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Scientific Article

OPERATIONAL PERFORMANCE OF B-DOUBLE VEHICLES WITH AND WITHOUT HUB REDUCTION IN EUCALYPTUS TRANSPORTATION IN SOUTHERN BRAZIL

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ABSTRACT

Forest road transport in Brazil faces challenges related to vehicle diversity and varying road conditions, with different proportions of roads having asphalt surfacing. In this context, the appropriate choice of vehicle type is decisive for operational performance and logistics costs. This study aimed to evaluate the operational performance of two B-double vehicle models in forest road transport under different road-surface conditions with asphalt surfacing. This research was based on telemetry data provided by a logistics company in the state of Paraná. Two types of Freight Vehicle Combinations (FVCs) were analyzed: heavy bogie (with hub reduction) and light bogie (without hub reduction), across four scenarios of roads with asphalt surfacing: C1 (up to 25%), C2 (25–50%), C3 (50–75%), and C4 (>75%). The evaluated variables included traveled distance, travel time, average speed, net load transported, and fuel consumption, from which indicators of operational efficiency, energy yield, and productive capacity were determined. Statistical analyses included univariate and multivariate tests (MANOVA and discriminant analysis). The results indicated significant differences between vehicle types and asphalt surfacing scenarios. The heavy bogie showed lower fuel consumption (8–12% less) and higher energy yield on routes with a lower proportion of asphalt surfacing, while the light bogie showed better performance on roads with a higher proportion of asphalt surfacing, with shorter travel time and higher average speed. The multivariate analysis confirmed that the proportion of asphalt surfacing is the main factor influencing average speed and energy efficiency. It is concluded that B-double vehicles with heavy bogies are more suitable for routes with low asphalt surfacing, while those with light bogies are more appropriate for predominantly asphalt-surfaced highways.

Keywords: Road forestry transport, Telemetry, Vehicle combinations, Asphalt pavement

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DESEMPENHO OPERACIONAL DE BITREM COM E SEM CUBO REDUZIDO NO TRANSPORTE DE EUCALIPTO NA REGIÃO SUL DO BRASIL

RESUMO O transporte rodoviário florestal no Brasil apresenta desafios relacionados à diversidade de veículos e à variação das condições viárias, com diferentes proporções de estradas com revestimento asfáltico. Nesse contexto, a escolha do tipo de veículo é determinante para o desempenho operacional e os custos logísticos. Esta pesquisa objetivou avaliar o desempenho operacional de dois modelos de veículos tipo bitrem no transporte rodoviário florestal em diferentes cenários com revestimento asfáltico. O estudo foi conduzido a partir de dados de telemetria fornecidos por uma empresa logística do Paraná. Foram analisadas duas Combinações Veiculares de Carga (FVCs): bogie pesado (com cubo redutor) e bogie leve (sem cubo redutor), em relação a pavimentação com revestimento asfáltico: C1 (até 25%), C2 (25–50%), C3 (50–75%) e C4 (>75%). As variáveis avaliadas incluíram distância percorrida, tempo de viagem, velocidade média, peso líquido transportado e consumo de combustível, a partir das quais foram determinados indicadores de eficiência operacional, rendimento energético e capacidade produtiva. As análises estatísticas compreenderam testes univariados e multivariados (MANOVA e análise discriminante). Os resultados indicaram diferenças significativas entre os tipos de veículo e os cenários de pavimentação. O bogie pesado apresentou menor consumo de combustível (8–12% inferior) e maior rendimento energético em rotas com menor proporção de pavimento, enquanto o bogie leve obteve melhor desempenho em estradas mais pavimentadas, com menor tempo de viagem e maior velocidade média. A análise multivariada confirmou que a proporção de revestimento asfáltico é o principal fator que influencia a velocidade média e a eficiência energética. Conclui-se que os bitrens com bogie pesado são mais indicados para rotas com baixa pavimentação, enquanto os com bogie leve são mais adequados para rodovias predominantemente asfaltadas.

Palavras-Chave: Transporte florestal rodoviário, Telemetria, Combinações veiculares, Pavimento asfáltico

1. INTRODUCTION

In Brazil, the logistics sector accounts for a significant share of the costs and competitiveness of production chains, with transportation responsible for approximately 60% of the total cost, predominantly through the road transport mode (Alves et al., 2013; Araújo et al., 2024). This mode accounts for 62% of the country's freight transportation matrix (CNT, 2025), driven by strategic historical decisions, the country's territorial extent, the availability of a vast road network, and operational and logistical advantages. However, factors such as deficiencies in road infrastructure, high fuel and toll costs, and precarious road maintenance further increase costs and reduce logistical efficiency (Silva et al., 2024).

In the forestry sector, this is aggravated by the fact that road transport deals with low-value-added products, moving large volumes over long distances between the forest and the industry. This requires the use of high-capacity Freight Vehicle Combinations (FVCs), notably: B-doubles (bitrem), B-triples (tritrem), and road trains (rodotrem). Furthermore, transportation represents the most expensive stage of the forestry production process, since the operational performance of the vehicles depends on the interaction among several variables, such as distance traveled, road pavement type, vehicle characteristics, and the efficiency of loading and unloading operations (Kärhä et al., 2024; Silva et al., 2024).

A highly relevant operational aspect of freight vehicles, which is scarcely addressed in the literature, is the performance of FVCs with or without a hub reduction gear on the drive axle in forestry transportation. This device consists of a gearset installed in the wheel hub, whose function is to modify the final drive ratio, increasing the torque available at the wheels and, consequently, the vehicles' traction capacity, especially under conditions of higher rolling resistance (Perkins, 1971; Greenbaum et al., 1994).

According to Perkins (1971) and Wong (2008), the hub reduction gear (heavy bogie) provides better vehicle performance on forestry roads with steep, uneven, and unpaved terrain, promoting greater wheel-to-ground adhesion and the movement of bulky loads in adverse terrain conditions. Conversely, vehicles without a hub reduction gear (light bogie) present lower mechanical complexity and are frequently used in road operations predominantly on paved roads and over long distances, where ground adhesion conditions are more stable.

Beyond the vehicles' structural characteristics, road paving conditions—due to the tire-soil interaction—represent a determining factor in operational efficiency and transport costs (Machado et al., 2009; Rocha et al., 2021). Unpaved roads (dirt or gravel) exhibit higher rolling resistance, which increases fuel consumption and travel time. In contrast, paved roads provide greater traffic fluidity and better energy efficiency.

In this context, understanding the operational performance of FVCs equipped with and without hub reduction gears across routes with different proportions of asphalt pavement will provide insights for selecting the most suitable vehicle configuration for each scenario, aiming to optimize and reduce the costs of road forestry transport. Additionally, the application of vehicle telemetry systems increases the accuracy of the analyses, allowing real-time monitoring of variables such as average speed, travel time, fuel consumption, and productivity. This information contributes to understanding the effects of road conditions on FVC performance and supports decision-making in logistics management (Szcześniak & Gorzelańczyk, 2024).

Therefore, this study aimed to evaluate the operational performance of two B-double Freight Vehicle Combinations (FVCs) configurations (heavy bogie and light bogie) in different road paving scenarios in road forestry transport, aiming to generate information to support the optimization of transport logistics.

2. MATERIAL AND METHODS

2.1 Study area

The research was developed from a telemetry database provided by a logistics company responsible for timber transport in a forestry enterprise located in the state of Paraná. The transportation covered the movement of Eucalyptus spp. logs from production areas to industrial units, encompassing a mesoregion with routes characterized by different proportions of paved and unpaved roads. During the experimental period, from January to August 2024, the climatic conditions of the study area were characterized by an average temperature of 18.5°C, relative air humidity above 70%, and monthly precipitation decreasing from summer to winter, with an average value of 216.0 mm in January, 84.5 mm in April, and 63.0 mm in August (SIMEPAR, 2024).

2.2 Vehicle characterization

The vehicles used in the analyzed timber transport corresponded to B-double FVCs configured with hub reduction gears on the drive axles (heavy bogie) and without hub reduction gears (light bogie). This characteristic directly influences operational performance based on power, torque, traction, transmission, and load capacity (Table 1).

The main differences between the vehicle configurations are centered on the presence of the hub reduction gear, traction capacity, and rear suspension system, which are characteristics that directly influence operational performance under different driving conditions.

2.3 Treatments evaluated in the study

The study covered timber transport between the production units (farms) and the industrial units, encompassing B-double FVCs with hub reduction gears (heavy bogie) and without hub reduction gears (light bogie) (Figure 1).

For the evaluation of operational performance, the routes traveled by the vehicles were classified into four transport scenarios, according to the proportion of paved and unpaved roads: Scenario C1: Corresponded to routes with up to 25% paved roads; Scenario C2: Between 25% and 50% paved roads; Scenario C3: Between 50% and 75% paved roads; and Scenario C4: Over 75% paved roads. This categorization allowed for the analysis of vehicle performance under different driving

Table 1. Technical specifications of the B-double vehicles (light bogie and heavy bogie)
Tabela 1. Especificações técnicas dos veículos bitrem (bogie leve e bogie pesado)

Technical specification	Heavy bogie	Light bogie
Hub reduction gear	Yes	No
Brand		
Engine	6-cylinder, diesel, 439 hp	6-cylinder, diesel, 495 hp
Torque	2.200 Nm	2.400 Nm
Transmission	12 to 16 gears, automated or semi-automated	12 gears, automated
Maximum traction capacity (MTC)	123.000 kg	80.000 kg
Gross vehicle weight (GVW)	23.000/33.500 kg	23.000/27.100 kg
Front suspension	Parabolic leaf springs with double-acting telescopic shock absorbers and stabilizer bar	Parabolic leaf springs with double-acting telescopic shock absorbers and stabilizer bar
Rear suspension	Trapezoidal leaf springs with double-acting telescopic shock absorbers and stabilizer bar	Pneumatic, 4 air bags per axle, double-acting telescopic shock absorbers, and stabilizer bar
Brake system	Air drum brake, ABS[1], conventional engine brake + Top Brake	Air drum brake, ABS[1], conventional engine brake + Top Brake

[1] ABS: Anti-lock Braking System.
[1] ABS: Sistema antitravamento.

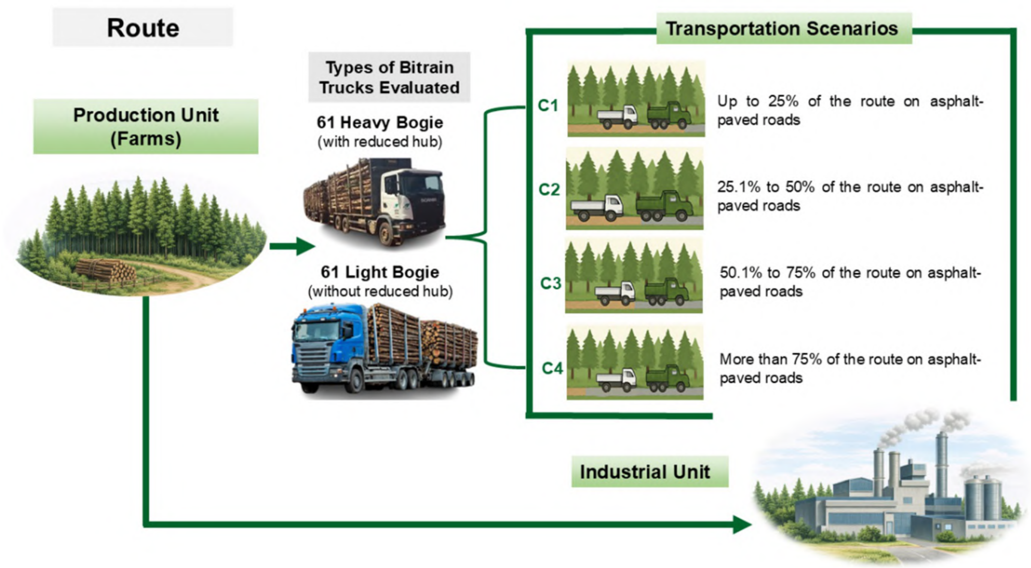

Figure 1. Schematic representation of the study design, indicating timber transport from production units (farms) to the industrial unit using two configurations of B-double Freight Vehicle Combinations (FVCs): heavy bogie (with hub reduction gear) and light bogie (without hub reduction gear), across four asphalt pavement transport scenarios: C1 (up to 25%), C2 (25.1–50%), C3 (50.1–75%), and C4 (over 75%)
Figura 1. Representação esquemática do delineamento do estudo, indicando o transporte de madeira das unidades de produção (fazendas) até a unidade industrial utilizando duas Combinações Veiculares de Carga (CVCs): bogie pesado (com cubo redutor) e bogie leve (sem cubo redutor) em quatro cenários de transporte quanto à proporção de pavimento asfáltico: C1 (até 25%), C2 (25,1–50%), C3 (50,1–75%), e C4 (acima de 75%)

conditions, ranging from routes predominantly on gravel or dirt roads to routes mostly on paved highways. The scenarios do not represent routes of a fixed length, as the analyzed trips presented different total distances, classified according to the proportion of paved roads along the route.

2.4 Sampling procedure

A total of 122 B-double vehicles were analyzed, of which 61 were heavy bogies and 61 were light bogies, each considered an independent experimental unit. The operational and performance variables—travel time, fuel consumption, average speed, and net weight—were aggregated per vehicle using the annual average to avoid pseudoreplication (Carvalho, 2024). The vehicles were distributed among the four paving scenarios (C1 to C4) according to operational availability. The analysis indicated sampling sufficiency to detect moderate effects (total power of 77%), with adequate values for C1 to C3 (≥70%) and lower sensitivity in C4 (37%), requiring cautious interpretation of the results in this scenario.

2.5 Data collection

The collection of operational data from the FVCs during log transport was carried out using reports extracted from the telemetry system installed in the vehicles. The system consisted of a GPS receiver, an onboard unit, and an interface with the vehicle's electronic system, which was activated by a magnetic card and transmitted information in real-time via a mobile network (GSM/GPRS) to the company's central server for storage and subsequent analysis.

The database comprised trips made between January and August 2024, covering movements between the farms and the industrial units. The information included records of distance traveled, travel time, average speed, fuel consumption, gross combination weight (GCW), tare weight, net weight, vehicle type, and trip dates.

2.5.1 Analysis of operational variables

The data provided by the company contained complete trip records, including the origin and destination points of the timber transport, which were coded to prevent location identification, as well as the following operational variables used to calculate the performance indicators:

- estimated travel time (h): the time obtained by the routing system between origin and destination;
- actual travel time (h) – the total travel time obtained by the difference between the departure and arrival times recorded by telemetry;
- distance traveled (km) – the total distance traveled by the vehicle obtained via GPS between the loading and unloading points;
- net weight transported (t) – the difference between the Gross Combination Weight (GCW) and the vehicle tare weight, obtained by electronic weighing at the industrial units' inbound scales;
- fuel consumption (L) – obtained by the vehicle's electronic system and transmitted via telemetry, allowing for the correlation of consumption, distance, and load; and
- average speed (km/h) – obtained automatically by the ratio between the distance traveled and the actual travel time.

2.5.2 Correlation analysis between operational variables and fuel consumption

The correlation between fuel consumption and the operational variables—operating time, average speed, and distance traveled—was evaluated using Pearson's linear correlation. The analyses were performed separately for each vehicle type (light bogie and heavy bogie) across the four road paving scenarios. For each FVC, the correlation coefficient (r) and the significance value (p) were calculated, considering a 95% confidence level ($\alpha = 0.05$). Coefficient interpretation followed Carvalho's (2024) classification: $|r| < 0.10$ (negligible); $0.10 \leq |r| < 0.40$ (weak); $0.40 \leq |r| < 0.70$ (moderate); $0.70 \leq |r| < 0.90$ (strong); and $|r| \leq 0.90$ (very strong). The r sign indicates the direction of the relationship, being positive for direct associations and negative for inverse ones.

2.5.3 Determination of performance indicators

Based on the operational variables obtained by the FVCs' telemetry system, three performance indicators were determined:

• Operation efficiency (Eo) (%):

Operational efficiency corresponded to the ratio between the actual working time—i.e., the period during which the vehicle was moving (empty and loaded), including loading and unloading times—and the total scheduled time for transport (Oliveira et al., 2006; Machado et al., 2009), using the following equation (Equation 1).

$$E_o = \frac{T_e}{T_p} \times 100 \quad \text{(Eq. 1)}$$

In which: Eo is operational efficiency (%); Te is actual working time (h); and Tp is scheduled transport time (h).

• Energy efficiency (EE) (t.km/L):

Energy efficiency represented the ratio between the payload of timber transported by the FVCs over the distances traveled and the fuel consumption (C), with use the equation 2 (Machado et al., 2009).

$$EE = \frac{M \times Q}{C} \quad \text{(Eq. 2)}$$

In which: EE is Energy efficiency (t.km/l); M is Net payload transported (t); Q is Distance traveled (km); and C is Fuel consumption (L).

• Productive capacity (PC):

Expresses the amount of timber transported per operating hour, representing the actual payload moved as a function of the operational cycle duration, that was calculated using the equation 3.

$$PC = \frac{Q}{T} \quad \text{(Eq. 3)}$$

In which: PC is Productive capacity (t/h); Q is payload weight (t); and T is Actual working time or operational cycle duration (h).

2.6 Data analysis

Data analysis was conducted in three stages. Initially, a descriptive analysis of the operational variables and performance indicators was performed, calculating the mean, maximum, minimum, standard deviation, and coefficient of variation (CV). Subsequently, Welch's t-test (Welch, 1947) was applied to compare performance between the FVC configurations across the different paving scenarios. This method was adopted because it does not assume homogeneity of variances, making it suitable for the sample analyzed set.

Mean comparisons were represented by boxplots, highlighting the data distribution, median, and dispersion. The significance level adopted was 5% ($p \leq 0,05$). All analyses were performed using the R software (R Core Team, 2025), employing the dplyr (Wickham et al., 2024), rstatix (Kassambara, 2019), and ggplot2 (Wickham, 2016) packages.

Finally, Multivariate Analysis of Variance (MANOVA) was used to evaluate the joint effect of operational variables on performance indicators, considering vehicle type, paving scenario, and the interaction between both as fixed factors. The significance of the effects was verified by Pillai's Trace, Wilks' Lambda, Hotelling's Trace, and Roy's Largest Root tests. When multivariate significance was identified, canonical discriminant analysis was performed to determine the variables with the greatest contribution to differentiation between groups. Discriminant functions were selected until reaching 95% of the explained variance, and canonical correlations were used to estimate the relative importance of the variables. Multivariate analyses were performed using IBM SPSS Statistics software, version 25.0 (IBM Corporation, Armonk, NY, USA).

3. RESULTS

3.1 Behavior of basic operational variables

Descriptive analysis (Table 2) showed a progressive reduction in average travel time as the proportion of paved roads increased, varying from 3.97 h (C1) to 2.53 h (C4) for the light bogie, and from 3.97 h to 2.77 h for the heavy bogie. Average speed showed an inverse trend, increasing from 19.26 to 25.55 km/h for the light bogie and from 18.68 to 25.41 km/h for the heavy bogie, while the average weight transported remained stable at around 36 t across all analyzed scenarios.

Inferential analyses indicated significant differences between vehicle types in certain scenarios (Figure 2A–D). Distance traveled differed in C3 ($p < 0,001$), with the light bogie covering longer average distances

Table 2. Descriptive statistics of operational variables for B-double vehicles (light bogie and heavy bogie) in timber transport across different road pavement scenarios
Tabela 2. Estatística descritiva das variáveis operacionais dos veículos bitrem (bogie leve e bogie pesado) no transporte da madeira em diferentes cenários de pavimentação de estradas

Vehicle type	Scenario	Distance traveled (km)	Travel time (h)	Average speed (km/h)	Net weight (t)
		Minimum-Maximum			
Light bogie	C_1	58.12 - 87.68	3.03 - 4.56	17.43 - 20.81	33.79 - 38.93
Heavy bogie		44.20 - 100.34	2.69 - 5.33	16.52 - 20.75	30.58 - 40.82
Light bogie	C_2	56.22 - 112.82	2.93 - 5.31	17.64 - 24.61	31.04 - 38.89
Heavy bogie		29.44 - 112.96	1.63 - 5.83	15.75 - 26.17	30.59 - 42.27
Light bogie	C_3	65.57 - 97.11	2.95 - 4.44	20.24 - 26.38	31.20 - 40.71
Heavy bogie		33.03 - 96.77	2.02 - 4.10	15.48 - 26.84	30.45 - 42.21
Light bogie	C_4	49.72 - 76.79	2.03 - 3.22	21.16 - 32.35	28.76 - 40.38
Heavy bogie		49.72 - 93.33	2.00 - 3.61	22.00 - 30.23	30.00 - 42.04
		Mean ± SD			
Light bogie	C_1	75.56 ± 6.21	3.97 ± 0.32	19.26 ± 0.81	36.81 ± 1.24
Heavy bogie		73.54 ± 9.29	3.97 ± 0.50	18.68 ± 1.10	36.47 ± 2.04
Light bogie	C_2	83.00 ± 11.48	4.01 ± 0.48	20.69 ± 1.42	35.99 ± 1.77
Heavy bogie		80.40 ± 16.70	4.00 ± 0.82	20.07 ± 2.13	36.98 ± 2.40
Light bogie	C_3	81.45 ± 5.94	3.64 ± 0.30	22.72 ± 1.27	35.42 ± 1.91
Heavy bogie		72.47 ± 13.91	3.26 ± 0.52	22.27 ± 2.55	36.06 ± 2.27
Light bogie	C_4	63.85 ± 8.39	2.53 ± 0.37	25.55 ± 2.80	35.27 ± 3.09
Heavy bogie		69.73 ± 10.4	2.77 ± 0.42	25.41 ± 2.16	35.41 ± 2.90
		Coefficient of Variation (%)			
Light bogie	C_1	8.22	8.11	4.21	3.38
Heavy bogie		12.63	12.48	5.89	5.59
Light bogie	C_2	13.83	11.97	6.87	4.93
Heavy bogie		20.77	20.46	10.60	6.49
Light bogie	C_3	7.30	8.12	5.60	5.38
Heavy bogie		19.19	15.99	11.46	6.30
Light bogie	C_4	13.14	14.69	10.96	8.76
Heavy bogie		14.92	15.19	8.51	8.19

In which: C1 is up to 25% of paved roads; C2 is from 25% to 50%; C3 is from 50% to 75%; C4 is greater than 75%; h is hours; km is kilometers; and L is liters; and t is tons.
Em que: C1 = até 25% de estradas com revestimento asfáltico; C2 = de 25% a 50%; C3 = de 50% a 75%; C4 = maior que 75%; h: horas; km: Quilômetros; L: litros; t: toneladas.

(81.45 km); in C4 (p = 0,049), the heavy bogie presented a higher mean (69.73 km) compared to the light bogie with 63.85 km (Figure 2A). Average travel time showed a difference only in C3 (p < 0,001), where the heavy bogie exhibited a shorter average time (3.26 h) compared to the light bogie (3.64 h), as illustrated in Figure 2B. For average speed, there was a difference in C1 (p = 0,0015), in which the light bogie presented a higher speed (19.26 km/h) compared to the heavy bogie with 18.68 km/h (Figure 2C). Net weight transported varied only in C2 (p = 0,011), where the vehicle with a heavy bogie transported a higher average payload (36.98 t) compared to the light bogie (35.99 t) (Figure 2D). In the remaining cases, no statistically significant differences were found (p > 0,05).

3.2 Fuel consumption

Fuel consumption showed a statistically significant difference in all scenarios (p < 0,01), being consistently lower in the heavy bogie assemblies. Average values ranged from 1.19 to 1.16 L/km for the heavy bogie and from 1.36 to 1.22 L/km for the light bogie, indicating an average savings of 8 to 12% (Table 3).

A downward trend in consumption was also observed as the percentage of asphalt pavement increased, with higher values found in scenarios C1 and C2 (up to 50% paved roads) (Figure 3).

Correlation analyses (Table 4) showed no significant relationship between fuel consumption and the variables time, speed, and distance for light bogie vehicles (|r| <

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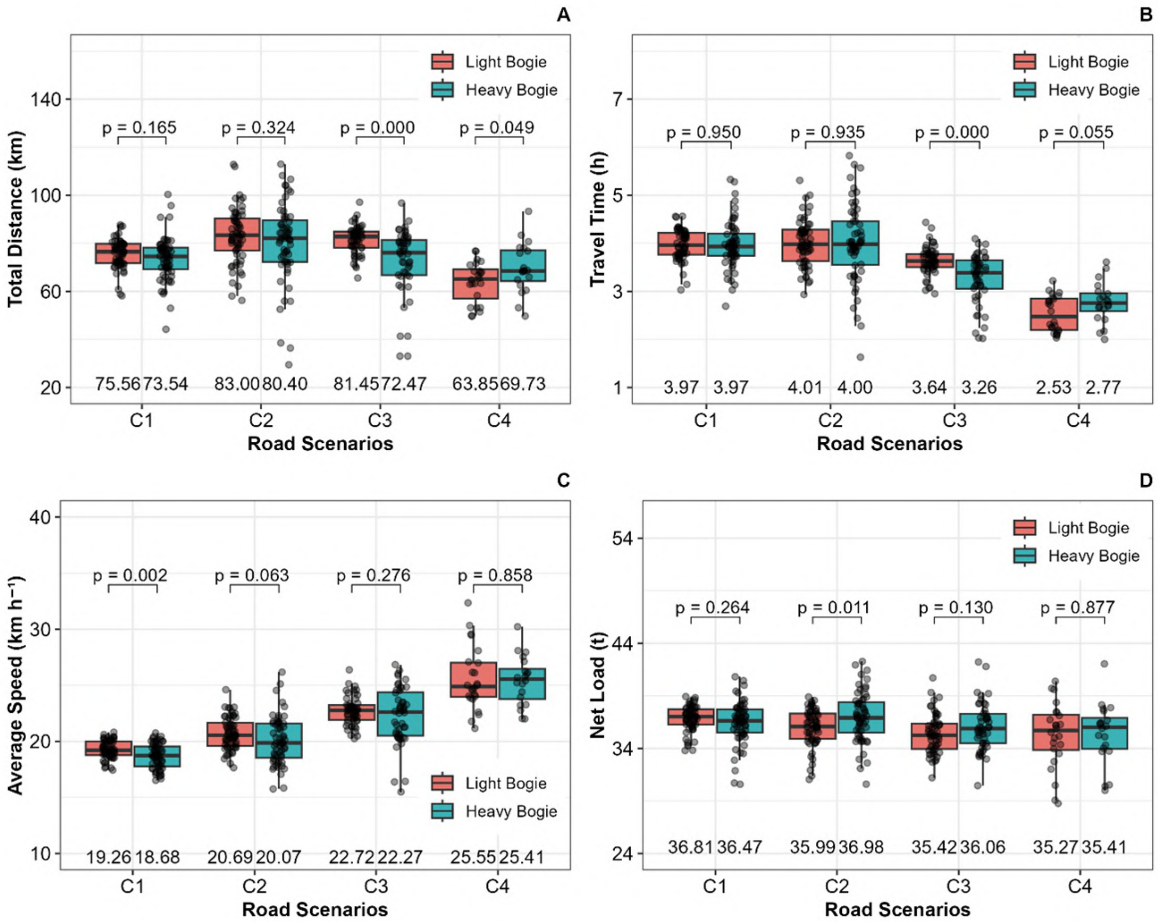

Figure 2. Total distance traveled (km) (A), travel time (h) (B), average speed (km/h) (C), and net weight transported (t) (D) by B-double FVCs (light bogie and heavy bogie) in timber transport across different asphalt-paved road scenarios. In which: C1 is up to 25% of paved roads; C2 is from 25% to 50%; C3 is from 50% to 75%; C4 is greater than 75%. Black dots represent individual trucks. Values below the scenarios correspond to the observed means; ns indicates a lack of statistical significance; *** represents p < 0.001

Figura 2. Distância total percorrida (km) (A), tempo da viagem (h) (B), velocidade média (km/h) (C)e peso líquido (t) (D) pelas CVCs tipo bitrem (bogie leve e bogie pesado) no transporte de madeira nos diferentes cenários de estradas com revestimento asfáltico. Em que: C1 = até 25% de estradas com revestimento asfáltico; C2 = de 25% a 50%; C3 = de 50% a 75%; C4 = maior que 75%. Os pontos em preto representam caminhões individuais. Os valores abaixo dos cenários correspondem às médias observadas, ns indica ausência de significância estatística; *** representa p < 0,001.

Table 3. Descriptive statistics of operational variables for B-double vehicles (light bogie and heavy bogie) in timber transport across different road pavement scenarios

Tabela 3. Estatística descritiva das variáveis operacionais dos veículos bitrem (bogie leve e bogie pesado) no transporte da madeira em diferentes cenários de pavimentação de estradas

Vehicle type	Scenario	Fuel Consumption (L/km)		
		Minimum - Maximum	Mean ± SD	CV (%)
Light bogie	C_1	1.18 - 1.59	1.36 ± 0.10	7.13
Heavy bogie		1.00 - 1.36	1.19 ± 0.07	6.13
Light bogie	C_2	1.11 - 1.52	1.35 ± 0.09	6.74
Heavy bogie		1.09 - 1.56	1.21 ± 0.09	7.14
Light bogie	C_3	1.03 - 1.49	1.25 ± 0.08	6.6
Heavy bogie		0.99 - 1.41	1.16 ± 0.08	6.56
Light bogie	C_4	1.03 - 1.39	1.22 ± 0.08	6.88
Heavy bogie		1.01 - 1.40	1.16 ± 0.10	11.77

In which: C1 is up to 25% of paved roads; C2 is from 25% to 50%; C3 is from 50% to 75%; C4 is greater than 75%; and CV is Coefficient of Variation (%).
Em que: C1 = até 25% de estradas com revestimento asfáltico; C2 =de 25% a 50%; C3 = de 50% a 75%; C4 = maior que 75%; CV = Coeficiente de Variação (%).

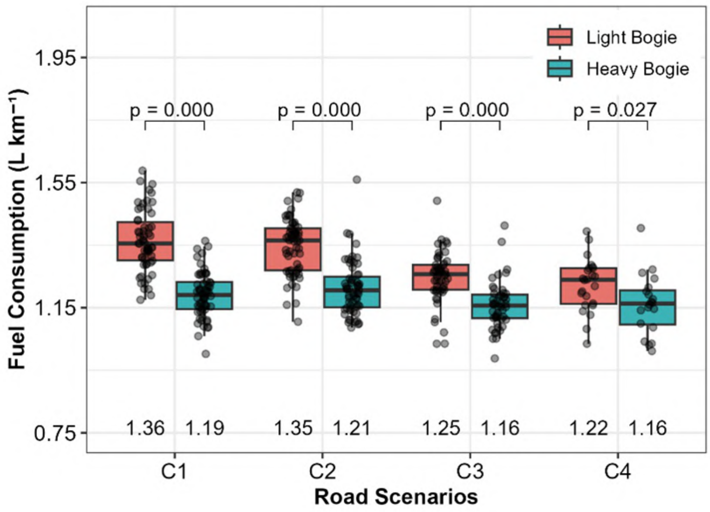

Figure 3. Fuel consumption (L/km) of B-double FVCs (light bogie and heavy bogie) in timber transport across different asphalt-paved road scenarios. In which: C1 is up to 25% of paved roads; C2 is from 25% to 50%; C3 is from 50% to 75%; C4 is greater than 75%. Black dots represent individual trucks. Values below the scenarios correspond to the observed means; ns indicates a lack of statistical significance; * represents $p < 0.05$; *** represents $p < 0.001$

Figura 3. Consumo de Combustível (L/km) pelas CVCs tipo bitrem (bogie leve e bogie pesado) no transporte de madeira nos diferentes cenários de estradas com revestimento asfáltico. Em que: C1 = até 25% de estradas com revestimento asfáltico; C2 = de 25% a 50%; C3 = de 50% a 75%; C4 = maior que 75%. Os pontos em preto representam caminhões individuais. Os valores abaixo dos cenários correspondem às médias observadas, ns indica ausência de significância estatística; * representa $p < 0,05$; *** representa $p < 0,001$.

0,25). For heavy bogie vehicles, there were positive correlations between consumption and travel time in all scenarios (r = 0,290–0,451; $p < 0,05$), (r = 0,290–0,451; $p < 0,05$), as well as significant correlations (though below 1%) with speed in scenarios C1 and C3, and for speed and distance (positive in C2).

3.3 Determination of performance indicators

The operational efficiency of the vehicles ranged between 71.51% (C1) and 76.87% (C4) for the light bogie, and between 73.11% and 78.52% for the heavy bogie (Table 5), increasing with a higher proportion

Table 4. Correlation between fuel consumption and operational variables of B-double vehicles (light bogie and heavy bogie) in timber transport across different asphalt-paved road scenarios

Tabela 4. Correlação entre o consumo de combustível e variáveis operacionais dos veículos bitrem (bogie leve e bogie pesado) no transporte de madeira nos diferentes cenários de estradas com revestimento asfáltico

Vehicle type	Scenario	Consumption × Time		Consumption × Speed		Consumption × Distance	
		r	p-value	r	p-value	r	p-value
Light bogie	C_1	−0.199	0.134 ns	0.171	0.200 ns	−0.106	0.428 ns
Heavy bogie		−0.300	0.020 *	0.314	0.015 *	−0.153	0.242 ns
Light bogie	C_2	0.160	0.217 ns	−0.148	0.254 ns	0.067	0.610 ns
Heavy bogie		0.425	<0.001 **	−0.222	0.091 ns	0.290	0.026 *
Light bogie	C_3	−0.235	0.091 ns	0.110	0.431 ns	−0.183	0.189 ns
Heavy bogie		0.290	0.045 *	−0.287	0.048 *	0.063	0.671 ns
Light bogie	C_4	0.210	0.324 ns	−0.194	0.364 ns	0.082	0.703 ns
Heavy bogie		0.451	0.046 *	−0.192	0.417 ns	0.386	0.092 ns

In which: C1 is up to 25% of paved roads; C2 is from 25% to 50%; C3 is from 50% to 75%; C4 is greater than 75%; * $p < 0.05$; ** $p < 0.001$; ns = non-significant.

Em que: C1 = até 25% de estradas com revestimento asfáltico; C2 = de 25% a 50%; C3 = de 50% a 75%; C4 = maior que 75%; * $p < 0,05$; ** $p < 0,001$; ns = não significativo.

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of asphalt pavement along the route. Energy efficiency was superior in the heavy bogie (30.71 to 31.32 t·km/L) when compared to the light bogie (27.30 to 29.05 t·km/L). The productive capacity of the vehicles increased with asphalt paving, ranging from 9.98 to 14.43 t/h for the light bogie and from 10.15 to 13.21 t/h for the heavy bogie.

Operational efficiency showed a significant difference only in scenario C1 ($p = 0,013$), where B-double vehicles equipped with heavy bogies showed superior performance (73.11%) compared to light bogies (71.51%), as shown in Figure 4A. Energy efficiency differed significantly between vehicle types in scenarios C1, C2, and C3 ($p < 0,001$), being superior for the heavy bogie (> 30 t.km L-1) across the three evaluated scenarios (Figure 4B). Regarding productive capacity (Figure 4C), a significant difference occurred only in scenario C3 ($p < 0.001$), with heavy bogie B-doubles showing superior performance (11.66 t/h), thus having greater productive capacity compared to light bogie B-doubles (10.20 t/h).

3.4 Variable x Indicator correlation

The Multivariate Analysis of Variance (MANOVA) showed a statistically significant

Table 5. Descriptive statistics of performance indicators for B-double vehicles (light bogie and heavy bogie) used in timber transport across different asphalt-paved road scenarios
Tabela 5. Estatística descritiva dos indicadores de desempenho dos veículos bitrem (bogie leve e bogie pesado) utilizados no transporte de madeira nos diferentes cenários de estradas com revestimento asfáltico

Vehicle type	Scenario	Operational Efficiency (%)	Energy Efficiency (t·km L⁻¹)	Productive Capacity (t/km)
			Minimum-Maximum	
Light bogie	C_1	66.26 - 78.92	24.13 - 33.79	8.25 - 13.54
Heavy bogie		63.59 - 82.86	24.91 - 36.37	6.78 - 14.22
Light bogie	C_2	65.55 - 83.91	23.39 - 31.20	6.56 - 13.59
Heavy bogie		62.38 - 89.55	25.34 - 38.33	5.98 - 20.22
Light bogie	C_3	67.67 - 88.71	24.36 - 36.31	7.10 - 13.78
Heavy bogie		62.51 - 88.68	24.42 - 38.77	8.65 - 18.93
Light bogie	C_4	59.27 - 85.34	21.25 - 39.02	9.47 - 19.04
Heavy bogie		66.44 - 88.80	25.13 - 37.44	9.21 - 17.15
			Mean ± SD	
Light bogie	C_1	71.51 ± 2.79	27.30 ± 1.94	9.98 ± 1.10
Heavy bogie		73.11 ± 4.03	30.87 ± 2.49	10.15 ± 1.47
Light bogie	C_2	74.63 ± 3.49	27.13 ± 1.89	9.78 ± 1.47
Heavy bogie		76.41 ± 6.50	30.80 ± 3.10	10.34 ± 2.73
Light bogie	C_3	77.39 ± 3.47	28.61 ± 2.28	10.20 ± 1.32
Heavy bogie		76.45 ± 6.46	31.32 ± 3.00	11.66 ± 2.43
Light bogie	C_4	76.87 ± 6.50	29.05 ± 4.01	14.43 ± 2.59
Heavy bogie		78.52 ± 6.19	30.71 ± 3.61	13.21 ± 2.27
			Coefficient of Variation (%)	
Light bogie	C_1	3.90	7.11	11.06
Heavy bogie		5.51	8.08	14.49
Light bogie	C_2	4.68	6.95	14.99
Heavy bogie		8.51	10.06	26.44
Light bogie	C_3	4.48	7.96	12.95
Heavy bogie		8.44	9.57	20.84
Light bogie	C_4	8.45	13.81	17.92
Heavy bogie		7.88	11.77	17.18

In which: C1 is up to 25% of paved roads; C2 is from 25% to 50%; C3 is from 50% to 75%; C4 is greater than 75%; % is percentage; km is kilometers; L is liters; and t is tons.
Em que: C1 = até 25% de estradas com revestimento asfáltico; C2 = de 25% a 50%; C3 = de 50% a 75%; C4 = maior que 75%; % = porcentagem; km: Quilômetros; L: litros; t: toneladas.

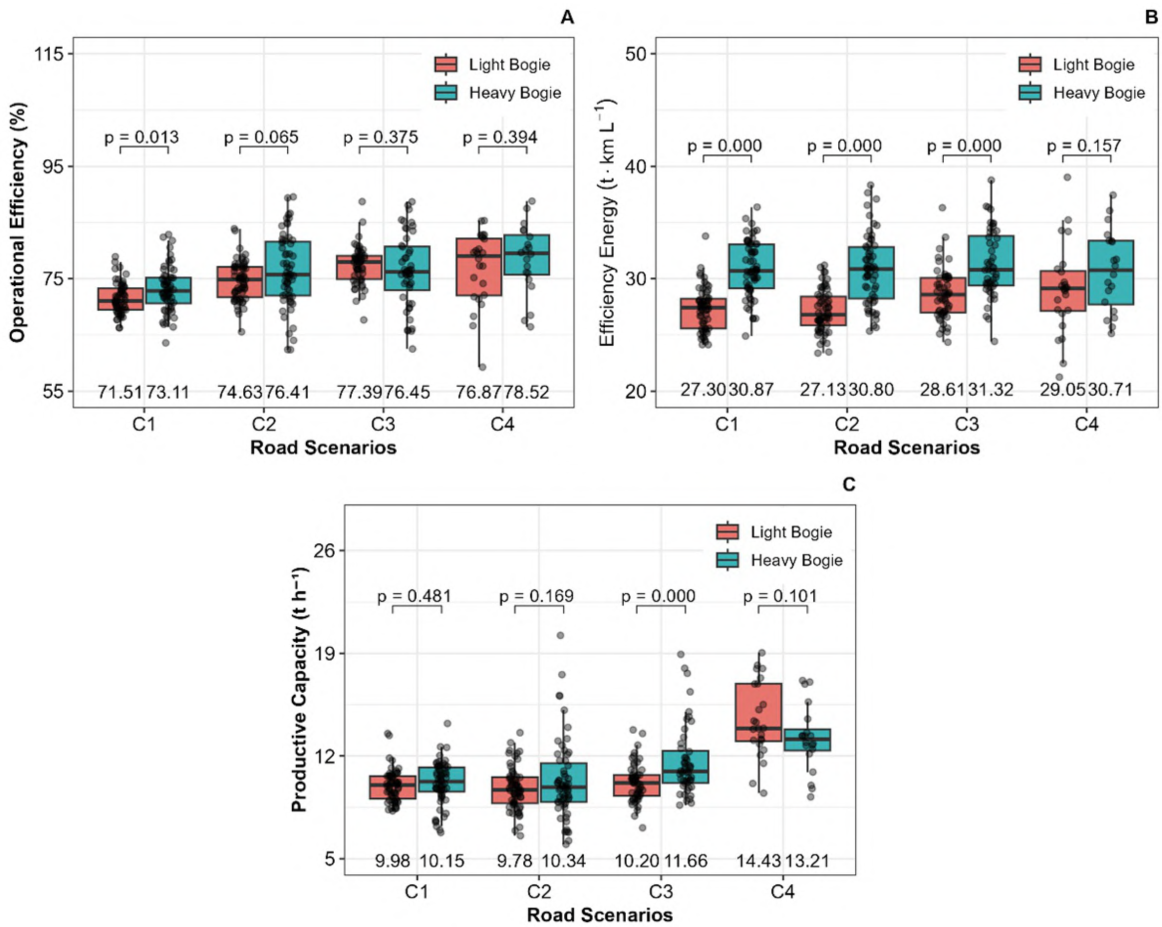

Figure 4. Operational efficiency (%) (A), energy efficiency (t·km/L) (B), and productive capacity (t/h) (C) of B-double FVCs (light bogie and heavy bogie) in timber transport across different asphalt-paved road scenarios. In which: C1 is up to 25% of paved roads; C2 is from 25% to 50%; C3 is from 50% to 75%; C4 is greater than 75%. Black dots represent individual trucks. Values below the scenarios correspond to the observed means; ns indicates a lack of statistical significance; *** represents $p < 0.001$

Figura 4. Eficiência Operacional (%) (A), rendimento energético (t·km L^{-1}) (B) e capacidade produtiva (t/h) (C) pelas CVCs tipo bitrem (bogie leve e bogie pesado) no transporte de madeira nos diferentes cenários de estradas com revestimento asfáltico. Em que: C1 = até 25% de estradas com revestimento asfáltico; C2 = de 25% a 50%; C3 = de 50% a 75%; C4 = maior que 75%. Os pontos em preto representam caminhões individuais. Os valores abaixo dos cenários correspondem às médias observadas, ns indica ausência de significância estatística; *** representa $p < 0{,}001$.

difference ($p < 0{,}01$) both for the main factors (vehicle type and paving scenario) and for the interaction between them across all applied tests (Pillai's Trace, Wilks' Lambda, Hotelling's Trace, and Roy's Largest Root). The significance of the interaction ($p < 0{,}001$) confirmed that the operational response of the FVCs varied according to the combination of vehicle type and the proportion of paved and unpaved roads.

Following the rejection of the multivariate null hypothesis, discriminant analysis was performed to identify the most relevant variables for group separation. The first two discriminant functions explained 96.6% of the total observed variance.

Table 6 presents the canonical correlations between the evaluated variables and the two main discriminant functions, allowing the identification of the variables most associated with group differentiation.

4. DISCUSSION

The results show that the proportion of paved roads had a direct influence on the operational performance of B-double FVCs, corroborating the importance of road conditions previously highlighted by Rocha et al. (2021) in the analysis of road transport.

Table 6. Canonical correlations between the evaluated variables and the discriminant functions obtained for B-double vehicles (light bogie and heavy bogie) across different asphalt-paved road scenarios
Tabela 6. Correlações canônicas entre as variáveis avaliadas e as funções discriminantes obtidas para o veículo bitrem (bogie leve e bogie pesado) nos diferentes cenários de estradas com revestimento asfáltico

Variables	Function	
	1	2
Average speed (km/h)	0.232	0.073
Average consumption (L/km)	-0.076	0.628
Energy efficiency (t km/L^{-1})	0.024	-0.473
Productive capacity (t/h)	0.109	-0.328
Actual time (h)	-0.160	0.336
Total distance (km)	-0.037	0.448
Operational efficiency (5)	0.073	0.080
Net weight (t)	-0.044	-0.041

The increase in the percentage of asphalt pavement on the roads reduced travel time and increased the average speed of the vehicles, confirming the findings of Anttila et al. (2023), which showed that road classification and condition directly influence the average speed of trucks in timber transport. Under these conditions, the differences between vehicles with light and heavy bogies were small, indicating that the lower weight of the light bogie favored agility on more paved routes, while the robustness of the heavy bogie was relevant in mixed sections or those with a lower proportion of asphalt pavement. The stability of the transported weight across the scenarios agrees with Guimarães et al. (2019), who observed that operational performance respects legal limits and load standards in road forestry transport.

Regarding fuel consumption, the vehicle with a heavy bogie showed lower consumption values, evidencing greater energy efficiency attributed to the hub reduction gear, which optimized traction on uneven pavement surfaces and reduced engine strain. The increase in fuel consumption of vehicles in scenarios with less paving corroborates the results of Ziółkowski et al. (2023), which show that unpaved roads increase engine strain and energy consumption. Positive correlations between consumption and travel time, especially in the heavy bogie, reinforce operational coherence, while the light bogie showed less consistent relationships, indicating greater sensitivity to transport route conditions.

The performance indicators also reflected the influence of road paving on vehicle performance. The operational efficiency and energy efficiency obtained in this study are in agreement with Guimarães et al. (2019), who showed that heavy vehicles with optimized traction systems have an advantage on unpaved sections, whereas on paved roads, light vehicles can achieve similar performance. Productive capacity increased with the increment in the proportion of asphalt pavement, with a significant difference only in C3, indicating that in mixed sections, the robustness and stability of the heavy bogie contributed to higher productivity. On homogeneous and paved roads, the light bogie showed equivalent or slightly superior performance, evidencing that the B-double type must be suited to the predominant conditions of the routes.

Multivariate analysis confirmed that average speed was the main variable determining vehicle performance, correlating strongly with the increase in road paving. This result is consistent with Anttila et al. (2023), who indicate average speed as the variable most sensitive to road conditions. Fuel consumption, energy efficiency, and productive capacity were the indicators that most differentiated the vehicle types, especially on roads with a low proportion of asphalt pavement, with the heavy bogie presenting lower fuel consumption and greater energy utilization. In paved scenarios, the differences between vehicles decreased, reinforcing that the mechanical advantage of the heavy bogie was more relevant on routes with less paving.

5. CONCLUSION

According to the analysis and discussion of the results, it was possible to draw the following conclusions from this study:

a) A significant difference was observed in the total distance traveled by vehicles in scenarios C3 and C4, while the average travel time differed only in scenario C3, with lower values for the heavy bogie configuration. Average speed showed a difference exclusively in scenario C1, where light bogie vehicles presented higher values. B-doubles equipped with heavy bogies presented lower fuel consumption across all evaluated scenarios, associated with the presence of the hub reduction gear, which favored an increase in traction and a reduction in engine strain, especially on routes with a lower proportion of asphalt pavement. Operational efficiency remained above 70% in all scenarios, indicating a high utilization of operating time. Furthermore, vehicles with heavy bogies showed better performance in sections with a lower proportion of asphalt pavement, achieving higher energy efficiency in scenarios C1, C2, and C3, while productive capacity stood out only in scenario C3.

b) The multivariate analysis showed that average speed was the operational variable with the greatest influence on FVC performance, presenting a strong relationship with the increase in road paving. With a higher proportion of paved roads, average speeds also increased, indicating better traffic fluidity.

c) In general, B-doubles equipped with heavy bogies were more suitable for use in scenarios with a lower proportion of asphalt pavement, primarily due to lower fuel consumption and higher energy efficiency, whereas light bogie B-doubles presented advantages on predominantly paved routes, mainly due to the reduction in travel time.

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AUTHOR CONTRIBUTIONS

Sperotto, J.: Investigation, Formal analysis, Data Curation, Visualization, Writing – Original Draft; Arce, J.E.: Formal analysis, Methodology, Review, Supervision; Lopes, E.S.: Conceptualization, Project administration; Methodology, Supervision, Writing – review & editing.

DATAAVAILABILITY

The entire dataset supporting the findings of this study has been published within the article.

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