the end of 2013 [8]. Rapid economic development has led to a surge of the total vehicle population in Macao, from 113 thousand in 2000 to 228 thousand in 2013 [8]. In particular, the population of LDPVs (note: passenger capacity except driver not higher than 8 or gross vehicle weight not higher than 3500 kg, excluding taxis in Macao that are powered by diesel), dominated by gasoline-powered cars, has nearly doubled over the past decade (see Fig. S1). The ownership rate of LDPVs in Macao has risen from 111 in 2000 to 160 vehicles per 1000 people in 2013, significantly higher than those of other highly populated cities in Asia (e.g., 60 of Hong Kong and 120 of Singapore) (see Fig. S2) [9]. Therefore, Macao's high density of vehicle population (~8000 vehicles per km^2) has created a series of challenges regarding oil consumption, greenhouse gas (GHG) emissions, air pollution [10] and traffic congestion [11]. For example, high exposure levels of air pollutants have been reported during the traffic congestion in Macao [12].

Unlike the Mainland China where increasingly stringent fuel economy standards (FES) of LDVPs have been implemented since 2005 [13], such FES programs are still not applicable in Macao. Up to now, several studies have examined energy consumption and CO_2 emission of Macao with major objectives to evaluate overall energy consumption and climate impacts at the city level or with a particular focus on the gaming industry [14]. However, as one of the most important vehicle categories, the status quo of real-world fuel consumption and CO_2 emissions of LDPVs in Macao and the in-depth policy implications have not been adequately addressed.

LDPVs registered in Macao are all imported from all over the world, including Japan, European countries, Korea, US and Mainland China. Up to May 2013, more than 99% of LDPVs are powered by gasoline and more than 90% of those gasoline LDPVs are manufactured in Japan and the European Union (EU). Investigating the trends of fuel consumption and CO_2 emissions of LDPVs manufactured in these regions is therefore essential to understand the state for the LDPV fleet in Macao. On the other hand, vehicle size indicated is another key factor influencing fuel consumption of LDPVs [15] and should be corrected to the actual conditions in Macao. Lightweight materials are seen as one of fundamental components of modern energy-saving vehicles [16]. In addition, real-world operating conditions like average speed, passenger occupancy and use of air conditioning have significant impacts on real-world vehicle fuel consumption and CO_2 emissions. For example, in 2010, the average speed of the road network in the Macao Peninsula was only 15 km/h during rush hours and significantly lower than type-approval cycle speeds applied in the world wide [17]. Furthermore, as a tropical city, mean monthly maximum temperature in Macao is 26 °C [8], which would increase the use of air conditioning as compared to temperate regions. Therefore, detailed profiles regarding vehicle specifications and local operating conditions shall be taken into account when evaluating energy performance for LDPVs in a traffic populated city.

This study aims to establish an empirical model based on historical fuel consumption data and studies on real-world corrections to estimate the vehicle-specific and total fuel consumption as well as CO_2 emissions for gasoline LDPVs registered in Macao. First, detailed type-approval fuel consumption data and local vehicle specifications were collected to establish the baseline fuel consumption and CO_2 emissions under the typical driving cycle. Second, the corrections of average speed, loading mass indicated by passenger occupancy and use of air conditioning were derived to estimate the impacts from real world driving conditions. Furthermore, with this model, total fuel consumption and CO_2 emissions for total LDPVs in Macao were estimated to observe the spatial and temporal distribution of fuel consumption and CO_2 emissions and the dynamic association with local traffic.

2. Methods

This section consists of three parts – first, presenting the modeling methodology of fuel consumption and CO_2 emission factors for local gasoline LDPVs in Macao; second, presenting the data input for calculating fuel consumption, CO_2 emissions and real-world operating conditions; and, third, illustrating the method of calculating fuel consumption and CO_2 emissions for the total LDPV fleet and at the link level.

2.1. Modeling methodology of fuel consumption and CO_2 emission factors

The overall calculation methodology of the distance-specific fuel consumption for LDPVs is illustrated in Fig. 1, which can be in general divided into two sections. First, the localized type-approval fuel consumption (L/100 km) is estimated by model year (MY) or for the fleet-average under a baseline cycle (i.e., the New European Driving Cycle, NEDC) that takes effects of local vehicle specifications (e.g., vehicle weight, engine displacement) into account. For example, Eq. (1) and Eq. (2) illustrate the method to account the impact on type-approval fuel consumption from different vehicle size for Macao's LDPVs manufactured in Europe; for Macao's LDPVs manufactured in Japan, Eq. (3) is applied to estimate the impact from local vehicle weight and convert the data to the European type-approval benchmark (i.e., NEDC); Eq. (4) illustrates the method to weight fleet-average fuel consumption under the type-approval conditions based on the detailed fuel consumption data for each model year. Second, the average fuel consumption is corrected to real-world operating conditions including impacts from on-road driving conditions, average speed, loading mass and use of air conditioning. For example, Eq. (5) illustrates the overall method to consider all the major impacts from operation conditions. Later Eq. (6) and Eq. (7) present the detailed corrections for driving conditions and air conditioning usage, respectively. Furthermore, this model is applied to establish the sophisticated inventory of total fleet fuel consumption and CO_2 emissions for LDPVs in Macao with detailed vehicle registrations or traffic demand as input data. CO_2 emissions can be estimated based on the carbon balance method, illustrated as Eq. (8).

$$FC_{TA\ \mathrm{r,y}} = FC_{TA\ original\ \ \mathrm{r,y}} \cdot C_{size\ \mathrm{r,\ y}} \tag{1}$$

where $FC_{TA\ \mathrm{r,\ y}}$ is the localized type-approval fuel consumption of Macao's LDPVs manufactured in region r and year y, L/100 km; $FC_{TA\ original\ \mathrm{r,\ y}}$ is the average type-approval fuel consumption of total gasoline LDPVs in region r and year y, L/100 km, which is released by official authorities of vehicle export regions; $C_{size\ \mathrm{r,\ y}}$ is the correction factor of vehicle size for Macao's LDPVs from region r and manufactured in year y.

To estimate localized type-approval fuel consumption, the NEDC is chosen as the baseline cycle for LDPVs in Macao. Although the average speed of the urban section of the NEDC (e.g., the urban driving cycle, UDC, has an average speed of 18.4 km/h) is more close to the congestion level in Macao, however, the entire NEDC is still applied as the baseline due to the following considerations. A major reason for using the entire NEDC lies in that we have reliable cycle convention factors from the JC08/10–15 cycles to the entire NEDC (see section 2.2). Considering the landscape of LDPVs' import in Macao (i.e., more than 90% of LDPVs are imported from EU and Japan), we collected type-approval fuel consumption data from EU and Japan by model year and corrected to local vehicle