

THE EFFECT OF ROAD DAMAGE ON GREENHOUSE GAS EMISSIONS (CASE STUDY OF KENDAL EASTERN HIGHWAY)

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Abstract

This article describes how road damage affects greenhouse gas (GHG) emissions. The object of this study is the 2 km East Kendal National Road, divided into 40 segments. To measure road damage, the Pavement Condition Index (PCI) method was used, while to measure greenhouse gas emissions, the IPCC (Intergovernmental Panel on Climate Change) method was used. There are three important findings in this study. First, the East Kendal National Road section is generally in poor to very poor condition with an average Pavement Condition Index (PCI) value of 33.83. Second, road damage affects the average speed of vehicles. Third, vehicle speed affects the amount of GHG emissions. When vehicle speed decreases due to road damage, fuel efficiency is reduced, so that CO₂, CH₄, and N₂O emissions increase. The results of the correlation analysis show a value of R = 0.648 for CO₂, R = 0.613 for CH₄, and R = 0.613 for N₂O, which means there is a fairly strong positive relationship between the level of road damage and greenhouse gas emissions. The conclusion is that the lower the PCI value (the more severe the road damage), the lower the average vehicle speed, and the lower the PCI, the higher the GHG emissions, namely CO₂, CH₄, and N₂O.

Keywords: *PCI, Road Damage, Emissions, GHG, East Kendal National Road.*

INTRODUCTION

Roads are a strategic infrastructure component of development. They support economic and social activities. Adequate roads not only influence the investment climate but also contribute to environmental preservation. This can be seen in various road infrastructure concepts, such as sustainable roads and green roads. However, many roads in Indonesia remain inadequate. Road damage is even common knowledge. Therefore, this article will explore how road damage affects greenhouse gas emissions. Road damage is caused by various conditions, including traffic overload, extreme weather, and lack of road maintenance. Road damage not only impacts the comfort and safety of road users but also damages the environment by increasing vehicle emissions. Vehicles traveling on damaged roads require longer travel times. This condition affects exhaust emissions, as travel time is directly proportional to emissions. The longer a vehicle travels, the greater the emissions. Furthermore, vehicles traveling on damaged roads often have to reduce speed suddenly, to avoid potholes or uneven road surfaces. Then, the vehicle must accelerate again to reach its original speed. This repeated acceleration and deceleration process increases fuel consumption, thus increasing exhaust emissions.

According to Erwin Setiawan and Agung Kurniawan (2025), vehicles traveling at inconsistent speeds (stop and go or acceleration and deceleration) or vehicles experience inertia. This condition makes the vehicle engine work harder so that it requires more fuel (Kompas.com, 2025). This incomplete combustion produces emissions. Meanwhile, Ismiyati, Marlita, and Saidah (2014) stated that emissions produced by vehicles are in the form of exhaust emissions containing lead (Pb), suspended particulate matter (SPM), nitrogen oxides (NO_x), sulfur oxides (SO₂), hydrocarbons (HC₂), carbon monoxide (CO), and photochemical oxides (OX) (BPLH DKI Jakarta in Marlitas, et al., 2014). Meanwhile, the Indonesian Ministry of Transportation states that fossil fuels (BBM) contribute the largest, or more than 80%, to the formation of greenhouse gas emissions. The systemic impact of road damage increases global warming (dephub.go.id, 2022). This increase in global temperature is directly influenced by CO₂, CH₄, and N₂O emissions. Therefore, there is an influence between road damage, travel time/speed, and greenhouse gas emissions. Road damage such as potholes, cracks, and waves cause vehicles to travel at inconsistent speeds, which can lead to increased fuel consumption and high vehicle emissions. The Pamungkas National Road Traffic Regulation (NRP) describes the traffic volume on the Semarang-Kendal Pantura

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road. It states that heavy vehicles are the main factor causing road damage, with a daily load of 10,214 tons passing through the Semarang-Kendal Pantura road. The very heavy daily load causes several road damages, resulting in slow vehicle travel times (NRP Pamungkas, 2019). Meanwhile, A. Setyawan, I. Kusdiantoro, and Syafi'i (2015) stated that when the road is in very poor condition, there will be a decrease in the average speed of vehicles. With this road condition, exhaust emissions are known to increase by 2.49%, in contrast to roads in very good condition (Setyawan, Kusdiantoro, and Syafi'i, 2015). Besides the Pantura road, the East Kendal Highway is a very strategic national road. The East Kendal Highway connects several regencies in Central Java Province. This road section also had a fairly high vehicle volume in 2023, amounting to 6,930,87 vehicles (Central Java National Road Implementation Center). In a study by Yudha et al. (2017), it was explained that the increase in the number of incoming and outgoing vehicles requires a level of road serviceability that should increase annually. However, road damage is still found on the Pantura route, including on the East Kendal Highway section. The damage that occurs on this road section occurs continuously every year, especially at STA 25+600 – STA 27+600 (Yudha et al., 2017). Kendal's East Highway has experienced several types of damage, one of which is rainwater pooling.

This pooling occurs due to the lack of drainage channels to channel rainwater. In addition to rainwater pooling, road damage is also caused by the type of vehicles passing along Kendal's East Highway. The increasing number of incoming and outgoing vehicles demands that the road's serviceability level increase annually. However, road damage continues, with sections of Kendal's East Highway experiencing continuous damage (Yudha et al., 2017). The pavement structure of the East Kendal Highway section is mostly in a state of structural and functional failure. 81% of the pavement structure is in a state of failure and 19% of the pavement structure is in a state of non-failure. This indicates that the East Kendal Highway section needs to be addressed or improved because 81% of the total length of the STA reviewed is experiencing structural and functional failure. Therefore, this article describes the effect of poor road conditions on greenhouse gas emissions. on Jalan Timur Kendal. This paper aims to provide a better understanding of the relationship between road damage, speed, and vehicle emissions, and to support decision-making in road infrastructure planning and repair.

THEORETICAL FRAMEWORK

PCI and Types of Road Damage

In calculating the road condition value using the Pavement Condition Index (PCI) method. At least there are types of damage to flexible pavement consisting of alligator cracking, bleeding, block cracking, bumps and sags, corrugation, depressions, edge cracking, joint reflection cracking, lane/shoulder drop off, longitudinal/transverse cracking, patching and utility cut patching, polished aggregate, potholes, shoving, slippage cracking, swell, weathering and roving (PCI in ASTM International, 1993)

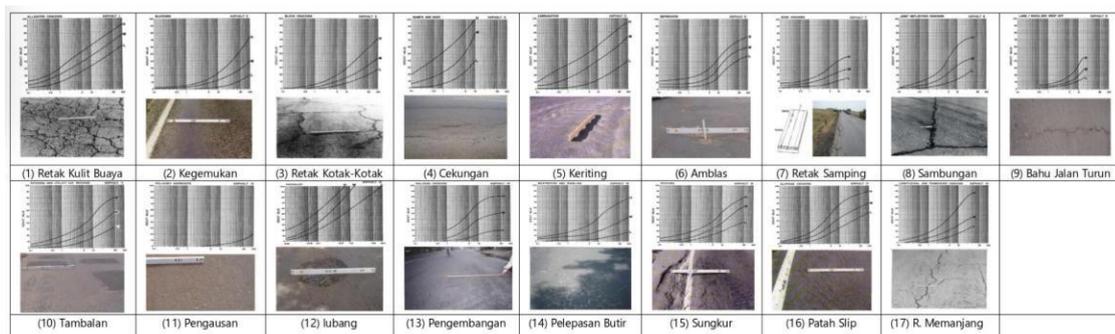


Figure 1: Graph and Road Damage Based on PCI

Pavement Condition Index The PCI (Performance Indices) is a method for assessing road pavement conditions based on the type, level, and extent of damage and maintenance efforts undertaken. PCI scores range from 0 to 100, with assessment categories ranging from excellent, very good, good, fair, poor, very poor, to failed. This index can be used as a reference in various road maintenance and management efforts (Suswandi et al., 2008).



Figure 2: PCI Value Standards

Before obtaining the PCI value, several other values must be understood. First, density, which is the level of damage, is the percentage of the area of a particular type of damage compared to the total area of a segment unit, measured in square meters or meters.

$$\text{Density (100\%)} = \frac{Ad}{As} \times 100$$

The density provisions are:

Ad = total area of damage at each level of damage (m²)

As = total area of the segment unit (m²).

Second, the maximum allowable value of the number of deduct values (m) is the calculation limit for the number of deduct value data in a segment consisting of more than one type. The number of deduct value (DV) data will be reduced until it reaches the value m, including the decimal part. If the available data is less than the value m, then all DV data in the segment can be directly used in the following formula:

$$m = 1 + [\times (100 - HDV)]$$

Information :

m = Deduct value (DV) allowance value per segment

HDV = The largest deduct value in that segment.

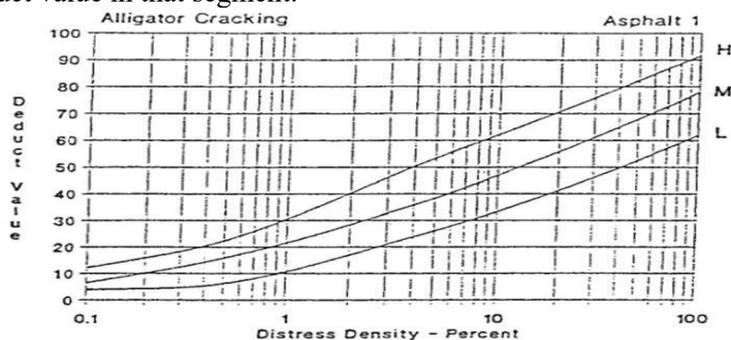


Figure 3. Total Deduct Value Graph

Third, Corrected Deduct Value (TDV). The total deductible value (TDV) is the total deductible value used as a weighting factor, indicating the combined impact of various types of damage and their severity on each research unit. The Corrected Deductive Value (CDV) is obtained through a curve connecting the TDV and CDV values, where the selected curve is adjusted for the sum of the individual deductible values that have a value greater than 2.

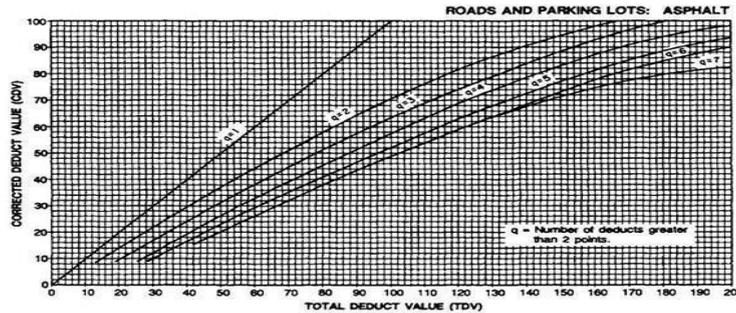


Figure 4: Total Deduct Value Graph

After the CDV value is obtained, the PCI value for each sample unit is calculated, this value uses the following equation:

$$PCI(s) = 100 - CDV$$

Where:

PCI(s) = Pavement Condition Index for each sample unit. CDV = Corrected Deduct Value from each for sample.

The overall PCI value for the road sections at this research location is shown in the following equation.

$$PCI = \frac{5 \sum PCI(S)}{N}$$

With :

PCI = The average PCI value of the entire study area;

PCI(s) = PCI value for each sample unit;

N = Number of sample units.

Table 1 : Types of Vehicles

Vehicle Code	Vehicle Type	Vehicle Type
SM	2 and 3 wheeled motor vehicles with a length < 2.5 meters	Bicycle motor three wheeled motor vehicles, sedans, minibuses, microbuses, pickups, small trucks
MP	4-seater passenger cars, 7-seater passenger cars, medium-sized freight cars with length < 5.5 meters.	Bus not quite enough, busmetro mini, medium truck
BK	Medium buses and 2-axle freight vehicles with a length of < 5.5 Meters	Intercity buses,
TB	3 axle freight vehicles, trailer trucks and trailer trucks with length > 12.0 meters	Tronton trucks, semi trucks trailer trailer truck

The formula used in calculating vehicle travel time is as follows:

$$t = s/v$$

Where :

- t = Travel Time
- s = Distance
- v = Speed

Meanwhile, traffic speed refers to the rate of movement of vehicles or a specific traffic flow, usually measured in kilometers per hour. Speed is calculated by dividing the distance traveled by the time required. The formula for calculating speed is as follows.

$$Vs = \frac{d}{t}$$

Where :

- Vs = Speed (km/h)
- d = Distance traveled
- t = Travel Time (hours)

Greenhouse Gas Emission Level Calculation Methodology (IPCC)

The IPCC (Intergovernmental Panel on Climate Change) Guideline for National Greenhouse Gas Inventories is a specific guideline for estimating increases and decreases in greenhouse gas emissions. According to the 2006 IPCC guidelines, accurate calculations of greenhouse gas (GHG) emissions require a variety of specific data, including fuel consumption, energy consumption, and information on transportation routes and distances.

Fuel consumption values have been generally determined, as shown in the table below:

Table 2. Fuel consumption value

Vehicle Type	Consumption Fuel 1/Km	Fuel Consumption /Liter
Motorcycle	0.052 l/km	0.104
Passenger Car	0.1333 l/km	0.2666
Small Bus	0.125 l/km	0.25
Big Bus	0.2926 l/km	0.5852
Light Trucks	0.2875 l/km	0.575
Heavy Trucks	0.6874 l/km	1.3748

After getting the fuel consumption value, the next step is to calculate the energy consumption value. To find out the energy consumption value, you can use the following formula:

$$\text{Energy Consumption} = \text{Fuel consumed (Liters)} \times \text{Calorific Value Tj/Liter}$$

Greenhouse Gas (GHG) emissions from fuel combustion in mobile sources include emissions from transportation activities, such as land transportation (including highways, off-road vehicles, and trains), water transportation (both rivers and seas), and air transportation (airplanes). Greenhouse gases produced from fuel combustion in the transportation sector include CO₂, CH₄, and N₂O.

The amount of greenhouse gas emissions resulting from the combustion of fossil fuels depends on the quantity and type of fuel used. The quantity of fuel is represented by activity data, while the type of fuel is represented by an emission factor. The general formula used to estimate greenhouse gas emissions from fuel combustion is as follows:

$$\text{Emission} = \frac{\text{kg}}{\text{year}} = \frac{\text{Energy Consumption}}{\text{physical science}} \times \frac{\text{Emission Factor}}{\text{Year}} \frac{\text{kg}}{\text{Year}}$$

Regression Analysis

The simple linear regression coefficient is a statistical method used to analyze the relationship between characteristics or variables in a problem being studied. The regression model

This linear model is able to model the relationship between two or more variables, where there is a dependent variable (Y) which is functionally influenced by one or more independent variables (X). In the simplest case, the relationship can be written in the following equation:

$$y = a + bx + e$$

Where:

- y = dependent variable,
- x = independent variable,
- a = is a constant or intercept,
- b = regression coefficient or slope of the line (slope),
- e = standard error or error.

METHOD

This research will use quantitative methods. Quantitative methods are generally a scientific approach that emphasizes the collection of numerical and quantitative data. Quantitative research provides a highly systematic analytical framework, enabling researchers to make precise measurements, carefully observe phenomena, and analyze data with a structured quantitative approach (Deryana, A. Jihad, and A. Ropii, 2024). This research was conducted through a field survey aimed at identifying various types of road damage using the PCI (Pavement Condition Index) method. Furthermore, this study also calculated the average speed of vehicles passing along Jalan Timur Kendal and measured the number and types of vehicles in the research area. The data sources for this article are primary and secondary data. Primary data were obtained through field surveys, including geometric surveys or road damage, traffic surveys or vehicle counts, and vehicle speed surveys. The field survey was conducted on Jalan Timur Kendal, a 2-km road, which was then divided into 40 segments, each 100 meters long, on the right and left sides of the road. Secondary data, meanwhile, come from documents and various reports related to the research. The data obtained is used to address the research problem or to test hypotheses. For a clearer understanding of the data sources, see the table below:

Table 3.Primary Data

No.	Data Types	Source	Allocation
1	Road type Types of road damage Level of road damage	Field survey	Analysis of the type and level of road damage PCI (pavement condition indexes) Look for the PCI value, look for the relationship between road damage and vehicle speed.
	Vehicle number data Average vehicle speed data Vehicle travel time	Surveyfield and agency (BPJN Central Java)	Analysis of vehicle speed and the relationship between damage and vehicle speed

2.	Data on the length of the road traveled Quantity data	Surveyfield and agency	Analysis of vehicle emission levels and damage relationships
	vehicles, Greenhouse Gas Emission Factors	(Central Java BPJN)	emission path towards

Table 4.Secondary Data

No.	Data Types	Source	Allocation
1.	LHR Data Vehicle Volume	HallCentral Java National Road Implementation Field survey	obtain greenhouse gas emission values
2.	Emission factor data Fuel emission factor data based on fuel type Usage stage data - Fuel - Fuel consumption - Mileage	IPCC 2006 Environmental ServiceLong live the Republic of Indonesia, IPCC 2006 Agency	To calculate the estimated value of GHG emissions CO ₂ , CH ₄ and N ₂ O in the transportation sector. Using IPCC 2006

The data analysis technique in this article is by calculating the Pavement Condition Index (PCI), calculating the average speed of vehicles, calculating vehicle emissions, and the relationship between road damage variables, speed and GHG emissions. In finding the relationship between variables using linear regression coefficients, a statistical method used to analyze the relationship between variables in a problem being studied. In this study, the regression equation is used to determine the effect of road damage on vehicle speed and the effect of road damage on greenhouse gas emissions. The variables used include the independent variable (X), namely road damage measured by the PCI value, and the dependent variable (Y), namely the average speed of vehicles and greenhouse gas emissions.

Testing using multiple linear analysis with SPSS is carried out through the t-test (partial) and normality test. In the t-test (partial), the relationship between variables is determined based on the significance value (sig), where if the sig value <0.05 then there is a correlation between the variables, whereas if the sig value ≥ 0.05 then there is no significant correlation. Meanwhile, the normality test is used to test whether the data used is normally distributed or not. Good data is data that has a normal distribution. Data normality testing is carried out using the Kolmogorov-Smirnov Test. The Kolmogorov-Smirnov Test criteria are as follows: If the p-value (Asymp Sig.) ≥ 0.05 then the data is normally distributed, but if the p-value (Asymp Sig.) <0.05 then the data is not normally distributed. The results of the normality test show that the p-value (Asymp Sig.) of the residuals of both regression models is ≥ 0.05. Therefore, it can be concluded that the data used in this study is normally distributed. Meanwhile, the influence test in the study was conducted using an Excel graph containing road damage data as variable x, average vehicle speed data, and greenhouse gas emissions as variable y. After creating a graph between variables x and y, conclusions can be drawn regarding the two variables and whether they have an influence on each other and can be seen from the correlation coefficient R and the termination coefficient R².

RESULTS AND FINDINGS

Pavement Condition Index (PCI) and Damage to East Kendal National Road

Based on field survey data on the damage to the 2 km long Kendal East National Road. Next, an assessment of the condition of the PCI (Pavement Condition Index) value on the road was carried out. The road section was divided into several segments, starting from segment 1 to segment 40. Next, an example of calculating

the PCI value was carried out on segment 1 (STA 0 + 000-0 + 100). It was found that road damage in Kendal consisted of raveling, shoving, patching, corrugation, bumps and sags, and alligator cracking. Visual field observations reveal the extent of damage, depth, and crack width, which are then used to determine the road damage class. The density of damage is influenced by the quantity of each type of damage and the area of the road segment being examined. The deductible value can be calculated immediately after the damage class and density are determined. The Total Deduct Value (TDV) and Corrected Deduct Value (CDV) can be calculated immediately after the above steps are known. The final stage of pavement condition analysis is determining the Pavement Condition Index (PCI), which can then be used to prioritize damage management. The calculation steps using the PCI method are as follows:

1. Deductive Value

The following are the results of calculations for the types of damage on the East Kendal National Road, with low, medium, and high levels of damage. However, each level of damage varies. Not all types of damage have the same level of damage when surveyed in the field using standard measurements. After the field survey, the total area of the segment unit was found to be 300 m². Therefore, the calculation of the deductible value for the East Kendal National Road damage type is as follows:

a) Grain release (raveling)

The following are the results of calculations of the types of traveling damage using equations with medium and high levels of damage.

$$\begin{aligned} \text{Extent of damage} &= 4.50 \text{ m}_2 \\ \text{Level of damage} &= \text{Medium}(M) \\ \text{Road damage level/density (\%)} &= \frac{4.50}{300} \times 100 = 1.50\% \end{aligned}$$

$$\begin{aligned} \text{Extent of damage} &= 3.00 \text{ m}_2 \\ \text{Level of damage} &= \text{High}(H) \\ \text{Road damage level/density (\%)} &= \frac{3.00}{300} \times 100 = 1.00 \% = 1.00 \% \end{aligned}$$

b) Shoving

The following are the calculation results of the type of shoving damage with the high level of damage.

$$\begin{aligned} \text{Extent of damage} &= 3.36 \text{ m}_2 \\ \text{Level of damage} &= \text{High}(H) \\ \text{Road damage level/density (\%)} &= \frac{3.36}{300} \times 100 = 1.12\% \end{aligned}$$

c) Patching

The following are the calculation results of the types of patching damage with low and medium levels of damage.

$$\begin{aligned} \text{Extent of damage} &= 3.36 \text{ m}_2 \\ \text{Level of damage} &= \text{Low}(L) \\ \text{Road damage level/density (\%)} &= \frac{0.48+1.08+1.8}{300} \times 100 = 1.12 \% \end{aligned}$$

$$\begin{aligned} \text{Extent of damage} &= 2.10 \text{ m}_2 \\ \text{Level of damage} &= \text{Medium}(M) \\ \text{Road damage level/density (\%)} &= \frac{2.1}{300} \times 100 = 0.70\% \end{aligned}$$

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d) Corrugation

The following are the calculation results of the type of corrugation damage with a medium level of damage.

Extent of damage = 1.21 m²
 Level of damage = *Medium*(M)
 Road damage level/density (%) = $\frac{1.21}{300} \times 100 = 0.40\%$

e) Bumps and sags

The following are the results of calculations of the types of damage to the basins (bumps and sags) with the level of high damage.

Extent of damage = 1.08 m²
 Level of damage = *Hight*(H)
 Road damage level/density (%) = $\frac{1.08}{300} \times 100 = 0.36\%$

f) Alligator cracking

The following are the calculation results of the alligator cracking type of damage with medium and high levels of damage.

Extent of damage = 5.20 m²
 Level of damage = *Medium*(M)
 Road damage level/density (%) = $\frac{0.7+4.5}{300} \times 100 = 1.73\%$

Extent of damage = 2.25 m²
 Level of damage = *Medium*(M)
 Road damage level/density (%) = $\frac{2.25}{300} \times 100 = 0.75\%$

2. Maximum Deduct Value Permit

In finding the maximum limit value of the deduct value, the largest deduct value obtained from the medium severity level of 40 for alligator skin crack damage (bumps and sags) was used, and the following values were found:

$$m = 1 + 9 \times 100 - 40 = 6.51$$

The result of the calculation is 6.51, which means 6.51 is higher than 9, and the number 9 represents the total data for the deduct value reduction. For more details on the density calculation and deduct value analysis, see the table below:

Table 4. Recapitulation of Density Value Calculation and Deduct Value Analysis

<i>Distress Severity</i>	<i>Quantity</i>			<i>Total Quantity</i>	<i>Density</i>	<i>Deductible Value</i>
19 M	4.5			4.50	1.50	9
19 H	3			3.00	1.00	15
16 H	3.36			3.36	1.12	28
11 L	0.48	1.08	1.8	3.36	1.12	6
11 M	2.1			2.10	0.70	8
5 M	1.21			1.21	0.40	10
4 H	1.08			1.08	0.36	40
1 L	0.7	4.5		5.20	1.73	15
1 M	2.25			2.25	0.75	20

3. Corrected Deduct Value (CDV)

To obtain the corrected deduct value, use the following graph.

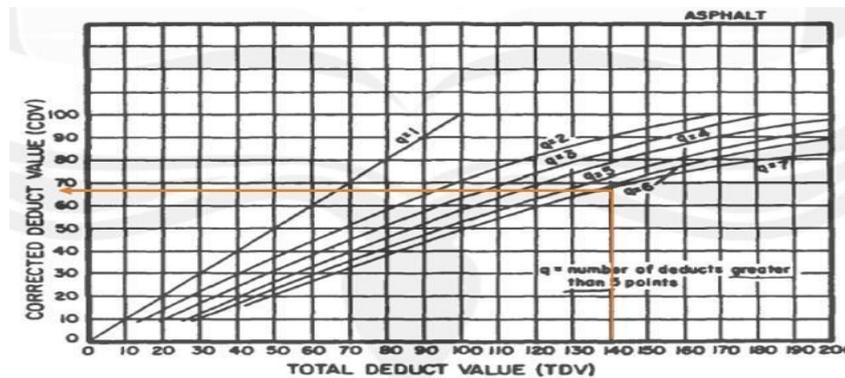


Figure 5. Plotting Corrected Deduct Value

Based on the results of the deduct value, to obtain the corrected deduct value (CDV) value, the deduct value (DV) is entered into the CDV graph. The method is to draw a vertical line from the DV value until it intersects the q line, then continue by drawing a horizontal line. To obtain the PCI value for each sample unit (PCIs), the calculation will be carried out for the maximum CDV value with the PCI value by subtracting the maximum CDV value from the PCI standard value (100). This will produce the pavement condition index value for each sample unit. An example of PCI calculation at STA 0+00 to STA 0+100 is as follows:

$$PCI = 100 - 69 = 31 \text{ (poor)}$$

From the results of these calculations, the condition of the road pavement being studied can be determined, whether it is classified as very good, good, or very bad, by referring to the parameters in the PCI method.

Table 5. TDV/CDV Max Calculation

Deduct Values									Total DV	Q	CDV	CDV Max	PCI
40	28	20	15	15	10	4.59	4.08	3.06	140	9	69	69	31
40	28	20	15	15	10	4.59	4.08	2	139	8	68		
40	28	20	15	15	10	4.59	2	2	137	7	67		
40	28	20	15	15	10	2	2	2	134	6	67		
40	28	20	15	15	2	2	2	2	126	5	66		
40	28	20	15	2	2	2	2	2	113	4	60		
40	28	20	2	2	2	2	2	2	100	3	62		
40	28	2	2	2	2	2	2	2	82	2	59		
40	2	2	2	2	2	2	2	2	56	1	53		

4. Pavement Condition Index (PCI) Recapitulation

From the example of PCI calculation results in each sample unit (PCIs) above, the pavement condition/PCI values obtained in all segments of the East Kendal National Road using the Pavement Condition Index (PCI) can be seen in the following table.

Table 6.PCI Recapitulation Results at Sta 0+000 SD Sta 2+000

Station	Max CDV	PCI	Levels
KM 0+000 - 0+100	69	31	Poor
KM 0+100 - 0+200	80	20	Very poor
KM 0+200 - 0+300	52	48	Fair
KM 0+300 - 0+400	56	44	Fair
KM 0+400 - 0+500	77	23	Very poor
KM 0+500 - 0+600	87	13	Very poor
KM 0+600 - 0+700	73	27	Poor
KM 0+700 - 0+800	80	20	Very poor
KM 0+800 - 0+900	67	33	Poor
KM 0+900 - 1+000	70	30	Poor
KM 1+000 - 1+100	69	31	Poor
KM 1+100 - 1+200	58	42	Fair
KM 1+200 - 1+300	72	28	Poor
KM 1+300 - 1+400	68	32	Poor
KM 1+400 - 1+500	76	24	Very poor
KM 1+500 - 1+600	54	46	Fair
KM 1+600 - 1+700	86	14	Very poor
KM 1+700 - 1+800	56	44	Fair
KM 1+900 - 1+900	76	24	Very poor
KM 1+900 - 2+000	78	22	Very poor
KM 2+000 - 2+100	78	22	Very poor
KM 2+100 - 2+200	75	25	Very poor
KM 2+200 - 2+300	43	57	Good
KM 2+300 - 2+400	88	12	Very poor
KM 2+400 - 2+500	65	35	Poor
KM 2+500 - 2+600	70	30	Poor
KM 2+600 - 2+700	63	37	Poor
KM 2+700 - 2+800	85	15	Very poor
KM 2+900 - 2+900	63	37	Poor
KM 3+900 - 3+000	68	32	Poor
KM 3+000 - 3+100	68	32	Poor
KM 3+100 - 3+200	58	42	Fair
KM 3+200 - 3+300	70	30	Poor
KM 3+300 - 3+400	58	42	Fair
KM 3+400 - 3+500	39	61	Good
KM 3+500 - 3+600	45	55	Good
KM 3+600 - 3+700	50	50	Fair
KM 3+700 - +800	81	19	Failed
KM 3+800 - 3+900	39	61	Good
KM 3+900 - 3+1000	37	63	Good

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In the table above, it can be seen that the damage to the road section with PCI (Pavement Condition Index) values and road condition levels for various kilometer stations (Sta) on the East Kendal National Road. The road condition levels are categorized as good, fair, poor, very poor, and failed. Road segments with good conditions have high PCI values, such as KM 200+300 with PCI 57, KM 400+500 with PCI 61, KM 500+600 with PCI 55, KM 800+900 with PCI 61, and KM 900+1000 with PCI 63. This indicates a relatively good road surface. The fair condition of this segment has a medium PCI, such as KM 0+100 (PCI 48), KM 600+700 (PCI 46), KM 800+900 (PCI 44), KM 100+200 (PCI 42), KM 200+300 (PCI 42), and KM 300+400 (PCI 42). The poor segment conditions have lower PCI, such as KM 0+100 (PCI 31), KM 600+700 (PCI 27), KM 800+900 (PCI 33), KM 900+1000 (PCI 30), and many other segments with PCI in the range of 28 to 37.

The very poor condition of this segment shows significant road damage, with very low PCI, for example KM 100+200 (PCI 20), KM 500+600 (PCI 13), KM 700+800 (PCI 20 and 14), KM 900+1000 (PCI 22 and 24), and KM 300+400 (PCI 12). For failed conditions, one segment was identified, namely KM 700+800 with PCI 19, indicating very severe damage. Below, you can see that the entire East Kendal National Road section is in poor or poor functional condition.

$$PCI = \frac{1,353}{40} = 33.83$$

Average Vehicle Speed

Based on a field survey, the method for measuring the speed of a number of vehicles passing through the East Kendal road section begins by determining the starting point (A) and the ending point (B) of the observation location. The time mean speed is the arithmetic mean value of the speed of all vehicles passing a point on the road at a certain time, while the speed of each vehicle is known as the spot speed. For more clarity regarding the speed of vehicles passing through the East Kendal road, see the table below:

Table 7. Recapitulation Results of the Speed of Each Type of Vehicle on the East Kendal National Road

Segmen	Motor cycle	Passenger Car	Small Bus	Big Bus	Medium Truck	Heavy Truk
KM 0+000 - 0+100	38.46	35.34	35.70	32.55	28.89	30.58
KM 0+100 - 0+200	32.25	33.32	37.23	33.67	21.5	28.98
KM 0+200 - 0+300	47.36	44.52	43.56	40.44	36.55	38.4
KM 0+300 - 0+400	45.21	40.26	40.74	39.66	34.12	36.1
KM 0+400 - 0+500	32.62	36.21	38.82	36.65	23.03	25.4
KM 0+500 - 0+600	48.3	41.98	43.74	40.98	34.04	37.21
KM 0+600 - 0+700	31.46	34.56	25.7	23.77	25.98	27.52
KM 0+700 - 0+800	28.81	32.32	37.91	33.44	21.56	28.88
KM 0+800 - 0+900	39.32	35.21	38.21	34.22	29.88	32.39
KM 0+900 - 1+000	36.2	30.88	34.61	20.22	28.06	29.60
KM 1+000 - 1+100	37.29	32.66	37.49	33.88	28.99	30.60
KM 1+100 - 1+200	40.21	39.44	38.29	34.55	32.40	35.40
KM 1+200 - 1+300	31.95	34.56	33.67	29.77	27.01	27.98
KM 1+300 - 1+400	37.96	33.78	36.46	32.77	30.03	31.13
KM 1+400 - 1+500	35.84	34.54	40.33	49.88	35.02	35.40
KM 1+500 - 1+600	45.21	41.32	44.89	41.77	33.45	37.77
KM 1+600 - 1+700	43.18	40.32	41.54	38.98	33.24	37.16
KM 1+700 - 1+800	42.18	40.21	40.74	38.77	32.06	36.07
KM 1+900 - 1+900	33.17	33.44	39.82	35.99	25.04	23.98
KM 1+900 - 2+000	30.19	33.89	37.43	34.32	22.03	24.23
KM 2+000 - 2+100	29.78	33.56	37.32	32.98	22.09	24.44
KM 2+100 - 2+200	33.48	35.99	37.54	32.99	24.06	25.99
KM 2+200 - 2+300	45.50	39.43	40.22	38.45	35.55	39.01
KM 2+300 - 2+400	41.50	39.44	40.11	39.99	31.99	35.78
KM 2+400 - 2+500	33.48	35.46	39.99	37.97	30.66	33.56
KM 2+500 - 2+600	39.87	33.54	35.77	32.21	27.89	29.67
KM 2+600 - 2+700	36.45	41.67	41.12	39.98	36.07	35.41

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Segmen	Motor cycle	Passenger Car	Small Bus	Big Bus	Medium Truck	Heavy Truk
KM 2+700 - 2+800	21.07	28.33	28.89	25.12	19.43	30.23
KM 2+900 - 2+900	36.04	41.34	41.88	39.89	32.43	35.54
KM 3+900 - 3+000	37.66	37.44	36.32	34.89	29.03	31.40
KM 3+000 - 3+100	37.21	36.88	35.66	31.04	29.11	31.34
KM 3+100 - 3+200	40.21	37.17	38.65	34.45	31.22	34.98
KM 3+200 - 3+300	38.42	34.44	34.77	31.23	28.04	29.88
KM 3+300 - 3+400	39.88	37.67	39.23	35.66	32.02	35.05
KM 3+400 - 3+200	50.50	43.89	43.99	40.98	36.87	40.99
KM 3+100 - 3+500	43.21	39.99	40.66	37.90	36.03	39.56
KM 3+500 - 3+600	39.89	39.88	39.56	36.99	33.88	37.99
KM 3+600 - 3+700	40.14	38.88	39.32	36.02	33.76	37.79
KM 3+700 - 3+800	51.21	43.42	43.09	40.02	37.04	40.87
KM 3+800 - 3+900	55.21	44.17	45.77	42.77	38.55	41.15

Based on the table above, the average speed value of vehicles passing through the Kendal East National Road is obtained. Recapitulation of the average speed of various types of vehicles on 40 different road segments. Each road segment is identified by kilometers (KM) such as KM 0+100, KM 100+200, and so on. The types of vehicles measured include motorcycles, passenger cars, small buses, large buses, medium trucks, and heavy trucks. In general, the average speed varies significantly between vehicle types and road segments. Light passenger vehicles such as motorcycles and passenger cars tend to have higher average speeds compared to heavy vehicles such as Medium Trucks and Heavy Trucks in many segments. For example, the highest speed of a Motorcycle was recorded at 55.21 km/h in the KM 900+1000 segment. Meanwhile, the lowest speed for a Medium Truck was found at KM 700+800 with 19.43 km/h.

Greenhouse Gas Emissions on the East Kendal National Road Section

Greenhouse gas emissions are obtained by calculating energy consumption and GHG emissions for each vehicle type. Energy consumption by vehicle is calculated by calculating fuel consumption per liter.

$$\begin{aligned} \text{Fuel consumption /Liter} &= \text{length of road} \times \text{fuel consumption l/Km.} \\ &= 2\text{Km} \times 0.052 \text{ Liters/section} \\ &= 0.104 \end{aligned}$$

Next, after obtaining the amount of fuel consumption, the results of the calculation are multiplied by the number of LHR and the amount of energy produced in each type of fuel combustion. It is known that the number of LHR motorcycles on Jl. Nasional Timur Kendal is 14098 vehicles/day and the amount of calorific value that occurs in the type of gasoline fuel is 0.000033 Tj/Liter. The amount of energy consumption of motorized vehicles can be seen below.

$$\begin{aligned} \text{Energy consumption of motorcycle vehicles} &= \text{Amount of fuel (L)} \times \text{Number of vehicles} \times \text{Calorific value (KLH, 2021)} \\ &= 0.104 \times 14.098 \times 0.000033 \times 10^{-6} \text{ (TJ/Liter)} \\ &= 0.483844 \text{ (TJ/Liter)} \end{aligned}$$

After calculating the energy consumption required by each vehicle type on the East Kendal National Road, a summary of GHG emissions was obtained. The types of gases produced include CO₂, CH₄, and N₂O. For more details, see the table below:

Table 8. Summary of GHG Emission Consumption on East Kendal National Road

Vehicle Type	Total Emission CO ₂	Total Emission CH ₄	Total Emission N ₂ O
Motorcycle	54962	15.966852	15.48300.8
Passenger Car	152.2755	261.72636	253.79526.4
Small Bus	98.347965	8.0145	8.0145
Big Bus	98.3479653	5.1762087	5.1762087
Light Trucks	90.359022	4.755738	4.755738
Heavy Trucks	103.928214	5.469906	5.469906

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Based on the above, it can be seen that motorcycle emission consumption produces a total CO₂ emission of 3353,034, CH₄ emission of 1.59668, and N₂O emission of 0.15483, passenger car vehicles have the highest total CO₂ emissions among all types of vehicles, namely 5498,162, with CH₄ emissions of 2.618172 and N₂O emissions of 0.253883, small bus vehicles and large buses show total CO₂ emissions of 182.7306 and 98.3480, respectively, with CH₄ and N₂O emissions which are also quite significant, while light trucks and heavy trucks produce lower CO₂ emissions than passenger cars, namely 9052.29 for light trucks and 103899.79 for heavy trucks. CH₄ and N₂O emissions from both types of trucks are also relatively lower. Heavy trucks (1.3748 liters) and large buses (0.5852 liters) had the highest daily fuel consumption, while small buses had the lowest (0.25 liters). It can be concluded that heavy trucks are the largest contributors to GHG emissions on the Kendal East National Road, followed by large buses and small trucks.

Relationship between Road Damage and Vehicle Speed

On the East Kendal National Road, damage, including potholes, cracks, and uneven surfaces, can reduce the average speed of passing vehicles. This reduction not only impacts travel time but also increases the risk of accidents and impacts fuel efficiency.

Table 9. The Relationship Between Road Damage and Average Vehicle Speed on National Roads in East Kendal

Recapitulation of Average Vehicle Speeds on Jl. Nasional Timur Kendal							
Station	PCI	Motor cycle	Passenger Car	Small Bus	Big Bus	Medium Truck	Heavy Truck
KM 0+000 - 0+100	31	38.46	35.34	35.70	32.55	28.89	30.58
KM 0+100 - 0+200	20	32.25	33.32	37.23	33.67	21.5	28.98
KM 0+200 - 0+300	48	47.36	44.52	43.56	40.44	36.55	38.4
KM 0+300 - 0+400	44	45.21	40.26	40.74	39.66	34.12	36.1
KM 0+400 - 0+500	23	32.62	36.21	38.82	36.65	23.03	25.4
KM 0+500 - 0+600	13	48.3	41.98	43.74	40.98	34.04	37.21
KM 0+600 - 0+700	27	31.46	34.56	25.7	23.77	25.98	27.52
KM 0+700 - 0+800	20	28.81	32.32	37.91	33.44	21.56	28.88
KM 0+800 - 0+900	33	39.32	35.21	38.21	34.22	29.88	32.39
KM 0+900 - 1+000	30	36.2	30.88	34.61	20.22	28.06	29.60
KM 1+000 - 1+100	31	37.29	32.66	37.49	33.88	28.99	30.60
KM 1+100 - 1+200	42	40.21	39.44	38.29	34.55	32.40	35.40
KM 1+200 - 1+300	28	31.95	34.56	33.67	29.77	27.01	27.98
KM 1+300 - 1+400	32	37.96	33.78	36.46	32.77	30.03	31.13
KM 1+400 - 1+500	24	35.84	34.54	40.33	49.88	35.02	35.40
KM 1+500 - 1+600	46	45.21	41.32	44.89	41.77	33.45	37.77
KM 1+600 - 1+700	14	43.18	40.32	41.54	38.98	33.24	37.16
KM 1+700 - 1+800	44	42.18	40.21	40.74	38.77	32.06	36.07
KM 1+900 - 1+900	24	33.17	33.44	39.82	35.99	25.04	23.98
KM 1+900 - 2+000	22	30.19	33.89	37.43	34.32	22.03	24.23
KM 2+000 - 2+100	22	29.78	33.56	37.32	32.98	22.09	24.44
KM 2+100 - 2+200	25	33.48	35.99	37.54	32.99	24.06	25.99
KM 2+200 - 2+300	57	45.50	39.43	40.22	38.45	35.55	39.01

Recapitulation of Average Vehicle Speeds on Jl. Nasional Timur Kendal							
Station	PCI	Motor cycle	Passenger Car	Small Bus	Big Bus	Medium Truck	Heavy Truck
KM 2+300 - 2+400	12	41.50	39.44	40.11	39.99	31.99	35.78
KM 2+400 - 2+500	35	33.48	35.46	39.99	37.97	30.66	33.56
KM 2+500 - 2+600	30	39.87	33.54	35.77	32.21	27.89	29.67
KM 2+600 - 2+700	37	36.45	41.67	41.12	39.98	36.07	35.41
KM 2+700 - 2+800	15	21.07	28.33	28.89	25.12	19.43	30.23
KM 2+900 - 2+900	37	36.04	41.34	41.88	39.89	32.43	35.54
KM 3+900 - 3+000	32	37.66	37.44	36.32	34.89	29.03	31.40
KM 3+000 - 3+100	32	37.21	36.88	35.66	31.04	29.11	31.34
KM 3+100 - 3+200	42	40.21	37.17	38.65	34.45	31.22	34.98
KM 3+200 - 3+300	30	38.42	34.44	34.77	31.23	28.04	29.88
KM 3+300 - 3+400	42	39.88	37.67	39.23	35.66	32.02	35.05
KM 3+400 - 3+200	61	50.50	43.89	43.99	40.98	36.87	40.99
KM 3+100 - 3+500	55	43.21	39.99	40.66	37.90	36.03	39.56
KM 3+500 - 3+600	50	39.89	39.88	39.56	36.99	33.88	37.99
KM 3+600 - 3+700	19	40.14	38.88	39.32	36.02	33.76	37.79
KM 3+700 - 3+800	61	51.21	43.42	43.09	40.02	37.04	40.87
KM 3+800 - 3+900	63	55.21	44.17	45.77	42.77	38.55	41.15

It can be seen that there is a positive relationship between the PCI value and motorcycle speed, which means that the higher the PCI value, the higher the motorcycle speed tends to be. Note that the lowest PCI values were recorded at KM 500+600 (No. 6) and KM 300+400 (No. 24) with PCI 13 and 12 respectively. The highest PCI values were recorded at KM 400+500 (No. 35) and KM 800+900 (No. 39) with

PCI 61, and KM 900+1000 (No. 40) with PCI 63. By looking at the correlation coefficient value R of 0.664, the relationship between the two variables is very significant, as can be seen with the example of the type of motorbike vehicle.

Table 10. PCI model summary with Motorcycle

Model Summary				
Model	R	R square	Adjusted R Square	Std. Error of the Estimate
1	0.664	441	426	5,13727
Predictors: (Constant), PCI				
Dependent variable: Motorcycle				

Based on the model summary table above, the R value representing the correlation coefficient or regression coefficient is 0.664. This value indicates that the relationship between the two variables, namely road damage (PCI) as the independent variable (X) and motorcycle speed as the dependent variable (Y), is included in the strong category. In addition, this table also shows the R Square value or coefficient of determination, which indicates how well the regression model explains the relationship between the independent and dependent variables. The coefficient of determination value obtained is 0.441 or 44.1%, which means that the road damage (PCI) variable contributes 44.1% to the variation in motorcycle speed.

Table 11. Anova PCI with Motorcycle

<i>Anova</i>						
Model		<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
1	<i>Regression</i>	789,937	1	789,937	29,931	001
	<i>Residual</i>	1002,879	38	26,392		
	<i>Total</i>	1792,815	39			
Dependent variable: Motorcycle						
Predictors: (Constant) PCI						

The ANOVA table above is used to determine the level of significance or linearity of the regression model. This assessment can be done through the F test or significance value (Sig.), with the simplest way using the Sig. test. If the Sig. value is less than 0.05, then the regression model is considered linear, and vice versa if the Sig. value is greater than or equal to 0.05. Based on the ANOVA table, the Sig. value is obtained at 0.001, which is smaller than the significance limit of 0.05. Therefore, the regression equation model from this research data is declared significant, which means the linear regression model meets the requirements for linearity. To support the smooth running of the survey, tools are needed during data collection.

Table 12. PCI Coefficients with Motorcycles

<i>Coefficients</i>						
Model		<i>Unstandardized Coefficients</i>		<i>Standardized Coefficients</i>	<i>T</i>	<i>Sig.</i>
		<i>B</i>	<i>Std. Error</i>	<i>Beta</i>		
1	<i>(Constant)</i>	27,669	2,173		12,372	001
	<i>(PCI)</i>	326	060	664	5,471	001
Independent Variable: Motorcycle						

Based on the results in the Coefficient Table, it can be seen that only variable X, namely Road Damage (PCI), has a significance value (Sig.) of 0.001, which is smaller than the probability limit of 0.05. Therefore, it can be concluded that there is an influence of Road Damage (PCI) on the speed of motorcycles (Y). In the table, the constant value of the unstandardized coefficients is 27.669. This figure shows that if there is no influence of Road Damage (PCI), then the speed of motorcycles remains at 27.669. Based on the table, the regression equation model obtained is:

$$y = 0.326x + 27.669 \text{ with an } R^2 \text{ value of } 0.441$$

Y = Motorbike speed

X = Road damage (PCI),

R² = Coefficient of Determination

R = Correlation Coefficient

R₂ = Termination Coefficient

To more clearly see the relationship between road damage (PCI) and the average speed of vehicles on the East Kendal National Road, please see the summary table below:

Table 13. Recapitulation of the Relationship between Road Damage and Average Vehicle Speed

Vehicle Type	Correlation Coefficient (R)	Regression Equation
Motorcycle	0.664	$y = 0.4994x + 20.083$
Passenger Car	0.612	$y = 0.2737x + 27.08$
Small Bus	0.463	$y = 0.2216x + 30.407$
Big Bus	0.332	$y = 0.2603x + 25.992$
Light Truck	0.665	$y = 0.3756x + 16.214$
Heavy Truck	0.639	$y = 0.371x + 19.304$

Based on the table above, the regression or correlation coefficient of 0.664 means a strong positive relationship between road damage or PCI value to the speed of Motorcycles, the correlation coefficient of Passenger Cars is 0.612, meaning there is a strong positive relationship between road damage or PCI value to the speed of Passenger Cars, the correlation coefficient of Small Buses is 0.463, meaning there is a fairly strong positive relationship between road damage or PCI value to the speed of Small Buses, the correlation coefficient of Large Buses is 0.332, meaning there is a fairly strong positive relationship between road damage or PCI value to the speed of Large Buses, the correlation coefficient of Light Trucks is 0.665, meaning there is a very strong positive relationship between road damage or PCI value to the speed of Light Trucks and the correlation coefficient of Heavy Trucks is 0.639, meaning there is a very strong positive relationship between road damage or PCI value to the speed of Light Trucks.

This means that the higher the road damage rating, the higher the average vehicle speed. Furthermore, the higher the road damage rating, the higher the average vehicle speed. Heavy trucks and medium trucks have the highest R and R² ratings, respectively, meaning that the average speed of these two types of vehicles is significantly affected by the level of road damage. Motorcycles are also significantly affected by road damage.

Although not as high as trucks, large buses have the weakest correlation (R = 0.332), but the R² is quite high, indicating that other factors may influence large bus speeds besides road damage. Passenger cars and small buses fall in the middle, with a significant but less pronounced effect on road damage than trucks.

The Relationship Between Road Damage and GHG Emissions

GHG emissions from road transportation are significantly influenced by pavement conditions. The relationship between PCI (Road Damaged Area) and GHG emissions is that low PCI (damaged roads on the Kendal Timur National Road) tends to result in high CO₂, CH₄, and N₂O emissions. To better understand the relationship between road damage and GHG emissions, see the table below:

Table 14. The Relationship Between Road Damage and GHG Emissions on East National Road, Kendal

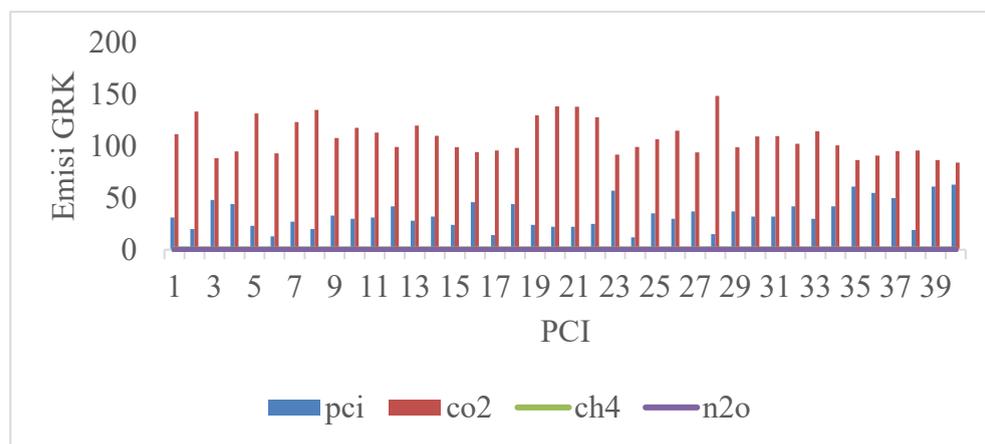
STA No.	PavaementCondi tion Index(PCI)	CO2/g/Km/Hour	CH4/g/Km/Hour	N2O/g/Km/Hour
KM 0+000 - 0+100	31	111.49	0.158	0.043
KM 0+100 - 0+200	20	133.59	0.174	0.048
KM 0+200 - 0+300	48	88.57	0.127	0.035
KM 0+300 - 0+400	44	95.09	0.135	0.037
KM 0+400 - 0+500	23	131.57	0.17	0.047
KM 0+500 - 0+600	13	93.22	0.13	0.036
KM 0+600 - 0+700	27	123.47	0.19	0.052
KM 0+700 - 0+800	20	135.16	0.178	0.049
KM 0+800 - 0+900	33	107.87	0.152	0.042
KM 0+900 - 1+000	30	117.72	0.182	0.05
KM 1+000 - 1+100	31	113.07	0.158	0.044
KM 1+100 - 1+200	42	99.2	0.144	0.04
KM 1+200 - 1+300	28	119.98	0.172	0.047
KM 1+300 - 1+400	32	109.96	0.157	0.043

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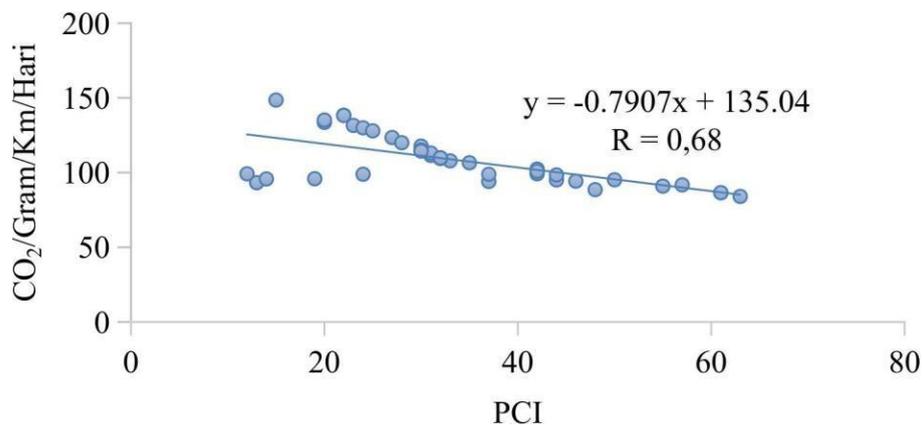
STA No.	PavaementCondition Index(PCI)	CO2/g/Km/Hour	CH4/g/Km/Hour	N2O/g/Km/Hour
KM 1+400 - 1+500	24	98.9	0.139	0.038
KM 1+500 - 1+600	46	94.25	0.13	0.036
KM 1+600 - 1+700	14	95.77	0.135	0.037
KM 1+700 - 1+800	44	98.41	0.138	0.038
KM 1+900 - 1+900	24	129.95	0.17	0.047
KM 1+900 - 2+000	22	138.4	0.18	0.049
KM 2+000 - 2+100	22	138.24	0.181	0.05
KM 2+100 - 2+200	25	127.94	0.17	0.047
KM 2+200 - 2+300	57	91.76	0.133	0.037
KM 2+300 - 2+400	12	99.18	0.139	0.038
KM 2+400 - 2+500	35	106.57	0.15	0.041
KM 2+500 - 2+600	30	115.11	0.161	0.044
KM 2+600 - 2+700	37	94.07	0.137	0.038
KM 2+700 - 2+800	15	148.54	0.212	0.058
KM 2+900 - 2+900	37	98.85	0.14	0.039
KM 3+900 - 3+000	32	109.42	0.154	0.042
KM 3+000 - 3+100	32	109.79	0.158	0.043
KM 3+100 - 3+200	42	102.35	0.146	0.04
KM 3+200 - 3+300	30	114.37	0.162	0.045
KM 3+300 - 3+400	42	100.87	0.144	0.04
KM 3+400 - 3+200	61	86.54	0.124	0.034
KM 3+100 - 3+500	55	90.92	0.133	0.037
KM 3+500 - 3+600	50	95.17	0.139	0.038
KM 3+600 - 3+700	19	95.89	0.14	0.039
KM 3+700 - 3+800	61	86.55	0.124	0.034
KM 3+800 - 3+900	63	84.04	0.119	0.033

Relationship between PCI and GHG emissions Low PCI (damaged roads), in rows with low PCI values (e.g., 12, 14, 15, 20, 22, 24, etc.), CO₂, CH₄, and N₂O emissions tend to be higher such as No. 24 (PCI 12): CO₂ = 99.18, CH₄ = 0.139, N₂O = 0.038 and No. 15 (PCI 13): CO₂ = 93.22, CH₄ = 0.130, N₂O = 0.036. For more clarity, see the graph below:



Graph 1. Relationship between PCI and CO GHG Emissions₂, CH₄ and N₂O on East Kendal National Road

Based on the graph above, CO₂ is the main contributor to GHG emissions from road transportation, strongly influenced by pavement conditions. Lower PCI allows for an increase in CO₂ emissions, although the correlation is not absolute, and for CH₄ and N₂O emissions are relatively constant and much smaller proportions. When the PCI value decreases, there are several times an increase in CO₂ emissions, but not always consistent across all observation points. This indicates that poor road conditions (low PCI) may make vehicles move less efficiently, resulting in higher CO₂ emissions. However, a perfect linear relationship is not seen because there are still other influencing variables such as traffic volume and vehicle characteristics. While CH₄ and N₂O emissions remain very low and are not significantly affected by PCI conditions on this section, confirming that the main source of emissions from road traffic at this location is CO₂. Furthermore, high PCI (good roads) in rows with high PCI values (e.g., 61, 63, 69), emissions tend to be lower, especially for CO₂ as below.



Graph 2. The Relationship between PCI and CO₂ GHG Emissions on the East Kendal National Road

Based on the graph in Figure 4.28 above, it can be seen that there is a relationship between PCI and CO₂ emissions, where the lower the PCI value, the higher the CO₂ emissions tend to be. Furthermore, with a correlation coefficient of 0.648, the relationship between these two variables is considered quite significant. The graph of the relationship between PCI and CO₂ GHG emissions indicates that data with a PCI value of 0.648 is significant. low (around 10–25) and CO₂ emissions tend to vary but are relatively high compared to the data points at a higher PCI. A low PCI (Pavement Condition Index) indicates severely damaged road surfaces, which can lead to unstable driving, frequent acceleration and braking, and increased fuel consumption, leading to higher CO₂ emissions.

Table 15. PCI Summary Model with Emi CO₂

<i>Model Summary</i>				
Model	R	<i>R square</i>	<i>Adjusted R Square</i>	<i>Std. Error of the Estimate</i>
1	648	419	404	13,00870
Predictors: (Constant), PCI				
Dependent variable: CO ₂				

Based on the table above, it can be seen that the R value which is a symbol of the correlation coefficient value is 0.648, this value can be interpreted that the relationship between the two road damage (PCI) (X) variables and CO₂ emissions (Y) in the study is in the fairly strong category. The coefficient of determination value obtained is 0.419 or 41.9% which can be interpreted that the independent variable (X), namely road damage (PCI) has a contribution effect of 37.6% on the Y variable of CO₂ emissions and the other 48.1% is influenced by other factors.

Table 16. Anova PCI with CO₂ Emissions

<i>Anova</i>						
Model		<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>Sig.</i>
1	<i>Regression</i>	4645,377	1	4645,377	27,451	.000
	<i>Residual</i>	6430,594	38	169,226		
	<i>Total</i>	1107,971	39			
Dependent variable: CO ₂						
Predictors: (Constant) PCI						

Based on the ANOVA table 4.33 above, which is used to obtain the level of significance or linearity of the regression. The criteria are obtained by conducting an F test or a Significance value test (Sig). With the provision, if the significance value is <0.05, then the regression model is linear and if the significance value is ≥ 0.05 then the regression model is not linear. Based on the ANOVA table, the Sig value is 0.001 which means it is smaller than the significance criterion (0.05), thus the regression equation model based on the research data is significant, meaning that the linear regression model meets the linearity criteria.

Table 17. PCI Coefficients with Co Emissions2

<i>Coefficients</i>						
Model		<i>Unstandardized Coefficients</i>		<i>Standardized Coefficients</i>	<i>T</i>	<i>Sig.</i>
		<i>B</i>	<i>Std. Error</i>	<i>Beta</i>		
1	<i>(Constant)</i>	135,037	5,503		24,539	.000
	<i>(PCI)</i>	-791	151	-.648	-5,239	.000
Dependent variable: CO ₂						

Based on the Coefficient Table 4.34 above, it can be seen that only variable X, namely road damage (PCI) has a significance value (Sig) of 0.001 which is smaller than the probability value of 0.05 so it can be concluded that there is an influence of road damage (PCI) on CO₂ emissions (Y). From the table above, the constant number of unstandardized coefficients is 135.037. This number is a constant number which means that if there is no influence of road damage (PCI), the attitude of CO₂ emissions is -0.791. Thus, based on this table, the regression equation model is obtained:

$$Y = 37.089x + X = 135.037 \quad R^2 = -0.791.$$

Y = CO₂ Emissions

X = Road damage (PCI),

R = Correlation Coefficient

R² = Termination Coefficient

To more clearly see the relationship between road damage (PCI) and GHG emissions on the East Kendal National Road, please see the summary table below:

Table 18. Summary of the Relationship between Road Damage and Vehicle GHG Emissions

Types of GHG	Correlation Coefficient (R)	Regression Equation
CO ₂	0.648	Y = -0.079 x + X = 135.04
CH ₄	0.613	Y = -0.0009x + X = 0.1836
N ₂ O	0.613	Y = -0.0003x + X = 0.0505

Based on the analysis results above, a correlation coefficient value of 0.648 was obtained, indicating a fairly strong positive relationship between road damage (PCI value) and CO₂ emissions. This means that the lower the PCI value (the more severe the road damage), the higher the CO₂ emissions produced tend to be. For CH₄ emissions, a fairly strong positive relationship was also found with a correlation coefficient value of 0.613 between road damage and CH₄ emissions, indicating that the lower the road quality, the higher the CH₄ emissions. Similarly, for N₂O emissions, there is a strong positive relationship with a correlation coefficient value of 0.613 between road damage and N₂O emissions, meaning that the worse the road conditions, the higher the N₂O emissions tend to be. Overall, the correlation coefficient (R) values for the three types of emissions indicate that there is a strong positive relationship between road damage and greenhouse gas (GHG) emissions.

CONCLUSION

The pavement condition on the East Kendal National Road section is generally in poor to very poor condition with an average Pavement Condition Index (PCI) value of 33.83. This indicates that most of the road section has experienced damage such as alligator cracking, patching, and depressions which affect the comfort and safety of road users. Road damage affects average vehicle speed. Regression analysis shows that the lower the PCI value (the more severe the road damage), the lower the average vehicle speed. This effect is significant for both light and heavy vehicles. Uneven road surfaces cause drivers to reduce speed to maintain stability and safety. Vehicle speed affects the amount of greenhouse gas emissions. When vehicle speed decreases due to road damage, fuel efficiency decreases, resulting in CO₂, CH₄ emissions, and N₂O increased. The results of the correlation analysis showed a value of R = 0.648 for CO₂, R = 0.613 for CH₄, and R = 0.613 for N₂O, which means there is a fairly strong positive relationship between the level of road damage and greenhouse gas emissions.

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THE EFFECT OF ROAD DAMAGE ON GREENHOUSE GAS EMISSIONS (CASE STUDY OF KENDAL EASTERN HIGHWAY)

St Marisa Haq et al
