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A Stochastic Analysis of VOC Emissions from the Distribution Process of the Gasoline

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Abstract

Estimating the emission rate of VOCs from a gasoline industry at national level can be a challenging task even though the estimation is mean-based. However, using the procedures in the US EPA AP-42 guidelines, it is possible to approximate the mean industry emission rate once enough data are available. However, this estimate can be misled in the sense that there exist many stochastic factors in the EPA's estimation procedures and also throughout the marketing channels of gasoline industry.

Addressing the stochasticity problem in EPA's procedure is hard to tackle because the detailed data needed to execute the estimation are not usually available even from refiners. Instead, this research tries to stay focused on the second type of stochasticity issue, raised from the mean-based metrological and marketing practice data collected from the 4 major refiners. To do so, emission rates from each marketing channels (8 marketing points by 3 transportation types and by storage facilities of 4 refiners) are estimated monthly, following AP-42 procedures and using Tank 4.0. Once these estimates are acquired, the distribution of VOC emission rate for each marketing channel of all 4 refiners is estimated through simulation method using @Risk. The mean-based emission rates are weighted by company quantities to estimate the emission rate from the whole gasoline industry. Simple economic implication is provided, based on the result. This study found that, on the mean-bases, about 0.66% of gasoline marketed are evaporated into air. Considering the stochasticity in the estimation, about 90% of simulation results fell into the range of 0.65 to 0.68%. For 90% chance, the estimated economic loss is $54.65 million to $57.17 million, not counting the cost caused by air quality degradation and associated health impact.

Key words : VOC emissions, Gasoline industry, Stochastic analysis

1. INTRODUCTION

Volatile Organic Compounds (VOCs) are a wide range of volatile hydrocarbons such as benzene, emitted by a variety of sources ranging from buildings to gasoline industry. Exposure to VOCs may lead to nasal and eye irritation during episodes of photochemical pollution. VOCs are also categorized as probable human carcinogen. Korea has controlled the emission of VOCs since 1996, focusing on the industrial complexes such as Yeochoen and Woolsahn-Meepo. However, it was

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predicted that the emission of VOCs would steadily increase since 1994. Only few of studies (Jang, 1999; Han, 1996) had focused estimating the emission rate of VOCs in Korea.

The purpose of this study is to estimate VOC emissions from 8 marketing points in the Korean gasoline industry in 1999 as shown in the Fig. 1. Eight marketing points are (1) loading from refinery to vessel, railroad tank car/tank truck (RTC/TT), or pipeline, (2) transit from refinery to storage tanks, (3) loading from vessel, railroad tank car/tank truck, or pipeline into storage tank, (4) storage tank, (5) loading from storage tank to tank trucks to service station, (6) transit from storage tank to service station, (7) loading from tank trucks to underground tank at service station, and (8) underground tank breathing. Meanwhile, estimation equations for VOC emissions rate are available from the US EPA (2000).

Stochasticity is a statistical terminology for uncertainty or risk.[1] To integrate the stochasticity into the estimation, a computer simulation model is built using @Risk™.[2] Instead of using mean values for the estimation, distributions of saturation factor (considering operation practices), temperature and gasoline Reid Vapor Pressure, and characteristics of equipment (age of storage tanks, etc) are fitted to the data and used to estimate the distribution of VOC emission rate. Once distribution of emission rates at different marketing stage are estimated, an integrated distribution of an annual industry level emission rate is reported. Also, most contributing factor to emission rate will be identified and discussed.

2. MODEL

Let i stand for refiners, j stand for transport mode (j = vessel, RTC/TT, pipeline), and k stand for marketing stage (k = 1, ..., 8). For example, v_{ijk} is the emission rate (%) of refiner i at marketing stage k via transport mode j.[3] In calculating v_{ijk}, annual average is used. Then the amount of gasoline marketed after 1 stage of marketing channel (k = 1) by refiner i via j, can be defined as

$$Q_{ij1} = Q_{ij0} - (v_{ij1}/100) \cdot Q_{ij0} \qquad (1)$$

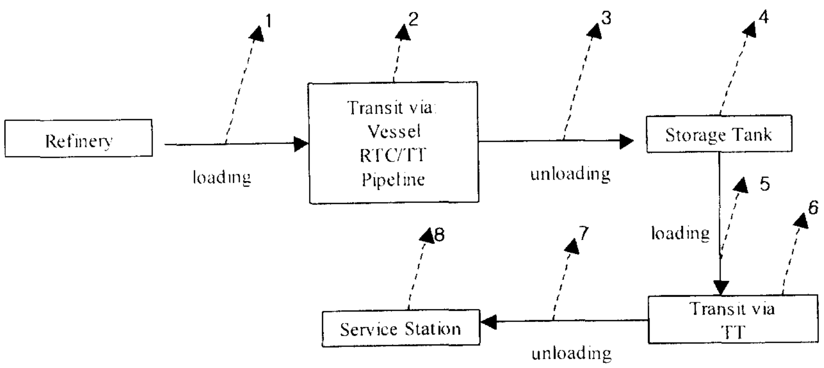

Fig. 1. Eight marketing points of VOC emissions.

[1] In estimating the yearly VOC emissions in Korea, many stochastic factors are involved. Two types of stochastic factors are identified in this study. One is the stochasticity inherent in the parameters that are used in the estimation of the model. The second type is the stochasticity in the data collected. In collecting the data (i.e., amount of gasoline marketed, duration of transportation, ambient temperature etc), the measurement error and variation due to seasons and regions are expected. These kinds of variations will contribute to the stochasticity in the collected data.

[2] @Risk is an Excel Add-in program developed by Palisade. It uses the Monte Carlo Simulation and/or the Latin Hyper Cube method to generate random numbers for the stochastic variables in the model. In each iteration, @Risk calculates the simulation outcome and save the result, which is used later to compile the final report. @Risk version 4.0 is used in this paper. Please refer to the web site, http://www.palisade.com, for more detailed information on the @Risk™ program.

[3] Regional and Monthly v_{ijk}'s are calculated and used to fit the distribution of annual v_{ijk}

where Q_{ij0} is the amount of gasoline produced at the refinery by refiner i and transported via j^{th} mode. Then after 2^{nd} stage, the amount that is being marketed is :

$$Q_{ij2} = Q_{ij1} - (v_{ij2}/100) \cdot Q_{ij1} \quad (2)$$

Generalized, the amount of gasoline after k^{th} stage by refiner i via j is

$$\begin{aligned} Q_{ijk} &= (1 - v_{ijk}/100) \cdot (1 - v_{ij(k-1)}/100) \\ &\Lambda(1 - v_{ij1}/100) \cdot Q_{ij0} \\ &\prod_k (1 - v_{ijk}/100) \cdot Q_{ij0} \end{aligned} \quad (3)$$

Therefore, the whole emission rate (%) of refiner i via j^{th} mode is

$$v_{ij} = \frac{Q_{ij0} - Q_{ijk}}{Q_{ij0}} \cdot 100 \quad (4)$$

Because the emission rate is different for each refiner and for each transport mode, a quantity weight is assigned to calculate the industry emission rate for all transport modes. The weight of the refiner i via j for emission rate, v_{ij}, is

$$w_{ij} = \frac{Q_{ij}}{\sum_{ij} Q_{ij}} \quad (5)$$

and the yearly total emission rate of the whole distribution process of the gasoline in Korea, v, can be calculated as

$$v = \sum_{ij} v_{ij} w_{ij} \quad (6)$$

3. DATA

3.1 Mean-based estimation

Necessary data to use the estimation equations for VOC emissions are collected from the 4 major refiners in Korea for the eight marketing points. The data are parametric (temperature, size of tank, transport period, saturation factor of the liquid, true vapor pressure, molecular weight, density of vapors, wind speed, insolation, etc) and non-parametric (loading type, condition of storage tanks, etc). When available, tables suggested in the AP-42 are used instead of equations. For the estimation of emission rate from the storage tanks, TANKS 4.0 is used as suggested by US EPA.[4]

Using the data collected and the model described in the previous section, a mean based estimation result is presented in Table 1.

The respective mean emission rate by refiners and by transport mode are presented in Table 2 below. In the table, the amount marketed (from refineries to storage tanks) through pipeline is the greatest and almost the same amount is marketed through vessel. Compared to pipeline and vessel, a small amount of gasoline is marketed via RTC and TT from refinery to storage tanks. After the storage tanks, Tank Trucks (TT)

Table 1. Mean based estimation of emission rate (%) in 1999.

Refiners marketing points	Emission rate by transportation mode (%)		
	Vessel	RTC/TT	Pipe line
Loading at refinery	0.0321 (0.0000)	0.1913 (0.0153)	0.0400 (0.0000)
Transit from refinery to storage tanks	0.0130 (0.0023)	0.0080 (0.0000)	0.0000 (0.0000)
Loading at storage tanks	0.1816 (0.0165)	0.1837 (0.0195)	0.1816 (0.0165)
Storage tank loss	0.0311 (0.0196)	0.0523 (0.0285)	0.0367 (0.0195)
Loading at storage tanks	0.1816 (0.0165)	0.1837 (0.0195)	0.1816 (0.0165)
Transit to service stations	0.0080 (0.0000)	0.0080 (0.0000)	0.0080 (0.0000)
Loading at service stations	0.1679 (0.0000)	0.1679 (0.0000)	0.1679 (0.0000)
Storage at service stations	0.0179 (0.0000)	0.0179 (0.0000)	0.0179 (0.0000)
Subtotal	0.6318	0.8103	0.6322
The annual emission rate		**0.6596**	

Note that figures in parenthesis indicate standard deviation

[4] For more detailed information of TANK 4.0, see USEPA (2000)

Table 2. Amount marketed, weights, and emission rates by transportation model in 1999.

	Vessel			RTC/TT			Pipe line		
	Weight	Amount 1000 bbl	Emission rate%	Weight	Amount 1000 bbl	Emission rate%	Weight	Amount 1000 bbl	Emission rate%
Average	0.1004 (0.0546)	917,513 (499,205)	0.6318 (0.0217)	0.0246 (0.0186)	225,217 (170,123)	0.6077 (0.1090)	0.1250 (0.0742)	1,141,974 (677,816)	0.6322 (0.0309)
Subtotal	0.4016	3670,052	0.0986	900,868	0.4998	4,567,898			

Note that figures in parenthesis indicate standard deviation

and Rail Tank Car (RTC) are the major transportation modes.

Even though the emission rate of RTC/TT marketing channel is high (0.8103%) the weight is much lower (0.0986) compared to that of Pipeline (0.4998) and Vessel (0.4016), which resulted in the overall emission rate for RTC/TT of 0.6596 in 1999.

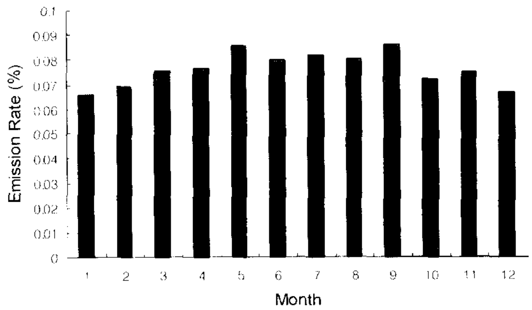

Fig. 2. Monthly mean emission rates from selected storage tanks in 1999.

3.2 Stochastic factors

The major stochastic factor is the temperature of the liquid, which is affected by ambient temperature. The ambient temperature is affected by season and location. From four refiners, 34 marketing channel data in 1999 (therefore, $34 \times 12 = 408$ monthly temperature data, for example) are collected. To be run on TANKS 4.0, the detailed data on 71 storage tanks are collected.

The list of the storage tank data includes Tank Type, Dimensions, Color, Seal Type, and metrological data such as regional insolation and temperature. In Fig. 2, monthly mean of emission rate from the storage tanks are illustrated.

From Fig. 2, it can be argued that emission rate is higher during summer time and lower in winter time. A possible explanation is as follows. From January to May, emission rate increases due to increase in temperature. Then, on June, refiners lower the Reid Vapor Pressure (RVP) to lower evaporation of gasoline. Then on September, refiners set the RVP back for winter (back to a higher RVP), which results in higher evaporation. It is interesting to look at the emission rate by storage tanks as illustrated in Fig. 3.

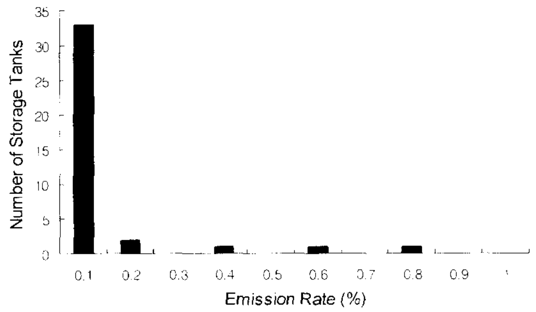

Fig. 3. Number of selected storage tanks by emission rate (0.01% to 1%).

In Fig. 3, most of storage tanks emit less than 0.1% even though there are some storage tanks that emit over than 0.2%. This distribution is skewed to left because many old storage tanks with fixed roof have been replaced recently with Internal/External Floating Roof Tanks to meet the new emission management requirement.

A magnified look of the Fig. 3 (which is Fig. 4) suggests that the distribution started to spread out so it is becoming a bell-shaped distribution. However, major

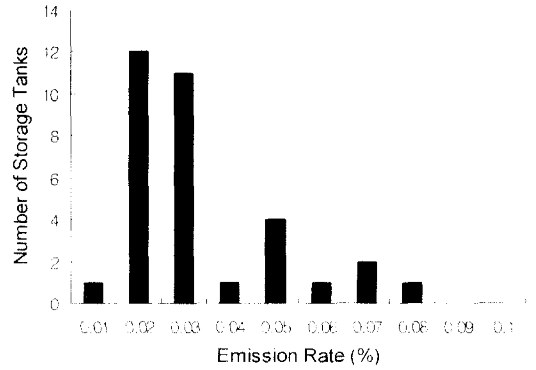

Fig. 4. Number of selected storage tanks by emission rate (0.01% to 0.1%).

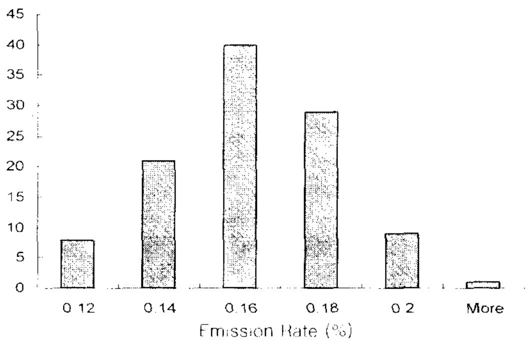

Fig. 5. A distribution of emission rate at loading to service station.

VOC emissions occur at loading of gasoline and there are 4 loadings out of 8 marketing points (i.e., loading from refinery to transportation, from transportation to storage tanks, from storage tank to tank trucks, and from tank trucks to underground tank). These four marketing points are the major sources of stochasticity in the model. In other marketing points such as transit, refiners reported almost the same result in practice. An example of distribution of emission rate at loading is illustrated in Fig. 5.

4. RESULTS AND DISCUSSION

Despite all the interesting implications we can draw

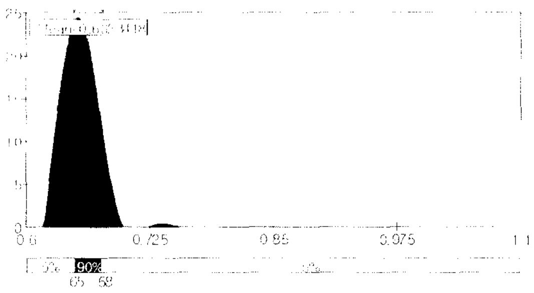

Fig. 6. A distribution of VOC emission rates at loading to service station.

from the mean based estimation, however, the emission rate estimate lacks the information on the 2nd and 3rd momentum of the distribution. To get more complete information, data are fitted to distribution using @Risk to estimate the other momentum as follows.

Once each monthly and regional v_{ijk} is calculated, v_{ijk}'s are fitted to distributions using @Risk. That is, the equation (3) is transformed into (7),

$$Q_{ijk}(\mu, \sigma) = \prod_k (1 - v_{ijk}(\mu, \sigma)/100) \cdot Q_{ij0} \tag{7}$$

where the emission rate v_{ijk} is now a distribution $v_{ijk}(\mu, \sigma)$. Therefore, quantity emitted Q_{ijk} is also a distribution, $Q_{ijk}(\mu, \sigma)$, as presented above. First, monthly emission rates are fitted to distribution with default options chosen (no data filtering and chose the distribution that had highest Chi-square). The result was not satisfactory in a sense that unrealistic VOC emission rates over 10% are simulated. Then, distributions that had extreme values were replaced with smoother distributions. However, the results were not satisfactory. To simulate a realistic distribution, therefore, the data that falls beyond the 1 standard deviation beyond the mean were filtered out. Also, smoother distributions are preferred and if a data shows a bi-modal or hardly recognizable pattern, uniform distribution is selected. Simulation result on the distribution of emission rate is presented in Fig. 6. In Fig. 6, 99.88% of simulation results fall into the emission range of 0.64% to 0.86%. That is, other than the major bell shaped distribution on

Table 3. Detailed statistics for the distribution.

Statistics	Value
Minimum	0.635718
Maximum	1.063675
Mean	0.662342
Std Deviation	0.012466
Variance	0.000155
Skewness	9.710670
Kurtosis	251.4483
Mode	0.646303

the left, other simulation outcomes to the right of it have negligible chance of occurring.

In addition, there is about 90% chance that the emission rate resides between 0.65% and 0.68%. Detailed statistics for the above distribution is presented in Table 3.

Using the emission rate estimated, the estimated gasoline evaporated is calculated as 40,613 ton (60,523,000 liter) in 1999 on average and there is 90% chance that evaporated amount is between 39,859 ton (59,400,000 liter) and 41,699 ton (62,142,000 liter). Applying the gasoline price of 1191.91 Won/liter ($0.92/liter at 1300Won = $1 exchange rate) at service stations in 1999, these numbers are equal to $54.65 million to $57.17 million.

5. CONCLUSIONS

In this study, estimation guideline of the US EPA AP-42 is used to estimate the emission rate of gasoline using data collected from major refiners. It is found that, on the mean-bases, about 0.66% of gasoline marketed are evaporated into air. Considering the stochasticity in the estimation, about 90% of simulation results fell into the range of 0.65% to 0.68% and, for 90% chance, the estimated economic loss is $54.65 million to $57.17 million, not counting the cost caused by air quality degradation and associated health impact. Therefore, both in economic and environmental sense, emission of VOCs should be controlled. These figures are expected to decrease significantly, when the law to control VOC emissions at loading facilities is in effect in 2004 in Korea. However, for more accurate assessment of the impact, more accurate estimation of VOCs emitted is necessary. To this end, inclusion of stochasticity in the estimation is a first forward step toward to it.

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