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Carbon dioxide emissions of plug-in hybrid electric vehicles: A life-cycle analysis in eight Canadian cities

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A R T I C L E I N F O

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A B S T R A C T

Plug-in hybrid electric vehicles (PHEVs) have the potential to decrease greenhouse gas emissions given certain power generation profiles. The adoption of PHEVs is associated with significant social, economic, environmental, and health benefits. However, most researchers in literature generally estimate emissions using national averages of emission data. The purpose of this paper is to address this gap. Specifically, we estimated CO_2 emissions of PHEVs using a life-cycle analysis in 8 Canadian cities (Vancouver, St John's, Charlottetown, Halifax, Montreal, Toronto, Regina, and Calgary). We found that across Canada the varying electricity generation profiles affected the potential reduction benefit in life-cycle CO_2 emissions. For example, 95% of the energy in the province of Alberta was generated from fossil fuels, which emited a high amount of GHGs. Consequently, Calgary (city located in Alberta) had the highest CO_2 life-cycle emissions for PHEVs, where electricity generation accounted for 61% of the total emissions. Conversely, the provinces of British Columbia (BC) and Quebec (QC) used 86% and 98% clean energy, respectively. The cities evaluated in our analysis that are located in these provinces (i.e., Vancouver, BC and Montreal, QC) presented the lowest CO_2 emissions from electricity generation with less than 4% of the total PHEV emissions. Our study provides insight for policy makers about direct investment in EV incentives across Canada and where these incentives could be focused. Our study results reiterated that to reduce CO_2 emissions considerably, promotion of PHEVs should be integrated with renewable electricity generation options.

1. Introduction

Governments, consumers and businesses have demonstrated concern with vehicular mobility based only on the internal combustion engine [1,2]. Traffic-related emissions is the primary concern associated with internal combustion engine vehicles [3–6]. Globally, emissions from traffic in urban areas accounts for 30% of nitrogen oxides (NO_x), 54% of carbon oxide (CO), 47% of non-methane hydrocarbons (NMHC), and 14% of carbon dioxide (CO_2) [7]. Traffic emissions impact human health including hospital admissions and premature deaths [8–11]. Jacobson (2008) [12] showed that gasoline and ethanol combustion is expected to cause at least 10,000 premature deaths in the United States in 2020. These implications suggest that the current prevailing transportation paradigm premised on the internal combustion engine is not sustainable.

Plug-in hybrid electrical vehicles -PHEVs (vehicle-powered by either gasoline or electricity) present themselves as an option that can transform the global transportation sector by providing sustainable mobility, improving energy security, and reducing greenhouse gases (GHG) and other air pollutant emissions. Consumers, business, and governments have been adopting this transformation, with several million PHEVs sold around the world in the last decade [13]. In 2009, the U.S. invested millions dollars to promote PHEVs [14]. The United States has 38% of the global Electric Vehicles (EVs) stock, with 474,000 PHEVs [15]. In China, the annual sales of plug-in cars increased from 5579 to 45,048 between 2011 and 2014 [16]. The sales of PHEVs in Europe is led by Norway with 105,000 vehicles registered in 2016 [17]. In Canada, approximately 2000 PHEVs were sold in 2012. It is predicted an average sale of 107,000 PHEVs per year between 2015 and 2020 [13]. The National Energy Board of Canada projects about 700,000 PHEVs to be in operation by 2035 in Canada [18].

Numerous studies have shown that, depending on power generation sources, the adoption of PHEVs provides significant social, economic, environmental and health benefits [19–24]. For example,

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according to the International Energy Agency (2013) [15], PHEVs can achieve 50 g of CO_2 per kilometer with a moderately clean electric grid, while the most efficient cars emit between 100 and 150 g of CO_2 per kilometer. Faria et al. [25] showed that for the present power generation profile in the European Union (EU), the emissions reduction impact from PHEVs is substantial. In the EU, conventional vehicles (gasoline combustion) emit approximately 2.58 MT CO_2/year, while a scenario with PHEVs is estimated to generate only 0.46 MT CO_2/year. In Texas, USA, gasoline-powered passenger cars have CO_2 emissions rates of 244 CO_2eq (g/km), whereas PHEVs could achieve 130 CO_2eq (g/km) considering a scenario with 25% increase in renewable energy [26]. The CO_2 emissions externalities from passenger cars (gasoline) in Texas is $94.49, and considering the PHEVs scenarios the emissions externalities would be reduced to $67.20 [26]. In China, EVs can reduce CO_2 emissions by 20% and are expected to have lower CO2 emission level than conventional vehicles [27].

Apart from CO_2 emissions during the life of the vehicle, studies have shown that EVs have higher emissions during vehicle manufacturing. The production of EV generates 10 t of CO_2, while the production of conventional vehicles results in 6 t [28,29]. However, Jochem et al. [30] showed that if EVs use clean electricity during their whole lifetime, it can compensate for the higher emissions during their production stage.

Prior research in literature generally estimates emissions using national average data which may have large uncertainty and lower levels of precision [27]. National averages have been found to underestimate or overestimate by approximately 120% [31]. Jochem et al. [30] recommend the use of consistent methodologies to address important aspects affecting CO_2 emissions by EVs since different assessment methods lead to significant differences in CO_2 emissions. In this paper, we estimated CO_2 emissions of PHEVs using a life-cycle analysis in 8 Canadian cities. We focused on the provincial and city level to overcome the potential bias in CO_2 emissions estimates, due to the ecological inference fallacy, that can occur when national adoption rates are applied across all sub-national regions. Within Canadian Provinces there is great variability in housing density, which results in different types of vehicles and driving patterns. We also examined the CO_2 emissions of PHEVs according to the power generation sources of profile in our study area and compared them to those from similar studies in the literature.

Our study provides guidance to public policymakers when making decisions about clean technologies. We focused on CO_2 traffic emissions because CO_2 is the most important GHG. In Canada, CO_2 emissions increased by 20% during the period 1990–2014, which was largely due to oil, gas and transportation sectors. In 2014, the transportation sector accounted for 23% (171 mega tonnes) of total CO_2 emission in Canada and was the second largest source of CO_2 [32]. GHG emissions are associated with indirect human health effects; however, some studies have suggested a causal link with mortality. Jacobson (2008) [12] showed that CO_2 emissions in U.S. may increase annual air pollution deaths by about 1000 per 1 K rise in CO_2-induced temperature.

2. Materials and methods

We examined 8 Canadian cities, which included Vancouver, St John's, Charlottetown, Halifax, Montreal, Toronto, Regina, and Calgary (Fig. 1). These cities were defined based on the locations available in the model used in this study.

We estimated CO_2 emissions with the PHEV-Charge Impact model (PEV-CIM) developed by Natural Resources Canada under the electric mobility program [33]. The model was developed to simulate the impact of PHEVs on the electricity grid and on emissions in Canada. PEV-CIM has four modes of operation, which include the grid impact mode, fleet comparison mode, emissions mode, and vehicle-to-grid mode. We used the emissions mode in our analysis, which identifies the emission reduction potential of PHEVs.

PEV-CIM uses standard vehicle performance data (liters/100 km) from Fuel Economy Data (www.fueleconomy.gov) and the Natural Resources Canada Office of Energy Efficiency (www.nrcan.gc.ca/energy/efficiency/transportation) to calculate emissions based upon a fixed emissions amount per liter of fuel used. The upstream full fuel cycle emissions were taken from GHGenius (www.ghgenius.ca), also in the form of a fixed amount per liter consumed. The GHGenius model has been developed for Natural Resources Canada. This model estimates emissions from power generation plus feedstock recovery, feedstock production, feedstock transportation, fuel production, fuel distribution and storage, and fuel used by vehicles.

For electric drive, PEV-CIM uses a similar approach, using average emission data for power production per province per kWh, potentially adding transmission and distribution losses. Upstream emissions are calculated using fixed emission factors per primary energy source (coal, natural gas, oil, hydro, nuclear, etc.) and weighing factors for the use of each source. Therefore, PEV-CIM accesses local databases from 8 Canadian cities (the same cities from our analysis), and allows users to specify their own inputs. Table 1 shows the parameters that we defined as input data.

We performed two steps to collect data on conventional vehicles fleet. First, we estimated the average of fuel consumption (Litre/100 km) for 10 vehicle classes: two-seater, subcompact, compact,

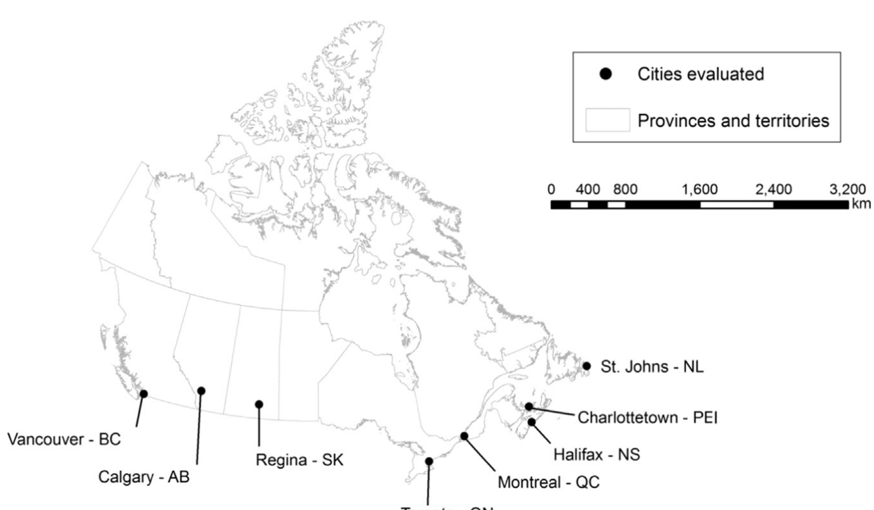

Fig. 1. Study area. Notes: British Columbia (BC); Alberta (AB); Saskatchewan (SK); Ontario (ON); Quebec (QC); Nova Scotia (NS); Prince Edward Island (PEI); Newfoundland and Labrador (NL).