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The gap between certified and real-world passenger vehicle fuel consumption in China measured using a mobile phone application data

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ABSTRACT

The gap between certified and real-world passenger vehicle emissions is widening and has driven vehicle policy transitions in the US and in Europe, particularly in the wake of emissions measurement scandals. Since carbon dioxide emissions are highly correlated with fuel consumption (FC), fuel consumption regulation is a useful policy instrument to combat climate change. Although the Chinese government set fuel economy standards in 2004, like many countries it does not conduct testing to confirm real-world FC rates comply with the standards. This paper employs a dataset of real-world FC measurements self-reported by over 1 million vehicle owners in China between 2008 and 2017 through a dedicated mobile phone application. By comparing this user-generated FC data with FC certification, the study provides an indication of discrepancies of FC gap and its characteristics, including: vehicle model year, transmission type, segment, weight bin, and market share. The study finds that while average certified FC decreased by 15% between 2008 and 2017, real-world FC remained unchanged, resulting in FC gap increase from 12% to 30%. The paper concludes that use of a local test-cycle, authoritative data collection, and stronger enforcement, may be useful policy tools for reducing China's real-world vehicle energy consumption.

1. Introduction

The transportation sector consumes nearly one-fifth of global fossil fuels annually and is growing rapidly, impeding global sustainability goals (Yamamoto and Ma, 2016; IRENA, 2013). The largest global increase in carbon emissions from the transportation sector in 2017, which, on average, account for one- quarter of total carbon emissions, was in China (International Energy Agency (IEA), 2018). While the measurement and capturing of carbon emissions post-combustion has proven useful in flue gases at power plants or other large point sources (Wang et al., 2010), particularly using chemical absorption that can be easily retrofitted into existing systems (Zhang et al., 2018a, 2018b), this approached was deemed inefficient for small and dispersed automobiles. Instead, reducing fuel consumed per distance traveled (fuel economy) has been a dominating method for removing tailpipe CO_2 emissions from passenger cars (He et al., 2005). Approaches for achieving fuel efficiency include the introduction of advanced engines, transmissions, thermal management, and off-cycle technologies (Xiao et al., 2018).

Real-world vehicle emissions and fuel consumption (FC) have previously been compared with certification values using a small sample of vehicles (Tong and Hung, 2016; Kudoh et al., 2007a, 2007b; Vasic and Weilenmann, 2006; Samuel et al., 2002; Pierson et al., 1996; Schipper et al., 1993). The gap between certified and real-world passenger vehicle emissions appears to be growing from 9% in 2001 to 42% in 2016 in the EU, for example (Tietge et al., 2017). The increase in gap is therefore driving vehicle policy transitions in the US and in Europe, particularly following recent high-profile emissions measurement scandals (Tietga et al., 2016; Vicente and Mock, 2015).

With China's sustained and rapid development, passenger vehicle ownership grew from 100 million in 2012 to over 217 million in 2017 (Ministry of Public Security, 2018). Not surprisingly, China's dependence on foreign oil, as opposed to domestic oil resources, rose to a record high of 67.4% during 2017 (CNPC, 2018), posing a threat to China's energy security. Road traffic emissions grew by 45% over the past 20 years, accounting for 17% of China's CO_2 emissions in 2015 (Cai, 2016). Understandably, China's transport emissions have become a focus of national carbon emissions mitigation efforts. In an attempt to

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curb oil consumption, promote the local auto industry, and mitigate emissions, China is gradually increasing the stringency of its national passenger FC standards (National Development and Reform Commission, 2015; Oliver et al., 2009; Wang et al., 2010). However, several attempts to evaluate China's fuel economy policy indicate policy inefficiencies (Huo et al., 2011; Zhang et al., 2014; Hu et al., 2012).

This paper assesses the gap between certified (type-approval test-based) and real-world FC rates in China. The research is based on the official certified FC data made available by the governing authority, China's Ministry of Industry and Information Technology (MIIT), and voluntary real-world FC data provided by car owners across China through an independent mobile application (BearOil). Since its creation in 2008, over 1 million car owners have downloaded the BearOil app in 31 provinces in China. This paper makes use of data from over 17,000 vehicle models, 20 billion kilometers driven, and over 45 million individual records.

The paper will first review China's FC policy and related research background (Section 2), describe certified FC data (Section 3.1) and the real-world FC data employed here including details about its collection, cleaning, and representativeness (Section 3.2). Section 4 presents and discusses research results, including overall FC gap trends (Section 4.1), FC gap variation by transmission type (Section 4.2), FC gap by vehicle segment (Section 4.3), FC gap differences by weight bin according to policy requirements (Section 4.4), and FC gaps of best-selling models (Section 4.5). Finally, Section 5 summarizes the findings of the research and provides an outlook on future progress.

2. Background

China initiated its vehicle FC standards and policy research in 2001. In 2004, the State Committee for Standardization and the State Administration of Quality Supervision Inspection and Quarantine (AQSIC) jointly issued China's "light vehicle fuel consumption test method" (Standard title: GB/T19233-2003). The standard that came into effect in November 2004 uses the EC European Union test cycle (2004/EC/3). During the same year, the implementation of China's first mandatory passenger car FC limits (Standard title: GB 19578–2004) began. The FC limits increases with vehicle curb-weight in a steps-based format. Since then, passenger car FC standards have been tightened over four phases, as depicted in Fig. 1. During the implementation of the third phase of the standards, certified average FC of new passenger cars declined from 7.77 L/100 km in 2009 to 7.22 L/100 km in 2015 (Kang et al., 2016). The fourth phase of the standard was approved in December 2014 and became effective in January 2016 (GB 19578–2014, GB 27999–2014), targeting a national average certified FC of 5.0 L/100 km by 2020 (which translates to 120 g/km carbon emissions).

Zhu et al. (2017) stipulated that "the limited understanding of vehicular emissions in China … is one obstacle to establishing tighter standards" (p. 305). An increasing number of studies seek to calibrate the linkage between FC and carbon emissions. They do so by assessing what emission factors (EFs) enable reliable passenger vehicle carbon emission evaluation (Li et al., 2017). Five methods for calculating CO_2 emission factors from passenger vehicles have been employed in the literature and in practice: engine dynamometer and bench test, tracing measurement, on-board emissions measurement, tunnel tests, and remote sensing. Each of these methods has its pros and cons, and since all are sample size test based, they can at best provide estimations based on which conformity tests could be conducted or EFs could be established. Only some of these methods have been employed for the case of China research in the literature, at least (Li et al., 2013; He et al., 2008; Guo et al., 2007; Wang et al., 2008). More recently, the Real Driving Emissions (RDE) test that uses portable emissions measurement system (PEMS) have been regulated in the EU and soon will be employed in China's emissions standards (China 6, entering force in 2020), yet not deemed effective in FC evaluations. Problems remain, however, such as traffic characteristics and driving behavior (for example, breaks slamming, open windows at speed above 60kmh, idling, time gap between engine start and acceleration) temporally and spatially within China and its evolving urban spaces, effecting actual carbon emissions (Li et al., 2017).

Nevertheless, China started reporting the certified FC rate of some models in 2006. However, the certified FC of many models remains unreported (Huo et al., 2011; Wagner et al., 2009). The requirement for China's certified FC labels were introduced in 2010 and revised in May 2017 (GB 22757.1/2–2017). A study conducted in 16 cities across China surveying car buyers at 114 dealerships during 2012 found that 93% of car purchasers were concerned with their vehicle's FC levels but lacked confidence in the accuracy of the official FC reporting system (Kang et al., 2012). Although accurate FC reporting is necessary to

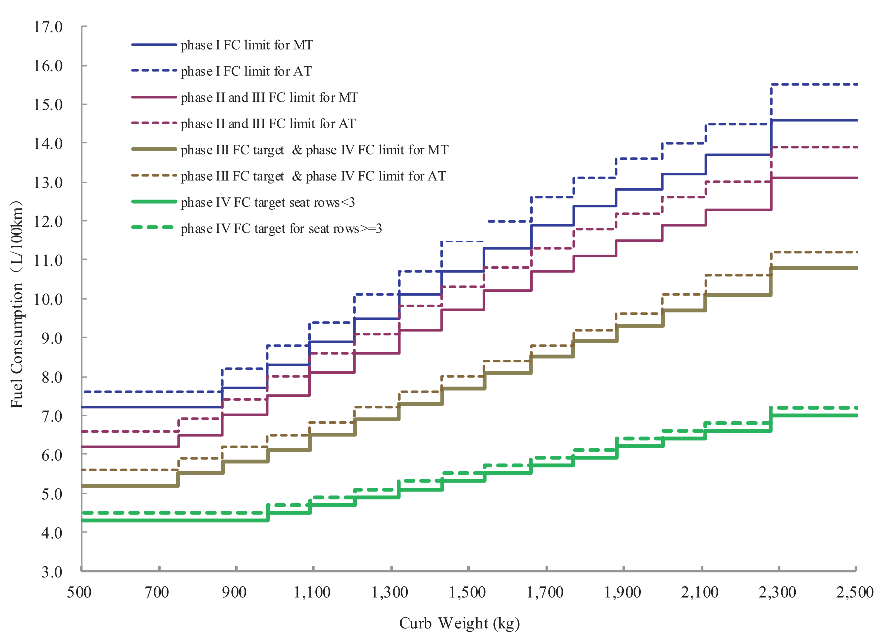

Fig. 1. The four phases of China's passenger vehicle fuel consumption standard.
Source: Kang et al. (2017)

provide consumers with accurate information, China has not yet addressed the issue of FC reporting accountability (Qin et al., 2016), and evidence of the discrepancy between certified and actual FC is based on unofficial studies (Huo et al., 2011; Zhang et al., 2014; Hu et al., 2012).

In their analysis of sales-weighted average real-world and certified FC in 2009, Huo et al. (2011) reveal a gap of 15.5% based on the driver's self-reported FC via a web portal for 153 car models (between 150 and 2000 observations per model). Hu et al. (2012) measured on-road emissions, including carbon emissions, from 16 passenger cars in Macao using a portable emissions measurement system (PEMS) and calculated the FC rates finding that the FC varied depending on differences in measured speed profiles. Zheng et al. (2014) used a portable emissions measurement system to investigate a set of real-world emissions from 16 diesel taxis driving on different roads in Macao, indicating some level of discrepancy in real-world FC rates for certified values. All of these studies conclude that in order to meet the regulatory objectives, FC standards need to be more accurate and better enforced, using measurements reflecting real-world FC values based on additional research.

3. Data

This study analyzes the gap between real-world and certified FC values across vehicle types and locations in China. The study compares average FC values from two distinct data sources: (i) test-based certified FC values, and (ii) self reported, in-use or “real-world” FC data provided by the BearOil app. The former is made official once posted on the Ministry of Industry and Information Technology (MIIT) fuel-economy website (MIIT, 2017). It is mandated since 2010, that FC information is displayed on the front window of the car at the time of purchase in accordance with the “China light-duty vehicle fuel consumption label regulation” (GB 22757–2008). The latter is calculated by a smart phone app based on a user's self-reported volume of fuel purchased at each current and previous refueling. In order to enhance the research's representation of passenger vehicles, vehicles were limited to model years (MY) 2008–2017 and category M1, which covers passenger cars, minivans, and sports utility vehicles with fewer than nine seats and weighing up to 3500 kg.

3.1. Reported FC data

The vehicle type-approval test conducted in China is in accordance with the FC standard's testing procedures specified in the "light vehicle fuel consumption test method" (GB/T 19233-2008) and is performed by one of eight certified testing sites in China (China Vehicle Technology Service Center, 2009). FC test results are submitted to MIIT by the vehicle manufacturer. The test simulates urban and suburban driving conditions designed to be representative of typical driving conditions. Carbon dioxide (CO_2), nitric oxide (NO), and hydrocarbon (HC) emissions as well as FC are measured by the authorized test site (GB/T 19233–2008). The test cycle FC value for each vehicle model is required on the standard label, shown in Fig. 2, placed on the front window of all new vehicles when offered for sale. The label was revised in May 2007 to highlight urban cycle FC values and to compare the composite FC value (weighted by 37% of the urban and 63% of the suburban FC rates) with the average FC value of all new passenger vehicles in that model year.

China's standards regime adopted the New European Driving Conditions (NEDC), a test cycle which was developed based on a typical driving cycle in Europe over twenty years ago; the characteristics of the cycle are listed in Table 1. Studies suggest the European test cycle does not accurately represent driving conditions in China, primarily due to varying urban layout, road conditions, and driving behaviors that greatly impact speed and acceleration, which are key factors influencing FC rates (Wang et al., 2008).

Table 2 shows the flexibilities in driving conditions allowed by the current testing procedures. Furthermore, all M1 vehicles with similar curb weight and components produced by the same manufacturer are authorized to use the similar FC values, if some conditions are met (specified in standard titled: GB/T 19233–2008). These flexibilities offered in the regulation can translate to gaps between certified and real-world FC. Nevertheless, the test-cycle structure was contested to derive the majority of FC deficiencies.

3.2. Real-world FC data

3.2.1. Data generation

Real-world FC data employed by the authors was generated by the BearOil app, an independent mobile application aimed at assessing real-world fuel costs since 2008. The dataset includes over 45 million FC records inputted by 1,167,915 car owners from 31 cities and provinces in China. Users voluntarily reported the amount of fuel they purchased, the expense, and the odometer reading each time they refueled. The dataset provides real-world FC values for over 17,000 models and 200 brands for model years 2008–2017. The BearOil app user can compare their own vehicle real-world FC performance with the average real-world FC values of users that drive the same vehicle model, or any other vehicle model that has the same engine displacement. Since each driver's real-world FC is dependent on their unique driving conditions, including anthropogenic (e.g. vehicle maintenance and load, driving styles) and external factors (e.g. weather, topography, congestion), the app enables simple comparisons between FC scores of the same model or engine displacement in specific locations in China that share similar external factors.

Initially, the app user is required to manually record the vehicle's odometer reading and the fuel expenditure for filling up a full tank. In second and subsequent uses, the user is requested to simply record the current odometer reading and the total fuel purchase price. The app uses stored data to calculate the user's FC since the previous refueling, based on the difference in odometer readings and the recorded fuel expenditure divided by the fixed local fuel price. For example, a user has recorded an odometer reading of 4236 km and a total fuel cost of RMB298.4 when filling their gas tank on day X. On day Y when the fuel tank alarm light comes on, the user fills their tank and again records the odometer reading (now 5041 km) and total fuel cost (RMB398.4). The app calculates the distance between refueling (5041–4236 = 805 km), estimates the volume of gas purchased based on the average daily price per liter in China per location (RMB398.4/RMB6.64 per gallon = 60 l), and calculates the real-world FC of the vehicle since the last refueling (60 L/(805 km/100) = 7.45 L per 100 km).

3.2.2. Data cleaning

Potential errors in the BearOil data set are primarily due to, (i) errors made by the user when entering the odometer and fuel expense values. Additionally, the data may be biased for other reasons including, (ii) limited usage period resulting in estimated real-world FC that is not representative of typical driving conditions (e.g. only weekend driving, or only during a certain season); (iii) user did not provide complete vehicle specifications which prevents comparison with certification FC; and (iv) small sample sizes for certain vehicle models, making the averages for that model not representative of all drivers of that model. In order to reduce possible errors, a detailed data cleaning process was formed and executed, as described in detailed in Table 3. Ninety-two percent of the original dataset data met the above requirements and comprised the post-cleaning sample employed in this study.

3.2.3. Data representation

By comparing the dataset by-vehicle model distribution with that of China's vehicle sales for 2017, as shown in Fig. 3, it is indicated that the dataset closely represents China's current car sales.

Fig. 2. China's Internal combustion vehicle fuel consumption Label: GB 22757–2008 (left), GB 22757.1–2017 (right).
Source: iCET (2017)

Table 1
China's type-approval test cycle procedure.

Test specifications	Suburban	Urban	Combine	% of total test time
Idling (s)	40	240	280	24%
Clutch disengagement (s)	10	36	46	4%
Shift (s)	6	32	38	3%
Acceleration (s)	103	144	247	21%
Cruise (s)	209	228	437	37%
Brake (s)	32	100	132	11%
Max. speed (km/h)	120	50	N/A	N/A
Average speed (km/h)	62.6	19	33.8	N/A
Max. acceleration (m/s^2)	3.7	3.0	3.2	N/A
Average Acceleration (m/s^2)	1.4	2.7	2.2	N/A

Table 2
China's type approval driving conditions requirements include flexibilities that may increase the gap between real-world and reported FC.

Type of test	Chassis dynamometer in laboratory
Test cycle	NEDC test cycle
Max. speed	120 km/h
Max. acceleration	3.7 m/s^2
Idling	24%
Vehicle weight	Curb weight + 100 kg
Temperature	20–30 °C
Tested vehicle's driving distance	3000–15000 km
State of charge starter battery	Fully charged battery
Air conditioning	Off
Tires pressure	Following suggested tires pressure provided by manufacturer
Transmission shift schedule	Following the test regulation

4. Results and discussion

This section presents the results from several analyses of the FC gap over time, by transmission type, vehicle segment, regulatory weight group, and best-selling models. To properly compare the gap by vehicle make or model, driving conditions must be accounted for. This type of analysis is not available with this dataset. When years are specified in the analyses results (figures and tables), these refer to model years. For each analysis, an average of FC inputs made until 2017 (inclusive) is considered. The gap between certified and real-world FC is calculated as follows:

$$\text{FC gap} = (\text{Real-world FC} - \text{Certification FC})/\text{Certification FC} \times 100\% \quad (1)$$

4.1. China's certified versus real-world FC trend

Between model years 2008 and 2017, nationwide production-weighted average certified FC values decreased from 7.99 L/100 km to 6.77 L/100 km, or by 15%. However, during this period the average real-world FC rate by model year in the data sample remained unchanged during this nine-year period, while average real-world FC fluctuated from year to year. Shown in Fig. 4, the gap between real-world and national average certified FC increased from 0.58 L/100 km in model year 2008–1.8 L/100 km in model year 2017, or from 7% to 21%. This increase in the FC gap in China follows a similar direction of that observed in Europe (an increase from 9% to 42% between model years 2001 and 2016) (Tietga et al., 2015, 2017).

4.2. FC gap by transmission type

The majority of vehicles sold in China in recent years have automatic transmissions (AT) rather than manual transmission (MT). The market share of AT vehicles has steadily increased since model year 2012, accounting for 60% of vehicles sold in 2015 (China Automotive Technology and Research Center CATARC, 2016), as illustrated in

Table 3
Data cleansing process.

Step	Cleansing description	Possible errors addressed
a.	Must include at least three data inputs from each user	(i) Manual odometer and fuel expense values insertion;
b.	Exclusion of vehicle models with average real-world FC higher than the standard deviation of the average FC of all models. Each model receives a real-world mean FC value that is calculated based on app user inputs, as follows: (1) $M = \frac{x_1 + x_2 + x_3 + \ldots + x_n}{n}$ Where, x_n is the FC score of an individual app user, n is the number of app users inserting information for a particular vehicle model, M is the model's mean real-world FC value. A mean variance is used for deciding whether or not the average figure is effective: (2) $S^2 = \frac{(x_1 - M)^2 + (x_2 - M)^2 + (x_3 - M)^2 + \ldots + (x_n - M)}{n}$ Where, M is the model average FC data, x_n is the FC score of an individual app user, n is the number of app users for a certain vehicle model, s^2 is average variance. In order to prevent bias, this study only uses real-world FC data that is within the standard deviations: $M\text{-}2s^2 < \text{data} < M + 2s^2$	(ii) Limited usage period.
c.	Removal of user data with incomplete model information (for example, missing information on transmission type or calculated FC data).	(i) incomplete vehicle specifications
d.	Models that have less than 20 valid user-data samples are excluded	(i) small sample sizes for certain vehicle models.

Note: The data cleansing process was established based on the number of records by user and by vehicle model.

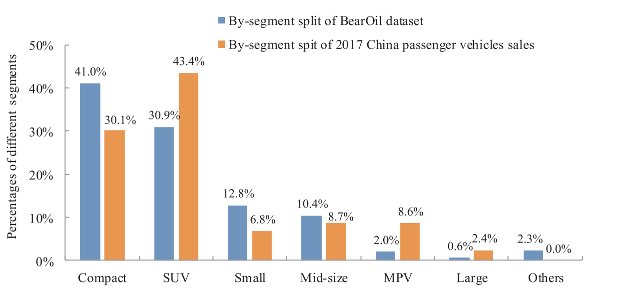

Fig. 3. Comparison of segmentation split of dataset and China's 2017 sales. **Note:** Mini cars (A00-type) are included within the small vehicle segment.

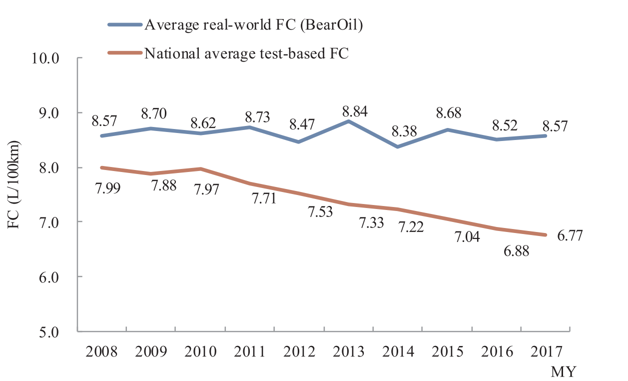

Fig. 4. Test-based and real-world FC development trends. **Note**: Real-world FC is based on BearOil app data and reported FC is based on national reporting and appropriate FC certification (MIIT's website).

Table 4. The real-world FC values dataset is dominated by AT vehicles, which account for 81% of the 2017 model year sample. Fig. 5A compares the FC gap overall and by transmission type, indicating that the overall gap increased from 12% in model year 2008–30% in model year 2017, with similar increases in the gap by transmission type. In this case, a fuel efficiency gain was achieved, while there was still a 1.98 L/100 km and 0.92 L/100 km gap between certified FC and real-world data for 2008 and 2017, respectively. AT vehicles consistently have higher FC gaps than MT vehicles: FC gaps for ATs and MTs were 18% and 6% for model year 2008, respectively, and 32% and 23% for model year 2017. In order to prevent bias in the analysis towards higher FC gap percentages, real-world overall FC gap results have been adjusted to the market share of AT versus MT vehicles, using the following formula:

$$S_2 = S_{AT1} \times \alpha_{AT2} + S_{MT1} \times (1 - \alpha_{AT2}) \quad (2)$$

Where: S_{AT1} represents the AT FC gap, S_{MT1} represents the MT FC gap, α_{AT2} represents the real-world AT market portion, and S_2 represents the adjusted overall FC gap.

Fig. 5B indicates that the adjusted FC gap is slightly lower than the FC gap observed in the real-world data: 10% (0.78 L/100 km) for model year 2008–29% (1.93 L/100 km) for model year 2017. Because China's current (and outdated) test procedure neglects recent gear shaft advancements (e.g. hydro-shaft, Continuously Variable Transmission etc.), which, it is argued, increase FC inefficiencies even further (Fu et al., 2014), the correlated analysis may present more moderate results than those in reality.

4.3. FC gap by vehicle type

An analysis of the gap between real-world and certified FC by vehicle type is based on the classification of vehicle types developed by China's largest automotive portal SINA, similar to that developed by the European Commission. The classification includes mini and small cars grouped under "small cars," sport utility vehicles (SUVs), multi-purpose vehicles (MPVs), compact cars, medium-size cars, and large cars. Sports and luxury cars are excluded in our analysis because of the relatively small number of measurements of these vehicles in the real-world FC sample, as well as small market share.

Table 5 presents three interesting characteristics of China's passenger vehicle fleet FC gap by vehicle type. First, MPVs had the smallest increase in the FC gap between 2012 and 2017 (7%), followed by, large vehicles (cars) (9%), small vehicles (11%), SUVs (13%), and compact vehicles (14%); medium-sized vehicles had the largest increase in the FC gap over the period, 15%. Second, SUVs, which are seeing

Table 4
AT vehicles proportions in real-world FC dataset versus national sales market.

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
AT vehicles proportion in dataset (%)	49.7	47.8	40.3	58.7	56.8	59.5	65.1	69.7	74.9	81.4
AT vehicles proportion in national market sales (%)	32.8	30.7	32.4	36.0	37.7	41.2	44.7	53.7	59.5	68.8

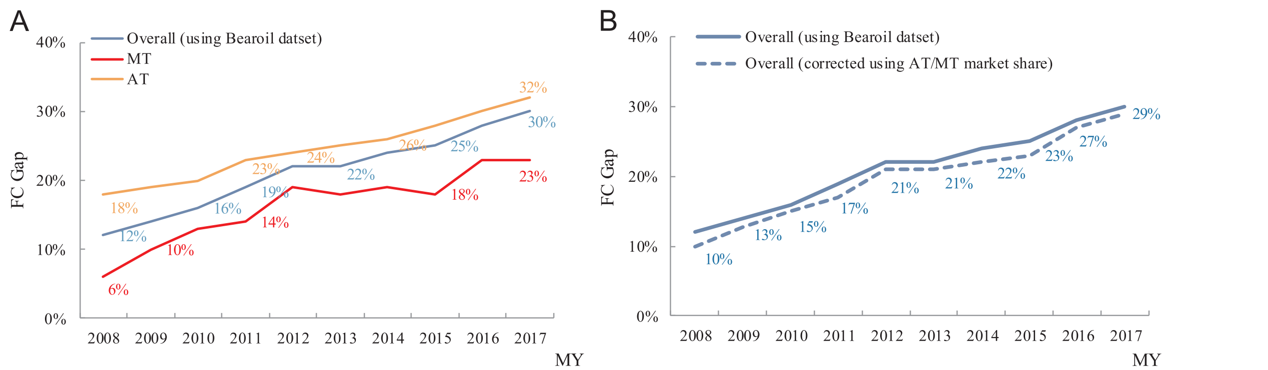

Fig. 5. Overall, AT and MT models' FC gap development. **Note:** A represents overall AT and MT models FC gap development using the BearOil dataset, while B compares between overall FC gap using BearOil dataset and overall FC gap adjusted according to real-world AT/MT market share in China.

significant market growth in recent years in China, showed a steady increase in FC gap reaching 30%, similar to that for other types of vehicles. Third, all car segments saw an increase in their FC gap between 2015 and 2017, reaching 24–31% (1.38–2.04 L/100 km) and 34% (2.36 L/100 km) respectively; the exception is MPVs which maintained a FC gap of 21%.

4.4. *FC gap by vehicle weight class*

Vehicle weight is considered a dominant factor in vehicle fuel efficiency, with heavier vehicles tending to have lower fuel efficiency/higher FC than lighter vehicles. The relationship between vehicle weight and FC has been studied extensively in recent years (Lammet et al., 2014; Middleton et al., 2016). Unlike the footprint-based fuel economy standards in the US, China's current FC limits and target regulations are based on 16 vehicle weight bins, where the heavier vehicles are allowed higher FC. This is similar to the approach used in Japan and Europe.

In this section certified and real-world FC gap values of the sampled vehicles are measured against the national FC standard (GB 19578–2014) by weight bins, listed in Table 6. Analysis of the FC gap by weight bin is worth examining to evaluate the weight-based FC standards, which discourage manufacturers from making vehicles lighter (Kang et al., 2017). Because 2016 was the first implementation year of Phase IV of China's passenger vehicle FC standard (GB 27999–2014), posing FC targets that gradually increase in stringency until 2020, comparing FC gaps with the standards may indicate how challenging implementation will be, and in turn, inform the next phase of standards beyond 2020, which is already under development.

Table 6 also shows that vehicles with curb weight ranging from 1090 kg to 1660 kg account for 79% of the real-world FC dataset, rendering the analysis for this weight bin more reliable than other weigh bins. This weight range is therefore the focus of this section's analysis. Fig. 6 compares the average real-world FC by weight bin with the standards; weight bins with less than 900 real-world observations or less than five vehicle models were excluded from the analysis. It indicates two interesting observations about the FC gap by vehicle

Table 6
China's weight-based fuel consumption standard- Phase IV.

Curb weight (kg)	Phase IV FC limits		Phase IV FC targets		By-weight vehicle proportion in the dataset (%)
	MT and/or < 3 seat rows	AT and/or > = 3 seat row	*> =3 seat row and CW < = 1090 kg*	*> =3 seat rows and CW > 1090 kg or > 3 seat rows*	
CW ≤ 750	5.2	5.6	4.3	4.5	0
750 < CW ≤ 865	5.5	5.9	4.3	4.5	0
865 < CW ≤ 980	5.8	6.2	4.3	4.5	1.4
980 < CW ≤ 1090	6.1	6.5	4.5	4.7	5.8
1090 < CW ≤ 1205	6.5	6.8	4.7	4.9	10.6
1205 < CW ≤ 1320	6.9	7.2	4.9	5.1	27.4
1320 < CW ≤ 1430	7.3	7.6	5.1	5.3	18.2
1430 < CW ≤ 1540	7.7	8.0	5.3	5.5	12.9
1540 < CW ≤ 1660	8.1	8.4	5.5	5.7	10.4
1660 < CW ≤ 1770	8.5	8.8	5.7	5.9	5.2
1770 < CW ≤ 1880	8.9	9.2	5.9	6.1	1.8
1880 < CW ≤ 2000	9.3	9.6	6.2	6.4	1.1
2000 < CW ≤ 2110	9.7	10.1	6.4	6.6	0.5
2110 < CW ≤ 2280	10.1	10.6	6.6	6.8	0.2
2280 < CW ≤ 2510	10.8	11.2	7.0	7.2	0.1
2510 < CW	11.5	11.9	7.3	7.5	0

Note: FC is abbreviation for fuel consumption (L/100 km); CW is abbreviation for curb weight (kg).

Table 5
By-segment FC (L/100 km) gap development.

Year/Segment	2010	2011	2012	2013	2014	2015	2016	2017	Annual average change in FC gap	Periodic gap increase
Small[a]	1.06 (17%)	1.13 (18%)	1.20 (20%)	1.24 (21%)	1.31 (23%)	1.38 (24%)	1.38 (25%)	1.49 (28%)	1.6%	11%
Compact	1.08 (15%)	1.29 (18%)	1.45 (22%)	1.38 (20%)	1.56 (26%)	1.47 (24%)	1.68 (29%)	1.68 (29%)	2.0%	14%
Medium	1.64 (19%)	1.96 (24%)	1.77 (21%)	2.20 (29%)	1.86 (24%)	2.04 (27%)	1.91 (27%)	2.36 (34%)	2.1%	15%
Large	1.85 (22%)	2.59 (30%)	2.56 (33%)	2.31 (30%)	2.31 (31%)	1.73 (25%)	2.43 (31%)	2.33 (31%)	1.3%	9%
MPV	1.14 (14%)	1.37 (17%)	1.50 (19%)	1.48 (18%)	1.18 (14%)	1.60 (21%)	1.49 (21%)	1.63 (21%)	1.0%	7%
SUV	1.55 (17%)	1.64 (18%)	1.69 (23%)	1.90 (24%)	1.65 (22%)	1.78 (25%)	2.10 (29%)	2.15 (30%)	1.8%	13%

[a] Weighted average calculation for the small vehicle segment include both small and mini-sized vehicles.

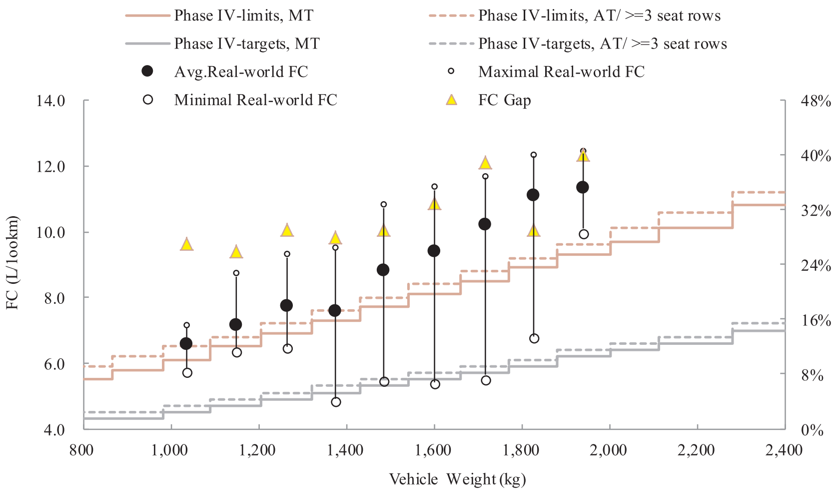

Fig. 6. Passenger vehicle real-world average weight-bin based FC compared with Phase IV weight-bin FC limit. **Note:** Weight-bin average real-world FC that was based on less than 900 data inputs and less than five models were excluded from this analysis; Average real-world FC represents the weighted-average real-world fuel consumption of the vehicles within the same weight-bin; Maximal real-world FC represents the maximal real-world fuel consumption within the same weight-bin; Minimal real-world FC represents the minimal real-world fuel consumption within the same weigh-bin.

weight. First, for any weight bin, real-world average FC is higher than the certification FC target, and even higher than the FC limit, singling standard's ineffectiveness. Second, the FC gap is smallest for vehicles weighing less than 1540 kg and larger for vehicles weighing more than 1540 kg; the FC gap tends to increase as the weight bin increases. Third, the FC gap by vehicle model is largest for weight bins 16,770–1880 kg and 1880–2000 kg.

Fig. 7 compares the average real-world FC values of 19 vehicle models with a certified FC of 6.4 L/100 km, the national FC target value for the 2017 model year, with the standard's limits and targets. The average FC of these was 8.3 L/100 km, 30% higher than their certified FC value. Although the 6.4 L/100 km FC standard only applies to vehicles weighing 980–1090 kg (approximately), the curb weight of vehicles from the data sample ranged from 1145 kg to 1590 kg. However, none of the models required to meet the 6.4 L/100 km standard met their own (often more relaxed) weight bin limit.

Based on voluntary FC reporting to an auto web portal in 2010, Huo et al. (2011) observed that, for ten vehicle models listed according to their curb weight, certified FC data was not increasing with curb weight, but the higher the model weight the higher the real-world FC was. By repeating this analysis for the same vehicle models based on the BearOil data, summarized in Table 7, it can be observed that the same trend of increasing average real-world FC as weight increases for ten model year 2017 models; the exception is the Citroen 307 which had higher real-world FC (7.95 L/100 km) than two models with heavier curb-weight. It is worth noting that because the data samples employed in Huo et al. (2011) and in this paper vary by origin and volume (a total of 7270 in the former and 29,206 in the latter), the comparison's validity can be challenged.

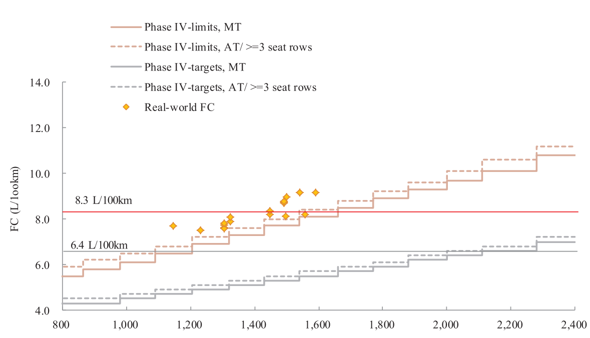

Fig. 7. Average real-world FC of dataset vehicle models certified 6.4 L/100 km. **Note:** Orange diamonds in the figure represent different MY2017 vehicle models with certified (test-based) fuel consumption of 6.4 L/100 km; Red line stands for the weighted average real-world fuel consumption of these vehicle models.

4.5. FC gap of best-selling models

Measurement of the gap between real-world and certified FC best-selling models, is both indicative of the pace of future FC gap increase as well as the severity of policy evaluation void, in particular that of high-volume selling car models. According to statistics released by the China Passenger Car Association, the annual sales of China's top 100 models was over 16.4 million in 2017, accounting for nearly 66% of the total national passenger car sales (China Passenger Car Association (CPCA), 2017). The weighted average real-world FC gap achieved by these bestselling models was 24%, lower than that for all in 2017, and ranged from 9% to 47%. Fig. 8 indicates that the top 40% of China's 2017 bestselling vehicles (with an average FC gap of 21–22%) perform better than the average bestselling vehicle, while the top-selling 41–80 models perform worse (with an average FC gap of 29%). This indicates that models with relatively low FC gaps are being sold in large volumes, and that there is no positive correlation between high sales volumes and good FC performance in China's passenger automotive market, as indicated in Fig. 9. In other words, automakers are not motivated to integrate fuel efficient technologies even in their best-selling passenger car models.

5. Conclusions and outlook

By quantifying the gap between certification and real-world FC rates in passenger vehicles using a mobile phone application data, we found that, on average, China's real-world FC was 30% higher than the certified value in 2017, and that this gap has increased annually since 2008. This translates to inefficiencies of China's fuel consumption standard: while the standard was supposedly met beginning in 2013, in reality, the FC rate appears to be 2.2 L/100 km higher than the current limit. There are several possible reasons for the gap between real-world and certified FC for a given passenger vehicle, including inadequate vehicle maintenance, additional weight added to the vehicle, driving styles, as well as temporal and spatial variations in driving conditions.

Because the real-world dataset does not provide information related to how these factors differ among individual vehicles, we focused on analyzing the gap by transmission type, vehicle type, weight class, by vehicle model and by sales volume. The results indicate that there is typically a higher FC gap for AT vehicle models, some ten percentage points more than MT vehicle models. AT vehicles consistently have higher FC gaps than MT vehicles: FC gaps for ATs and MTs were 18% and 6% for model year 2008, respectively, and 32% and 23% for model year 2017. Medium, Compact cars and SUVs tend to have a higher FC gap than other segments, while MPVs have an exceptionally lower gap,

Table 7
Fuel consumption level of 10 selected car models (listed by curb-weight).

Manufacturers	Car Models	Weight (kg)	Reported car volume	Sales in 2017	Ratio of sample numbers to sales in 2017 (%)	Laboratory values[a] (L/100 km)	Real-world mean[b] (L/100 km)	Real-world median (L/100 km)	Real-world standard Deviation (L/100 km)	FC Gap between real-world mean and laboratory[c] (%)
Chery	QQ3,1.1 L	890	264	21,412	1.2	6.70	6.93	6.94	± 0.04	3.4
BYD	F3,1.5 L	1200	3866	124,000	3.1	6.30	7.55	7.47	± 0.42	19.8
Beijing Hyundai	Elantra,1.6 L	1268	2040	19,615	10.4	7.59	8.13	8.40	± 0.65	7.1
Dongfeng Citroen	307,1.6 L	1280	2351	/	–[e]	7.96	9.07	9.18	± 0.66	13.9
FAW VW	Sagitar,1.6 L	1332	8311	332,733	2.5	7.09	8.39	8.40	± 0.76	18.3
Shanghai GM	Cruze,1.6 L	1375	7654	81,012	9.4	7.32	8.68	8.83	± 0.65	18.6
Shanghai VW	Passat,1.8 L	1544	2499	159,547	1.6	7.30	8.98	8.94	± 0.20	23.0
Huachen BMW	Series 3	1540	1754	123,690	1.4	6.95	9.49	9.50	± 0.64	36.5
Guangzhou Toyota	Camry,2.4 L	1518	394	74,329	0.5	10.30	10.53	10.57	± 0.19	2.2
FAW VW	Audi A6L, 2.4 L	1762	73	141,785	0.05	8.80	12.64	12.63	± 0.04	43.6

[a] Laboratory values are the weighted-averages of combined cycle results.
[b] Real-world mean are the weighted-averages of real-world FC values.
[c] FC gap calculation formula: [(mean of model dataset real-world FC)–(model test-based FC value)]/ model test-based FC value *100%.
[e] Due to the limited sales of the Citroen 307 model, the ratio of sample numbers to sales in 2017 was excluded.

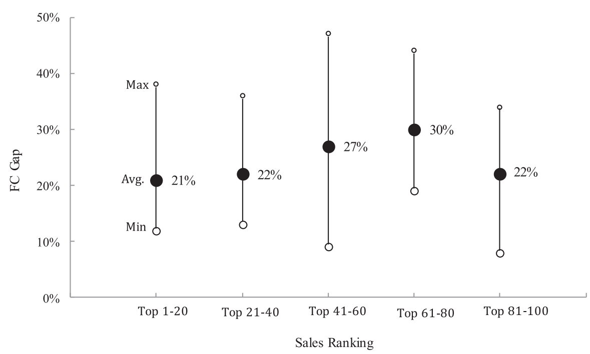

Fig. 8. FC gap of the top 100 best-selling models in 2017.

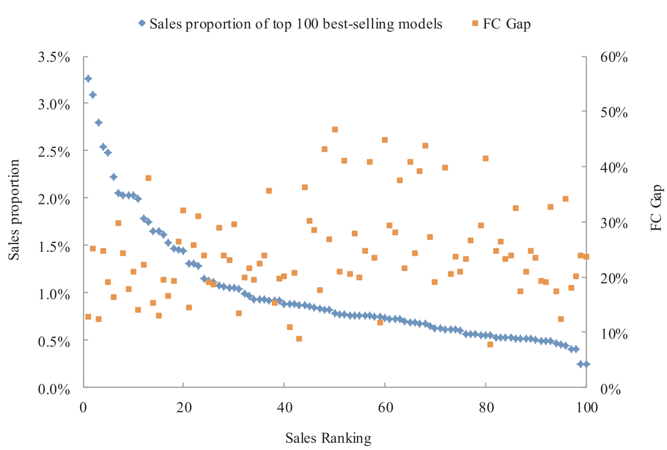

Fig. 9. FC gap plotted with by sales proportion of China's 2017 top 100 selling models.

maintained at 21% over recent years. Heavier vehicles typically have higher FC gaps. The growth in percentage of heavy vehicles as part of the car fleet is likely to drive the increase in the FC gap. These findings, supported by other research (Tong and Hung, 2016; Kudoh et al., 2007a, 2007b; Vasic and Weilenmann, 2006; Samuel et al., 2002; Pierson et al., 1996; Schipper et al., 1993), reaffirm the dataset adequacy. This study also analyzes the FC gap of selected top-selling models with an average FC target of 2017 (6.4 L/100 km) and finds that the top best-selling models have a milder gap (21–22%), indicating that good performance does not necessarily compromises sales or profitability.

By assessing the impact of the FC gap on the implementation of China's FC standard, this paper shows that the standard is not being met although it is increasing in stringency, hence, the FC gap continues to grow. The research results suggest that a lack of scrutiny of certified FC values (or real-world compliance with fuel economy standards) weakens the effectiveness of China's FC standards, and likely weakens FC standards elsewhere. Furthermore, carbon emission estimates derived from vehicle type-approval test misrepresent real-world FC values to the extent that the FC standard loses its effectiveness, despite the gradual advancements indicated by test-based data. A previous study of China's FC rate gap published in 2011 shows half of the gap values that this study finds, with analysis based on only a fraction of the size and scope of the dataset used in this study (Huo et al., 2011).

Given the increased attention placed on the fuel economy policy regime by Chinese policy-makers, demonstrated in the recently released passenger vehicle labeling standard and FC management mechanism, research on China's FC regulation is timely. In particular, the gap between real-world and certified FC is currently being studied by the government with the goal of devising a new driving cycle that better represents real-world FC. This paper therefore addresses a prominent loophole in FC policy: a lack of accountable data that can devise efficient FC policy. Because real world FC is increasing and so are the number of vehicles on the road, and because every new car is projected to remain on the road for a lifespan of about 10 years (Huo et al., 2012), by addressing FC policy inefficiencies, significant carbon mitigation could be delivered.

One study suggests that if no control measures are sufficiently implemented over China's passenger car vehicle fuel consumption, China's annual oil demand will reach 363 million tons by 2030, while high fuel economy improvement could result in up to 85 million tons savings during this period (He et al., 2005). Another study estimated that fuel efficiency can reduce carbon emissions by 35% by 2050 (Huo et al., 2012). The adoption of commercialized fuel efficiency technologies, another study indicates, can reduce passenger vehicle fuel consumption by 31%, while emerging technologies would increase saving to 51% (Xiao et al., 2018).

Finally, this paper demonstrates how the utilization of a cost-effective app can provide information on the gap between certified and real-world FC, in China and elsewhere. Policy makers can use these data to revisit the accuracy of the existing emission test cycle, and perhaps develop a test cycle more representative of actual real-world emissions. Based on real-world FC data, policy-makers may consider using location-specific FC estimates that better account for local driving conditions. Future collection of, and research using, large datasets of real-world FC data can be used to examine the impacts of various factors on the FC gap, including geographical and temporal variations, climatic change, traffic conditions, and anthropogenic issues.

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