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Exergy-based assessment for waste gas emissions from Chinese transportation

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ABSTRACT

As an effective measure for environmental impact associated with the waste emissions, exergy is used to unify the assessment of the waste gases of CO, NO_x, and SO_2 emitted from fossil fuel consumption by the transportation system in China. An index of emission exergy intensity defined as the ratio of the total chemical exergy of the emissions and the total converted turnover of the transportation is proposed to quantify the environmental impact per unit of traffic service. Time series analyses are presented for the emission exergy and emission exergy intensity of the whole Chinese transportation as well as for its four sectors of highways, railways, waterways and civil aviation from 1978 to 2004. For the increasing emission exergy with CO taking the largest share, the highways sector was the major contributor, while the railways sector initially standing as the second main contributor developed into the least after 1995. The temporal and structural variations of the emissions are illustrated against the transition of the transportation system in a socio-economic perspective, with emphasis on policy-making implications.

1. Introduction

There have been various assessment metrics used for waste gases emitted from transportation sectors, of which mass weight units are employed frequently to assess the transportation emissions (Federici et al., 2003; Soylu, 2007; Federici et al., 2008), and monetary unit and other enquiries-based weighting factors are sometimes applied for a total evaluation of the related environmental impact (Hu et al., 2004). As different waste gases of the same mass have diverse environmental impacts, metrics based on mass fail to distinguish the intrinsic differences among various gases in terms of the real environmental cost or pressure (Ayres et al., 1998; Daniel and Rosen, 2002) and thereupon blur the picture of total environmental impact. The alternative measure based on the monetary approaches has attracted increasing debates. Although monetary metrics account for differences in quality (Cleveland et al., 2000, 2004), human bias is unavoidable in the monetary compensation disregarding the physical cost (Odum, 1996) and monetary prices-based aggregation may fail in efficient and equitable allocation of resources without, or even with, market prices (Common, 2007). Common to various weighting factors is the unavoidable subjectivity involved, with contradictory evaluations often resulted for the same data with different specialist groups (Chen and Ji, 2007).

Wall (1977, 1986, 1997) suggested exergy as a suitable measure of environmental impact of waste emissions and asserted that all utilization of resources and disposal of waste products affect nature and the effect is strongly related to the amount of exergy in the utilized resource or the disposed waste. Later, exergy as the thermodynamic departure between a substance and its surrounding has been gradually accepted as a unified measure for the environmental impact of waste emissions (Ayres et al., 1996, 1998; Rosen and Dincer, 1997, 1999; Sciubba, 1999; Rosen et al., 2008). Out of a combination of the first and second laws in thermodynamics, this measure provides a scientific and objective base for the assessment of environmental emissions (Rosen and Dincer, 2003; Ayres et al., 2004; Ukidwe and Bakshi, 2004; Chen, 2006). With an extension of labor theory of value and integration of some other holistic evaluation methods, like life cycle analysis, cumulative exergy content, and so forth, Sciubba (2001, 2003) also proposed a theory of extended exergy as a possible metric for both environmental impact assessment and sustainability issues.

As a unitary thermodynamic indicator, exergy has gained wide acceptance in environmental impact assessment that is more eco-oriented, with much attention paid to explain the relationship

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between exergy and environmental impacts (Szargut et al., 1988; Crane et al., 1992; Ayres et al., 1996, 1998, 2004; Rosen and Dincer, 1997, 1999, 2001, 2003; Creyts and Carey, 1997; Dincer, 2000, 2002; Wall and Gong, 2001; Gong and Wall, 2001; Rosen, 2004; Ukidwe and Bakshi, 2004, 2007; Dincer and Rosen, 2005; Chen, 2005, 2006; Rosen et al., 2008). In their early study, Rosen and his colleagues pointed out that exergy may be considered a measure of the potential environmental impact of the emissions (Crane et al., 1992). Years later, Rosen and Dincer (1997, 1999, 2001) further stressed that the exergy embodied in waste emissions indicates the mechanical, thermal, and/or chemical distance among the emissions and the reference environment and represents a potential for environmental change. Gunnewick and Rosen (2003) compared standard chemical exergy to environmental pollutant cost for atmospheric pollutants. According to them, whether an exergy carrier represents a resource or an environmental impact depends on its being constrained or unconstrained, and exergy emitted to the environment is an unconstrained driving potential for environmental damage. Daniel and Rosen (2002) stressed the importance of the exergy of waste emissions representing their disequilibrium with environment as the driving force for the processes to bring the emissions into equilibrium with the reference environment, and carried out the initial application of the exergy-based approaches in assessing waste gases of transportation system to investigate the emissions produced in the life cycles of thirteen automobile fuels. Taking the greenhouse emissions as an example, Rosen and his partners pointed out that exergy embodied in emissions into the environment has an influence on the net exergy availability of the ecosystem associated with solar radiation to the earth (Rosen, 2004; Rosen et al., 2008). Meanwhile, Ayres et al. (1996, 1998) pointed out that exergy can be used to aggregate wastes, and the exergy of wastes is a proxy for their potential harm to environment, and more remarkably, they suggested the ratio of exergy embodied in waste outputs to that embodied in resource inputs as the most general measure of pollution. They insisted that exergy-based evaluation of wastes is superior than the mass-based assessment, and the specific exergy (exergy per mass unit) would represent the specific environmental impact (Ayres et al., 2004). Additionally, there are several other typical notions about exergy-based evaluation of wastes. Creyts and Carey (1997) attempted to devise unified objective measures for environmental impact assessment based upon exergy, via either estimating the exergy embodied in a waste stream or the total exergy consumption associated with corresponding human-helped treatment courses of the waste stream. Ukidwe and Bakshi (2004, 2007) defined the ecological cumulative exergy consumption (ECEC) to account for the exergy of emissions, besides the exergy consumption in labor and capital and the conventional exergy consumed by industrial activities, and the exergetic value of some emissions are calculated and developed for life cycle impact assessment. In the scheme for ecological evaluation based on scarcity of exergy (Chen, 2006), the negative ecological value of a waste stream is equal in magnitude to the embodied exergy as the total exergy consumed directly and indirectly in human helped treatment or natural degradation of the waste stream. In our recent study, chemical exergy-based analysis has been used in water quality assessment by calculating the exergy embodied in the substances involved in water body (Chen and Ji, 2007).

It is easy to demonstrate that toxicity for human beings associated with current pollution standards is not well correlated with exergy content. However, exergy, as a ‘direct’ measure or at least as a proxy stated by Ayres, of the environmental impact, can be used to elucidate the ‘eco-toxicity’ that disturb the structure and function of the total complex system including both human beings and environment, and thereby, measure the environmental impact of transport activities and highlight the correlations between exergy consumption and atmospheric emissions on whether the impact of transport activity has been decoupled from its volume (Gasparatos et al., 2008). For the waste gas emissions from the Chinese transportation system, based on conventional mass and monetary metrics there have been various studies, (e.g., Wang, 1994; He et al., 2005; Deng, 2006; Cai and Xie, 2007; Wang et al., 2007, 2008; Fan et al., 2007; Liu et al., 2008), with most of them focusing on highways vehicles based on mass account. A systematic unified assessment of the whole Chinese transportation system consisting of highways, railways, waterways and civil aviation based on the novel metrics of chemical exergy remains to be carried out to shed light on the overall structure and emission status of Chinese transportation.

As a continuation of our earlier effort of unified analysis based on exergy for the energy consumption in Chinese transportation (Ji and Chen, 2006), the present work provides an exergy-based overall assessment of the waste gas emissions from fossil fuel consumption by the Chinese transportation system in the period from 1978 to 2004, with emphasis on energy policy implications.

2. Methodology

2.1. Chemical exergy of waste gas

Chemical exergy of a waste gas is the minimum work to bring the gas into chemical equilibrium with corresponding component in the reference environment. A lower concentration in the environment corresponds to a larger chemical exergy of the waste gas, and conversely, the more abundant the substance found in the environment, the less the chemical exergy the waste gas carries (Chen and Ji, 2007). To account the chemical exergy of waste gas emissions, the globally averaged model of the standard atmosphere defined by Morris and Szargut (1986) is applied for a large-scale system, such as the transportation system in China. Listed in Table 1 based on Szargut et al. (1988) are the specific chemical exergy (SCEx) values for main waste gases of CO, NO_x, and SO_2 associated with fossil fuel consumption of vehicles.

2.2. Emission exergy (EE) and emission exergy intensity (EEI)

To quantify the total environmental impact, the sum of chemical exergy values embodied in the waste gases are referred to as the emission exergy as

$$EE \equiv \sum_i m_i SCEx_i, \tag{1}$$

where m is the mass, the footnote i denotes the ith waste gas. The emission exergy intensity (EEI) is then defined to quantify the environmental impact per unit traffic service as

$$\begin{aligned} EEI &\equiv EE/CT \\ &= \sum_i m_i SCEx_i/(FTK + C \times PK), \end{aligned} \tag{2}$$

Table 1
Specific chemical exergy of involved waste gas emissions.

Waste gas	SCEx (kJ/kg)
CO	9825.0
NO_x	2963.3
SO_2	4892.3

Note: the specific chemical exergy of NO is applied for that of NO_x (Daniel and Rosen, 2002).