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Can UK passenger vehicles be designed to meet 2020 emissions targets? A novel methodology to forecast fuel consumption with uncertainty analysis ☆

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HIGHLIGHTS

- This paper introduces a Bayesian methodology to quantify new car fuel consumption.
- Model presents user with more realistic, on-road, fuel consumption estimates.
- Sources of NEDC uncertainty attributed to imprecise assumptions for resistances.
- Fuel consumption of average UK car projected to exceed 2020 emissions standards.

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ABSTRACT

Vehicle manufacturers are required to reduce their European sales-weighted emissions to 95 g CO_2/km by 2020, with the aim of reducing on-road fleet fuel consumption. Nevertheless, current fuel consumption models are not suited for the European market and are unable to account for uncertainties when used to forecast passenger vehicle energy-use. Therefore, a new methodology is detailed herein to quantify new car fleet fuel consumption based on vehicle design metrics. The New European Driving Cycle (NEDC) is shown to underestimate on-road fuel consumption in Spark (SI) and Compression Ignition (CI) vehicles by an average of 16% and 13%, respectively. A Bayesian fuel consumption model attributes these discrepancies to differences in rolling, frictional and aerodynamic resistances. Using projected inputs for engine size, vehicle mass, and compression ratio, the likely average 2020 on-road fuel consumption was estimated to be 7.6 L/100 km for SI and 6.4 L/100 km for CI vehicles. These compared to NEDC based estimates of 5.34 L/100 km (SI) and 4.28 L/100 km (CI), both of which exceeded mandatory 2020 fuel equivalent emissions standards by 30.2% and 18.9%, respectively. The results highlight the need for more stringent technological developments for manufacturers to ensure adherence to targets, and the requirements for more accurate measurement techniques that account for discrepancies between standardised and on-road fuel consumption.

1. Introduction

The UK government is required to achieve an 80% reduction in national emissions by 2050, of which passenger vehicles contributed to 12.5% (73.3 $MtCO_{2\text{-eq}}$) in 2010 [1,2]. A sales weighted emission target was correspondingly imposed on vehicle manufacturers for 95 g CO_2/km by 2020 [3], all of which helped passenger vehicle emissions to decline by 22% between 2007 and 2013 [4]. These reductions have been largely achieved with modifications to internal combustion engine (ICE) vehicles [4], though our capacity rely on such design improvements for additional emissions reductions is largely uncertainty. Since no model is available to relate individual vehicle design changes to likely 'on-road' fleet fuel consumption, we are limited in about abilities to assess manufacturer's efforts to reduce emissions.

A particular source of ambiguity stems from the New European Driving Cycle (NEDC) [5], which is estimated to under-represent

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Nomenclature

Acronym	Definition
NEDC	New European Driving Cycle
SI	Spark ignition
CI	Compression Ignition
CARma	Cambridge Automotive Research Modelling Application
ICE	internal combustion engine
NEDC-M	New European Driving Cycle model
OR-M	on-road model
θ	CARma model parameter
β	CARma model variable
imep	indicated mean effective pressure
bmep	break mean effective pressure
fmep	frictional mean effective pressure
Wi	total indicated work
V_d	engine size
$\dot{m}_f$	fuel mass flow rate
Q_{LCV}	lower calorific value
$\eta_{f,i}$	engine efficiency
W_b	normalized break work
P_b	break power
N	engine speed
n_R	number of crank revolutions for each power stroke per cylinder
r_c	compression ratio
A	coefficient distinguishing between idealised constant-volume and constant-pressure thermodynamic process
γ	heat capacity coefficient of idealised constant- volume and constant-pressure thermodynamic processes
Sr_c	simplified compression ratio
M_v	vehicle mass
C_R	coefficient of rolling resistance
S_v	vehicle speed
ρ	air density
C_D	coefficient of drag
A_v	vehicle frontal area
kg	kilograms
cc	cubic centimetres
rpm	revolutions per minute
g	acceleration due to gravity
VIF	variance information factors
R^2	coefficient of determination
$p(\theta\|D)$	Bayesian posterior distribution
$p(D\|\theta)$	Bayesian likelihood function
$p(\theta)$	Bayesian prior distribution
SD	standard deviation
WHLV	Worldwide Harmonized Light Vehicles

on-road passenger vehicle fuel consumption by approximately 20–25% [6]. Considering that the NEDC test is used to determine manufacturers' adherence to legislative standards, this failure has particular repercussions for the 2020 emissions targets that equate to fuel consumption ratings of approximately 4.1 L/100 km for Spark-Ignition (SI) vehicles and 3.6 L/100 km for Compression-Ignition (CI) [7]. Such NEDC testing discrepancies could allow for significant variations of up to 1.0 L/100 km (SI) and 0.9 L/100 km (CI) from real world fuel consumption, which must be considered when modelling manufacturer's adherence to fuel consumption targets.

This paper addresses two limitations of available top-down deterministic models that are used to quantify national transport energy consumption [8–10]. Firstly, the single point (i.e. deterministic) outputs from these models can be misleading to both academics and regulators, where underlying model structures and input variables are themselves subject to uncertainty. Secondly, current models are not designed to account for detailed vehicle design changes, as aggregate fuel consumption values are used to estimate annual fleet-wide energy demands. These limitations collectively hinder our ability to assess the influence of new national passenger vehicle policies and design changed on national fuel consumption. Recognising this, a new Bayesian methodology is presented in this paper, called the Cambridge Automotive Research Modelling Application (CARma), to estimate likely SI and CI fuel consumption of UK passenger vehicles from their inductive design inputs (i.e. vehicle mass, engine size and compression ratio). CARma is consequently designed to represent both NEDC and real-world driving cycles in its results, and is characterised by the following unique features:

(1) *Hybrid Model Derivation* – CARma is formulated from both engineering and statistical principals that relate fuel consumption to vehicle fleet properties (engine size, compression ratio, vehicle mass and engine speeds).
(2) *Prior Uncertainty Quantification* – Sources of uncertainty are categorised, and mitigation methods proposed. NEDC fuel consumption data is used to estimate uncertainties in the coefficients for the rolling resistance, aerodynamic drag, frictional powertrain loss and annual design improvements. These estimates are subsequently calibrated with open-source on-road fuel consumption data.
(3) *Bayesian Model* – A Bayesian methodology is introduced to calibrate uncertain parameters, ensuring that combined information from NEDC and on-road datasets are incorporated into CARma's outputs. Results are presented as probability distribution functions.
(4) *On-Road Fuel Consumption Estimation* – Stochastic passenger vehicle fuel consumption is estimated using both NEDC and real world data, allowing fleet-wide energy consumption to be uniquely linked with inductive vehicle design variables.

Having developed the CARma methodology, the model was used to quantify the likelihood of the average SI and CI vehicle, made available for sale in the UK, achieving its 2020 fuel consumption target (Section 4.4). Modelling uncertainties are similarly discussed in Section 4.2, before evolutionary projections for SI and CI vehicle mass, engine size and compression ratios are outlined in Section 4.3.

2. Background

2.1. Political context

Environmentally sustainable growth is a cornerstone for the current UK government [11], though decarbonisation of the transport fleet is particularly difficult to achieve [12–14]. The King Review's recommendations on environmentally sustainable transport policies dismissed the existence of a single technology to reduce passenger vehicle emissions, though an emphasis on ICE vehicle development was recommend for near-term reductions [15,16]. Policies effecting UK transport emissions have henceforth avoided the promotion of one particular method to reduce passenger vehicle energy demands [17], instead choosing technological options that assume society's preferences will not change [18]. This landscape has defined how vehicle manufacturers primarily relied on ICE efficiency improvements to reduce new car emissions

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