# Impact of Road Gradient on Fuel Consumption, Fuel Rate and $CO_2$ Emissions of Freight Transport

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## ABSTRACT

This study investigates the impact of road gradient on fuel consumption, fuel rate (*FR*), and $CO_2$ emissions in freight transport vehicles with two-axle and three-axle configurations. The research was conducted on a 250-meter road segment with a 0.067 rad (~7%) gradient in front of Taman Rekreasi Datae, Sidenreng Rappang Regency, South Sulawesi, Indonesia. A quantitative mathematical model, based on vehicle technical parameters and empirical formulations from previous studies, was applied. Results show that increasing the gradient from 0 to 0.067 rad raised fuel consumption in two-axle trucks from 0.0356 L to 0.0857 L and in three-axle trucks from 0.1463 L to 0.3269 L. The FR for two-axle trucks increased from 0.0014 L/s to 0.0056 L/s, while for three-axle trucks it rose from 0.0033 L/s to 0.0124 L/s. $CO_2$ emissions from two-axle trucks increased from 0.0958 kg to 0.3941 kg, and from 0.2310 kg to 0.8807 kg for three-axle trucks. The relative increase was higher for two-axle trucks (311%) than for three-axle trucks (281%), due to axle load distribution, engine capacity, and transmission ratio. These findings highlight the need to consider vehicle configuration and topography in route planning to minimize fuel consumption and emissions in hilly regions.

**Keywords:** fuel consumption, fuel rate, $CO_2$ emissions, road gradient, freight transport.

## INTRODUCTION

The development of the land transportation sector, particularly freight transport, has become the backbone of logistics distribution in many countries, including Indonesia. While playing a strategic role in supporting economic growth and supply chain efficiency, this activity also represents a significant contributor to greenhouse gas (GHG) emissions and fossil fuel consumption. Reports from the European Environment Agency [1] and the International Energy Agency [2] indicate that diesel-powered heavy-duty vehicles account for more than one-quarter of total emissions from the transportation sector. This contribution is projected to increase in line with rising trade volumes, urbanization, and freight movement intensity [3], [4], [5], [6].

One of the most influential variables affecting the energy efficiency and emission levels of heavy-duty vehicles is road geometric characteristics, particularly road gradient. International studies have demonstrated that variations in road grade can induce substantial changes in fuel consumption and emissions. [7] emphasized that gradient increases, particularly for heavily loaded vehicles, contribute nonlinearly to higher fuel consumption. A study by [8] in China revealed that gradients as small as 0.5% to 6% can increase fuel consumption by up to 140% and NOx emissions by 115%, a finding further supported by [9] and [10]. Furthermore, [11] highlighted that neglecting road gradient effects in transportation planning could result in an underestimation of energy consumption by nearly 29%.

In addition, the impact of gradient is often amplified by operational factors such as vehicle speed, total mass, and engine technical condition. [12] identified gradient and speed as the primary determinants of tailpipe emissions in heavy-duty vehicles, while [13] found that routes with moderate-to-steep inclines generate higher emissions compared to flat routes. Mitigation strategies that account for topographical factors, as recommended by [14] and [15], have been shown to improve energy efficiency while reducing environmental impacts.

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In Indonesia, studies addressing the effect of road gradient on fuel consumption and emissions in freight vehicles remain relatively limited. Most domestic research has focused on over-dimension and over-load (ODOL) issues, road safety, and operational costs [16], [17], [18]. However, Indonesia's diverse geography and the presence of freight distribution routes with hilly terrain such as those in South Sulawesi make this topic particularly relevant for investigation.

Addressing this research gap, the present study aims to analyze fuel consumption and $CO_2$ emissions in two-axle and three-axle trucks operating along the main road in front of Taman Rekreasi Datae, Sidenreng Rappang (Sidrap) Regency, South Sulawesi. A quantitative mathematical modeling approach was employed to assess the effect of a moderate road gradient. The findings are expected to provide scientific insights into the relationship between topography and energy efficiency, serving as a reference for formulating sustainable road freight transport policies [19], [20], [21], [22].

## RESEARCH METHODS

### Reasearch Design

This study employed a quantitative approach based on mathematical analysis to evaluate the effect of road gradient on fuel consumption and $CO_2$ emissions in freight transport. The selection of this approach was driven by its ability to provide measurable estimations, ensure ease of replication, and maintain consistency with similar studies at the international level [7], [8], [9], [11], [12].

### Research Location

Data collection was conducted on the main road in front of Taman Rekreasi Datae, Sidenreng Rappang (Sidrap) Regency, South Sulawesi, Indonesia. This location was selected because it features a moderate road gradient, representing typical uphill conditions encountered on freight distribution routes in the region. Furthermore, the proximity of the Datae Motor Vehicle Weighing Implementation Unit (UPPKB) allowed for accurate verification of vehicle technical specifications.


**Figure 1.** Research track map on the main road in front of Taman Rekreasi Datae, Sidenreng Rappang (Sidrap) Regency, South Sulawesi, Indonesia.

### Track Condition

The research track has a horizontal length of 250 meters with a vertical elevation difference of 17 meters. These parameters served as the basis for calculating the road gradient, which is one of the primary factors influencing fuel consumption and emissions in heavy-duty vehicles. The gradient was calculated using the formulation adapted from [9], as shown in Equation ($1$). This equation models the relationship between the slope angle ($\theta$) the change in elevation ($\Delta h$) and the horizontal track length ($L$). In general, the gradient can be defined as the ratio of vertical rise to horizontal distance, expressed as a percentage. For low-to-moderate gradients, the value of tan $\theta$ can be approximated by sin $\theta$, thereby simplifying the formulation.

$$i = tan\, \theta = \frac{\Delta h}{L} \times 100\% \approx sin\, \theta = \frac{\Delta h}{X} = \frac{\Delta h}{\int v\, dt} \quad (1)$$

**Table 1.** Geometric parameters of the research track

| Description | Value |
|---|---|
| Elevation difference (m) | 17 |
| Horizontal length (m) | 250 |

Referring to the geometric road design classification, the gradient value derived from these parameters falls within the moderate slope category [23], which can significantly affect fuel consumption in heavy-duty vehicles, particularly when operating under full load conditions.

**Vehicle Specifications**

This study analyzed two types of freight transport vehicles commonly operating along distribution routes in South Sulawesi: two-axle and three-axle trucks. The two-axle truck represents a medium-load vehicle with a two-axle wheel configuration, a 3.9-liter engine capacity, and an unladen weight of 2,900 kg. In contrast, the three-axle truck is a heavy-load vehicle with a three-axle wheel configuration, a 7.7-liter engine capacity, and an unladen weight of 7,000 kg. These two vehicle types were selected as they represent the most frequently used load capacity variations in Indonesia's logistics distribution. The technical specifications were obtained from manufacturer documentation, records from the Datae Motor Vehicle Weighing Implementation Unit (UPPKB), and relevant technical literature [7], [24], [25].

**Table 2.** Technical parameters of the vehicles

| Notation | Description | Value two-axle | Value three-axle |
|---|---|---|---|
| $\xi$ | Fuel-to-air mass ratio | 1 | 1 |
| $K$ | Heating value of conventional diesel fuel (kJ/g) | 44 | 44 |
| $\psi$ | Conversion factor (g/l) | 830 | 830 |
| $k$ | Engine friction factor (kJ/(rev/l)) | 0.2 | 0.2 |
| $N_e$ | Engine speed (rev/s) | 37 | 38 |
| $V$ | Engine displacement (l) | 3.9 | 7.7 |
| $\rho$ | Air density (kg/m$^3$) | 1.18 | 1.18 |
| $A$ | Frontal surface area (m$^2$) | 4.4 | 5.3 |
| $\mu$ | Curb weight (kg) | 2900 | 7000 |
| $g$ | Gravitational acceleration (m/s2) | 9.81 | 9.81 |
| $C_d$ | Coefficient of aerodynamic drag | 0.65 | 0.75 |
| $C_r$ | Coefficient of rolling resistance | 0.007 | 0.008 |
| $\varepsilon$ | Vehicle drive train efficiency | 0.85 | 0.85 |
| $\varpi$ | Efficiency parameter for diesel engines | 0.42 | 0.45 |
| $f$ | Vehicle mass (kg) | 5720 | 13120 |
| $v$ | Vehicle speed (m/s) | 9.722 | 9.722 |

These parameters will be used in the calculation model for fuel consumption and $CO_2$ emissions. The selection of parameters was based on their relevance to actual vehicle operating conditions in the field and their consistency with previous studies [7], [8].

**Calculation Model**

The calculations in this study comprise three main components: total fuel consumption (*F*), instantaneous fuel rate (*FR*), and the conversion of fuel consumption into $CO_2$ emissions (*C*). The fuel consumption formulation was adapted from [7], while the $CO_2$ emission calculation model followed the approach proposed by [8], which is consistent with the guidelines of the Intergovernmental Panel on Climate Change [26]. Total fuel consumption was calculated using Equation (*2*):

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$$F = \lambda\left(kN_eV\frac{d}{v} + \gamma\beta dv^2 + \gamma\alpha(\mu + f)d\right) \quad (2)$$

Where $\lambda = \xi/K\psi$, represents the ratio of fuel mass to air mass ($\xi$), the calorific value of diesel fuel ($K$), and the mass–volume conversion factor ($\psi$). Meanwhile, $\gamma = 1/(1000\varepsilon\varpi$ accounts for drivetrain efficiency ($\varepsilon$) and diesel engine efficiency ($\varpi$). The first component, $kN_eV\frac{d}{v}$, represents the base engine fuel consumption, which is influenced by the engine friction factor ($k$), engine speed ($N_e$), and engine displacement ($V$). The second component, $\gamma\beta dv^2$, describes the additional fuel consumption due to aerodynamic resistance, where $\beta = 0.5C_dA\rho$ is derived from the aerodynamic drag coefficient ($C_d$), vehicle frontal area ($A$), and air density ($\rho$). The third component, $\gamma\alpha(\mu + f)d$, reflects the influence of vehicle mass and road gradient, with $\alpha = gsin\theta + gC_rcos\theta$, where g is gravitational acceleration, $C_r$ is the rolling resistance coefficient, and θ is the road gradient angle. The instantaneous fuel rate ($FR$) is calculated using Equation (*3*):

$$FR = \lambda(kN_eV + \gamma(\beta v^3 + \alpha(\mu + f)v) \quad (3)$$

Equation (*3*) has a similar structure to Equation (*2*), but omits the distance variable ($d$) as the calculation is based on a time unit. The term $kN_eV$ represents the base engine fuel consumption per unit of time. The term $\beta v^3$ describes the additional load due to aerodynamic drag as a cubic function of vehicle speed. The term $\alpha(\mu + f)v$ quantifies the contribution of vehicle weight and road gradient to dynamic fuel consumption. The conversion of fuel consumption into $CO_2$ emissions is calculated using Equation (*4*):

$$C = ABJKdQ \times 10^{-3} \quad (4)$$

In Equation (*4*), $Q$ is the amount of fuel consumed (liters), $A$ is the net calorific value of diesel fuel (TJ/Gg), $B$ is the carbon oxidation ratio, $J$ is the carbon emission factor (t/TJ), $K$ is the carbon-to-$CO_2$ conversion factor, and $d$ is the diesel fuel density (kg/L). The values of these parameters are presented in Table 3.

**Table 3.** Diesel fuel emission parameters

| Notation | Description | Value |
|---|---|---|
| *A* | Net calorific value of diesel fuel (TJ/Gg) | 44 |
| *B* | Carbon oxidation ratio | 0.99 |
| *J* | Carbon emission factor (t/TJ) | 20.2 |
| *K* | Carbon-to-$CO_2$ conversion factor | 3.67 |
| *d* | Diesel fuel density (kg/L) | 0.835 |

This formulation ensures that the relationship between track physical conditions, vehicle technical specifications, and the resulting emissions can be quantitatively analyzed and compared with relevant international studies.

## RESULT AND DISCUSSION

### Total Fuel Consumption (*F*)

The calculation results indicate that total fuel consumption increases significantly with the rise in road gradient angle. Under flat road conditions ($\theta = 0$), the two-axle truck consumed 0.0356 liters of fuel, while the three-axle truck consumed 0.1463 liters. When the road gradient increased to 0.067 radians (~7%), fuel consumption rose to 0.0857 liters for the two-axle truck and 0.3269 liters for the three-axle truck.

**Table 4.** Total fuel consumption at different road angles

| Road angle ($\theta$) | Two-axle (liters) | Three-axle (liters) |
|---|---|---|
| 0 | 0.0356 | 0.1463 |
| 0.067 | 0.0857 | 0.3269 |

This pattern is illustrated in Figure 4, which shows a significant difference between the two vehicle types, particularly under uphill gradient conditions. The three-axle truck consistently exhibited higher fuel consumption than the two-axle truck at the same road angle. This can be explained by the greater total mass and larger engine capacity of the three-axle truck, which require more energy to overcome gravitational forces and rolling resistance. The steeper increase in fuel consumption observed in the three-axle configuration is also consistent with the findings of [7] and [9], who reported that the effect of road gradient becomes more pronounced in vehicles with higher mass and payload. These results suggest that energy savings can be achieved by optimizing vehicle deployment according to the topographical conditions of distribution routes.

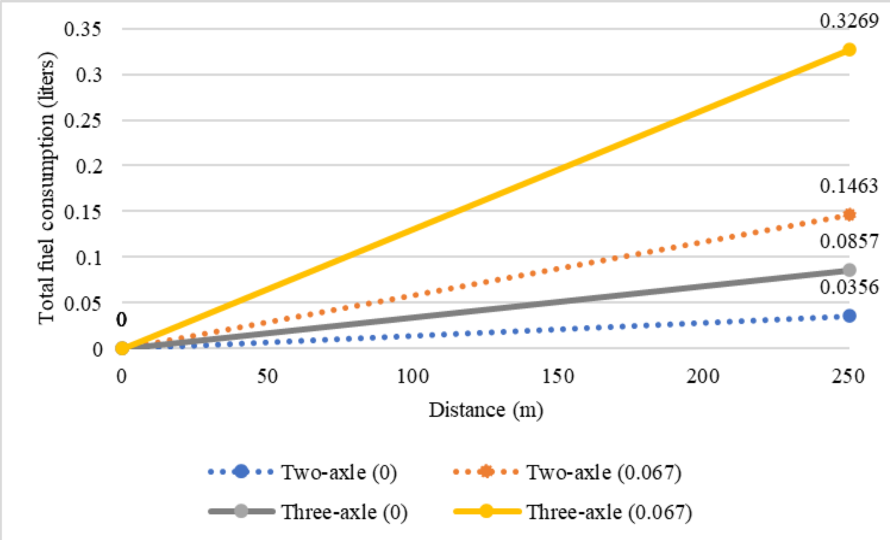


**Figure 2.** Effect of road angle on total fuel consumption

**Instantaneous Fuel Rate (*FR*)**

The calculation results show that the instantaneous fuel rate represents the amount of fuel consumed by the vehicle per second while traversing the track. The results in Table 5 indicate that increasing the road gradient from 0 to 0.067 radians (~7%) has a significant impact on FR values for both two-axle and three-axle trucks.

**Table 5.** Instantaneous fuel rate (*FR*)

| Road angle ($\theta$) | Two-axle (liters/second) | Three-axle (liters/second) |
|---|---|---|
| 0 | 0.0014 | 0.0033 |
| 0.067 | 0.0056 | 0.0124 |

As shown in Figure 3, the three-axle truck exhibits a higher *FR* than the two-axle truck under all conditions. On a flat road, the *FR* for the three-axle truck reaches 0.0033 liters/s, approximately 2.36 times higher than that of the two-axle truck. This difference becomes more pronounced at a gradient of 0.067 radians, where the *FR* for the three-axle truck increases to 0.0124 liters/s, while the two-axle truck reaches only 0.0056 liters/s. The increase in *FR* is consistent with the vehicle energy consumption theory proposed by [7], which states that road gradient influences the gravitational force component that must be overcome by the vehicle. Vehicles with greater mass and larger engine capacity tend to exhibit a more substantial rise in instantaneous fuel consumption. This is further supported by [9], who reported that rolling resistance and gravitational effects play a dominant role on uphill routes, particularly for heavy-duty vehicles.

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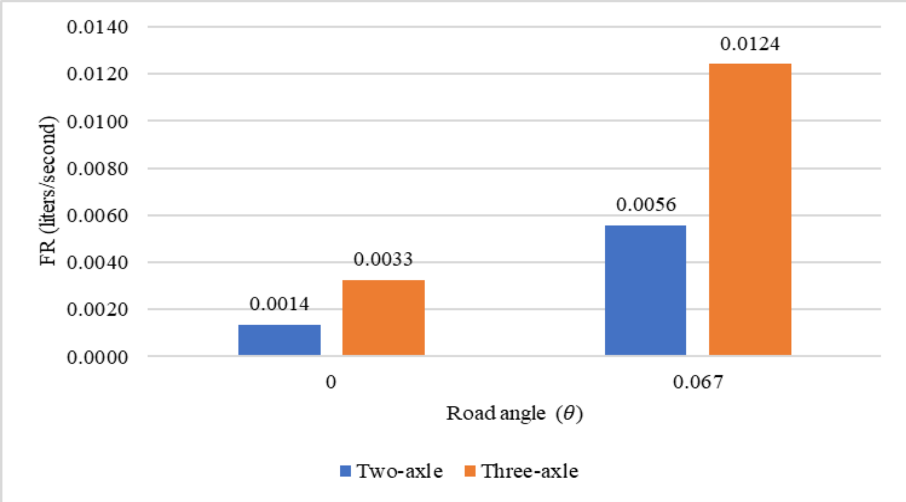


**Figure 3.** Comparison of instantaneous fuel rate under two road gradient conditions

**$CO_2$ Emissions (*C*)**

$CO_2$ emissions were calculated based on total fuel consumption and the diesel fuel emission parameters presented in Table 3. The results (Table 6) show that an increase in road gradient significantly raises $CO_2$ emissions for both vehicle types.

**Table 6.** $CO_2$ emissions at different road angles

| Road angle ($\theta$) | Two-axle (kg) | Three-axle (kg) |
|---|---|---|
| 0 | 0.0958 | 0.2310 |
| 0.067 | 0.3941 | 0.8807 |

As shown in Figure 4, on a flat road ($\theta = 0$), the $CO_2$ emissions of the three-axle truck were recorded at 0.2310 kg, nearly 2.4 times higher than those of the two-axle truck (0.0958 kg). When the gradient increased to 0.067 radians (~7%), $CO_2$ emissions rose sharply to 0.8807 kg for the three-axle truck and 0.3941 kg for the two-axle truck. This sharp increase is consistent with the findings of [7], which indicate that the additional load due to gravitational forces on uphill roads directly impacts fuel consumption and emissions. Furthermore, [11] emphasized that neglecting gradient effects can result in underestimating emissions by more than 20% for heavy-duty vehicles. These results suggest that freight route management should take topographical factors into account, particularly on uphill segments, to reduce the carbon footprint of freight transport. Strategies such as deploying lighter vehicles on high-gradient routes or implementing energy-efficient propulsion technologies can help lower emissions.

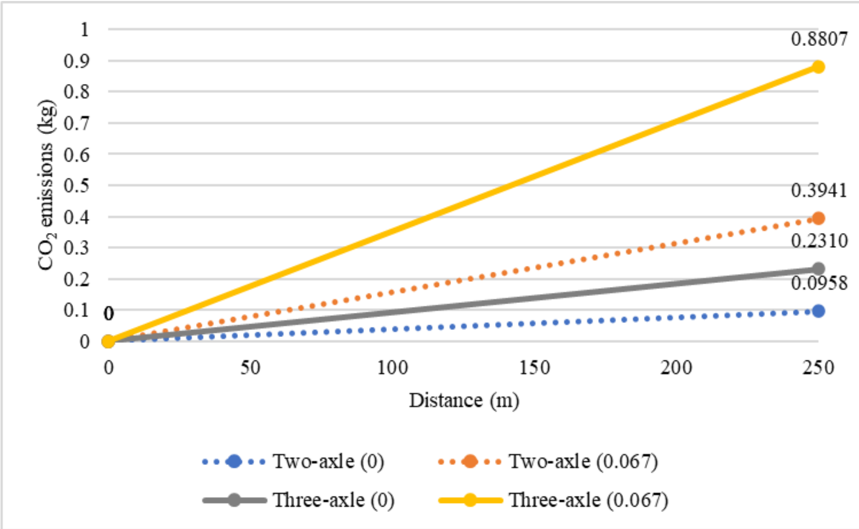


**Figure 4.** Effect of road angle on $CO_2$ emissions

**Increase Rasio Analysis**

The results presented in Figure 5 show that, at a road gradient of 0.067 radians (~7%), the two-axle truck experienced an increase ratio in fuel consumption and emissions of 311%, while the three-axle truck recorded a 281% increase compared to flat road conditions. Although the three-axle truck has a larger payload capacity and higher total weight, its percentage increase was comparatively lower. This can be explained by several interrelated technical factors. First, the load distribution in the three-axle truck is more evenly spread across the axles, reducing wheel pressure per unit contact area and consequently lowering the increase in rolling resistance on uphill roads. [7] stated that a more efficient load distribution can mitigate the rate of fuel consumption increase due to gradient. Second, the larger engine capacity of the three-axle truck allows it to maintain combustion efficiency under high-load conditions, thereby controlling the rise in fuel consumption. This is consistent with [11], who found that trucks with optimized engine torque curves incur relatively lower fuel consumption penalties on uphill routes compared to vehicles with limited power. Third, the transmission gear ratio in three-axle trucks is designed to support heavy-load hauling, enabling the vehicle to meet additional power demands on moderate gradients without significant increases in engine speed or fuel consumption rate. Thus, the additional load from road gradient exerts a proportionally greater impact on vehicles with fewer axles, mainly due to engine capacity limitations and less uniform load distribution. These findings reinforce the importance of considering both topographical factors and vehicle configuration in route planning to minimize fuel consumption and exhaust emissions.

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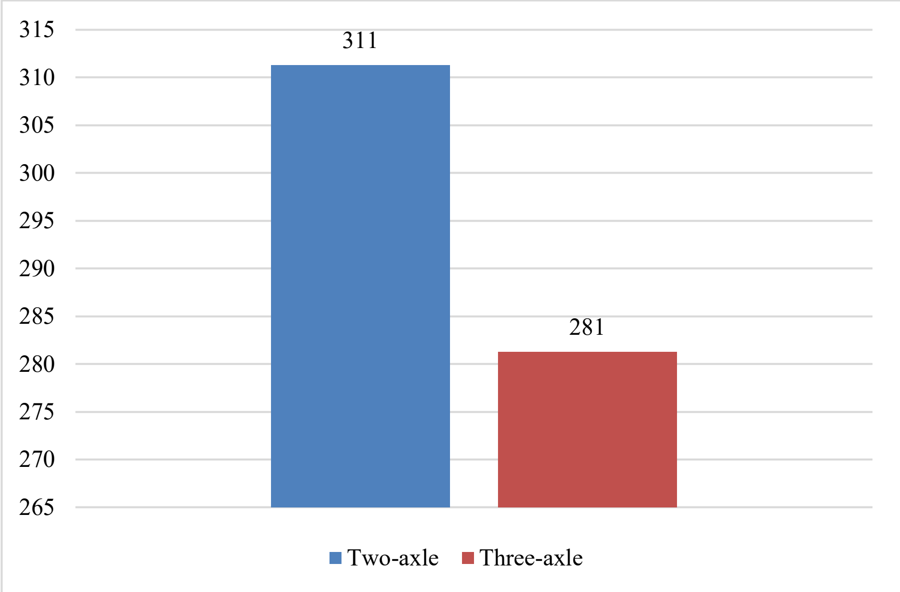


**Figure 5.** Ratio of fuel consumption and emission increases at a road gradient of 0.067 radians

**Limitations and Recomendations for Future Research**

This study has several limitations that should be considered when interpreting the results. First, gradient and track length measurements were obtained from spatial information using digital mapping software; therefore, the accuracy of elevation measurements may be influenced by data resolution and the interpolation methods applied. Previous studies have shown that medium-resolution satellite-derived topographic data can exhibit significant elevation deviations, particularly in areas with sharp contours [23]. Second, fuel consumption and emissions were calculated using a theoretical approach based on vehicle parameters and empirical formulas adapted from previous studies [7], [8], [9], [11], [12], thus representing ideal estimates that may not fully capture real-world variations such as weather conditions, road surface quality, or driver behavior. Third, the analyzed track variation was limited to a single road length (250 meters) and a single gradient level (0.067 rad), meaning that the results do not encompass more complex scenarios involving multiple gradients and varying road lengths.

For future research, it is recommended that gradient and elevation measurements be conducted directly in the field using high-precision geodetic instruments to improve topographic data accuracy. This approach aligns with the recommendations of [11], which emphasize the importance of field verification to avoid slope estimation bias. Furthermore, integrating empirical data from on-road tests using fuel consumption and emission sensors will provide a more realistic representation of vehicle performance under various conditions [27]. Future studies should also consider a wider range of gradient levels, road lengths, and payload conditions, as well as evaluate the effects of external factors such as ambient temperature, wind direction, and traffic density. Such an approach is expected to yield more practical technical recommendations for planning and managing freight distribution routes in hilly areas.

**Policy Implications**

The findings of this study carry important implications for formulating transportation policies, particularly in managing freight transport in regions with hilly topography. The substantial increase in fuel consumption and $CO_2$ emissions observed at a gradient of 0.067 radians (~7%) underscores the need for mitigation strategies based on route planning, vehicle technology, and operational management. Local governments can utilize these results to design route regulation policies that avoid high-gradient segments for vehicles with low engine capacity or limited axle configurations. This approach is consistent with the recommendations of [7] and [15], which emphasize that route planning based on topography can significantly reduce energy demand and emissions.

In addition, the adoption of energy-efficient propulsion technologies, such as engines meeting Euro 4 or higher emission standards, along with the integration of telematics-based fuel consumption monitoring systems, can help optimize operational efficiency [1], [2], [27]. Moreover, these results can serve as a basis for strengthening regulations on vehicle load and dimensional limits for routes with specific gradient thresholds, as stipulated in Indonesian Ministry of Environment and Forestry Regulation No. 20/2017 [28], to minimize environmental impacts and logistics costs. Considering topographical factors in transportation planning enables logistics managers and policymakers to establish distribution systems that are more efficient, sustainable, and environmentally friendly. This approach not only helps reduce energy consumption and greenhouse gas emissions but also has the potential to lower operational costs and extend vehicle service life by reducing engine workload on uphill routes [11].

## CONCLUSION

At a gradient of 0.067 radians (~7%) compared to flat road conditions, all three indicators showed a marked increase. For total fuel consumption, the two-axle truck increased from 0.0356 L ($\theta = 0$) to 0.0857 L ($\theta = 0.067$), while the three-axle truck rose from 0.1463 L to 0.3269 L. For FR, the two-axle truck increased from 0.0014 L/s to 0.0056 L/s, whereas the three-axle truck rose from 0.0033 L/s to 0.0124 L/s. For $CO_2$ emissions, the two-axle truck increased from 0.0958 kg to 0.3941 kg, and the three-axle truck from 0.2310 kg to 0.8807 kg. In relative terms, the increase ratio for fuel consumption and emissions in the two-axle truck (311%) was higher than in the three-axle truck (281%), indicating greater sensitivity in vehicles with fewer axles. This difference is mainly attributed to the more uniform axle load distribution in the three-axle truck, its larger engine capacity, and a transmission ratio optimized for heavy loads, which collectively help keep the escalation of energy use and emissions on uphill routes more controlled. These findings confirm that vehicle configuration and topographical characteristics are key factors in distribution route planning; prioritizing vehicle selection and gradient-based route allocation is essential to minimizing fuel consumption, FR, and emissions along hilly corridors.

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