On-road NO_X emission factors from heavy-duty vehicles in China and the challenge to NO_X emission control

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Backgrounds

China's vehicle registrations have been rapidly increasing since 1990s due to its impressive economic growth and urbanization. By the end of 2010, China's total stock of civil motor vehicles (including include rural trucks) has already exceed 100 million (NBSC, 2011). As a result of the surge of vehicle population, it triggered great concerns about air pollution caused by vehicle emissions, especially in vehicle populated metropolis such as Beijing, Shanghai, Guangzhou and etc. Among all major air pollutants (e.g., CO, THC, NO_X and $PM_{2.5}$) from on-road vehicles, NO_X emissions increased most significantly during 2006-2010 (i.e., 11th Five Year Plan, 11th FYP) by an annually rate of 2.7% (MEP, 2011a). The recent air quality data from ground monitoring stations also identified this trend. Average NO_2 concentration of China's 113 key environmental protection cities increased by 5.7% during the first half of 2011 compared to same period of 2010 (MEP, 2011b). As a response to the NO_X increase, the new 12th FYP establishes a target for total NO_X emission reduction of 10% for the period of 2011-2015. Furthermore, on February 29th, 2012, China's State Council approved the National Ambient Air Quality Standards (NAAQs) Amendment, which will be fully in effect in 2016 (MEP and AQSIQ, 2012). Newly revised NAAQs call for more stringent controls of NO_X emissions, especially in high-emitting sectors that include on-road vehicles (Zhang et al., 2012).

Among all vehicle categories, attention has been focused on heavy-duty diesel vehicles (HDDVs, including both buses and trucks) due to their significantly higher NO_X emission factors and vehicle use intensity (i.e., annual vehicle travelled kilometres, annual VKT) relative to gasoline cars. Beijing is the pioneer in controlling vehicle emissions within China (Wu et al., 2011), where Selective Catalytic Reduction (SCR) technology has been required for new buses in Beijing since 2008 to comply with the Euro IV standard (see Table 1). Beijing also launched a comprehensive vehicle emission test program beginning in 2008. This program included a sub-task for measuring second-by-second on-road emission profiles using portable emission measurement systems (PEMS) and developing a new emission database for the HDDV fleet in Beijing. This study represents the real-world on-road NO_X emission profiles of more than 130 HDDVs (including both buses and trucks) within the Beijing test program. We then compare and discuss the new NO_X emission factors of HDDVs with other previous estimates and suggest an update of the NO_X emission inventory for the HDDV fleet in China.

Table 1: Timetable of emission standards implemented for new HDDVs in Beijing and China

Emission standard	Date of standard implementation (type approval)		NO_X emission limits
	Beijing	National	(g kWh^{-1})
Euro I	2000-1-1	2000-9-1	8.0
Euro II	2003-1-1	2003-9-1	7.0
Euro III	2005-12-30	2007-7-1	5.0
Euro IV	2008-7-1 [a]	2013 [b]	3.5
Euro IV	2012-10-1 [c]	Not available so far	2.0

Note: [a] Only adopted in public fleets including public buses, postal and sanitation vehicles; [b] It was postponed by MEP primarily due to a lack of low sulfur diesel. The most recent update is that the national Euro IV emission standard for HDDVs might be implemented in 2013; [c] Ultra low sulfur diesel that complied with Euro V standard has been delivered in the Beijing market from June 1st, 2012;

Experimental sections and data processing

We conducted the on-road tests in Beijing, during 2008-2010. A total of 135 HDDVs were measured, including 55 heavy-duty diesel buses and 80 diesel trucks, summarized in Table 2. They were recruited from public bus and freight transportation companies in Beijing and considered to represent typical vehicle technology and maintenance conditions in Beijing. Besides, low sulfur diesel was used during those tests that set sulfur content limit at 50 ppm.

For tested buses, almost all samples have a length of 11-12 m and gross vehicle weight (GVW) of 15-18 tons, which are dominant public bus type in Beijing. As those public buses over 8 years are to be phased out from the public bus fleet in Beijing, our bus samples are grouped into 3 emission standard categories, i.e., Euro II, Euro III and Euro IV. For diesel trucks, the latest emission standard adopted in Beijing is Euro III (see Table 1). They are classified into 3 emission standard categories, i.e., Euro I, Euro II and Euro III. As Figure 1 illustrates, those truck samples varied significantly in GVW and displacement. We further classified them into 3 GVW classifications, i.e., HDDT1, HDDT2 and HDDT3, which are consistent with national regulations (see Table 2).

Table 2: Summary of test HDDVs

Vehicle category	GVW (tons)	Emission standard	Sample numbers
Bus	~15-18	Euro II	9
		Euro III	22
		Euro IV	24
HDDT1	3.5≤GVW<4.5	Euro I	8
		Euro II	9
		Euro III	4
HDDT2	4.5≤GVW<12	Euro I	3
		Euro II	6
		Euro III	5
HDDT3	GVW≥12.0	Euro I	11
		Euro II	6
		Euro III	28

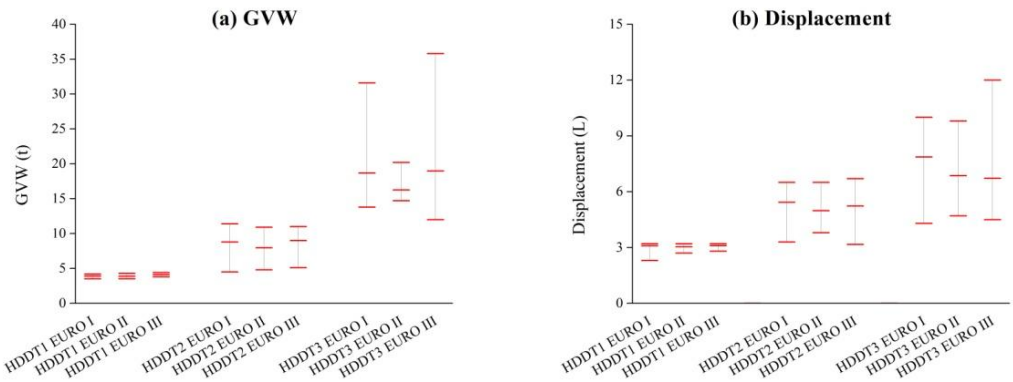

Figure 1: Distribution of (a) gross vehicle weight (GVW) and (b) engine displacement of tested trucks by weight classification and emission standard category.

Two types of PEMS were applied in on-road emission measurement of gaseous pollutants, the Sensor Inc. SEMTECH-D (Liu et al., 2009) and the Horiba OBS-2200 PEMS (Bougher et al., 2010). The SEMTECH-D employs a non-dispersive ultraviolet analyzer to measure NO_X, a

flame ionization detector to measure THC, and a non-dispersive infrared analyzer to measure CO and CO_2. The SEMTECH exhaust flow meter (SEMTECH-EFM) was used to measure the exhaust flow. The OBS-2200 PEMS employs a heated chemiluminescence detector to measure NO_X, a heated flame ionization detector to measure THC, and a heated non-dispersive infrared analyzer to measure CO and CO_2. The flow measurement is conducted with a factory calibrated pitot tube exhaust flow meter in the a tailpipe attachment unit. They have both passed validation testing with laboratory systems for in-use compliance testing and were demonstrated to be both accurate and precise, meeting the CFR Section 40, Part 1065 of U.S. Environmental Protection Agency (EPA) (Durbin et al., 2007; U.S. EPA, 2005). Instantaneous vehicle speed and location data were recorded second-by-second by GPS receivers.

For public buses, the designed test routes in Beijing included both urban and highway (e.g., Fourth Ring Road) driving segments. For trucks, as heavy-duty trucks are not allowed within the Fourth Ring Road during the daytime (i.e., 6 a.m.-23 p.m.), the driving cycles for tested trucks are mainly on and outside Fifth Ring Road. A total of more than 323,000 second-by-second data for trucks and more than 163,000 second-by-second emission profiles coupled with driving condition data for buses were collected. Furthermore, we employed hand-hold GPS receivers to record the driving condition data for more than 1 million seconds on 18 typical bus routes to determine a typical driving cycle for urban buses in Beijing.

Vehicle specific power (VSP) and vehicle speed are selected as two indicators of instantaneous driving conditions with reference to the MOVE model (U.S. EPA, 2009). VSP, defined as the instantaneous power demand by the engine per unit vehicle mass, was first proposed by Jimenez in 1999 and then widely used in vehicle emission models (e.g., the IVE model by U.C. Riverside and the MOVES model by U.S. EPA) (Jimenez, 1999; CE-CERT et al., 2008; U.S. EPA, 2009). In this study, we applied the equation from the MOVES model for VSP calculation by vehicle category, illustrated as Equation 1 (Koupal et al., 2005).

$$VSP = \frac{A}{m} \cdot v + \frac{B}{m} \cdot v^2 + \frac{C}{m} \cdot v^3 + av + gv\sin\theta \quad (1)$$

where m is vehicle weight, tons; v is instantaneous vehicle speed, m s^{-1}; a is instantaneous vehicle acceleration, m s^{-2}; θ is road grade, radians; A is the rolling resistance coefficient, kW s m^{-1}; B is the rotational resistance coefficient, kW s^2 m^{-2}; C is the aerodynamic drag coefficient, kW s^3 m^{-3}. These road-load coefficients (i.e., A, B, and C) by each major HDDV category used in this study are summarized in Table 3. According to the availability of test data in all VSP and vehicle speed sections, we eventually established 22 operating modes as presented in Figure 2, which include a deceleration or braking bin, an idling bin, and 20 bins to represent cruise or acceleration driving modes.

Table 3: Summary of road-load coefficient values for calculating VSP of each major HDDV category

Road-load coefficient	HDDT1	HDDT2	HDDT3	Bus
A/m, kW s m^{-1} ton^{-1}	0.0996	0.0875	0.0875	0.0643
B/m, kW s^2 m^{-2} ton^{-1}	0	0	0	0
C/m, kW s^3 m^{-3} ton^{-1}	0.000542	0.000356	0.000331	0.000279

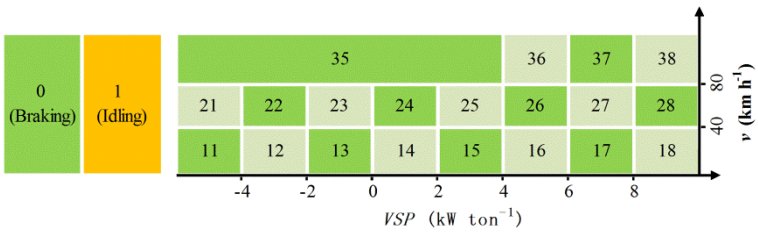

Figure 2: Definition of operating mode bins by using VSP and vehicle speed (v)

The instantaneous emission rates (in g s^{-1}) for each individual sample were collected. Equation 2 summaries the way we calculated the average emission rate for each group by emission standard, GVW and operating mode bin (U.S. EPA, 2009).

$$\overline{ER}_{i,j,k} = \frac{1}{N_i}\sum_1^{N_i}\left(\frac{1}{T_k}\sum_1^{T_k} ER_j\right) \qquad (2)$$

where T_k is the number of second-by-second data for each vehicle in operating mode bin k; N_i is the total number of vehicles in vehicle category i; ER_j is the instantaneous emission rate of pollutant j, g s^{-1}; and $\overline{ER}_{i,j,k}$ is the average emission rate of pollutant j for vehicle category i and operating mode bin k, g s^{-1}.

The distance-specific emission factor in g km^{-1} was further developed based on the average emission rates and time distribution of operating mode bins within a specific driving cycle, as shown in Equation 3.

$$EF_{i,j} = \frac{3600\sum_k(\overline{ER}_{i,j,k}\cdot P_k\cdot T)}{L} \qquad (3)$$

where $EF_{i,j}$ is the emission factor for vehicle category i of pollutant j, g km^{-1}; $\overline{ER}_{i,j,k}$ is the average emission rate of pollutant j for vehicle category i and operating mode bin k, g s^{-1}; P_k is the time percentage of operating mode bin k to the total driving cycle; T is the total time of the driving cycle, s; and L is the total distance of the cycle, km. For comparison with previous studies, we convert the distance-specific emission factors into the fuel mass based NO_X emission factors (g kg fuel $^{-1}$) with Equation 4 (Liu et al., 2009).

$$EF_{NO_X-\text{fuel}} = \frac{EF_{NO_X-\text{distance}}\cdot W_{C\ \text{diesel}}}{0.273EF_{CO_2-\text{distance}}+0.429EF_{CO-\text{distance}}+0.866EF_{THC-\text{distance}}} \qquad (4)$$

where $W_{C\ \text{diesel}}$ is the carbon mass in diesel fuel, 870 g carbon per kg diesel.

Results and discussion

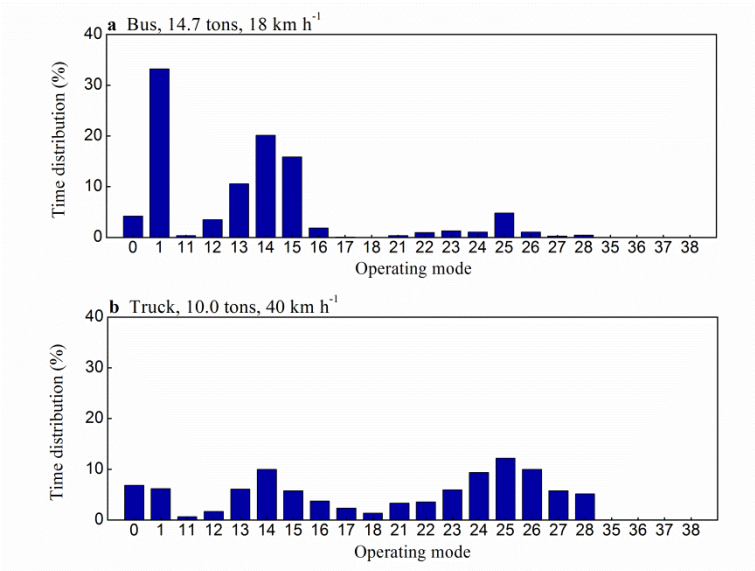

Figure 3: Allocation of time of each operating mode bin to total time of the typical driving cycles for (a) bus and (b) trucks in Beijing.

Figure 4 presents normalized fuel mass based emission factors of NO_X under the typical bus driving cycle for 3 emission standard categories, from Euro II to Euro IV. The NO_X emission limits of certification testing for heavy-duty diesel engines have been significantly tightened (see Table 1). NO_X emission limits under the European Stable Cycle (ESC) for Euro III and Euro IV HDDVs are reduced by 29% and 50%, respectively, relative to Euro II HDDVs. However, the on-road NO_X emission factors for diesel buses in this study did not improve as expected. The average NO_X emission factors (95% CI) for Euro II, Euro III and Euro IV urban buses are 46.0±4.0 g kg^{-1}, 46.6±4.0 g kg^{-1}, and 41.7±5.9 g kg^{-1}, respectively. With one-way ANOVA method, no statistically significant difference in NO_X emission factors has been observed between Euro II and III buses. Even Euro IV buses equipped with an SCR system specifically to control NO_X did not have significantly lower NO_X emission factors than Euro III buses as expected. Furthermore, we obtained detailed real-time engine profiles and exhaust temperature for two Euro IV diesel buses. First, exhaust temperature was lower than 170° C during 29% and 68% of its operating time, respectively. It is a major reason for the unsatisfactory SCR performance of these two buses. Second, the engine speed was below 1400 rpm 85% of the time based on real-time their OBD data regarding engine speed and engine power, which indicates for a majority of the real-world operation the engines worked beyond the ESC control zone. As a result, average fuel mass based and brake-specific NO_X emission factors were 38.3 g kg^{-1} and 8.0 g kWh^{-1}, compared with 3.5 g kWh^{-1} of NO_X emission limit for Euro IV HDDVs. However, those two situations could be frequent symptom, especially when the average speed and load mass of a bus both are low. Therefore, a great challenge remains for bus manufacturers to ensure satisfactory performance of SCR systems for urban transit buses under real-world conditions. Similar results have been also found in Europe. Several on-road PEMS and remote sensing studies for the European fleet also indicated unsatisfactory performance of SCR systems for Euro IV and even Euro V HDDVs in low-speed urban driving circumstances (Carslaw et al., 2011; Velders et al., 2011).

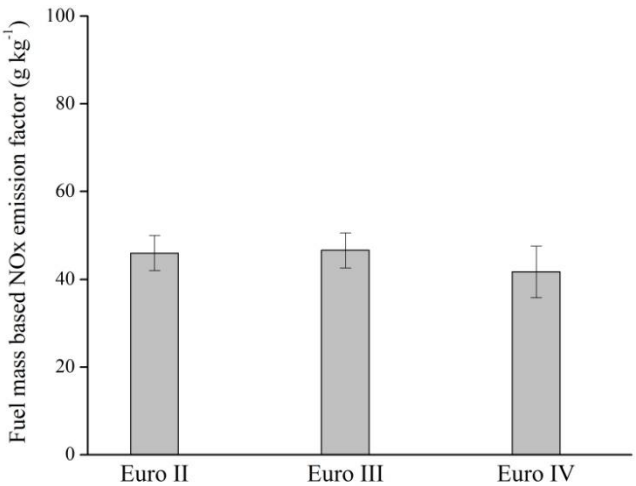

Figure 4: Average fuel mass based NO_X emission factors (95% CI) of diesel buses from Euro II to Euro IV under the typical driving cycles for buses.

Figure 5 shows the on-road fuel mass based emission factors of NO_X under the typical truck driving cycle for three emission standard categories and three vehicle weight classifications. Although distance-specific NO_X emission factors generally increase with gross vehicle weight due to higher powered engines equipped, fuel mass based NO_X emission factors for most truck groups are around 40 g kg^{-1}. For example, the average NO_X emission factors (95% CI) for Euro I, Euro II and Euro III HDDT1 are 39.3±9.6 g kg^{-1}, 37.7±13.9 g kg^{-1}, 27.8±9.7 g kg^{-1}, respectively. For HDDT2 the average NO_X emission factors (95% CI) for Euro I, Euro II and Euro III are 37.9±44.6 g kg^{-1}, 34.6±15.1 g km^{-1} and 41.2±12.9 g km^{-1}, respectively. For HDDT3, the average NO_X emission factors (95% CI) for Euro I, Euro II and Euro III are 47.3±11.8 g km^{-1}, 36.6±10.9 g km^{-1}, 45.9±5.6 g km^{-1}, respectively. The trends in on-road NO_X emission factors with emission standards for HDDTs are similar with diesel buses. For example, from Euro II to Euro III, we found no statistically significant reductions of fuel mass based NO_X emission factors for 3 weight classifications with one-way ANOVA, although NO_X emission limit decreased from 7.0 to 5.0 g kWh^{-1}. As Euro III trucks have penetrated the market of mega cities (e.g., Beijing) since 2006 and nationwide since mid 2007 and Euro IV standards for HDDT were postponed to no sooner

than 2013, Euro III HDDT has become the dominant category in the HDDT fleet, especially in big cities. Therefore, similar to the bus fleet, an update in total NO_X emissions for the HDDT fleet would be expected.

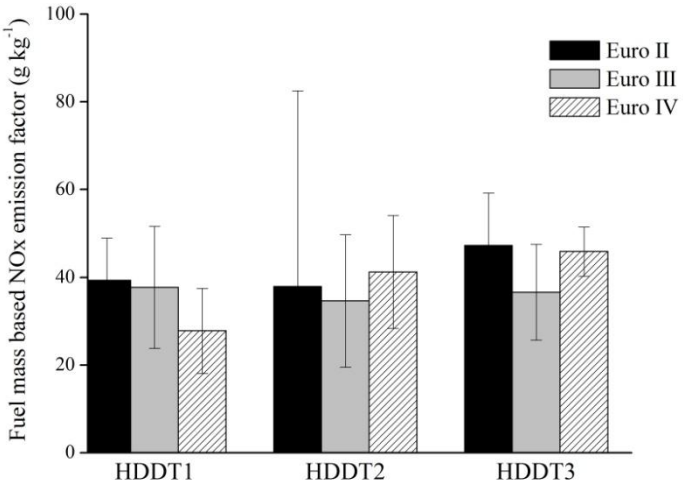

Figure 5: Average fuel mass based NO_X emission factors (95% CI) of HDDTs from Euro I to Euro III under the typical driving cycles for trucks.

We compared our on-road fuel mass based NO_X emission factors for HDDTs in China with other recent results together with estimates by the COPERT4 v7.1 model (Ntziachristos et al., 2009), illustrated as Table 4. Huo et al. (2012) also employed SMETECH-DS PEMS to measure 175 diesel trucks in 5 China's cities, during June 2007-April 2011. Wang et al. (2012) applied a mobile platform to collected on-road emission profiles for more than 400 diesel trucks in Beijing and Chongqing during 2010. The results from those two on-road test programs both match well with our results. Furthermore, two major implications of on-road NO_X emission factors have been point out, which are rather unlike the trends of other pollutants (e.g., CO, THC, $PM_{2.5}$, and Black Carbon, i.e., BC). First, emission certification limits for HDDTs (e.g., Euro III) implemented currently in Beijing and nationwide have very limited impact on NO_X emission control. Second, Beijing-registered HDDTs did not show lower real-world NO_X emission factors than those from other cities or provinces, although Beijing adopted more stringent standards for vehicle emission and fuel quality earlier than national requirements. In addition, our on-road measurement results are generally higher than estimates by the COPERT4 v7.1 model, by ~0-50% on average.

Table 4: Comparison of fuel mass based NO_X emission factors for HDDTs

Vehicle category	Emission standard	Fuel mass based NO_X emission factors (Ave.±SD) ($g\ kg^{-1}$)			
		This study (Ave.±SD)	Huo et al., 2012 (Ave.±SD)	Wang et al., 2012 (1st Q, 3rd Q)	The COPERT4 model [a]
HDDT1	Euro I	39.3±11.5	49±17	Beijing: 38.1-62.5	30.9
	Euro II	37.7±18.1	44±15		34.6
	Euro III	27.8±6.1	36±8	Chongqing Uphill: 36.1-58.0	25.0
HDDT2	Euro I	37.9±17.9	54±14		31.9
	Euro II	34.6±14.4	34±11		35.2
	Euro III	41.2±10.4	49±6	Chongqing downhill: 31.7-48.1	26.3
HDDT3	Euro I	47.3±17.5	50±23		33.4
	Euro II	36.6±10.4	44±25		37.1

Euro III	45.9±14.6	51±15		28.9

Note: [a] Operating conditions for estimation with the COPERT4 model: 50% load coefficient, 0% grade, and 40 km h^{-1} for average speed.

Finally, we made a rough estimate of total NO_X emissions for the national HDDV fleet (not including rural trucks) based on their diesel consumption mass. In 2010, diesel buses (including medium-duty passenger buses) and freight trucks in China were estimated to consume 10.5 million tons and 66.6 million tons diesel (CAERC, 2012). Using statistical data and published reports and papers (CACART and CAAM, 2011, MEP et al., 2011a, NBSC, 2011), we gathered HDDV fleet registration data by major vehicle category and vehicle activity data. We estimated total NO_X emissions for the national HDDV fleet in 2010 are 3.6±0.6 (95% CI) million tons. In particular, diesel buses were estimated to be responsible for 0.53±0.16 (95% CI) million tons NO_X in 2010. Meanwhile, HDDTs contributed 3.0±0.6 (95%CI) million tons NO_X in 2010. We also compare our estimate with official result. For example, MEP reported that national total NO_X emissions from vehicles were 5.4 million tons in 2010, of which diesel vehicles contributed 60%, close to 3.2 million tons (MEP, 2011a). With the data split between the HDDV and light-duty diesel passenger vehicles, we estimate that HDDV contribute roughly 95% of total diesel vehicle NO_X emissions. Thus, the reported NO_X emission data for the HDDV fleet should be around 3.1 million tons. In a word, our new estimate in this study based on fuel mass consumptions indicates a total increment of 0.5±0.6 million tons of NO_X for the national HDDV fleet.

As mentioned earlier, the 12th FYP establishes a control target for NO_X emission reductions of 10% for the period of 2011-2015. Based on our estimated emissions, HDDVs in China contributed 15±3% (95% CI) of national anthropogenic NO_X emissions in 2010 (State Council, 2011). Therefore, HDDVs are a major target sector of NO_X emission mitigation during 12th FYP. We didn't observe the decrease in NO_X emissions from Euro II to Euro III HDDV based on on-road PEMS results, which pose great challenge to NO_X emission control from on-road vehicles. Policy-makers may have to rely on other effective control measures such as promotion of natural gas buses (Wang et al., 2011), the development of an effective in-use compliance testing program and relevant regulations for HDDVs, and the implementation of Euro IV for heavy-duty diesel trucks nationwide (Huo et al., 2012 ; Velders et al., 2012).

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