TRANSPORTES
revistatransportes.org.br
anpet
associação nacional de pesquisa e ensino em transportes
anpet.org.br

Technical, economical, and socio-environmental analysis of forest road maintenance using the HDM-4 software

Análise técnica, econômica e socioambiental da manutenção de estradas florestais com uso do software HDM-4

Breno Santos Arrivabeni[1], **Carlos Cardoso Machado**[1], **Raiane Ribeiro Machado Gomes**[1], **Ana Paula Mendes Teixeira**[1]

[1]Universidade Federal de Viçosa, Viçosa, Minas Gerais, Brasil

Contact: breno.arrivabeni@hotmail.com, (BSA); machado@ufv.br, (CCM); raianemachado@ufv.br, (RRMG); anapaulamendesteixeira@gmail.com, (APMT)

Submitted:
29 December, 2021
Accepted for publication:
4 June, 2023
Published:
31 August, 2023

Associate Editor:
Kamilla Vasconcelos, Universidade de São Paulo, Brasil

Keywords:
Forest roads.
HDM-4.
Maintenance.

Palavras-chave:
Estradas florestais.
HDM-4.
Manutenção.

DOI: 10.58922/transportes.v31i2.2699

ABSTRACT
As they do not have a sealant coating, forest roads are more susceptible to degradation and traffic obstruction, requiring better construction and maintenance attention. This study aimed to assess the performance of maintenance carried out on unpaved roads in technical, economic, and socio-environmental scopes by application of the *Highway Development & Management Model* (HDM-4) and to show the best project proposals. The analyses consisted of inputting the HDM-4 with the characteristic data of roads, of and the maintenance to be adopted and the type of used vehicle. The association of this information made it possible to envision scenarios that consider either the replacement or non-replacement of gravel materials on the roads as a methodology. For management without gravel replacement, the most effective scenario was that of roads with gravel under the bed, located in a tropical climate, with flat features and 90 kilometers in length, initial thickness of 175 mm of gravel, high volume of traffic, and subject high-level maintenance at 30-day intervals. For the management with gravel replacement, the ideal scenario was that of roads with gravel under the bed, located in a temperate climate, on rolling terrain and 30 kilometers long, initial thickness of 175 mm of gravel, high traffic intensity, and subjected to high-level maintenance every 30 days. High-level maintenance was the best option for maximizing the quality of the roads and providing the best total net benefit, lowest gas emission rates, least fuel, and tire consumption, and adequate pavement condition by the end of the project.

RESUMO
Pelo fato de não possuírem uma camada selante, estradas florestais tornam-se mais susceptíveis aos efeitos de degradação e inviabilização do tráfego, requerendo maior atenção em sua construção e manutenção. Este trabalho objetivou analisar o desempenho de manutenções em estradas não pavimentadas no âmbito técnico, econômico e socioambiental, através do modelo *Highway Development & Management* (HDM-4), evidenciando as melhores propostas a nível de projeto. As análises se basearam na configuração do HDM-4 com dados característicos das estradas, da

manutenção a ser adotada e do tipo de veículo utilizado. A associação dessas informações permitiu a formação de cenários, considerando-se a reposição e a não reposição de cascalho sobre as vias como metodologia de estudo. O cenário mais eficaz sem reposição de cascalho foi o de subleito cascalhoso, situado em clima tropical, com vias planas de 90 km de distância, espessura inicial de 175 mm de cascalho, alta intensidade de tráfego e submetidas a manutenções de alto nível a cada 30 dias. Ao se considerar a reposição, o panorama ideal foi o de subleito cascalhoso, situado em clima temperado, com vias onduladas de 30 km de distância, espessura inicial de 175 mm de cascalho, alta intensidade de tráfego e também submetidas a manutenções de alto nível a cada 30 dias. A alta manutenção apresentou-se como a mais viável por maximizar a qualidade das vias e proporcionar melhores benefícios líquidos totais, menores índices de emissão de gases, consumo mais baixo de combustível e pneus e suficiente condição do pavimento ao final do projeto.

1. INTRODUCTION

In Brazil, road transportation is essential for the flow of raw materials, labor, products, and services of a wide range of economic activities. The national road network has 1,720,700 km of highways, but only 41% are in good or excellent condition (CNT, 2019). In this sense, unpaved roads correspond to 78.5% of the total number of roads in the country, thus categorizing the vast majority.

The flow of forest products is one of the activities particularly subjected to road quality problems. The forestry road network is estimated to be greater than 700,000 km in length, and it is rapidly increasing due to the growing number of forestry projects in Brazil (Machado, 2002).

Forestry roads have been characterized by a low volume of traffic (usually in a single direction) and the employment of heavy vehicles, with a load capacity of 30 to 40 tons, and extra and heavy ones, with a load capacity above 40 tons (Lopes, 2002). In addition, forestry roads do not have a sealant coating and require more attention in their construction and a distinct set of techniques for their maintenance (Sant'anna, 2006). Forestry companies estimate that traffic on poorly maintained dirt roads and highways generates an extra transportation cost of 25%, due to the greater need for vehicle maintenance (Brasil, 2018). In this context, the development of systems to help the management and rehabilitation of forestry roads are necessary.

Highway Development & Management (HDM-4) has been considered one promising solution to optimize road management problems due to its capacity to include specific conditions of each client and the possibility to use simulation systems (Martins, 2015). Besides the economic aspects of road management, it is also important to evaluate the socio-environmental features of road management. According to Bonsu (2016), fuel consumption and vehicular emissions from traffic are the main restrictions to sustainable environmental development. In Brazil, in 2019, the transport sector was responsible for about 45.4% of total greenhouse gas (GHG) emissions, corresponding to 190.5 million tons of carbon dioxide (CO_2) released (Brasil, 2019).

This study aims to present the effects of maintaining unpaved roads on the forest transport process as a whole, highlighting the best proposals at the project level. As a specific objective, there is the analysis of the effects of performing periodic preventive maintenance on forest roads, providing information that can guarantee gains in quality, performance, and cost of operations, encouraging the choice of the most viable decisions from the technical, economic, and environmental points of view. We also sought to discuss the application of the Highway Development and Management Model (HDM-4) in the management of unpaved networks in forestry projects.

2. METHODOLOGY AND DATA

The data processing was performed using the software Highway Development and Management (HDM- 4).

2.1. System calibration

The HDM-4 software was set up with the following configurations:

2.1.1. Type of soil

Two subgrade types were chosen to represent the roads of interest: stony soil and clayey soil defined respectively as GC and CH according to the Unified Soil Classification System (USCS). This was based on the most common soils used for traffic by forestry companies in Brazil. According to the Classification Transportation Research Board (TRB), the GC group has good to excellent behavior as a layer of the subgrade, while the CH group has poor to weak behavior as a subgrade (DNIT, 2006).

2.1.2. Climate

The climatic zones were defined as Tropical and Temperate (IBGE, 2002), which comprise the most significant regions in terms of forestry planted in Brazil.

2.1.3. Geometry

The HDM-4 system has, in its functionality, different classes of geometry that vary with slope, from the flattest to the steepest. Thus, to represent all the classes present, we chose to work with three classes of geometry: the flattest, the steepest, and the intermediate between them.

2.1.4. Fleet and distance

Based on the main characteristics of the forestry companies in the study region, the triple trailer was adopted as a vehicle for transporting loads. This choice is based on tests carried out in companies in the forestry sector, which confirmed the vehicle's efficiency. In addition, the use of a triple trailer as a vehicle for transporting wood presents the lowest costs of cubic meters (m^3) transported per kilometer (km), which makes such a vehicle an economically viable alternative (Alves et al., 2013).

Then, the HDM-4 software was calibrated using the vehicle's features of interest, as described below:

Total hours/year = 8.760 (24 h × 365 days); Total effective hours = 7.096 (81% operational efficiency, with 90% mechanical availability and 90% operational availability); Wood volume per trip = 54 m^3 or 50 tons (t); Wood density: 0.92 t/m^3; Average guideline speed (project) = 34.29 km/h (40 km/h unloaded and 30 km/h loaded); Total loading and unloading time = 2 h/trip; ESALF (Equivalent Standard Axle Load Factor) = 1.8×10^6.

As for the definition of the distances to be covered by the fleet, the mileage adopted was analyzed in the context of harvesting and transport considering variations of distances, opting, in this sense, for the routes of 30, 60, and 90 km as the most representatives.

The use of these distances seeks to cover real scenarios that range from short trips (as close to the factory or industrial loading yard) to longer distances, which require more driving time on roads.

2.1.5. Replacement of gravel

The data on the thickness and strength of the replacement material was processed using a combination of equations. The first, originating from the software itself (Equation 1), expresses the criteria developed by the US Army Corps of Engineers for the thickness of the required coverage on roads, depending on the strength of the roadbed and the coating materials (USACE, 2006).

The others are represented by a constituent (Equation 2) of the initial equation and the other, based on the correlation between the number N of the vehicle standard axle and the CBR value of the subgrade, which is used for dimensioning the pavement of rural and forest roads, according to DNIT (2006) (Equation 3).

$$log_{10}HG = 1.4 + 12.3\ C1^{-0,466} \times C2^{-0,142} \times NE^{0,124} \times RD^{-0,5} \qquad (1)$$

where: HG = thickness of the primary coating (mm); $C1$ = Primary coating CBR (%) determined by Equation 2; $C2$ = subgrade CBR (%); NE = equivalent cumulative load of 40 kN on a single wheel at 550 kPa tire pressure. N expressed in power 10 (1,000,000 = 106; therefore, 6 is used); RD = strain depth (mm).

Being $C1$:

$$C1 = \exp\left(\frac{-\ln\left(\frac{(\log_{10}(HG)-1,4)}{12,3 \times C2^{(-0,142)} \times NE^{(0,124)} \times RD^{(-0,5)}}\right)}{0.466}\right) \qquad (2)$$

where:

$$Ht = 77.67 \times N^{0,0482} \times CBR^{-0,598} \quad (3)$$

Where: Ht = Thickness of the primary coating layer (cm); N = Number of loadings of the standard axle of 8.2 t; CBR = CBR value (%) of the subgrade.

Such an association of equations is justified by the fact that the one related to software (Equation 1), once thickness, fleet, and deformation data are provided, provides the CBR value directly and in such a way that it is impossible to change or insert arbitrary values for that characteristic in the system.

However, by incorporating Equation 3 into the original software equation, through the dismemberment of $C1$, it becomes possible to work the system by entering CBR values for the soils of interest, which allowed to dimension the minimum gravel thickness that the pavement must have to meet the existing CBR support standards.

As the CBR index required for paved roads is 80% (DNIT, 2006), once using the set of equations, it was found that the thickness of gravel lining (HG) in the roads of interest should be at least 70 mm. Such value serves as a minimum basis, below which there would be such initial gravel wear to the point where the subgrade layer can be reached.

Based on this, the data entry for the coating layer took into account, in the present study, the use of type A-2-4 gravel, a group of soil that shows excellent to good behavior as a road pavement layer. Then, two amounts of this gravel were considered for road application: 125 mm and 175 mm thick. Such quantities were defined based on the average between the thickness classes 100-150 mm and 150-200 mm, respectively, commonly adopted in road extensions of forestry companies for maintenance of unpaved roads.

Thus, each amount was simulated in turn; first being applied as the initial lining of the road, there is no replacement regardless of the wear presented and, in a second moment, being replenished every time the initial amount is worn below the minimum 70 mm.

Still, it was possible to work on the material loss ratio of the subgrade and the primary coating according to the characteristics of the soil of interest, loss that directly impacts the thickness of the applied coating and implies its replacement. The annual amount of material lost is thus given according to Equations 4 and 5 below:

$$MLA = K_{gl}\ 3.65\ [3.46+0.246\ (\frac{MMP}{1000})(RF)+(KT)(AADT)] \quad (4)$$

where:

$$KT = K_{kt}\ max\ [0.022+0.969\ (\frac{HC}{57300})+0.00342\ (\frac{MMP}{1000})(P075) \quad (5)$$

$$-0.0092\ (\frac{MMP}{1000})(PI) - 0.101\ (\frac{MMP}{1000})]$$

MLA = Annual material loss, in mm/year; KT = Traffic-induced material whip-off coefficient; $AADT$ = Annual average daily traffic, in veh/day; MMP = Mean monthly precipitation, in mm/month; RF = Average rise plus fall of the road, in m/km; HC =

Average horizontal curvature of the road, in deg/km; PI = plasticity index of the material, in per cent; K_{gl}= Calibration factor for material loss; K_{kt} = Calibration factor for traffic-induced material whip-off coefficient.

2.1.6. Type of maintenance

Maintenance and rehabilitation works are the necessary actions so that an acceptable level of conservation is maintained on the pathways of interest. Among the suggestions of pre-established intervention by HDM-4, the present study considered three types: HMG: High maintenance (leads to a more complete treatment of roads, including patrolling, wetting, and mechanical compaction operations); LMG: Medium maintenance (it is referred to an intermediate treatment referring only to the patrol operation); NMG: Low maintenance (minimal improvement services are used, there is practically no intervention).

2.1.7. Frequency

The structure of the pavements, regardless of their nature, needs periodic analysis and repairs. Aiming at a maintenance horizon close to that adopted by the main forestry companies in the study region, three-time intervals were considered for the analysis: maintenance every 30 days; maintenance every 90 days, and maintenance every 150 days, to highlight the time needed to repair the stretches.

2.1.8. Traffic intensity

The Average Annual Daily Traffic (AADT) is the parameter that defines the average daily volume of vehicles on the roads, that is, the sum of the total number of vehicles traveling on a highway or road for one year, divided by 365 days.

To cover from a small volume of traffic to a larger flow, in this study, we chose to work with three values of AADT: 40, 80 e 120. Considering that the previously mentioned values were based on directional flow counts (round trips), the traffic intensity corresponded to 20, 40, and 60 trips per day, respectively.

2.2. Compilation of data

Once the input parameters were defined and calibrated in the software, it was generated, through the combination of all of them, an extensive database containing different scenarios of interest, representing different realities for the present project. In this way, 3,888 different scenarios were created, which, when projected for the six categories of results of interest, were grouped in areas (Technical: Pavement conditions – gravel wear –; Economic: Total benefits, fuel costs and taking costs; Socio-environmental: CO and CO2 emissions), amounted to 23,328 total scenarios.

2.2.1. Technical aspect

The description of the technical aspect was based on the analysis of the gravel reduction initially used to cover the road, methodologically addressed in the topic of this work, which allowed to define the condition and quality of the pavement according to its greater or lesser protection and the consequent need for intervention.

2.2.2. Economic aspect

For the determination of costs in the economic part, the models that make up the HDM-4 simulated the road conditions for a pre-established analysis period of 7 years, considering the financial balance inherent to the process.

In this sense, the compilation of data generated in this study was restricted to the analysis of the parameters of greatest relevance to obtain expected results, thus returning to the total benefits and expenses related to fuel and tires.

As for the diagnosis of the mentioned benefits, Nunes (2012) affirms that it is customary to analyze and prioritize the possible investments to be made by selecting the most advantageous alternative. In these terms, the most common project selection criteria adopted by HDM-4 are the Net Present Value (NPV), the Internal Rate of Return (IRR), and the Benefit-Cost Ratio (BCR).

To perform the calculations, economic analysis was used by the NET, which can be defined as the present value of benefits (expected capital returns) minus the present value of costs (investments made) (Nunes, 2012). This choice was based on the easy elaboration and the clear form that the method presents, revealing in monetary terms the economic benefits that the project will bring and representing them by their NET value. In addition, HDM-4, as it is widely used for project feasibility analyzes, has highlighted this index as the most important criterion in public investment decisions. Next, in Equation 6, the method of calculating the NPV is shown:

$$NPV=\sum_{t=0}^{T}(B_t - C_t) \times (1+r)^{-t} \tag{6}$$

Where: T: project period (years); Bt: number of benefits in year t; Ct: the costs in year t; r: discount rate.

In terms of fixed costs, interest and depreciation act as representative components in the quantification of the economic benefits represented. As for variable costs, Klein (2005) states that fuel consumption is based on several factors, such as total power required by the engine, type of vehicle, distance, and direction of travel (uphill and downhill), directly affecting its cost. Thus, the determination of fuel costs made by HDM-4, considering factors of the system itself, was generally based on Equation 7:

$$Comb = Cmm \times Pu \tag{7}$$

where: $Comb$ = cost-effective fuel per hour (R$/1000 km.vehicle); Cmm = average hourly consumption of the machine (l/1000 km.vehicle); Pu = price per liter of fuel (R$/l).

The cost of tires, on the other hand, is directly related to their wear, which, according to the aforementioned author, is manifested proportionally according to the strength acting on each wheel of the vehicle (radial, lateral and normal strength). The irregularity of the pavement, the type of tire, and the type of traffic are, therefore, preponderant factors in the consumption and expenditure of this asset. And just like for fuel, the software adds its references for its calculation, based on Equation 8 below:

$$CP = \frac{(N \times Vp)}{H} \tag{8}$$

where: CP = cost of tires per effective hour (R$/1000 km.vehicle); N = number of machine tires; Vp = tire purchase value (R$); H = tire life (1000 km.vehicle).

Once these inventories were exposed, in addition to obtaining individual values for the target costs, the system was able to project the capital value to be saved for each scenario, defining a specific net benefit for each panorama of interest. Thus, the economic simulation produced was based on the combination of total expenses, originating from the interrelationship between fixed costs and variable costs.

2.2.3. Socioenvironmental aspect

Concerning monitoring the release of gases, HDM-4 produces in its output reports estimates of CO_2, HC, CO, NOx, SO_2, and particulate matter, released due to the expected traffic with the implementation of the road work target. The present work considered CO and CO_2 as GHGs of interest, due to their notoriety and relevance to the topic, making it possible to quantify and evaluate the net differences of these pollutants for each investment option.

The following are Equations 9 and 10, used to calculate the emissions of carbon CO and CO_2, respectively.

$$\mathrm{EOE_{CO}} = \mathrm{a_{CO}FC} \tag{9}$$

where: $\mathrm{EOE_{CO}}$- Engine-out carbon monoxide emissions (g/veh.km); a_{CO}- ratio of engine-out emissions per gram of fuel consumed for emission CO(gCO/gfuel); FC - Fuel consumption.

$$\mathrm{TPE_{CO2}}=44.011\left[\left(\frac{\mathrm{FC}}{12.011+1.088\mathrm{a_{CO2}}}-\frac{\mathrm{TPE_{CO}}}{28.011}-\frac{\mathrm{TPE_{HC}}}{13.018}-\frac{\mathrm{TPE_{PM}}}{12.011}\right)\right] \tag{10}$$

where: $\mathrm{TPE_{CO2}}$ – Tail pipe carbon dioxide emissions(g/veh-km); FC - Fuel consumption; a_{CO2}-Fuel dependent model parameter representing the ratio of hydrogen to carbon atoms in the fuel; $\mathrm{TPE_{CO}}$-Tail pipe carbon monoxide emissions(g/veh-km); $\mathrm{TPE_{HC}}$ – Tail pipe hydrocarbon emissions(g/veh.km); $\mathrm{TPE_{PM}}$ – Tail pipe particulate matter emissions(g/veh.km).

Thus, the use of the HDM-4 software as a tool to assist Road Management Systems, through the compilation of technical, economic, and socio-environmental results, comes in this study to subsidizes the best alternatives for road management among the various scenarios constructed.

3 RESULTS

The HDM-4 software generated 23,328 scenarios, which were extensively filtered, prioritizing the choice of those with the highest Net Present Value (NPV). We proceeded in this way until we obtained two final scenarios, considered more viable, referring to the maintenance of roads with and without the replacement of gravel (Table 1).

Table 1: Best scenarios for the maintenance of roads without the replacement of gravel (scenario 1) and with the replacement of gravel (scenario 2)

				Scenario 1			
Soil	**Climate**	**Geometry**	**Distance (km)**	**Gravel thickness (mm)**	**Type of intervention**	**Frequency (days)**	**Traffic (AADT)**
GC	**Tropical**	**Flat**	**90**	**175**	**HMG**	**30**	**120**
				Type of intervention			
Category			**High (HMG)**	**Medium (LMG)**	**Low (NMG)**		
Total Net Benefits			1,380.10	1,367.30	0	Millions of reais	
CO emissions			229.73	234.63	356.05	Tons	
CO_2 emissions			71,511.04	73,030.01	110,825.93	Tons	
Fuel consumption			6,925.47	7,072.57	10,732.93	Liters per vehicle /1000 km	
Tire Spending			1.54	1.59	2.19	Number of tires per vehicle /1000 km	
Pavement condition			124	124	124	mm (gravel loss)	
				Scenario 2			
Soil	**Climate**	**Geometry**	**Distance (km)**	**Gravel thickness (mm)**	**Type of intervention**	**Frequency (days)**	**Traffic (AADT)**
GC	**Temperate**	**Wavy**	**30**	**175**	**HMG**	**30**	**120**
				Type of intervention			
Category			**High (HMG)**	**Medium (LMG)**	**Low (NMG)**		
Total Net Benefits			406	406	0	Millions of reais	
CO emissions			73.66	75.17	122.22	Tons	
CO_2 emissions			22,922.83	23,390.18	38,041.23	Tons	
Fuel consumption			6,659.88	6,795.65	11,052.31	Liters per vehicle /1000 km	
Tire Spending			1.75	1.76	2.58	Number of tires per vehicle /1000 km	
Pavement condition			57	57	57	mm (gravel loss)	

3.1. Road management without gravel replacement

For roads where gravel replacement was not intended, for a 7-year project horizon, the best scenario to be adopted was as follows: gravel soil, located in a tropical climate, with pathways of flat geometry with 90 km distance, where 175 mm of gravel is applied for the initial covering of the road and high-level maintenance is done every 30 days, such stretch is characterized by a high intensity of traffic (Table 1 Scenario 1).

A flat geometry presents facilities regarding reparative tracts and greater natural stability, providing lower levels of severity and defects (Silva, 2009). The lower concentration of runoff over this geometry favors the reduction of erosive processes (Moreira, 2018), generally implying a need for later replacement and a reduction in economic expenses in this option.

Furthermore, the scenario presented a better economic return with the adoption of high maintenance (HMG) on the roads, with this type of intervention representing a greater saving of resources, with gains in the order of 1,380.1 million reais for the entire project horizon.

Despite the average maintenance (LMG) implies a less complete treatment of the stretch, requiring fewer resources and a lesser investment, its associated NPV proved to be inferior to high maintenance. Compared to this, its adoption represented an additional expense of 12.8 million reais at the end of the project, making it, therefore, less economically attractive. This is explained by the fact that the final quality of the road is strictly linked to the intensity of the maintenance adopted, making the economy of investing in a lower level of repair not overlap with the reflexes brought by a lower quality road.

Low maintenance (NMG) was characterized by practically not changing the natural state of the road and, due to this behavior of almost no intervention, the economic gain from adopting this type of maintenance was nil.

For gas emissions, estimates showed that almost 230 tons of CO and more than 71,500 tons of CO_2 would be released by traffic over the 7 years of the project, adopting high maintenance. Such values would suffer increases if medium and low interventions were chosen, which can be explained by the lower performance of vehicles on less-treated roads.

Holes, cracks, undulations, and erosions are some of the factors that lead to an increase in fuel consumption and, consequently, in atmospheric emissions. According to CNT (2019), when driving on poor quality tracks, the driver has greater difficulty in maintaining a constant speed, needing to brake and accelerate more frequently, which leads to an increase in such parameters.

In the case of carbon dioxide, opting for medium maintenance about the high would imply releasing 1,518.97 tons more of CO_2 into the atmosphere, while when choosing the low this excess would be even greater, at 39,314.89 tons. The CO_2 in high amounts in the air becomes harmful, being one of those responsible for global warming, but, in contrast, it is also a raw material for the photosynthesis of trees. Therefore, to repair the environmental damage resulting from pavement deficiencies, it was estimated how many trees should be planted to compensate for such additional emissions.

According to a study about reforestation in Atlantic Forest (ESALQ-USP, 2013), each tree can absorb approximately 163.14 kg of CO_2 throughout its first 20 years of life. Thus, it would be necessary to plant 9,311 trees for average maintenance and 240,989 trees for low to balance the emissions from the excess diesel consumed in the project in question. In this sense, the amount of gases emitted becomes a direct reflection of the amount of fuel spent, as both are closely related to the quality of the roads. And taking into account that in Brazil the car fleet grew 80.8% in the last 11 years (CNT, 2019), the poor quality of the tracks only contributes to the worsening of this problem.

The enhanced fuel consumption showed a growing estimate similar to emissions, increasing as the maintenance intensity of the stretches was reduced. In high intervention, consumption was higher than 6,900 liters per vehicle/1000 km, increasing this value by 147.1 liters when opting for the average intervention and by more than 3,800 liters when opting for low maintenance.

Considering that the average price of diesel oil passed on to the consumer in 2021 according to the National Agency of Petroleum, Natural Gas and Biofuels (ANP, 2022) was R$ 4.562 per liter, it can be said that, for the scenario presented, the excessive consumption of this fuel represented a financial loss of R$ 671.07 with the adoption of average maintenance and R$ 17,369.63 with the adoption of low, both calculated by vehicle/1000 km.

Thus, the higher quality of the road provided by the application of high intervention was found to be preponderant in the lower value of fuel consumption. Francisconi Jr et al. (2017) states that routes with better infrastructure conditions result in both economic and environmental benefits regarding this consumption. Therefore, improvement works, interventions and a significant change in the vehicle fleet are actions that influence the reduction of GHG by providing better traffic quality on the road and consequently lower fuel consumption.

Regarding the estimated expense with tires, this followed the same growing pattern presented by the previous parameters, presenting itself lower in high maintenance and increasing in the direction from average to low. Such behavior is linked to how tires, fuel, and emissions are associated with each other, in a unique and interconnected dynamic.

The tire is an essential component of the vehicle, as it is solely responsible for making the interface between it and the pavement, an interface in which vehicles end up consuming fuel to overcome the strength contrary to its displacement (Leandro, 2018). This way, the aforementioned author states that the pavement texture is the characteristic that most influences the rolling resistance, directly impacting the consumption of tires, fuel, and the emission of polluting gases, being significant, therefore, from an economic and environmental point of view. Thus, a track with a low repair pattern, presenting a more irregular and uneven texture, supports the greater number of associated worn tires.

As for the condition of the pavement, it was characterized due to the loss of the initial layer of gravel on the track. Freitas (2019) states that gravel material is commonly used for works on unpaved roads, being part of it used as a sacrifice layer since due to the traffic of vehicles and time, a certain amount is lost from the road.

In the scenario presented, this loss was shown to be the same for the three levels of maintenance, indicating that the wear of this material was not influenced by the type of intervention, since in these repair services, performed in periodic cycles of 30 days, the replacement did not include gravel, only works and improvements of other natures. Thus, both the material that was being worn out and the one that remained at the end of the project horizon came from the initial quantity applied in the first year.

However, it is important to note that the reduction of gravel for both maintenances has guaranteed a minimum level of coverage until the seventh year. According to the CNT (2019), deformations and problems in the rolling platform are generally associated with the wear of the lining, combined with the lack of support, the heavy traffic, and the overload of heavy vehicles on the track.

3.2. Road management with gravel replacement

On the roads where it was considered to make the replacement of gravel for a 7-year project horizon, it was stipulated that this would be carried out as soon as the thickness of the same reached 70 mm. Thus, the scenario that presented the best net benefit, in addition to having presented the need for replacement only in the last year of the project, was the following: gravel soil, located in a temperate climate, with wavy pathways with 30 km of distance, where 175 mm of gravel thickness is applied for the initial covering of the road and high-level maintenance is carried out every 30 days, with this section characterized by a high traffic intensity (Table 1 Scenario 2).

Among the three road geometries, the wavy and steep are the ones that tend to lose gravel more easily and reach the minimum for replacement first, the flat geometry figuring in the need, usually, for a later replacement. This fact is reinforced by Cabette (2018), which states that the surface gravel loss rates in the coating layers increase significantly at higher gradients and in areas of heavy rainfall, resulting in a greater need for replacement before the lower layers are exposed.

Thus, in how the trigger for overcoating tends to be hit first, an early intervention ends up saving more accentuated wear and consequently covering a longer period of the project horizon, implying the recovery of the quality of the section and possible benefits in the benefit final economic value.

In this way, even the HDM-4 system understands that the advantages of the corrugated path may outweigh those of the steep one, because, even after replacement, the latter still represents expenses and efforts arising from its conformity and characteristics that, throughout the project, reduce the economic benefits brought by the coating. In other words, in corrugated geometry, replacement and maintenance compensate for the unfavorable efforts and reflexes of the type of road to the point that its financial benefit is greater than its disadvantages and stands out from other geometric categories.

With regard to the intensity of the interventions, it was evident that the best economic return was shown to be the same for both high and medium maintenance, standing in the order of R$ 406 million. This could imply that it would not be necessary to opt for a high intervention, which consequently requires more labor and costs when an average intervention would provide the same financial result and would place itself as a more attractive alternative.

However, it should be taken into account that average maintenance implies a road with a lower final quality compared to high maintenance, having direct impacts on vehicle performance and income by category, which was reflected in the higher expenses with tires and fuel. Thus, despite having presented the same value in net benefits, the option for high intervention still proved to be more advantageous due mainly to environmental bias.

In the gas emission parameter, the HMG maintenance showed the lowest indexes, which means that by opting for this intervention, 467.35 tons more of CO_2 would be saved in the atmosphere compared to average maintenance and avoided 15,118.40 extra tons in comparison to the low. In the case of CO, the quantities not emitted would follow the same increasing pattern.

Thus, following the reasoning presented in the previous scenario regarding the neutralization of additional CO_2 emissions, it was estimated the number of trees necessary for such compensation to be achieved. The calculation revealed that 2,865 trees should be planted for average maintenance, while low intervention would require a total of 92,672 of these individuals for the correct balance of emissions from excess diesel.

Coupled with emissions, the estimate of fuel consumption was also lower with the adoption of high maintenance, presenting an increase according to the choice of medium and low interventions, respectively. In comparison, the difference in fuel consumed from HMG maintenance to LMG was almost 136 liters, whereas from HMG to NMG this increase was close to 4,400 liters.

In the same way, as for the scenario without replacement, it can be said that, for the current scenario, the excessive and unnecessary consumption of this fuel represented a noticeable financial loss, being R$ 619.38 per vehicle/1000 km with the adoption of the average maintenance and R$ 20,038.26, in the same unit, with the adoption of the write-off.

The same growing behavior could be observed in terms of tire spending: with the high intervention, consumption of 1.75 new tires per vehicle/1000 km was estimated, which increased with the adoption of average and low maintenance, respectively, reflecting thus the effects of the quality of the road on the expenses of this element.

As for the condition of the pavement, the results showed that the proposed scenario only reached the level of 70 mm of gravel required for replacement in the last year of the project, which sets up a positive parameter regarding the temporality of such replacement.

For the three maintenance levels, after being replaced, the reduction of the gravel was the same, 57 mm, implying that just as in the previous scenario, the loss of coating is not linked to the type of intervention adopted. As the different types of maintenance did not consider the replacement of gravel in their activities, the interventions along the project horizon happened in the same way both for the scenario without and for the one with replacement. In the latter, however, reapplication was carried out when the trigger level for it was reached, which occurred only in the last year, thus, making it a factor foreign to the type of assistance work adopted.

4 CONCLUSIONS

The HDM-4 software can help decision-making regarding highways, also covering unpaved roads in this sense.

Comparatively among the generated scenarios, for the management of roads without gravel replacement, the technical, economic, and environmental analysis showed better feasibility for the scenario with gravel subgrade, located in a tropical climate, with flat paths 90 km away, initial thickness of 175 mm of gravel, high traffic intensity and subjected to high-level maintenance every 30 days.

As for the management of roads with gravel replacement, the scenario analyzed as the most viable among the proposed ones was the gravel subgrade, located in a temperate climate, with wavy paths of 30 km of distance, initial thickness of 175 mm of gravel, high traffic intensity, and subjected to high-level maintenance every 30 days.

The option for high maintenance (HMG) presents itself as the most viable among the others, providing better total net benefits, lower gas emission rates, lower consumption of both fuel and tires, and sufficient condition of the pavement at the end of the horizon of the project.

REFERENCES

Alves, R.T.; N.C. Fiedler; E.N. Silva et al. (2013) Análise técnica e de custos do transporte de madeira com diferentes composições veiculares, *Revista Árvore*, v. 37, n. 5, p. 897-904. DOI: 10.1590/S0100-67622013000500012.

ANP (2022) *Anuário Estatístico Brasileiro do Petróleo, Gás Natutal e Biocombustíveis 2022*. Available at: <https://www.gov.br/anp/pt-br/centrais-de-conteudo/publicacoes/anuario-estatistico/anuario-estatistico-2022> (accessed 06/04/2023).

Bonsu, E.O. (2016) *Estimation of Vehicular Emissions and Fuel Consumption on Road Links Using HDM-IV in Ghana - A Case Study on the George Walker Bush Motorway (14.1 km) Accra*. Thesis (PhD). Department of Civil Engineering, Kwame Nkrumah University of Science and Technology, Kumasi. Available at: <https://ir.knust.edu.gh/handle/123456789/10201> (accessed 06/04/2023).

Brasil, Ministério da Agricultura, Pecuária e Abastecimento. (2018) *Plano Nacional de Desenvolvimento de Florestas Plantadas*. Available at: <https://www.gov.br/agricultura/pt-br/assuntos/politica-agricola/outras-publicacoes/plano-nacional-de-desenvolvimento-de-florestas-plantadas.pdf> (accessed 06/04/2023).

Brasil, Ministério de Minas e Energia, Empresa de Pesquisa Energética. (2019) *Balanço Energético Nacional*. Available at: <https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-2020> (accessed 06/04/2023).

Cabette, M.M. (2018) *Caracterização Geotécnica de Estradas Não Pavimentadas de Baixo Volume de Tráfego: Estudo de Caso*. Dissertation (Master). Escola Superior de Tecnologia e de Gestão, Instituto Politécnico de Bragança, Bragança. Available at: <http://hdl.handle.net/10198/19159> (accessed 06/04/2023).

CNT (2019) *Pesquisa CNT de Rodovias*. Available at: <https://pesquisarodovias.cnt.org.br/downloads/ultimaversao/gerencial.pdf> (accessed 06/04/2023).

DNIT (2006) *Manual de Pavimentação: IPR 719* (3. ed.). Rio de Janeiro: DNIT.

ESALQ-USP (2013) *Reflorestamento da Mata Atlântica Absorve 1,2 Milhão de Toneladas de CO_2*. Available at: <http://www.esalq.usp.br/acom/clipping/arquivos/16-03-2013_Reflorestamento_da_Mata_Atlantica_absorve_1_2_milhores_e_toneladas_de_CO2_UOL.pdf> (accessed 06/04/2023).

Francisconi Jr, J.P.; M.M. Reis; J.C.C. Amorim et al. (2017) Contribuição do programa de infraestrutura logística de Santa Catarina na redução das emissões de gases de efeito estufa, *Gestão & Sustentabilidade Ambiental*, v. 5, n. 2, p. 694-710. DOI: 10.19177/rgsa.v5e22016694-710.

Freitas, B.T. (2019) *Avaliação e Caracterização Geotécnica de uma Estrada de Baixo Volume de Tráfego*. Dissertação (mestrado). Escola Superior de Tecnologia e de Gestão, Instituto Politécnico de Bragança. Portugal. Available at: <http://hdl.handle.net/10198/22124> (accessed 06/04/2023).

IBGE (2002) *Mapa de Climas Zonais do Brasil*. Rio de Janeiro: IBGE. Available at: <https://atlasescolar.ibge.gov.br/images/atlas/mapas_brasil/brasil_clima.pdf> (accessed 06/04/2023).

Klein, F.C. (2005) *Análise da Influência de Características Geométricas de Rodovias nos Custos dos Usuários Utilizando o Programa HDM-4*. Dissertação (mestrado). Escola de Engenharia de São Carlos, Universidade de São Paulo. São Carlos. DOI: 10.11606/D.18.2005.tde-11122006-161658.

Leandro, R.X. (2018) *Influência da Textura dos Pavimentos e Diferentes Tipos de Pneus na Resistência ao Rolamento*. Dissertação (mestrado). Programa de Pós-Graduação em Engenharia Mecânica, Universidade Federal de Pernambuco. Recife. Available at: <https://repositorio.ufpe.br/handle/123456789/33071> (accessed 06/04/2023).

Lopes, W.G.R. (2002) *Solo-Cimento Reforçado com Bambu: Características Físico-Mecânicas*. Tese (doutorado). Faculdade de Engenharia Agrícola, Universidade Estadual de Campinas. São Paulo. DOI: 10.47749/T/UNICAMP.2002.280894

Machado, C.C. (2002) *Colheita Florestal* (1. ed.). Viçosa: Editora UFV.

Martins, L.D. (2015) *Levantamento da Utilização de Sistemas de Gerência de Pavimentos no Brasil e Estudo de Caso*. Dissertação (mestrado). Programa de Engenharia Civil, Universidade Federal do Rio de Janeiro. Rio de Janeiro. Available at: <http://www.coc.ufrj.br/pt/dissertacoes-de-mestrado/388-msc-pt-2015/4574-lidia-diniz-martins> (accessed 06/04/2023).

Moreira, A.N.H. (2018) *Modelo Geolocalizado para Conservação de Estradas Não Pavimentadas*. Dissertação (mestrado). Programa de Pós-Graduação em Agronomia, Universidade Federal de Goiás. Goiânia. Available at: <http://repositorio.bc.ufg.br/tede/handle/tede/8406> (accessed 06/04/2023).

Nunes, D.F. (2012) *Procedimento para Análise de Sensibilidade do Programa HDM-4.* Dissertação (mestrado). Escola de Engenharia de São Carlos, Universidade de São Paulo. São Paulo. DOI: 10.11606/D.18.2005.tde-11122006-161658.

Sant'anna, G.L. (2006) *Estradas Florestais: Caracterização Geotécnica e Comportamento Mecânico de Solos e Misturas Solo-Grits, Cargas de Tráfego e seus Efeitos*. Tese (doutorado). Programa de Pós-Graduação em Ciência Florestal, Universidade Federal de Viçosa. Viçosa. Available at: <https://locus.ufv.br//handle/123456789/557> (accessed 06/04/2023).

Silva, T. (2009) *Estudo de Estradas não Pavimentadas da Malha Viária do Município de Viçosa – MG*. Tese (doutorado). Programa de Pós-Graduação em Engenharia Civil, Universidade Federal de Viçosa. Viçosa. Available at: <https://locus.ufv.br//handle/123456789/808> (accessed 06/04/2023).

USACE (2006) *Building Information Modeling (BIM): A Road Map for Implementation to Support MILCON Transformation and Civil Works Projects within the U.S. Army Corps of Engineers*. Washington, DC: USACE.