



Gradient-induced fuel consumption and CO₂ emission sensitivity: a comparative analysis of two and three-axle trucks on short uphill segments



Hakzah Hakzah*, Abdul Rahman, Andriyani Andriyani, Jasman Jasman, Kasmaida Kasmaida
Department of Civil Engineering, Universitas Muhammadiyah Parepare, Indonesia

Abstract

Road freight transport significantly contributes to global energy use and greenhouse gas emissions, yet the influence of short uphill gradients on fuel consumption and CO₂ emissions remains insufficiently studied in Indonesia. While prior research has examined slope effects on long-haul operations, limited evidence quantifies sensitivity on short ascending segments (50–250 m) and compares two- and three-axle trucks. This study addresses this gap by applying a mathematical modeling framework that integrates technical parameters collected from the Datae Motor Vehicle Weigh Station (UPPKB Datae), Sidenreng Rappang Regency, South Sulawesi Province, Indonesia, with established fuel consumption and emission formulations. Gradient variations of 0–15% and travel distances of 50–250 m were analyzed, and fuel consumption results were converted into CO₂ emissions using IPCC guidelines. The findings reveal a sharp escalation in both fuel demand and emissions, with the slope increasing. At a 15% gradient and 250 m distance, CO₂ emissions rose by approximately 692% for two-axle trucks and 625% for three-axle trucks compared with the flat baseline. Although heavier trucks recorded higher absolute values, two-axle trucks exhibited greater relative sensitivity to changes in gradient. These results provide novel evidence on slope-induced inefficiencies in short segments, offering practical insights for eco-routing, operational planning, and gradient-sensitive decarbonization strategies in freight transport.

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Corresponding Author:

Hakzah Hakzah
Department of Civil Engineering,
Universitas Muhammadiyah
Parepare, Indonesia
Email: hakzah@umpar.ac.id

INTRODUCTION

Road freight transport remains a cornerstone of global logistics, yet it is also one of the largest contributors to energy demand and greenhouse gas emissions. Heavy-duty diesel trucks alone account for more than one-quarter of transport-related CO₂ emissions, creating significant challenges for decarbonization strategies worldwide [1, 2, 3]. Growing urbanization and trade volumes further amplify the demand for freight services, underscoring the urgency of developing sustainable mobility solutions that reconcile efficiency with emission reduction [4][5].

Among the multiple determinants of energy use, road gradient has been consistently recognized as a decisive factor. Early formulations of the pollution-routing problem demonstrated that slopes increase fuel demand nonlinearly due to the combined effects of mass, gravitational resistance, and rolling friction [6]. Empirical research in China confirmed that even modest gradients significantly elevate CO₂ emissions from diesel trucks [7], while large-scale connected vehicle data revealed that inclines as small as 0.5–6% can raise fuel consumption by up to 140% and NO_x emissions by more than 100% [8]. Neglecting slope in

energy modeling has been shown to produce systematic underestimations of nearly 30% [9]. Technical factors including engine capacity, vehicle weight, aerodynamic drag, and drivetrain efficiency further amplify the gradient effect on energy demand [10, 11, 12].

Despite these insights, important research gaps persist. Most international studies emphasize long-haul operations and average gradient conditions, while short uphill segments of 50–250 meters commonly encountered in freight corridors remain underexplored [13][14]. Comparative assessments of two-axle versus three-axle trucks are also scarce, even though axle configuration directly influences energy performance [15, 16, 17].

In Indonesia, research has largely centered on over-dimension and overloading practices, safety, and operational cost analysis, with limited attention to slope-induced energy penalties [18][19]. Yet in regions such as South Sulawesi, where freight networks traverse steep and uneven terrains, road gradient plays a critical role in shaping distribution efficiency and fuel demand [20][21].

The present study addresses these gaps by quantifying fuel consumption and CO₂ emissions of two-axle and three-axle freight trucks across road gradients of 0–20% and distances of 50–250 meters. Technical parameters were collected from the Motor Vehicle Weigh Station and analyzed using established formulations of the Pollution Routing Problem with IPCC-based emission factors. The contribution of this study is threefold: (i) providing novel evidence of slope-induced inefficiencies on short uphill segments, (ii) introducing increment ratio analysis to compare the relative sensitivity of two- and three-axle trucks, and (iii) offering policy-relevant insights for gradient-sensitive freight planning and decarbonization strategies in Indonesia.

METHOD

Research Design

The research design of this study follows a structured modeling framework to quantify the influence of road gradients on truck fuel consumption and CO₂ emissions. The first stage involved collecting technical specifications of two-axle and three-axle trucks, including engine capacity, curb weight, and axle configuration, from the Datae Motor Vehicle Weigh Station (UPPKB Datae), Sidenreng Rappang Regency, South Sulawesi Province, Indonesia. These parameters served as the primary input for energy demand modeling, consistent with established freight

transport studies [10][18].

In the second stage, the experimental scenarios were defined by varying road gradients from 0% to 15% at 1% intervals, combined with three short ascending segment lengths of 50 m, 150 m, and 250 m. This approach reflects realistic uphill conditions frequently encountered in Indonesian freight corridors, which remain underrepresented in emission inventories and eco-routing analyses [7, 8, 9].

The third stage estimated fuel demand using the Pollution Routing Problem formulation, which accounts for vehicle mass, rolling resistance, and gravitational forces along ascending slopes [6]. Fuel demand was expressed both as total fuel consumption (F) and fuel rate (FR), ensuring that results capture absolute and instantaneous effects.

In the fourth stage, fuel demand values were converted into CO₂ emissions using emission factors from the IPCC Guidelines for National Greenhouse Gas Inventories [22][23]. This method aligns the study with international standards for greenhouse gas accounting and enables cross-study comparability.

Finally, the fifth stage introduced an increment ratio analysis, which compared each gradient level to the flat-road baseline (0%). This sensitivity analysis highlights the relative differences between two-axle and three-axle trucks, providing insights into how axle configuration influences gradient-induced inefficiencies [9][16]. The overall design allows validation against international findings while generating context-specific evidence for eco-routing and decarbonization strategies in Indonesia.

Vehicle Specifications

The technical parameters used in the modeling process were derived from the Datae Motor Vehicle Weigh Station (UPPKB Datae), Sidenreng Rappang Regency, South Sulawesi Province, Indonesia, and complemented with standard references for heavy-duty vehicles. These specifications cover mass, engine displacement, frontal surface area, and aerodynamic properties, which are widely recognized as critical determinants of fuel consumption and emission performance in slope-related studies [7, 10, 11]. Table 1 presents the complete set of technical parameters applied in the analysis for both two-axle and three-axle trucks

Table 1. Technical parameters applied in the analysis for both two-axle and three-axle trucks

Notation	Description	Value two-axle	Value three-axle
ξ	Fuel-to-air mass ratio	1	1
K	Heating value of conventional diesel fuel (kJ/g)	44	44
ψ	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
ρ	Air density (kg/m ³)	1.18	1.18
A	Frontal surface area (m ²)	4.4	5.3
μ	Curb weight (kg)	2900	7000
g	Gravitational acceleration (m/s ²)	9.81	9.81
C_d	Coefficient of aerodynamic drag	0.65	0.75
C_r	Coefficient of rolling resistance	0.007	0.008
ε	Vehicle drive train efficiency	0.85	0.85
ω	Efficiency parameter for diesel engines	0.42	0.45
f	Vehicle mass (kg)	5720	13120
v	Vehicle speed (m/s)	9.722	9.722

Two-axle trucks, representing the medium-duty category, were characterized by a curb weight of 2,900 kg, an engine displacement of 3.9 L, and a gross vehicle mass of 5,720 kg. In contrast, three-axle trucks, representing the heavy-duty category, exhibited substantially higher values, including a curb weight of 7,000 kg, an engine displacement of 7.7 L, and a gross vehicle mass of 13,120 kg. These differences directly influence absolute fuel demand, as larger vehicle mass and engine size lead to higher baseline energy requirements.

Other parameters such as vehicle drive train efficiency, rolling resistance coefficients, and aerodynamic drag coefficients were kept consistent with typical values adopted in prior freight energy modeling studies [6][8]. The vehicle speed was fixed at approximately 9.7 m/s (~35 km/h) to represent an average climbing velocity on short uphill segments.

Road Distance and Gradient Variations

The experimental scenarios were designed to represent short ascending segments that are commonly encountered in Indonesian freight corridors. Gradients were systematically varied from 0% to 15% in 1% increments, while the distance was set between 50 m and 250 m, reflecting realistic uphill sections along regional highways. Such short segments, although often overlooked in emission inventories, have been identified in prior studies as critical points where fuel consumption increases disproportionately due to sudden elevation gains [7][9].

As shown in Table 2, the incremental increase in gradient was accompanied by proportional changes in road angle (θ), ranging from 0.010 radians at 1% slope to 0.149 radians at 15% slope.

Table 2. Road Distance and Gradient Variations

Distance (m)	Gradient (%)	Road angle (θ)
50-250	0%	0.000
50-250	1%	0.010
50-250	2%	0.020
50-250	3%	0.030
50-250	4%	0.040
50-250	5%	0.050
50-250	6%	0.060
50-250	7%	0.070
50-250	8%	0.080
50-250	9%	0.090
50-250	10%	0.100
50-250	11%	0.110
50-250	12%	0.119
50-250	13%	0.129
50-250	14%	0.139
50-250	15%	0.149

These variations allowed for a detailed assessment of both absolute and relative fuel consumption changes across vehicle categories. The inclusion of fine-grained gradient intervals ensured that slope sensitivity could be captured more accurately, providing a robust basis for increment ratio analysis and comparative evaluation between two-axle and three-axle trucks.

Fuel Consumption Model (F)

The fuel consumption model adopted in this study is based on the Pollution Routing Problem (PRP) formulation originally proposed by Bektaş and Laporte [24] and further refined by Franceschetti et al. [6] to represent the operational characteristics of heavy-duty freight vehicles. This model integrates engine workload, aerodynamic drag, rolling resistance, vehicle mass, and

gravitational resistance induced by road gradients. The total fuel consumption (F) is calculated using (1, which estimates the energy demand of trucks under varying gradient and distance conditions by explicitly accounting for slope-induced forces. Previous studies have validated the importance of incorporating road gradient into fuel consumption modeling, demonstrating that gradients significantly increase fuel demand [8], while neglecting slope effects may lead to underestimations of fuel consumption by up to 29% [9]. Similar formulations have also been applied in freight emission studies, highlighting the critical role of gradient in shaping fuel use and pollutant outputs [11].

$$F = \lambda \left(kN_e V \frac{d}{v} + \gamma \beta d v^2 + \gamma \alpha (\mu + f) d \right) \quad (1)$$

The equation consists of three main modules. The first module, $kN_e V d/v$, represents the energy consumed by the engine to maintain motion over a distance (d) at a velocity (v). The second module, $\gamma \beta d v^2$, illustrates the additional fuel consumption caused by aerodynamic resistance, with the coefficient β calculated as 0.5 multiplied by the drag coefficient (C_d), the frontal surface area of the vehicle (A) and the air density (ρ). The third module, $\gamma \alpha (\mu + f) d$, indicates the extra consumption resulting from the vehicle mass, including both curb weight (μ) and payload (f). The gradient effect is incorporated through the parameter $\alpha = g \sin \theta + g C_r \cos \theta$, which accounts for the combined influence of gravitational force and rolling resistance. Consequently, total fuel consumption is affected by the interplay of engine workload, aerodynamic drag, gravitational forces, and rolling resistance when operating on ascending road segments.

Instantaneous Fuel Consumption Rate Model (FR)

The instantaneous fuel consumption rate (FR) model applied in this study is derived from the Pollution Routing Problem (PRP) framework originally proposed by Bektaş and Laporte [24] and further refined by Franceschetti et al. [6] to represent the dynamic energy requirements of heavy-duty freight vehicles. This model incorporates vehicle speed, engine characteristics, aerodynamic drag, rolling resistance, and vehicle mass to estimate fuel use over short time intervals. Unlike total fuel consumption models, the FR approach captures instantaneous variations in engine workload, making it particularly suitable for analyzing truck performance on ascending road segments. Previous studies have demonstrated that road

gradient significantly amplifies instantaneous fuel demand and that neglecting slope effects may lead to systematic underestimation of fuel consumption [8][9]. Empirical evidence from real-world measurements further confirms the relevance of instantaneous fuel rate modeling in freight transport energy and emission analysis [10].

$$FR = \lambda (kN_e V + \gamma (\beta v^3 + \alpha (\mu + f) v)) \quad (2)$$

With $\lambda = \xi / K \psi$, the parameter represents the fuel-to-air mass ratio (ξ), the calorific value of diesel fuel (K) and the conversion factor for fuel volume (ψ). The coefficient $\gamma = 1 / (1000 \varepsilon \omega)$ is used to accommodate drivetrain efficiency (ε), and diesel engine efficiency (ω). The first component, $kN_e V$, reflects the baseline engine consumption, which is influenced by the engine friction factor, rotational speed, and displacement, as described in prior studies [6], which is determined by the engine friction factor (k), engine speed (N_e) and engine displacement (V). The second component, βv^3 , represents the additional consumption attributed to aerodynamic resistance, with β defined by drag coefficient, frontal area, and air density, consistent with approaches applied in large-scale vehicle energy assessments [8]. The third component, $\alpha (\mu + f) v$, captures the role of vehicle mass, encompassing curb weight and payload, under varying slope conditions. The gradient effect itself is incorporated through the parameter α , which combines gravitational force and rolling resistance. Previous studies indicated that neglecting slope can result in underestimations of fuel consumption by up to 29% [9], while others emphasized that the combined effects of gradient and vehicle speed have a direct relationship with the increase in tailpipe emissions [13].

CO₂ Emission Model

The calculation of exhaust gas emissions in this study focuses on carbon dioxide (CO₂), as it represents the dominant greenhouse gas produced by the transportation sector [1][2]. CO₂ emissions were estimated using a fuel-based emission model following the Tier 1 methodology of the IPCC Guidelines for National Greenhouse Gas Inventories [22]. This approach converts fuel consumption into CO₂ emissions using standardized emission factors and carbon oxidation parameters, ensuring consistency with international greenhouse gas accounting practices. The applied emission model is also aligned with national regulatory standards issued by the Ministry of Environment and Forestry of

Indonesia [25]. Previous studies have consistently demonstrated that road gradient substantially increases CO₂ emissions from freight transport, reinforcing the necessity of incorporating slope effects into emission modeling [8, 9, 11, 26]. The use of the IPCC fuel-based emission model enables reliable translation of fuel consumption into CO₂ output while maintaining both international comparability and local regulatory relevance [7][27].

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

With C denoting the total CO₂ emissions (kg), the calculation employs several key parameters. Parameter A represents the net calorific value of diesel fuel, set at 44 TJ/Gg in accordance with the IPCC guidelines [22]. Parameter B corresponds to the carbon oxidation ratio, assigned a value of nearly 1.0 (≈ 0.99) under the assumption of nearly complete combustion [22][25]. Factor J refers to the carbon emission factor for diesel fuel, equal to 20.2 t/TJ, while K is the conversion factor from carbon to CO₂, set at 3.67 to reflect the molecular weight ratio of CO₂ to carbon (44/12). Parameter d denotes the density of diesel fuel commonly used in Indonesia, valued at 0.835 kg/L in accordance with the specifications of the national diesel standard. Finally, Q represents the total fuel consumption (liters), as derived from the calculations of the total fuel consumption model (F) and the instantaneous fuel rate model (FR).

By employing these parameters (as shown in Table 3), the estimation of CO₂ emissions in this study can be benchmarked globally against findings from international research, while remaining consistent with national policies particularly the Ministry of Environment and Forestry Regulation [25], which governs motor vehicle emission standards in Indonesia. This dual alignment ensures that the results are both internationally comparable and locally relevant, thereby strengthening their applicability for sustainable freight transport policy and planning.

Table 3. Emission Parameters for Diesel Fuel

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

Analysis Procedure

The analysis procedure in this study began with the input of technical vehicle parameters as the primary basis for calculation. Total fuel consumption for each combination of distance and gradient was then estimated using established formulations previously applied in freight energy research [6]. To capture the dynamic intensity of fuel use, the instantaneous fuel consumption rate (FR) was subsequently computed, reflecting variations in demand on a per-unit-time basis [24]. The calculated fuel consumption values were further converted into CO₂ emissions by applying standardized emission models that align with international and national regulatory guidelines [7]. A comparative analysis was then conducted between two-axle and three-axle trucks, with the 0% gradient serving as the baseline for assessing percentage increases in both fuel consumption and emission outputs. This sequential methodological approach has been validated in prior studies that examined energy efficiency and emission modeling in heavy-duty freight operations, ensuring both reliability and replicability of the results [10][13].

Theoretical Validation

The validation of the findings in this study was carried out conceptually by benchmarking the observed patterns against established results in international literature. Prior research has shown that fuel consumption tends to increase nonlinearly with changes in road gradient [6], while other studies have demonstrated that even relatively small inclines can lead to substantial rises in CO₂ emissions [7]. Large-scale analyses further confirmed that gradients between 0.5% and 6% may elevate fuel consumption by up to 140% and NO_x emissions by about 115% [8]. Evidence also indicates that disregarding slope effects could underestimate fuel demand by nearly 29%, highlighting the critical role of gradient in energy modeling [9]. The alignment of the present results with these findings reinforces the robustness of the applied methodology. Moreover, the consistency of emission parameters with the regulatory framework of the Indonesian Ministry of Environment and Forestry [25] ensures both national relevance and international comparability. This dual conformity not only strengthens the academic contribution of the study but also enhances its practical value for informing sustainable freight transport planning and policymaking.

RESULTS AND DISCUSSION

Fuel consumption and CO₂ emissions in freight transport were found to increase consistently as road gradients and travel distances rose. The analysis, conducted on two-axle and three-axle trucks at gradients ranging from 0% to 15% and distances of 50 to 250 meters, confirmed that both slope and distance serve as critical determinants of energy demand. Prior research has long emphasized that topography exerts a nonlinear influence on vehicle efficiency, with gradient variations significantly amplifying fuel consumption and emissions under heavy-duty operating conditions [6][8]. Other studies have shown that even relatively moderate inclines can cause disproportionate increases in diesel truck emissions, reinforcing the importance of accounting for gradient effects in transport energy assessments [7].

In the Indonesian context, the results align with previous findings that the hilly terrain of South Sulawesi elevates operational costs in freight distribution. Such conditions highlight the practical relevance of integrating topographic factors into planning frameworks, as neglecting slope effects may result in underestimations of both energy use and emissions in real-world operations [19]. By linking global evidence with regional realities, this study demonstrates that gradient variation is not only a theoretical concern but also a pressing practical issue for freight transport systems. The integration of these perspectives provides a robust empirical basis for the development of sustainable logistics strategies and energy efficiency policies, particularly in regions with diverse topographic conditions.

Total Fuel Consumption (F)

The results indicate that total fuel consumption increases progressively with both road gradient and travel distance for two-axle and three-axle trucks. At the baseline condition of 0%, fuel use remains relatively low, ranging from 0.0069 to 0.0347 liters for two-axle trucks and from 0.0167 to 0.0837 liters for three-axle trucks at distances between 50 and 250 meters. However, as gradients increase, consumption rises substantially. At the maximum slope of 15% and a distance of 250 meters, the two-axle truck records a consumption of 0.2751 liters, while the three-axle truck reaches 0.6074 liters (Table 4 and Table 5). These results demonstrate that while heavier trucks consistently consume more fuel in absolute terms, both vehicle types exhibit high sensitivity to slope variation.

The graphical trends presented in Figure 1 and Figure 2 confirm these patterns, showing a nearly linear relationship between travel distance and fuel use, with increasingly steep slopes of the trend lines at higher gradients. This reflects the additional workload imposed on the engine by gravitational resistance and vehicle mass during uphill driving. Studies have shown that gradients substantially alter fuel demand, with even small slope variations significantly increasing consumption in diesel trucks [6, 7, 8]. Other research emphasized that neglecting slope factors in transport energy assessments may lead to underestimations of fuel consumption by up to 29% [9].

Table 4. Total fuel consumption of two-axle trucks at different gradients and distances

Gradient	Distance (m)				
	50	100	150	200	250
0%	0.0069	0.0139	0.0208	0.0278	0.0347
1%	0.0102	0.0204	0.0306	0.0408	0.0509
2%	0.0134	0.0269	0.0403	0.0537	0.0672
3%	0.0167	0.0333	0.0500	0.0667	0.0833
4%	0.0199	0.0398	0.0597	0.0796	0.0995
5%	0.0231	0.0463	0.0694	0.0926	0.1157
6%	0.0264	0.0527	0.0791	0.1055	0.1318
7%	0.0296	0.0592	0.0888	0.1183	0.1479
8%	0.0328	0.0656	0.0984	0.1312	0.1640
9%	0.0360	0.0720	0.1080	0.1440	0.1800
10%	0.0392	0.0784	0.1176	0.1568	0.1960
11%	0.0424	0.0848	0.1272	0.1696	0.2120
12%	0.0456	0.0911	0.1367	0.1823	0.2278
13%	0.0487	0.0975	0.1462	0.1949	0.2437
14%	0.0519	0.1038	0.1557	0.2076	0.2594
15%	0.0550	0.1101	0.1651	0.2201	0.2751

Table 5. Total fuel consumption of three-axle trucks at different gradients and distances

Gradient	Distance (m)				
	50	100	150	200	250
0%	0.0167	0.0335	0.0502	0.0670	0.0837
1%	0.0238	0.0476	0.0714	0.0952	0.1191
2%	0.0309	0.0617	0.0926	0.1235	0.1544
3%	0.0379	0.0759	0.1138	0.1517	0.1896
4%	0.0450	0.0900	0.1349	0.1799	0.2249
5%	0.0520	0.1040	0.1561	0.2081	0.2601
6%	0.0590	0.1181	0.1771	0.2362	0.2952
7%	0.0661	0.1321	0.1982	0.2643	0.3303
8%	0.0731	0.1461	0.2192	0.2923	0.3653
9%	0.0801	0.1601	0.2402	0.3202	0.4003
10%	0.0870	0.1740	0.2611	0.3481	0.4351
11%	0.0940	0.1879	0.2819	0.3758	0.4698
12%	0.1009	0.2018	0.3026	0.4035	0.5044
13%	0.1078	0.2156	0.3233	0.4311	0.5389
14%	0.1146	0.2293	0.3439	0.4586	0.5732
15%	0.1215	0.2430	0.3645	0.4859	0.6074

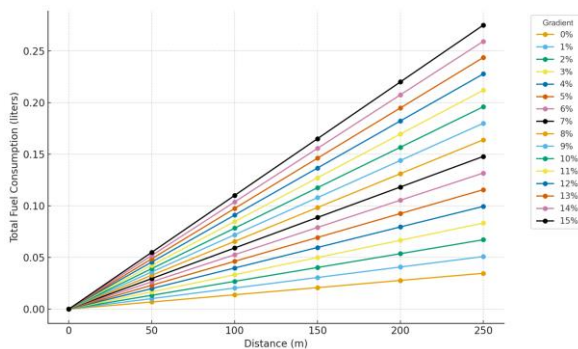


Figure 1. Impact of gradient on fuel consumption of two-axle trucks

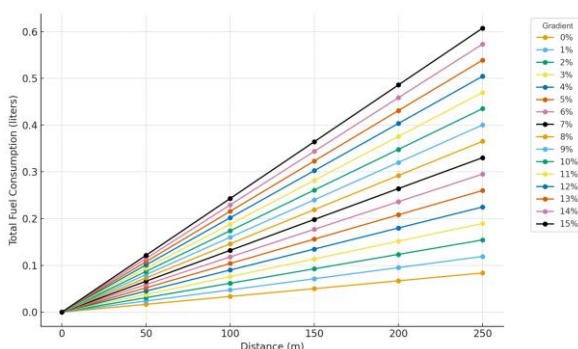


Figure 2. Impact of gradient on fuel consumption of three-axle trucks.

A comparative assessment further highlights consistent differences between the two vehicle categories. As illustrated in Figure 3, three-axle trucks consume more fuel under all gradient conditions, with the difference becoming increasingly pronounced at steeper slopes. For instance, at a 15% gradient and a 250-meter

distance, the additional fuel required by three-axle trucks compared to two-axle trucks reaches 0.332 liters. This confirms that vehicle mass exerts a critical influence on energy performance, particularly on steep slopes, a trend also identified in studies addressing heavy-duty vehicle operations on hilly terrain [10][11].

These findings are consistent with a broad body of literature emphasizing that slope is among the most decisive topographic factors affecting vehicle energy efficiency. Prior research has demonstrated that gradients between 0.5% and 6% can already raise fuel use by more than 100%, with greater effects observed at steeper inclines [8][28].

Moreover, slope effects are amplified when combined with heavy loads and aerodynamic resistance, further increasing total consumption [6][13]. In the Indonesian context, the results resonate with earlier findings that the hilly terrain of South Sulawesi significantly raises freight operational costs, underlining the practical relevance of incorporating slope into fuel demand modeling [19]. Overall, the results reinforce the need to account for topographic conditions in sustainable transport planning and decarbonization strategies [1, 2, 3].

Instantaneous Fuel Consumption Rate (FR)

The analysis revealed that the instantaneous fuel consumption rate (FR) increases in tandem with rising road gradients for both vehicle types. At the baseline condition of 0%, the FR of the two-axle truck was recorded at only 0.0014 liters/second, while the three-axle truck reached 0.0033 liters/second.

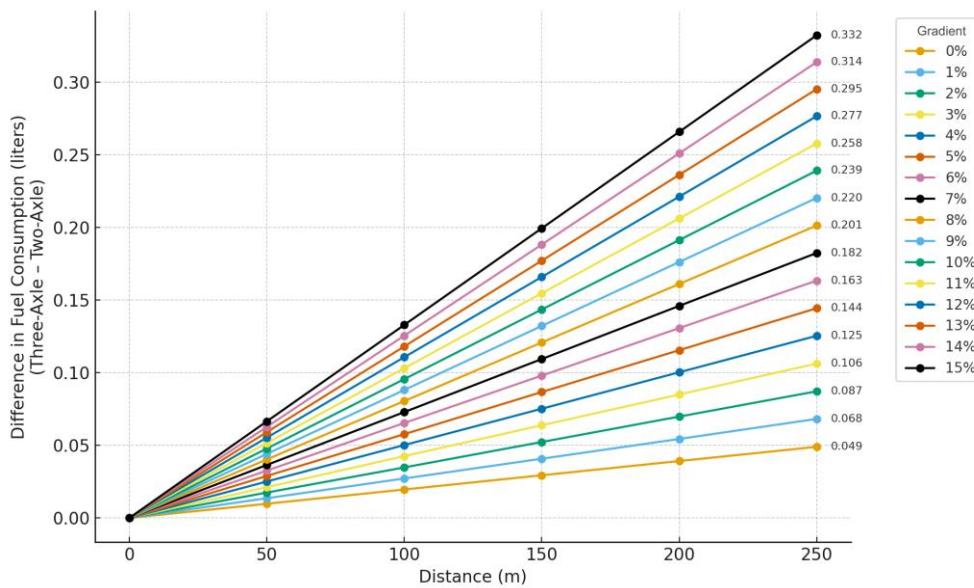


Figure 3. Difference in fuel consumption between three-axle and two-axle trucks.

At the steepest gradient of 15%, these values rose sharply to 0.0107 liters/second for the two-axle truck and 0.0236 liters/second for the three-axle truck (Table 6).

This finding indicates that vehicles with greater mass consistently exhibit higher energy demand at every gradient level, a trend also emphasized in prior studies that highlighted the strong correlation between vehicle weight and slope resistance in shaping energy demand [6, 7, 10].

Table 6. Instantaneous fuel consumption rate (FR) at different gradients for two-axle and three-axle trucks.

Gradient (%)	Two-axle (L/s)	Three-axle (L/s)
0%	0.0014	0.0033
1%	0.0020	0.0046
2%	0.0026	0.0060
3%	0.0032	0.0074
4%	0.0039	0.0087
5%	0.0045	0.0101
6%	0.0051	0.0115
7%	0.0058	0.0128
8%	0.0064	0.0142
9%	0.0070	0.0156
10%	0.0076	0.0169
11%	0.0082	0.0183
12%	0.0089	0.0196
13%	0.0095	0.0210
14%	0.0101	0.0223
15%	0.0107	0.0236

The graphical representation in Figure 4 reinforces this pattern, showing that three-axle trucks consistently record higher FR values across all gradient variations compared to two-axle trucks. The nearly linear upward trend suggests that each incremental increase in gradient directly raises engine workload and resistance, thereby intensifying fuel demand on a per-second basis. Similar tendencies have been observed in studies using large-scale connected vehicle data, which demonstrated that even relatively small gradients can significantly elevate instantaneous fuel consumption [8][28]. Other research also indicated that slope variations, when combined with vehicle speed, exert a compounding effect on energy use and emission levels [9, 10, 13].

These results are consistent with previous studies highlighting the dominant role of gradient in determining the intensity of energy use in heavy-duty vehicles. Evidence suggests that road slope is among the most influential topographic variables, often resulting in underestimations of fuel consumption and emissions when not adequately accounted for in transport energy models [9, 11, 15]. Research on diesel trucks in China further confirmed that even moderate slopes disproportionately raise FR due to the additional mechanical load imposed on the engine [7]. In addition, global assessments of freight transport performance have identified slope, vehicle weight, and rolling resistance as critical parameters influencing both total and instantaneous fuel use [6, 8, 10, 11].

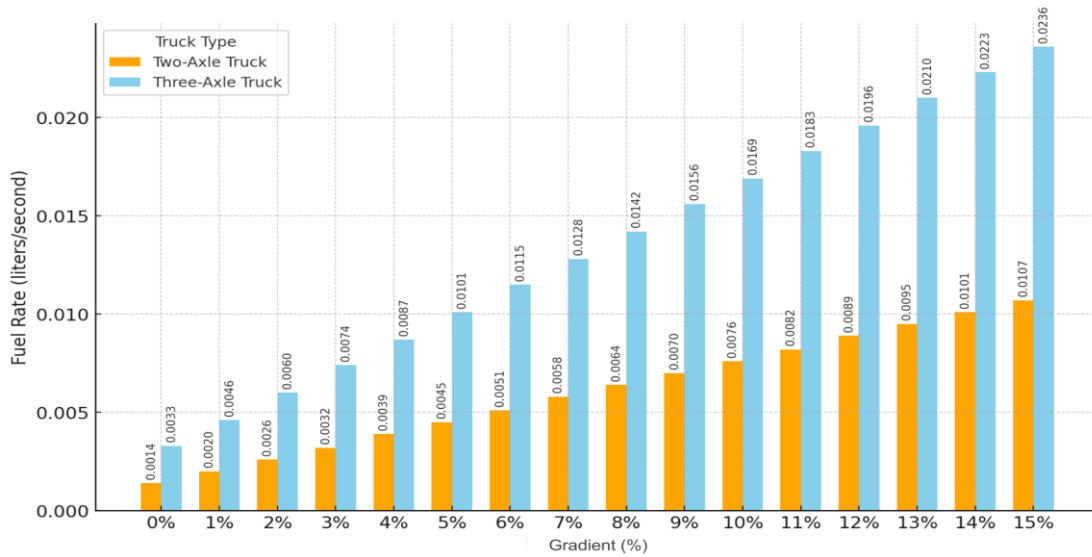


Figure 4. Comparison of instantaneous fuel consumption rate (FR) between two-axle and three-axle trucks

Accordingly, FR not only reflects the escalation of total fuel consumption but also illustrates the sensitivity of energy dynamics to topographic conditions encountered by freight vehicles, underscoring the need for integrating slope considerations into sustainable freight planning and decarbonization strategies [3][4].

Carbon Dioxide (CO₂) Emissions

The results reveal that CO₂ emissions from freight trucks increase substantially with both road gradient and travel distance. As shown in Table 7 and Table 8, emissions at the baseline gradient of

0% remain relatively low, ranging from 0.0187 to 0.0936 kg for two-axle trucks and from 0.0451 to 0.2256 kg for three-axle trucks. However, at the steepest gradient of 15% and a travel distance of 250 meters, the values rise dramatically to 0.7412 kg for the two-axle truck and 1.6364 kg for the three-axle truck. These findings highlight the critical role of slope in amplifying emission outputs, as previously noted in studies that demonstrated a strong nonlinear relationship between gradient, fuel consumption, and CO₂ emissions in heavy-duty vehicles [6, 7, 8].

Table 7. CO₂ emissions of two-axle trucks at different road gradients and distances.

Gradient	Distance (m)				
	50	100	150	200	250
0%	0.0187	0.0374	0.0561	0.0748	0.0936
1%	0.0274	0.0549	0.0823	0.1098	0.1372
2%	0.0362	0.0724	0.1085	0.1447	0.1809
3%	0.0449	0.0898	0.1347	0.1796	0.2245
4%	0.0536	0.1073	0.1609	0.2145	0.2681
5%	0.0623	0.1247	0.1870	0.2493	0.3117
6%	0.0710	0.1421	0.2131	0.2841	0.3551
7%	0.0797	0.1594	0.2391	0.3188	0.3985
8%	0.0884	0.1767	0.2651	0.3535	0.4418
9%	0.0970	0.1940	0.2910	0.3880	0.4850
10%	0.1056	0.2112	0.3168	0.4225	0.5281
11%	0.1142	0.2284	0.3426	0.4568	0.5710
12%	0.1228	0.2455	0.3683	0.4910	0.6138
13%	0.1313	0.2626	0.3939	0.5252	0.6565
14%	0.1398	0.2796	0.4194	0.5591	0.6989
15%	0.1482	0.2965	0.4447	0.5930	0.7412

Table 8. CO₂ emissions of three-axle trucks at different road gradients and distances.

Gradient	Distance (m)				
	50	100	150	200	250
0%	0.0451	0.0902	0.1353	0.1805	0.2256
1%	0.0641	0.1283	0.1924	0.2566	0.3207
2%	0.0832	0.1663	0.2495	0.3327	0.4159
3%	0.1022	0.2044	0.3065	0.4087	0.5109
4%	0.1212	0.2423	0.3635	0.4847	0.6059
5%	0.1401	0.2803	0.4204	0.5606	0.7007
6%	0.1591	0.3182	0.4772	0.6363	0.7954
7%	0.1780	0.3560	0.5339	0.7119	0.8899
8%	0.1968	0.3937	0.5905	0.7874	0.9842
9%	0.2157	0.4313	0.6470	0.8626	1.0783
10%	0.2344	0.4688	0.7033	0.9377	1.1721
11%	0.2531	0.5063	0.7594	1.0125	1.2656
12%	0.2718	0.5435	0.8153	1.0871	1.3589
13%	0.2904	0.5807	0.8711	1.1614	1.4518
14%	0.3089	0.6177	0.9266	1.2354	1.5443
15%	0.3273	0.6546	0.9818	1.3091	1.6364

The graphical representations in Figure 5 and Figure 6 confirm these patterns. Emissions rise nearly linearly with distance, but the slope of the trend lines becomes increasingly steep as gradients intensify. This reflects the compounding effect of gravitational force and rolling resistance on engine workload, leading to higher combustion rates and subsequently greater CO₂ output. Prior research emphasized that even small inclines can disproportionately raise greenhouse gas emissions, especially under diesel-powered operations [7][9]. Furthermore, evidence from real-world vehicle monitoring suggests that failure to account for slope may lead to significant underestimations of emissions, with deviations reported as high as 30% in urban freight contexts [9][11].

A comparative analysis between two-axle and three-axle trucks is presented in Figure 7, which illustrates the difference in CO₂ emissions under varying slope conditions. Across all gradients, three-axle trucks consistently generate higher emissions.

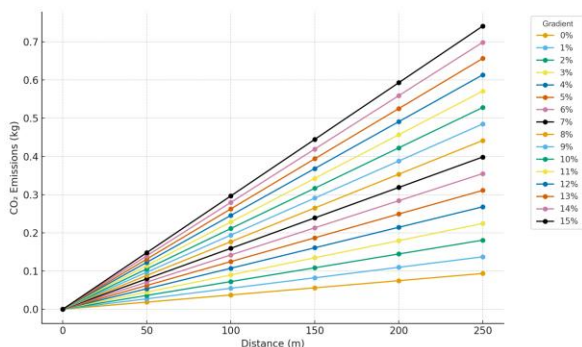


Figure 5. CO₂ emissions of two-axle trucks at different gradients

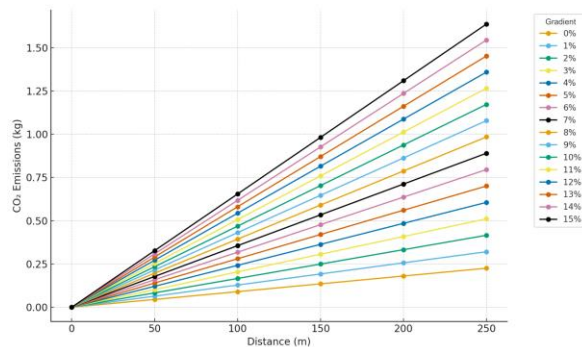


Figure 6. CO₂ emissions of three-axle trucks at different gradients.

At a gradient of 15% and a distance of 250 meters, the additional CO₂ released by three-axle trucks compared to two-axle trucks amounts to 0.895 kg. This aligns with international evidence that vehicle mass and gradient act as dominant factors in determining greenhouse gas emissions from freight transport [10][11]. Such results reinforce the necessity of incorporating vehicle weight and slope factors into emission modeling frameworks.

These findings resonate with a broad body of literature that has consistently identified slope as a major determinant of vehicular emissions. Studies have shown that gradients between 0.5% and 6% can already elevate fuel consumption by up to 140% and NO_x emissions by more than 115%, suggesting similar implications for CO₂ output [8][28].

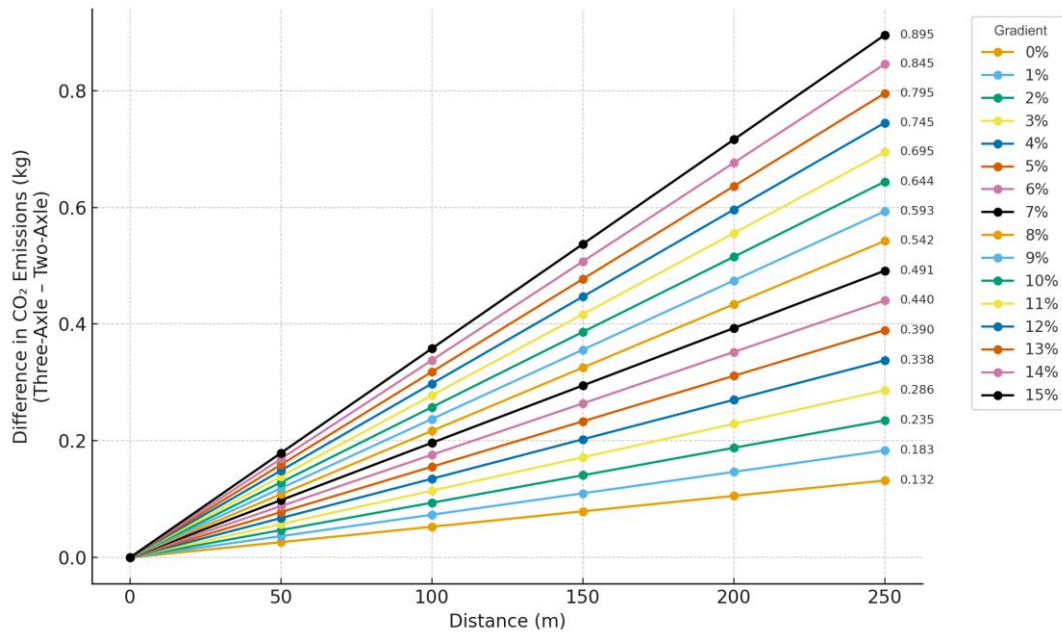


Figure 7. Difference in CO₂ emissions between three-axle and two-axle trucks.

Moreover, neglecting gradient effects has been linked to systematic underestimations of energy demand in emission inventories, thereby limiting the accuracy of both global and local mitigation strategies [9][15]. In the Indonesian context, the amplification of operational costs in South Sulawesi due to hilly terrain provides additional confirmation of the practical significance of these results [19]. Ultimately, the outcomes underline the urgent need to integrate topographic factors into freight transport policies, in line with global decarbonization goals [1][3].

Increment Ratio Analysis

The increment ratio analysis provides further insights into the relative sensitivity of two-axle and three-axle trucks to slope variations. As presented in Table 9, both vehicle types experienced significant increases in fuel consumption and CO₂ emissions relative to the baseline condition (0% gradient). At a 1% slope, the fuel and emission levels of two-axle trucks rose by 47% compared to the baseline, while three-axle trucks increased by 42%. At the steepest slope of 15%, these values surged to 692% for two-axle trucks and 625% for three-axle trucks. These findings highlight that while heavier vehicles generate greater absolute consumption, medium-duty trucks display higher relative sensitivity when compared to their baseline conditions.

Table 9. Increment Ratios (%) of Fuel Consumption and CO₂ Emissions Relative to the Baseline (0% Gradient)

Gradient	Two-axle	Three-axle
1%	47	42
2%	93	84
3%	140	126
4%	187	169
5%	233	211
6%	280	253
7%	326	295
8%	372	336
9%	418	378
10%	464	420
11%	510	461
12%	556	502
13%	602	544
14%	647	585
15%	692	625

The trends are further visualized in Figure 8, which shows that the increment ratios for two-axle trucks consistently exceed those of three-axle trucks across all gradient levels. This outcome can be explained by the relatively lower baseline consumption of two-axle trucks; therefore, additional consumption at higher slopes translates into larger percentage increases. At the same time, three-axle trucks, which already record higher initial values, display smaller proportional changes despite higher absolute consumption.

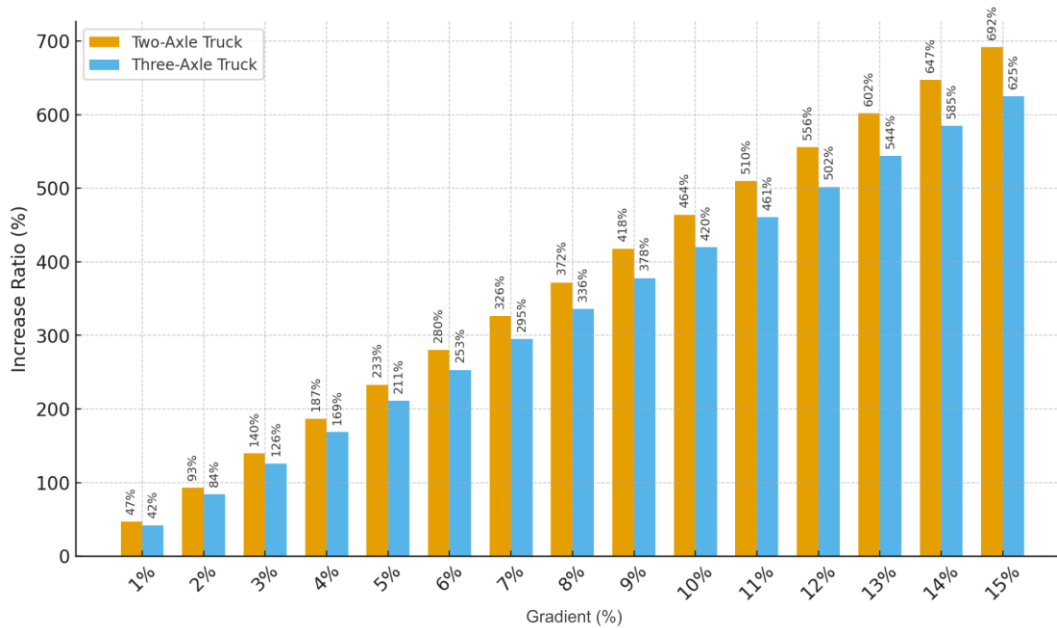


Figure 8. Increment ratios (%) of fuel consumption and CO₂ emissions relative to the baseline (0% gradient)

These results are consistent with earlier studies that identified baseline vehicle characteristics as a determinant of relative sensitivity to slope [6, 7, 8]. Research further suggests that vehicles with lower initial energy use are more susceptible to large proportional increases under topographic stress, whereas heavier vehicles with higher baseline demand exhibit more stable ratios despite steep terrain [9][10]. Other evidence also indicates that technical parameters such as mass, engine displacement, aerodynamic drag, and rolling resistance strongly influence gradient-induced sensitivity [11][13].

From a practical perspective, these findings underscore that medium-duty trucks, despite producing lower absolute emissions, may contribute disproportionately to energy inefficiencies when operating in hilly terrain. This observation aligns with prior research that emphasized the role of slope in distorting energy estimations and increasing operational costs in freight transport, particularly in regions such as South Sulawesi [19]. Ultimately, the analysis reaffirms that slope effects should be incorporated not only for heavy trucks but also for medium-sized vehicles in order to support accurate modeling, mitigation planning, and decarbonization strategies [1, 2, 3].

Comparative Discussion with Literature

The results of this study confirm that road gradient is a key determinant of both fuel

consumption and CO₂ emissions in freight transport. Franceschetti et al. [6] demonstrated that fuel consumption increases nonlinearly with road gradient due to the combined effects of vehicle mass and gravitational resistance. Similarly, Dong et al. [7] and Fan et al. [8] reported that even relatively small increases in gradient can substantially elevate fuel consumption and CO₂ emissions from diesel-powered freight vehicles. Consistent with these findings, the present study observed a disproportionate increase in energy demand as road gradient increased, with nonlinear escalation becoming particularly evident at gradients exceeding 10%. Beyond gradient alone, several studies have emphasized that the impact of road slope on energy demand is closely associated with vehicle speed. Dong et al. [7] showed that diesel truck emissions on longitudinal slopes are highly sensitive to speed variations, with higher operating speeds leading to accelerated fuel consumption and CO₂ output. Likewise, Gebisa et al. [13] demonstrated that the combined effect of vehicle speed and positive road slope significantly intensifies tailpipe emissions, indicating that speed acts as an amplifying factor in slope-induced energy penalties. Real-world measurements further support this interaction, as Weller et al. [10] observed that heavy-duty vehicles operating at moderate to high speeds on uphill road segments experienced substantially higher fuel consumption and emission levels compared to low-speed conditions under similar gradients. Zhang et al.

[28] also emphasized that road grade effects on emissions become more pronounced as vehicle speed increases due to the combined influence of aerodynamic drag and engine workload.

In the present study, vehicle speed was fixed at approximately 35 km/h to represent a typical climbing speed on short uphill segments commonly encountered in Indonesian freight corridors. This controlled-speed assumption enables isolation of gradient effects and ensures comparability between two-axle and three-axle trucks. While this approach is consistent with prior modeling-based freight energy studies that adopt constant speed scenarios for sensitivity analysis [6][9], it also implies that the reported fuel consumption and emission values represent conservative estimates. Under higher operating speeds, as highlighted in previous literature, the combined influence of speed and gradient would likely result in even greater fuel demand and CO₂ emissions. Previous studies have further shown that technical vehicle characteristics intensify the impact of road gradient. Aminzadegan et al. [11] identified engine displacement, aerodynamic drag, and drivetrain efficiency as critical factors influencing emission levels under varying operating conditions. The present study supports these conclusions, as three-axle trucks consistently exhibited higher absolute fuel consumption and CO₂ emissions due to their greater mass and engine capacity. However, the comparative analysis revealed that two-axle trucks experienced sharper proportional increases in fuel consumption and emissions relative to their baseline conditions, indicating greater relative sensitivity to gradient changes. Similar observations regarding baseline-dependent sensitivity were reported by Dong et al. [7] and Núñez et al. [9].

At a broader level, Núñez et al. [9] demonstrated that neglecting road slope in freight routing and energy models may lead to systematic underestimations of fuel consumption and emissions of up to 29%. Comparable conclusions were drawn by Colovic et al. [15] and Soliani et al. [29], who emphasized that topographic factors are essential for accurate freight transport energy assessment. These considerations have also been incorporated into recent studies on eco-routing and sustainable freight planning, as highlighted by Miklautsch and Woschank [3], Pahwa and Jaller [16], and Meng et al. [30]. In the Indonesian context, Hakzah et al. [19] reported that the hilly terrain of South Sulawesi significantly increases freight operational costs and energy inefficiencies. The findings of the present study reinforce this regional evidence by quantitatively demonstrating how short uphill segments

exacerbate fuel consumption and CO₂ emissions for different axle configurations. By explicitly linking international findings with local freight conditions and incorporating the role of vehicle speed, this study provides context-specific insights that support the development of gradient- and speed-sensitive freight planning as well as national decarbonization strategies [1, 2, 4, 31, 32].

Limitations and Suggestions for Future Research

Although This study provides valuable insights into the effect of road gradient on fuel consumption and CO₂ emissions in freight transport, but several limitations should be acknowledged. The analysis relied on mathematical models based on technical parameters and slope variations, which do not fully capture dynamic real-world conditions such as traffic flow, acceleration patterns, driver behavior, or weather influences. Previous studies have shown that ignoring these variables may create discrepancies when compared to empirical measurements, as contextual factors like congestion and driving cycles can substantially alter energy demand [7, 8, 10, 11].

Another limitation relates to the emission factors applied in this study, which were adapted from international guidelines such as the IPCC framework. While these ensure global comparability, they may not fully reflect local variations in fuel quality, vehicle age, and maintenance conditions. Prior research emphasized that national-level emission factors are often more appropriate for policymaking, as they account for regional differences that influence accuracy [9, 11, 19]. Furthermore, the scope of this study was restricted to two-axle and three-axle trucks under short-distance slope scenarios of up to 250 meters and gradients of up to 15%. In practice, freight networks include a wider variety of vehicle configurations, longer-haul operations, and more complex road geometries, which may display different sensitivity patterns [6, 10, 13].

Future research is therefore recommended to integrate empirical data collection through on-board diagnostics (OBD), GPS-based telemetry, or vehicle sensors to validate and refine model results. The use of region-specific emission factors would enhance relevance for national policy, while comparative studies across regions with varying topographic conditions could improve generalizability [8, 15, 16]. Additionally, hybrid approaches that combine mathematical modeling with machine learning techniques hold promise for more robust forecasting, as they can better capture the complex interplay between

topography, vehicle characteristics, and operational practices [11][33]. Addressing these limitations will ensure that future studies provide more comprehensive, context-sensitive, and policy-relevant insights into freight transport energy efficiency and emissions.

Policy Implications

The findings of this study confirm that road gradient has a substantial influence on fuel consumption and CO₂ emissions, highlighting the need to systematically integrate topographic factors into freight transport planning. Neglecting slope effects can lead to significant underestimations of energy demand and emissions, thereby reducing the accuracy of transport decarbonization strategies [6, 7, 9]. Policy formulation in the freight sector should therefore be supported by gradient-sensitive models that enable more realistic assessments of both operational costs and environmental impacts.

In addition, the results underscore the importance of technological innovation to mitigate the energy penalties associated with hilly terrain. Potential measures include the use of fuel-efficient engines, adaptive transmission systems, and improved aerodynamic designs [10][11]. Beyond these, a transition toward alternative fuels and the adoption of hybrid or electric vehicles have been identified as key pathways for achieving long-term emission reductions in freight transport [3, 4, 34].

Furthermore, the study highlights the necessity of accurate and context-specific emission monitoring frameworks. While international standards such as the IPCC guidelines provide methodological consistency, region-specific emission factors are more suitable for capturing the real conditions of Indonesian freight vehicles [11][19]. Enhanced data collection through vehicle telemetry and real-time monitoring is recommended to reduce the gap between model estimates and actual performance [8][28]. Importantly, policies should not only focus on heavy-duty trucks but also on medium-duty vehicles, which exhibit greater relative sensitivity to gradient variations. Consequently, freight decarbonization requires a multi-level strategy that considers vehicle type, operating conditions, and topographic constraints [1, 2, 15, 16].

CONCLUSION

This study demonstrates that road gradient and short uphill distance have a significant impact on fuel consumption and CO₂ emissions in freight transport. The results show that increasing road gradient leads to a disproportionate rise in energy demand for both two-axle and three-axle trucks, with sharp escalation observed at gradients above

10%. At a 15% gradient and a travel distance of 250 m, fuel consumption and CO₂ emissions increased by approximately 692% for two-axle trucks and 625% for three-axle trucks compared to flat road conditions.

Although three-axle trucks produced higher absolute fuel consumption and emissions, two-axle trucks exhibited greater relative sensitivity to gradient changes due to their lower baseline energy demand. This finding highlights that medium-duty trucks can experience substantial efficiency losses when operating on steep short uphill segments.

Overall, the findings emphasize the importance of incorporating road gradient into freight energy modeling, eco-routing strategies, and operational planning, particularly in hilly regions such as South Sulawesi. Accounting for slope effects is essential to improve the accuracy of fuel consumption estimation and to support effective freight transport decarbonization policies.

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