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Vehicular volatile organic compounds losses due to refueling and diurnal process in China: 2010–2050

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ABSTRACT

Volatile organic compounds (VOCs) are crucial to control air pollution in major Chinese cities since VOCs are the dominant factor influencing ambient ozone level, and also an important precursor of secondary organic aerosols. Vehicular evaporative emissions have become a major and growing source of VOC emissions in China. This study consists of lab tests, technology evaluation, emissions modeling, policy projections and cost-benefit analysis to draw a roadmap for China for controlling vehicular evaporative emissions. The analysis suggests that evaporative VOC emissions from China's light-duty gasoline vehicles were approximately 185,000 ton in 2010 and would peak at 1,200,000 ton in 2040 without control. The current control strategy implemented in China, as shown in business as usual (BAU) scenario, will barely reduce the long-term growth in emissions. Even if Stage II gasoline station vapor control policies were extended national wide (BAU + extended Stage II), there would still be over 400,000 ton fuel loss in 2050. In contrast, the implementation of on-board refueling vapor recovery (ORVR) on new cars could reduce 97.5% of evaporative VOCs by 2050 (BAU + ORVR/BAU + delayed ORVR). According to the results, a combined Stage II and ORVR program is a comprehensive solution that provides both short-term and long-term benefits. The net cost to achieve the optimal total evaporative VOC control is approximately 62 billion CNY in 2025 and 149 billion CNY in 2050.

Introduction

Understanding volatile organic compound (VOC) emission is crucial to control air pollution in major Chinese cities since VOCs are the dominant factor influencing ambient ozone level as well as secondary organic aerosols (SOAs) (Guo et al., 2011a; Lei et al., 2011; Duan et al., 2008; Chan and Yao, 2008; Geng et al., 2007; Liu et al., 2010). In major city clusters, vehicular emissions have become the most important source in VOC emission inventory. For example, vehicles were responsible for 26%–50% of VOC emissions in inland Pearl River Delta (PRD) cities in 2004–2007, and 48% ± 4% in Hong Kong from 2001 to 2007 (Srivastava et al., 2005; Guo et al., 2011b; Gentner et al., 2009; Lee et al., 2002; Liu et al., 2008; Walsh, 2014). Vehicular VOC emissions include tailpipe emissions and evaporative losses, *e.g.*, release of gasoline vapors resulting from diurnal temperature variations, refueling, hot soak, running losses and permeation. In developed countries, vehicular evaporative VOC emission

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without accounting losses during refueling process usually account for 30% of gasoline-related VOCs. A 2007 research study notes that evaporative emissions contribute to 12% of total VOC emissions in Beijing with an ozone formation potential that is higher than for most other VOC sources (Song et al., 2007).

Although vehicular evaporative VOC losses are important, the regulating and controlling process is just getting started in China and the roadmap of evaporative emission control is still a controversy. In this article, we evaluated different VOC control scenarios based on two existing technologies: the Stage II vapor recovery system (Stage II) and on-board refueling vapor recovery (ORVR). Stage II collects gasoline vapors from vehicle fuel tanks while customers dispense gasoline at gasoline dispensing facilities (US EPA, 1991). ORVR systems are carbon canisters installed in automobiles to capture gasoline vapors evacuated from the gasoline tank. In China, Stage II has already been required in some major urban areas since 2007, whereas numerous service stations, scattered across medium and small cities, suburbs and freeways, remain uncontrolled. Stage II is widely used in Europe, while both Stage II and ORVR were used in the US until 2012. The US EPA has started to phase-out Stage II because of the widespread penetration of ORVR. The US EPA identified ORVR as the best available control technology (BACT) because of its high efficiency, ability to function without specific monitoring or maintenance, and low cost.

The purposes of this article include: (1) understanding current controls and evaporative emissions from vehicles' refueling and diurnal processes in China; (2) evaluating a possible future control roadmap and estimating the effects on emissions reductions; (3) generating cost-benefit analyses for the scenarios evaluated. In this paper, we established emission models to evaluate total evaporative emissions. Five policy scenarios were designed for future vehicular VOC control based on two available technologies. For each technology, the basic emission rates were generated by theoretical calculation, while control efficiency of different technologies was measured by laboratory tests. In addition, cost and benefits of each scenario were further evaluated to provide a comprehensive understanding of future policy options.

1. Methodology

1.1. *Real-world emission rates calculation (non-control)*

The basic emission rate of refueling VOCs without any control can by calculated by the Reddy–Wade equation. This equation was developed in 2010 and now is widely used in all over the world (Reddy, 2010; US EPA, 2008). The real-world refueling vapor emission is influenced by local temperature and the Reid vapor pressure (RVP) of the gasoline. According to a fuel survey in China (Huo et al., 2012a), the RVP of market fuel ranges from 42.5 to 89.0 kPa, and the average is 61.3 kPa. Thus 60 kPa was selected as a representative value in this analysis. For the emission inventory, temperatures in each province from 6:00 am to 21:00 pm, during which most refueling occurs, were used.

$$Q = 18.2 \times \left[\frac{f \times P_{\text{atm}}}{R \times T_{\text{d}}} + \frac{P_{\text{atm}} - P_{\text{tank}}}{R \times T_{\text{v}}}\right] \times \left[\frac{P_{\text{disp}}}{P_{\text{atm}} - P_{\text{disp}}}\right] \tag{1}$$

where, Q(g/L) is the concentration of VOCs in the air that is displaced to the environment, R(gal·psi)/(g·mol·K) is the universal gas constant 0.3187, f(g/gal) is the air entrainment 0.2, T_{d}(K) is the temperature of the dispensed fuel, T_{v}(K) is the temperature of the vehicle's fuel tank, and T_{v}–T_{d} is approximately 2 K. P_{atm}(psi) is the atmosphere pressure, P_{tank}(psi) is the tank fuel vapor pressure, and P_{disp}(psi) is the dispensed fuel vapor pressure. P_{tank} and P_{disp} could be further calculated by the RVP and temperature:

$$P = A \times T \times \text{RVP} \times \exp(-B/T) \tag{2}$$

where, A and B are the constants 25.61 and 2789.78, respectively, RVP is the fuel RVP in psi, and T(K) is the temperature.

Evaporative VOC emissions also include hot soak and diurnal emissions. Evaporative emissions from a vehicle not related to refueling are very complex. They range from breathing losses from the vehicle tank to leaks around gaskets and hoses. Additionally, VOCs can escape around engine cylinders and then leak from the oil pan. The US EPA developed an empirical equation for a 24-hr evaporative emission factor (US EPA, 2001, 2012a). The International Vehicle Emission (IVE) model uses adjustment factors for evaporative emission factors to address the difference between real fuel vapor pressure and the EPA experience value (CE-CERT (Center for Environmental Research) et al., 2008). We use both the US EPA equation and the IVE adjustment factors to generate diurnal emission rates for Chinese fuel vapor pressure (8.7 psi).

To convert the gasoline consumption-based emission factor into a distance-specific emission factor, the average mileage of Chinese passenger vehicles was introduced using data from previous research (Huo et al., 2012a).

1.2. *Lab tests of ORVR control efficiency*

A series of refueling emission tests were finished to determine efficiency of ORVR technology using local vehicles and gasoline. Two in-use vehicles equipped with original ORVR systems were recruited: (1) a 2009 Chrysler–Dodge Journey with a 2.7 L ORVR canister and 77.6 L fuel tank and (2) a 2012 Chrysler–Jeep Compass with a 2.0 L ORVR canister and a 51.1 L fuel tank.

The whole test was conducted in Gas-tight Imtech Variable Temperature Sealed Housing for Evaporative Determination chambers (VT-SHED, VT-SHED software, Imtech Automotive Testing Solutions Beijing Co., Ltd. Beijing, China). This SHED is the most advanced one in China. This system is equipped with a canister loading device, fuel temperature control system, as well as total evaporative emission test system. China Automotive Technology & Research Center Beijing laboratory (CATARC) provided all the facilities and technical support.

Each vehicle was tested five times to ensure the reliability. For each test, the processes include canister purge, canister adsorption to breakthrough, type VII driving defined by China vehicle emission control standard, fuel drain, soak, refueling test and canister weighing in quadruplicate. A detailed test procedure was provided in supporting materials, Fig. S1.

1.3. *Current control policy and future scenario design*

The Chinese government launched regulation of emissions from service stations in 2007, requiring Stage II to be installed