Correlation Model of Horizontal Geometric and Road Grade on CO_2 and $PM_{2.5}$ Vehicle Emission In Bandung City

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ABSTRACT

Based on the GHG and MVP Report in 2018, the transportation sector has become the second largest contributor of GHG emissions in Indonesia. Efforts to reduce emissions have been made, but still focus on improving the transportation mode which are still less optimal. Some researchers have proposed ideas that the design of road infrastructure could also contribute in reducing vehicle emissions. This was confirmed by some correlation models that show the impact of the road geometric on vehicle emissions. This study aims to estimate the value of vehicle emission based on the geometric conditions of urban roads in Indonesia. The estimation of vehicle emission is conducted using a correlation model that has been developed by other researcher in other country which then compared with emission standards in Indonesia. Road geometric data are obtained by remote sensing method from Digital Elevation Model (DEM) database. The analysis conducted are evaluation of vehicle emission compliance and conformity of road geometric to some regulations. The results of the analysis indicate that the geometric conditions of urban roads in Bandung also affect the production of CO_2 and $PM_{2.5}$ vehicle emissions and have the same pattern as previous studies. Some of the results and the reviewed road samples exceed the applicable standards. The results of this study can be used as a basic idea about the importance of establishing the road technical provisions on environmental impacts in urban roads geometric planning guidelines in Indonesia and to contribute on government program to reduce GHG emissions by 41% in 2030.

Keywords: emission, horizontal geometric, road grade, carbon deoxide (CO_2), *particulate matter 2.5* ($PM_{2.5}$)

1. INTRODUCTION

The transportation sector has become one of major impact on the environment, mainly due to the use of fossil fuel which is the main cause of air pollution in urban areas [1]. This is supported by Greenhouse Gas Inventory and Monitoring, Reporting and Verification Report in 2018 published by the Ministry of Environment and Forestry regarding the level of Greenhouse Gasses (GHG) emissions in the energy sector.

From 2000 to 2017 emissions from transportation sector increased every year and it ranks second largest contributor of GHG emissions [2]. From all of the transportation sub-sectors, roads generate enormous energy consumption, which is 90.7% of energy consumption [3]. This shows the efforts are less optimal, especially the National Action Plan-

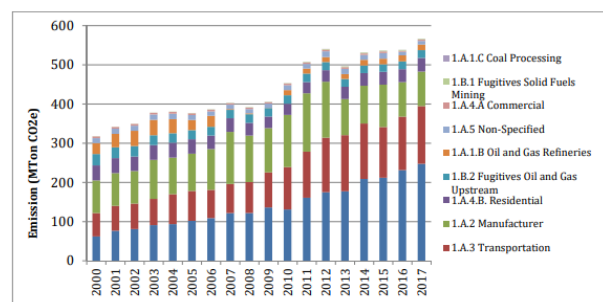Greenhouse Gasses [4] in reducing vehicle emissions on the road.

Figure 1 GHG Emission Level based on Sub-Sector Activities of Energy Sector from 2000 - 2017

Besides CO_2, there are other air pollutants produced by motor vehicles, it is particulate matter < 2.5 µm ($PM_{2.5}$).
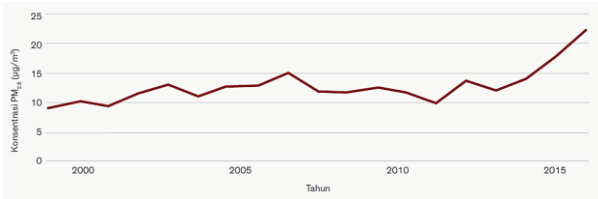
Figure 2 Indonesia's annual average PM$_{2.5}$ Concentration, 1998 - 2016

From 1998 to 2016, PM$_{2.5}$ concentrations increased from 8 μg/m^3 to 22μg /m^3 [5]. This number exceeds the ambient air quality standard listed in regulation for PM$_{2.5}$ measured in one year which is 15 μg/m^3 [6].

The government has tried to reduce the level of emissions by set regulations and mitigation strategies in the RAN-GRK. However, the entire strategy that has applied only focus on transportation mode, while road infrastructure control was given less attention. Whereas designing road infrastructure could also contribute to vehicle emissions if it is designed by considering road technical provisions, one of them is road geometric. In Spain and America researches about the impact of road geometric on emission has been carried out and produced correlation model [7,8].

Castello et al. [7] studied the impact of road horizontal alignment on CO$_2$ emissions produced by passenger cars and the results show that vehicles produce more CO$_2$ emission at road with higher Curvature Change Rate (CCR). High CCR values indicate that the road segment is mainly constituted by sharp curve and more curves than another road with lower CCR, thus allowing drivers to perform at higher speeds without heavy accelerations.

Beside horizontal geometry, another road geometric component that affect vehicle emissions is the road grade. Research related to these variables was developed by Liu et al. [8] which resulted a polynomial relationship between the road grade and PM$_{2.5}$. The increase of road grade causes higher production of PM$_{2.5}$ vehicle emission. From the result, it is necessary to know further the relationship between road grade and vehicle emission in Indonesia.

In terms of geographical conditions, Indonesia has various topographical conditions from lowlands, hills and mountains which require the road design should follow topographic conditions. Including in Bandung City, considering that several areas are hilly with slope between 3 to 25%. With this geographical condition, several roads in Bandung potentially produce higher vehicle emission compared to other cities or relatively flat areas.

Studies about the impact of road geometric on vehicle emissions has been started and developed in other countries. While in Indonesian urban roads, especially in Bandung city, there has never been a modelling or testing of the correlation model between road geometric and vehicle emission.

1.1. Related Research

In Indonesia, studies related to vehicle emissions and road technical provisions have been carried out, these are the effect of: vehicle growth [1] , vehicle operation [9], degree of saturation [10] and road surface conditions [11], but correlation between road geometric and vehicle emission has never been developed.

There are researches in several countries show that vehicle emission production also affected by horizontal geometric [7,12]. One of the studies conducted by Castello et al. in Spain concluded that CO$_2$ emissions increase when the curvature change rate (CCR) increases. CCR is defined as the number of bend angles divided by the road distance. A low CCR value indicates that the road segment character is dominated by straight sections and flat curves so that the driver can drive at a higher speed without heavy acceleration. Speed data collected using GPS, which is then processed into actual individual second-by-second speed profiles. To estimate CO$_2$ emissions, Castello using the VT-Micro microsimulation model which predicts the emissions of each vehicle. Vehicle type simulated in this study is only light duty vehicles (LDV) / passenger car.

In United States, Liu et al. [8] studied about the effect of longitudinal road grade on PM$_{2.5}$ emissions in highway. There are several variables for developing model correlation. The road grade data were obtained by processing the height of the road profile from a high resolution (1/27 arc-sec) digital elevation model (DEM) database. The DEM data were obtained from the 3-Dimensional Elevation Program (3DEP) and LIDAR. The data was collected by placing GPS on the test vehicle to obtain the second-by-second vehicle track and speed-acceleration joint distribution (SAJD) data, or real-world vehicle activity. The calculation of PM$_{2.5}$ emissions in this study using Motor Vehicle Emission Simulator (MOVES) which is based on speed and driving patterns.

1.2. Objective

The purpose of this study is to estimate the value of emissions based on the geometric conditions of urban roads in Indonesia using a correlation model that has been developed in another countries, then compare these results with emission standards in Indonesia. This research also provides knowledge and also contribute to the Ministry of Environment and Forestry program on the implementation of adaptation-mitigation programs and strategies to reduce GHG emissions by 41% in 2030 according to the Republic of Indonesia's First Nationally Determined Contribution (NDC) in 2017.

2. BACKGROUND

2.1. Methodology

Several correaltion models of road geometric and vehicle emissions which has developed abroad were adopted in the study areas. Road geometric characteristic data obtained by road measurement and remote sensing integration method from the DEM database. The analysis conducted are evaluation of vehicle emission compliance to Minister of Environment and Foresty Regulation Number 12/2010 [6], latest vehicle emission regulation Number 20/Setjen/Kum.1/3/2017 [13] and conformity of road geometric to RSNI T-14-2004 [14].

2.1.1. Road Geometric Data

This study was conducted by identifying 15 segments of urban roads in Bandung that have different horizontal geometric characteristics with flat terrain and each sample ranged from 1 to 9 km. The road classification for horizontal geometric sample was chosen to represent arterial, collector, and local roads. Data related to the road grade was obtained by taking 5 road samples that have different gradient value ranged from 3% to 10%.

Every road samples was characterized by geometric component: L – length (m), CCR (gon/km), AR – Average radius (m), $Rmax$ – maximum radius (m), $Rmin$ – minimum radius (m), g(+) – average positive grade (%), g(-) – average negative grade (%), W – width (m) and Δh – height (m).

Table 1. Horizontal geometric road sample characteristics

Road	Function	Sample	L	CCR	AR	Rmax	Rmin	g(+)	g(-)
Ahmad Yani		1.1	4752.039	0.099	2000	2000	2000	0.7	-0.5
A.H. Nasution	Primary Arterial	1.2	8387.378	61.267	452	3000	100	1.4	-1.3
PHH Mustofa		1.3	3352.389	50.637	570	3000	90	1.7	-0.7
Sukarno Hatta		1.4	5723.022	2.373	3500	3500	3500	0.8	-1.8
Trs. Buah Batu		2.1	4741.231	13.389	790	2000	250	1.0	-0.8
LLRE Martadinata	Primary collector	2.2	2648.386	60.346	482	1000	200	1.6	-0.8
Leuwipanjang		2.3	2799.086	139.299	200	600	50	1.1	-0.4
BKR – Pelajar Pejuang	Seconday arterial	3.1	7364.874	42.221	444	1500	90	0.8	-0.8
Ir. H. Djuanda		4.1	2306.424	82.222	284	800	100	3.1	-1.4
Tubagus Ismail		4.2	2567.043	176.543	282	1160	40	1.2	-2.9
Dipatiukur	Secondary collector	4.3	1624.170	106.929	363	800	100	2.6	-0.8
Cemara		4.4	1249.707	351.534	61	100	40	3.0	-1.5
Antapani Lama		4.5	1340.227	384.702	106	40	31	0.8	-1.8
Cibodas Raya		4.6	1735.949	276.894	73	200	18	0.7	-1.4
Kapten Tatanegara	Local	5.1	1695.506	227.111	185	500	31	1.2	-2.2

Table 2. Road gradient sample characteristics

Road	Sample	Road Function	W	L	Δh	g(+)
Gegerkalong Hilir	1	Collector	6.0	95.0	2.800	2.95
Ciumbuleuit	2	Collector	6.5	130.0	5.966	4.50
Siliwangi	3	Collector	10.0	138.8	8.529	6.15
Tubagus Ismail	4	Collector	6.6	70.0	7.800	8.19
Lemahnendeut	5	Collector	6.0	50.0	5.729	10.57

2.1.2. Emission Model

Research of the horizontal geometric effect on CO_2 emissions that developed by Castello [7] and Nobili [12]

defined several correlation models based on LDV vehicle types (Table 3). Research about the road grade effect on $PM_{2.5}$ emissions by Liu [8] defined correlation

model on light vehicles and heavy vehicles with two variations of average speed at 30 km/h and 100 km/h (Table 4).

Table 3. CO_2 emission model based on horizontal geometric by Castello, 2018 and Nobili, 2019

Vehicle type	Model	R^2
Castello, 2018		
LDV 3	$E_{CO_2} = 141{,}45 + 0{,}0553 \cdot CCR$	0.6962
LDV 4	$E_{CO_2} = 132{,}25 + 0{,}0419 \cdot CCR$	0.6673
Nobili, 2019		
LDV 3	$E_{CO_2} = 0.0553 \cdot CCR_C + 137.93$	0.790
LDV 4	$E_{CO_2} = 0.0444 \cdot CCR_C + 129.19$	0.770
Where E_{CO_2} is CO_2 emission rate (g/km) ; CCR is the Curvatura Change Rate (gon/km) ; R is correlation value		

Table 4. $PM_{2.5}$ emission model based on road grade

Speed	Model	R^2
Light Vehicle		
30	$E_{PM_{2.5}} = 0.0002\,g^2 + 0.0023\,g + 0.00373$	0.9918
100	$E_{PM_{2.5}} = 0.0037\,g^2 + 0.0253\,g + 0.1055$	0.9915
Heavy Vehicle		
30	$E_{PM_{2.5}} = 0.0050\,g^2 + 0.0672\,g + 0.4154$	0.9995
100	$E_{PM_{2.5}} = 0.0153\,g^2 + 0.1026\,g + 0.4890$	0.9854
Where $E_{PM_{2.5}}$ is $PM_{2.5}$ emission rate (g/h) ; g is the road grade (%) ; R is correlation value		

2.2. Result

The analysis was built by comparing the calculated emissions from the adopted model with applicable emission quality standards in Indonesia. The latest regulations regarding vehicle emission threshold is regulation No. 20 / Setjen / Kum.1 / 3/2017 [13] or better known as the EURO IV Emission Standard.

2.2.1. Impact of horizontal geometry on CO_2 vehicle emission

Horizontal geometric is composed of various components, therefore to know the horizontal geometric correlation with emission, it is necessary to select component that represent horizontal geometric characteristics. According to Castello [7] CCR is a variable that clearly and has a strong relationship with CO_2 emissions. The results of CO_2 emissions calculated by Castello model correlation in each sample for various vehicles type can be seen in Table 5.

Table 5. CO_2 emission rate on each road sample

Sample	CCR	CO_2 (g/km)	
		LDV3	LDV4
1.1	0.099	141.46	132.25
1.2	61.267	144.84	134.82
1.3	50.637	144.25	134.37
1.4	2.373	141.58	132.35
2.1	13.389	142.19	132.81
2.2	60.346	144.79	134.78
2.3	139.299	149.15	138.09
3.1	42.221	143.78	134.02
4.1	82.222	146.00	135.70
4.2	176.543	151.21	139.65
4.3	106.929	147.36	136.73
4.4	351.534	160.89	146.98
4.5	384.702	162.72	148.37
4.6	276.894	156.76	143.85
5.1	227.111	154.01	141.77

Notes: : exceed the emission threshold

In Regulation [13], CO_2 emission threshold has not been regulated. However regulation [6] stated that cars produce 3180 gCO_2/kg of fuel. If assumed that the specific gravity of the fuel (pertalite) is 0.742 kg/liter and the average car fuel consumption is 12.8 km/liter [15], then 3180 gCO_2/kg of fuel is equivalent to 184.3 gCO_2/km. As a comparison, the Japan Light-Duty Passenger emission target in 2010 which is 153.8 gCO_2/km was also used, considering that Japan was the largest exporter of motorized vehicles in Indonesia from 1990 - 2012 [16].
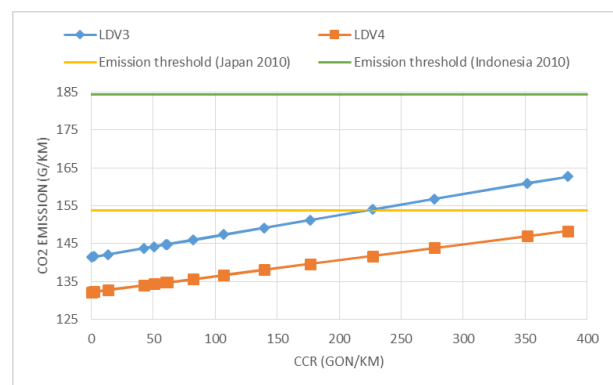

Figure 3 Correlation between CO_2 and CCR

2.2.2. Impact of road grade on $PM_{2.5}$ vehicle emission

The traffic conditions was under uncongested conditions so the driver could operate more "gently" on each road grade. Referring to Liu's research, the

relationship between road grade and PM$_{2.5}$ emissions was tested when the vehicle operates on average speed at 30 km/h and 100 km/h without slowing down due to the other vehicle activities.

Latest regulation [13] in Indonesia only list the PM emissions threshold for various categories of vehicles (diesel) ranged between 0.025 to 0.060 g/km, but further provision about PM$_{2.5}$ threshold is not listed. As comparison, this study uses the average of PM$_{2.5}$ emission for each type of vehicle on each speed operation developed by Rabl & Nazelle [17] which refers to EURO IV. Average PM$_{2.5}$ produced by light vehicle is 0.0117 g/km (at 30 km/h) and 0.009 g/km (at 100 km/h). While for heavy vehicle is 0.0463 g/km (at 30 km/h) and 0.02207 g/km (at 100 km/h)

**Table 6.** PM$_{2.5}$ emission rate on each road sample

Sample	g(+)	PM$_{2.5}$ (g/km)			
		Light Vehicle		Heavy Vehicle	
		30km/h	100km/h	30km/h	100km/h
1	2.95	0.0015	0.0021	0.0219	0.0092
2	4.50	0.0017	0.0029	0.0273	0.0126
3	6.15	0.0020	0.0040	0.0339	0.0170
4	8.19	0.0023	0.0056	0.0434	0.0236
5	10.57	0.0028	0.0079	0.0561	0.0328

Notes: ▭ : exceed the average PM$_{2.5}$ vehicle emission

It is known that PM$_{2.5}$ emission increase along with the road grade value. But beside road grade, the vehicle operating differences expressed in speed also have significant impact on emission. At the study areas, known that light vehicle doesn't exceed the average PM$_{2.5}$ value produced by vehicle. However based on calculation, when heavy vehicle operated at road grade $\geq$ 8% at both speed operation, the emission exceed the average PM$_{2.5}$ value.
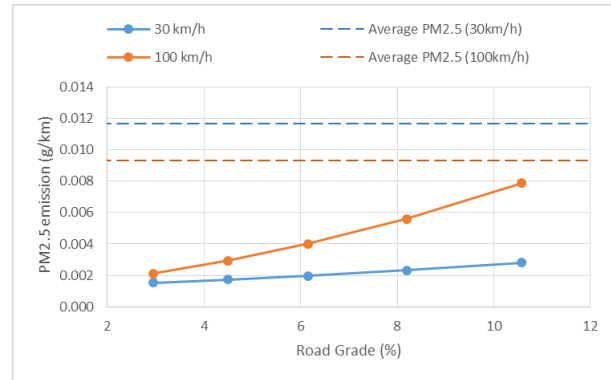
(a) Light Vehicle
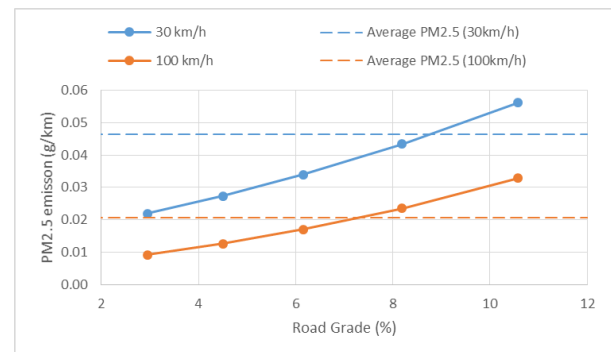
(b) Heavy Vehicle

**Figure 4** Correlation between PM$_{2.5}$ and road grade

2.2.3. Road geometric conformity with RSNI-T-14-2004

According to RSNI [14] there are two kinds of compound horizontal curves, named unidirectional curve and reverse-direction curve. In designing horizontal geometric roads, there are two provisions for multiple curve: for unidirectional curves, the length of tangent section between two curves shall be $\geq$ 20 m; and in reverse-directional curve, the length of tangent shall be $\geq$ 30 m.

From the identification results, there are some location that don't meet the requirement: in sample 4.4 there are two locations; in sample 4.5 there are four locations; in sample 4.6 there are three locations; and in sample 5.1 there are four locations. Incoformity of minimum tangent length and high number of curves in a road segment might be the causes of high CCR value which has an impact on the emission production. Figure 5 show several locations with tangent length below the regulated provision value.

(a) Tangent length < 30 meters at sample 4.5
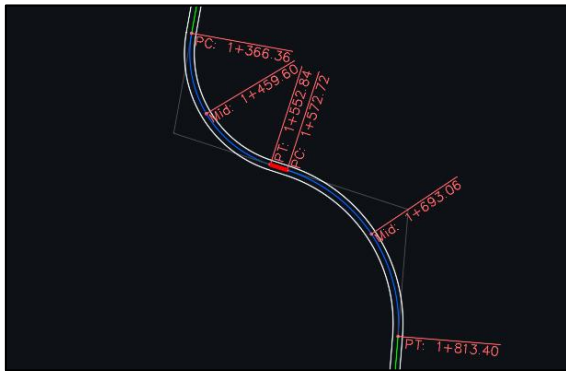
(b) Tangent length < 30 meters at sample 5.1

Figure 5 Nonconformity of compound curves

Figure 6 Sample 5 (secondary collector) with road grade at 10.57%

According to standard [14] stated that urban roads with speed design ≤ 40 km/h the road grade set maximal 10%. Meanwhile, on the reviewed location in the sample 5 (secondary collector) it exceed the technical provisions of road gradients at 10.57%. Based on calculation this condition has a significant effect on the results of $PM_{2.5}$ produced by heavy vehicle.

3. CONCLUSION

The results of the analysis indicate that the geometric conditions of urban roads in Indonesia also affect the production of CO_2 and $PM_{2.5}$ vehicle emissions and it has the same pattern as previous studies. CCR as a component that represents horizontal geometric characteristics is very influential on the results of CO_2 emissions. Road geometries with higher CCR values increase vehicle CO_2 emissions production linearly. In the horizontal geometric segment reviewed there are emission results that exceed the threshold provisions, it's LDV3 vehicles when crossing the segment with CCR ≥ 220 gon/km. Whereas on the road gradient review, emissions that exceed the emission threshold include: heavy vehicles when across 7.5% road grade while operated at 30 km/h; and HV vehicles when across ≥ 8.8% road grade while operated at 100 km/h.

The results show that the arterial and primary collector roads samples on this research have fulfilled the geometric technical provision of urban roads and the emissions are below the threshold value. However, there are several samples of secondary collector and local roads in Bandung that doesn't meet the provisions and this also give an impact on vehicle emissions production and environmental conditions. The results of this study can be used as a basic idea about the importance of establishing the technical provisions of roads on environmental impacts in the geometric design guidelines for urban roads in Indonesia.

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