Emission factors of NOx and PM of heavy construction equipment used in toll road project in Indonesia – Case study: Rembang-Pasuruan Toll Section II

A M Hajji¹, A Yulistyorini¹, Huang Yue² and D C Patulak¹

¹ Civil Engineering Dept., Universitas Negeri Malang, Indonesia
² Institute of Transport Studies, University of Leeds, UK

Abstract. Heavy duty diesel (HDD) equipment play an important role in constructing Indonesian infrastructure. This paper proposes a methodology for recording an emission inventory for HDD equipment that formulates emission factors as a baseline of current emissions quantities. The sample case of the proposed emissions inventory technique is based on a small part of Indonesia’s national toll road project: Rembang-Pasuruan toll road project. Rembang-Pasuruan toll road is a part of Gempol-Pasuruan toll road, a piece of national infrastructure project called Trans-Java Toll road that runs from Merak, Northwestern end of Java, to Banyuwangi, the eastern end of the island. This toll road connects almost all major cities and landmarks of the island with the total length of the road is nearly 1,167 km. The length of Gempol-Pasuruan toll road is about 34.15 km, and consists of three section: Section I, Gempol-Rembang 13.9 km, Section II, Rembang-Pasuruan 6.6 km, and Section III, Pasuruan-Grati 13.65 km. This toll road project utilizes a HDD fleet that includes 9 excavators, 2 bulldozers, 2 roller compactors, 1 motor-grader and 1 paver. This equipment consumes large quantities of diesel fuel and release air pollutants, including nitrogen oxides (NOx) and particulate matters (PM). The proposed inventory technique in this paper addresses the key attributes of the equipment on how long it is used during its operational life and how emission rates of NOx and PM are estimated. By using emission factors calculated from equipment’s key attributes, it is revealed that all equipment in the project release approximately 452.12 gr/hr of NOx or 3400.97 gr/day on average, and emit 31.99 gr/hr of PM or equals to 252.92 gr/day.

1. Introduction

Heavy duty diesel (HDD) equipment play an important role in constructing Indonesian infrastructure. Most of this equipment fleets are owned and operated by public entities, such as local governments and government-owned construction companies, that have limited budgets and are wondering how to acquire, maintain, and update their fleets. Not only does this equipment needs comprehensive fleet management but it also has a significant impact on national energy consumption in the form of diesel fuel, and an impact on the environment in the form of hazardous air pollutants.

This paper proposes a methodology for recording an emission inventory for HDD equipment that formulates emission factors as a baseline of current emissions quantities. The emission inventory technique proposed in this paper can help fleet managers or equipment operator to quantify emissions air pollutants for each individual item of equipment and possibly the entire fleet used in an infrastructure project. Furthermore, this technique can also help some public entities or stakeholders determine strategies to make infrastructure project more environmentally-sound. The sample case of the proposed emissions inventory technique is based on a small part of Indonesia’s national toll road project: Rembang-Pasuruan toll road project. Rembang-Pasuruan toll road is a part of Gempol-Pasuruan toll road, a piece of national infrastructure project called Trans-Java Toll road that runs from Merak, Northwestern end of Java, to Banyuwangi, the eastern end of the island. This toll road connects almost all major cities and landmarks of the island with the total length of the road is nearly 1,167 km. The length of Gempol-Pasuruan toll road is about 34.15 km, and consists of three section: Section I, Gempol-
Rembang 13.9 km, Section II, Rembang-Pasuruan 6.6 km, and Section III, Pasuruan-Grati 13.65 km. This toll road project utilizes a HDD fleet that includes excavators, bulldozers, roller compactors, and pavers. These equipment consume large quantities of diesel fuel and release air pollutants, including nitrogen oxides (NOx) and particulate matters (PM). The proposed inventory technique in this paper addresses the key attributes of the equipment on how long it is used during its operational life and how emission rates of NOx and PM are estimated.

2. Related studies
HDD equipment consumes large amounts of fuel and releases significant quantities of pollutants. The partial load of the HDD engine, which associates with working modes, had the greatest impact on fuel use and emissions rate estimates [1], [2]. By using information regarding working modes and partial loads of the HDD engine, the equipment managers can estimate the energy and environmental impacts of their equipment fleet [3]. Measuring and monitoring real-time emissions will provide practitioners with information to assess environmental impacts and improve the sustainability of construction [4], [5]. Monitoring of the environmental impacts of the use of HDD equipment will also help country’s transportation agencies and boards to plan investigation strategies to reduce emissions from construction and rehabilitation of toll road infrastructures [6-8].

Models and other prediction models have been developed to estimates the emissions from HDD equipment, such as discrete event simulations [9] or regression models from HDD equipment productivity rate [10]. Some case studies are also conducted in observing construction activities associated with the emission potentials [11], [12]. The estimates of emissions released by HDD equipment can also be predicted during planning stage of the project. In this stage, the estimates of emissions can be taken off from construction project scope, engineering schedules, working volumes, or specifications [13-17].

3. Method
To develop an emission inventory of NOx and PM, the key attributes of selected HDD used in the project were collected. According to the EPA Construction Fleet Inventory Guide [18], these attributes included equipment type, engine model year, engine horsepower, and annual activity. In addition to these attributes, this inventory techniques also takes into account the engine tier classification; engine tier classifications - a hybrid attribute based on horsepower rating and model year - were identified. Engine tiers are emissions standards adopted by EPA for all new nonroad diesel engines [18].

In order to develop the inventory for Rembang-Pasuruan toll road project, emission factors of HDD fleet were needed. These factors are approximations of the amount of pollutants emitted by a particular type of equipment during a unit of use. The factors used for this inventory were based on calculations and the methodology employed by the EPA NONROAD model. For pollutants, emission factors are reported in grams per horsepower-hour (g/hp-hr). For NOx, HC, and CO, the emission factor for a specific type of nonroad equipment with a particular model year and age is calculated as follows:

\[ EF_{adj}(NOx) = EF_{ss} \times TAF \times DF \]

where:
- \( EF_{adj} \) = final emission factor used in NONROAD, after adjustments for transient operation and deterioration (g/hp-hr)
- \( EF_{ss} \) = zero-hour, steady-state emission factor (g/hp-hr)
- \( TAF \) = transient adjustment factor (unitless)
- \( DF \) = deterioration factor (unitless)

The zero-hour, steady-state emission factor (\( EF_{ss} \)) is a function of the engine’s model year and horsepower rating, which defines the engine tier category. Transient adjustment factors are applied to Tier 0, 1, 2, and 3 engines but are not applied to Tier 4 engines because transient emission controls will be a part of all Tier 4 engine design considerations. Transient adjustment factors are calculated as the ratio of the transient emission factor to the corresponding steady-state emission factor and may be greater than or less than 1.0. Deterioration factors are used to account for increases in emissions over
time above a new engines base emission level. Emissions may increase over time for numerous reasons including engine wear, poor maintenance, or modification of emission control systems. Emissions performance typically deteriorates at a slow rate for well-maintained engines but rapidly for poorly-maintained engines [18], [19].

Since PM emissions are dependent on the sulfur content of the fuel consumed by the engine, the equation for the PM emission factor is modified from Equation 1 as follows:

\[ EF_{adj} (PM) = EF_{ss} \times TAF \times DF - S_{PMadj} \]  

(2)

where:

\[ S_{PMadj} = \text{adjustment to PM emission factor for variations in fuel sulfur content (g/hp-hr)} \]

For BSFC (or fuel use factor), deterioration factors are not applied, thus, the equation is simplified as follows:

\[ EF_{adj} (BSFC) = EF_{ss} \times TAF \]  

(3)

The engine rated horsepower is the maximum level of power that an engine is designed to produce at its rated engine speed. Nonroad equipment seldom operates at its rated power for extended periods and frequently operates at a variety of speeds and loads. NONROAD uses a load factor \( (LF) \) to indicate the average proportion of rated power used to account for the effects of operation at idle and partial load conditions. For example, a 100 hp engine with a load factor of 0.3 (or 30%) will produce an average of 30 hp over the course of normal operation. Depending on equipment usage patterns, load factors may vary widely for nonroad engines and can be difficult to quantify. Since equipment usage patterns for Rembang-Pasuruan toll road project were not observed or measured, the NONROAD model default load factors were used. The NONROAD model also provides default values for average annual activity for many types of equipment; however, the default values were not used here. For the Rembang-Pasuruan project fleet, average annual activity was determined based on the total usage divided by the age of the equipment. This information was obtained from the fleet management database as well as field data collection; thus, the emissions results presented here are specific to the project fleet.

4. Results

The nonroad HDD fleet used in Rembang-Pasuruan Section II toll road project consists of 15 units, including nine excavators, two bulldozers, one motor grader, and two roller compactors, and one paver. The individual equipment attributes of each unit is provided in Table 1.

Of the 15 HDD equipment used in the project, 80% are categorized as new equipment manufactured in 2008-2015, 13% made in 2005-2007, and only 1% (one roller compactor) released by the factory in 2000-2004. As for the engine size, 53% HDD equipment have 100-175 HP, 27% equipped with 175-300 HP of engine, 13% between 50-75 HP, and only one HDD equipment has 76-100 HP (one excavator). Based on the model year and engine size, the majority of HDD equipment deployed in the project or 53% are categorized as Tier 4 engine (8 equipment), 40% at Tier 3, and 7% (one roller compactor) at Tier 1. The newest HDD equipment in the project is 54 HP excavator, which is manufactured in 2015 (Tier 4), while the oldest one is 131 HP roller compactor, which is produced in 2002 (Tier 1).

As displayed in Table 2, following the EPA NONROAD’s estimates of cumulative hours, all HDD equipment have an accumulated total activity of 130,370 hours. While observed at the odometer reading of each equipment, the total accumulated total activity of those 15 HDD equipment is 84,203 hours. The oldest equipment, a 131 HP roller compactor does not have the longest hours of activity, which is only 6,420 hours during its operational age, compared to the activity hours estimated by the EPA NONROAD (13,680 hours). The newest equipment, a 54 HP excavator has longer activity hours (7,093 hours) compared to those estimated by the EPA NONROAD (5,460 hours). The other HDD equipment which have longer activity hours than its estimates are 148 HP and 156 HP excavators. Some equipment are also found rarely used in its operational age compared to its estimate hours, they are 147 HP (2010
model), 201 HP, 268 HP, and 91 HP excavators, all two bulldozers and roller compactors, and one motor grader. The total activity hours for paver is not available.

### Table 1. HDD fleet in Rembang-Pasuruan Section II

| Equipment Type | Make       | Type       | Horsepower (hp) | Model year | Engine Tier |
|----------------|------------|------------|-----------------|------------|-------------|
| Excavator 1    | Komatsu    | PC200      | 147             | 2010       | 3           |
| Excavator 2    | Komatsu    | PC490LC    | 201             | 2013       | 4           |
| Excavator 3    | Kobelco    | SK330      | 268             | 2014       | 4           |
| Excavator 4    | CAT        | 312E       | 91              | 2014       | 4           |
| Excavator 5    | Hyundai    | R220-9SH   | 148             | 2014       | 4           |
| Excavator 6    | Komatsu    | PC200      | 147             | 2010       | 3           |
| Excavator 7    | Komatsu    | PC78US     | 54              | 2008       | 3           |
| Excavator 8    | Komatsu    | PC78UU     | 54              | 2015       | 4           |
| Excavator 9    | Sumitomo   | SH210      | 156             | 2014       | 4           |
| Bulldozer 1    | Komatsu    | D65PX      | 207             | 2008       | 3           |
| Bulldozer 2    | Komatsu    | D68ESS     | 174             | 2007       | 3           |
| Motor grader 1 | Komatsu    | GD511A     | 135             | 2013       | 4           |
| Roller Compactor 1 | Dynapac | CA25       | 131             | 2002       | 1           |
| Roller Compactor 2 | Ingersroll Rand | SD1000 | 124             | 2008       | 3           |
| Paver 1        | Wirtgen    | SP500      | 176             | 2015       | 4           |

### Table 2. Cumulative hours of HDD fleet in Rembang-Pasuruan Section II

| Equipment Type | Horsepower (hp) | Model year | Engine Tier | Cumulative hours | Odometer hours |
|----------------|-----------------|------------|-------------|------------------|----------------|
| Excavator 1    | 147             | 2010       | 3           | 10920            | 1578           |
| Excavator 2    | 201             | 2013       | 4           | 7644             | 1398           |
| Excavator 3    | 268             | 2014       | 4           | 6552             | 1092           |
| Excavator 4    | 91              | 2014       | 4           | 6552             | 1491           |
| Excavator 5    | 148             | 2014       | 4           | 6552             | 9661           |
| Excavator 6    | 147             | 2010       | 3           | 10920            | 4606           |
| Excavator 7    | 54              | 2008       | 3           | 13104            | 14876          |
| Excavator 8    | 54              | 2015       | 4           | 5460             | 7093           |
| Excavator 9    | 156             | 2014       | 4           | 6552             | 23210          |
| Bulldozer 1    | 207             | 2008       | 3           | 10788            | 2805           |
| Bulldozer 2    | 174             | 2007       | 3           | 11687            | 3354           |
| Motor grader 1 | 135             | 2013       | 4           | 6734             | 1829           |
| Roller Compactor 1 | 131     | 2002       | 1           | 13680            | 6420           |
| Roller Compactor 2 | 124     | 2008       | 3           | 9120             | 4790           |
| Paver 1        | 176             | 2015       | 4           | 4105             | 0              |

Table 3 presents a summary of emissions inventory of NOx and PM for HDD equipment fleet deployed in Rembang-Pasuruan Section II toll road project. The emission factors (EF) are shown for each item of equipment, along with the total emission rates (per-hour and per-day) of each unit. By using emission factors calculated from equipment’s key attributes, it is revealed that all equipment in the
project release approximately 6,377 grams per-hour or 51,015 grams of NOx per-day, and 480 grams of PM per-hour, which equals to 3,839 grams per-day.

**Table 3. Emission factors and emission rates of NOx and PM of HDD fleet in Rembang-Pasuruan Section II**

| Equipment Type | HP | Model year | EF NOx (g/hp-hr) | EF PM (g/hp-hr) | NOx (gr/hr) | NOx (gr/day) | PM (gr/hr) | PM (gr/day) |
|----------------|----|------------|-----------------|----------------|-------------|--------------|------------|-------------|
| Excavator 1    | 147| 2010       | 2.629           | 0.513          | 386.42      | 3091.37     | 75.47      | 603.78      |
| Excavator 2    | 201| 2013       | 2.620           | 0.000          | 526.64      | 4213.12     | 0.00       | 0.00        |
| Excavator 3    | 268| 2014       | 2.617           | 0.000          | 701.42      | 5611.34     | 0.00       | 0.00        |
| Excavator 4    | 91 | 2014       | 3.141           | 0.000          | 285.80      | 2286.41     | 0.00       | 0.00        |
| Excavator 5    | 148| 2014       | 2.617           | 0.000          | 387.35      | 3098.80     | 0.00       | 0.00        |
| Excavator 6    | 147| 2010       | 2.629           | 0.513          | 386.42      | 3091.37     | 75.47      | 603.78      |
| Excavator 7    | 54 | 2008       | 3.161           | 0.504          | 170.71      | 1365.70     | 27.05      | 216.37      |
| Excavator 8    | 54 | 2015       | 3.137           | 0.012          | 169.41      | 1355.28     | 0.67       | 5.34        |
| Excavator 9    | 156| 2014       | 3.141           | 0.000          | 489.95      | 3919.56     | 0.00       | 0.00        |
| Bulldozer 1    | 207| 2008       | 2.628           | 0.342          | 544.07      | 4352.58     | 70.71      | 565.66      |
| Bulldozer 2    | 174| 2007       | 2.631           | 0.528          | 457.75      | 3661.98     | 91.92      | 735.32      |
| Motor grader 1 | 135| 2013       | 2.618           | 0.000          | 353.39      | 2827.12     | 0.00       | 0.00        |
| Roller Compactor 1 | 131| 2002     | 5.593           | 0.605          | 732.63      | 5861.00     | 79.22      | 633.77      |
| Roller Compactor 2 | 124| 2008     | 2.624           | 0.479          | 325.37      | 2602.99     | 59.35      | 474.78      |
| Paver 1        | 176| 2015       | 2.611           | 0.000          | 459.50      | 3676.00     | 0.00       | 0.00        |

On an individual basis, all Tier 4 engines (201 HP, 268 HP, 91 HP, 148 HP, 54 HP, and 156 HP excavators) emits very low or zero PM emission. Meanwhile, two oldest equipment (174 HP bulldozer and 131 HP roller compactor) release the highest PM emissions, which are 735 grams and 634 grams per day respectively. It shows that the newer the engine, the Tier level will be higher, and the PM emissions will be lower. The same proof is also shown in NOx emissions. 131 HP roller compactor release the highest NOx emission rate, which is 5,861 grams per-day. High NOx emission rate is also occurred at the biggest engine size (268 HP excavator), which is 5,611 grams per-day. It shows that the emission rate of NOx is not only determined by the age of equipment, but also the size of the engine. The other case is 207 HP bulldozer, which also emits significantly high NOx emission per-day (4,353 grams). The lowest emission rate of NOx is released by the newest equipment with the smallest engine size (54 HP excavator 2015 model), which is 1,355 grams per-day.

5. Conclusions
The toll road project of Rembang-Pasuruan Section II has a substantial fleet of nonroad HDD equipment with respect to the diversity and total number of units, annual activity, and emissions of NOx and PM. The environmental inventory methodology presented is this paper was successful at quantifying the fleet emissions by using the data that was available from the data that was collected by visual inspection from the actual equipment. By examining the results of environmental inventory, it is possible to determine which equipment subgroups, as well as which individual equipment units, are responsible for the most pollutants emitted. For example, roller compactor and bulldozer rank first and second, respectively, in NOx and PM emissions based on equipment type. This type of information is useful in identifying which equipment has the highest environmental impacts and can be used as a new metric for fleet management decisions.

6. References
[1] Lewis P, Fitriani H, Arocho I 2015 *Transportation Research Record*. 2482 (1) 8-15.
[2] Cao T, Durbin, TD, Russell, RL, Cocker III DR, Scora G, Maldonado H, Johnson KC 2016 *Atmospheric environment*. 147 234-245.

[3] Lewis P, Rasdorf W 2016 *Journal of Management in Engineering*. 33 (2) 04016038.

[4] Heidari B, Marr LC 2015 *Journal of the Air & Waste Management Association*. 65 (2) 115-125.

[5] Hajji AM, Muladi, Larasati A 2016 *AIP Conference Proceedings*. 1778 (1) 030008.

[6] Quiros DC, Thiruvengadam A, Pradhan S, Besch M, Thiruvengadam P, Demirgok B, Hu S 2016 *Emission Control Science and Technology*. 2 (3) 156-172.

[7] Ma F, Sha A, Lin R, Huang Y, Wang C 2016 *International journal of environmental research and public health*. 13 (3) 351.

[8] Kar SS, Behl A, Shukla A, Jain PK 2015 *J. Civil Environ. Eng*. 5 (198).

[9] Lim Sawasd C, Athigakunagorn N 2017 *Engineering Journal*. 21 (7) 197-211.

[10] Hajji AM, Lewis MP, Larasati A 2017 *AIP Conference Proceedings*. 1887 (1) 020051.

[11] Wang X, Duan Z, Wu L, Yang D 2015 *Journal of Cleaner Production*. 103 705-714.

[12] Liu Y, Wang Y, Li D 2017 *Journal of cleaner production*. 144 337-346.

[13] Park JY, Lee DE, Kim BS 2016 *KSCE Journal of Civil Engineering*. 20 (6) 2162-2169.

[14] Lim TK, Gwak HS, Kim BS, Lee DE 2016 *KSCE Journal of Civil Engineering*. 20 (4) 1211-1220.

[15] Rasdorf W, Lewis P, Arocho I, Hummer J 2015 *Smart and Sustainable Built Environment*. 4 (3) 315-328.

[16] Setiawati A, Prasetyo SCA, Hatmoko JUD, Hidayat A 2015 *Jurnal Karya Teknik Sipil*. 4 (1) 83-92.

[17] Wirahadikusumah RD, Sahana HP 2012 *Journal of Civil Engineering*. 19 (1) 25-36.

[18] EPA 2010 Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling - Compression Ignition.

[19] Hajji AM, Lewis P 2013 *Smart and Sustainable Built Environment*. 2 (1) 84-100.

**Acknowledgement**

The authors express gratitude to the Institute of Research and Community Services, Universitas Negeri Malang for their generousness and cooperation in providing research fund and management in order to complete this study.