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Influence of traffic load on the environmental impacts of roads: A1 and A2 highways in Austria

E Hoxha[1,2]*, M Scherz[2] and A Passer[2*]

[1] Aalborg University, Department of the Built Environment, A. C. Meyers Vaenge 15, 2450 Copenhagen SW, Denmark.
[2] Graz University of Technology, Institute of Structural Design, Working Group Sustainable Construction, Technikerstraße 4, 8010 Graz, Austria

*enho@build.aau.dk; alexander.passer@tugraz.at

Abstract. Professionals should aim to significantly reduce greenhouse gas (GHG) emissions by implementing the best road construction technologies to develop low-carbon projects. Although the traffic loads vary over the road length, the environmental impacts are assessed based on the average values of the traffic loads. Consequently, there is a gap between reality and the impacts calculated with fixed traffic load. This paper aims to assess the gap in terms of the environmental impacts of two roads by considering both a constant and a variable traffic load. With the help of a life cycle assessment (LCA), the environmental impacts of the A1 and A2 highways in Austria are calculated. We have calculated the impacts in the first scenario by considering an average traffic load. In the second scenario, based on real measurements, the environmental impacts of both highways are calculated for a variable traffic load. In the end, the results show a gap in the range of 25 %. This difference was because some parts of the roads required frequent repair. Besides, we figured out the optimal thickness of the wearing course, which improves the impact calculation and makes it less likely that the results will be different along the length of the road.

Keywords: flexible and rigid pavement, sustainable road construction, bituminous pavement, performance related approach

1. Introduction

Within the Paris Agreement, 197 countries have committed to limiting greenhouse gas (GHG) emissions released into the atmosphere. The degree of limitation must prevent the average global temperature from rising above 1,5 degrees Celsius before 2050 [1]. On the other hand, the total road network is expected to increase by 50 %. Furthermore, the existing road network shall be properly maintained, which will require an extensive quantity of materials [2]. Consequently, to reach the goals set in the Paris Agreement, the road stakeholders must develop projects with low environmental impacts.

Several low-embodied carbon materials and road design techniques for reducing highway environmental impacts have been developed and published in the literature [3]. To reduce the environmental impacts of flexible pavements, the scientific community has proposed the reduction of the asphalt temperature production, using modifiers to improve the properties of asphalt, and the reuse of reclaimed asphalt pavement (RAP) [4-8]. In the case of rigid pavement, efforts have been directed toward reducing the carbon content of cement, reusing aggregates, reducing cement quantity, and even developing alternative binders to cement [9-11].

However, identifying the best solutions is a real challenge, yet a problem faced every day by designers. In a recent literature review studying 417 road case studies, Hoxha et al. [12-13] identified barriers related to the road design parameters and features related to the calculation method.

Among the design parameters analyzed, information on the climate zone is provided in 9,5 % of the studies, soil support in 2 %, speed limit in 11 %, and average annual daily traffic in 42 %. Except for the lack of transparency related to the information about the design parameters, none of the studies have analyzed their influence on the environmental impacts of roads. Motivated by this knowledge gap, the objective of this study is to analyze the influence of traffic load on the environmental impacts of roads.

Furthermore, the literature review shows that all road design options are defined based on an average annual traffic load. In reality, the traffic load is variable over the length of highways. For this reason, this study extends to analyzing the influence of the variation of traffic load over the highways´ length on the environmental impacts of roads. In the end, we have calculated the optimal thickness of the wearing course for each section of the A1 and A2 Austrian highways, allowing us to strengthen the calculation and minimize impacts.

2. Methodology and data

A four-step method is applied to calculate the influence that traffic load has on the environmental impacts of roads. First, the Austrian database of ASFiNAG [14] collected information on the traffic load over the length of the road. Following the methodology recommended in the Austrian pavement design norm RVS 03.08.63 [15], an average traffic load is defined as the most compatible road design option.

Second, with the help of the performance-related approach [16], based on the dynamic of traffic change in different sections of the road, the defined road design option is calculated over the service life of the road over the length of the highway. Third, the assessment of the embodied environmental performance of the highway is undertaken according to the European standard EN-15804 [17]. Fourth, the optimized thickness of the road wearing layer for each section of highway with different traffic loads is calculated. Then, the environmental impacts of optimized road design options are calculated.

2.1. Design of bituminous pavement

2.2. The RVS 03.08.63 norm [15] or the performance-based approach published in [16] can be used to design a bituminous pavement that will work in Austria.

2.2.1. Design according Austrian norm RVS 03.08.63. According to the Austrian pavement design norm RVS 03.08.63 [15], bituminous roads are classified in ten categories in function to the traffic load. Based on the annual average traffic load the norm recommend indicatively options of road design options. The traffic load is expressed in equivalent 10 t standard axle load referred to as the design standard load (BNLW), which is calculated from the following equation:

$$BNLW = BNLW_y \cdot n = NLW_{tägl} \cdot R \cdot V \cdot S \cdot 365 \cdot z \quad (1)$$

where: $BNLW_y$ presents the yearly design traffic load expressed in the equivalent number of transitions for a standard axle load of 10t; $NLW_{tägl}$ presents the number of average daily load changes for the entire cross-section; R presents the directional factor for the distribution of the load traffic; V presents the factor to consider the distribution of the load traffic over several lanes; S presents the factor to consider the lane distribution; n presents the calculation period that is recommended for 20 years for bituminous pavements; z presents the annual traffic growth factor.

The number of equivalent average daily load ($NLW_{tägl}$) depends on the average daily traffic and on the road category coefficient ($Ä_i$) of the respective vehicle category (i).

$$NLW_{tägl} = \sum JDTV_i * Ä_i \tag{2}$$

The annual traffic growth factor function of the percentage increase p of heavy traffic is calculated with the following equation.

$$z = \frac{q^n - 1}{n \cdot (q-1)} \quad with \quad q = 1 + \frac{p}{100} \tag{3}$$

The data related to traffic load necessary for the calculation of the $NLW_{tägl}$ are extracted from ASFiNAG database. An increase of 2% is considered for the annual traffic growth factor. Based on the standard axle load referred to as the design standard load (BNLW) in the tables of the RVS 03.08.63 is identified as the most adequate road option.

2.2.2. Design according performance related approach. Eberhardsteiner & Blab [16] have proposed the performance-related approach to strengthen the calculation of the bituminous pavement's service life. This method considers the whole spectrum of traffic load, climatic conditions and road´s material behaviors. The following equation is used for the calculation of the road´s lifetime (SL):

$$SL = \frac{N_{all}}{BNLW_y} \tag{4}$$

where N_{all} presents the allowed number of vehicles for a predefined road design option and is calculated with the equation:

$$N_{all} = k_1(T) \cdot \left(\frac{S_{mix}}{\sigma_e}\right)^{k_2(T)} \tag{5}$$

The $k_1(T)$ and $k_2(T)$ are fatigue parameters of asphalt calculated with the equations provided in (3). Within the aim of this study, an average soil temperature of 13,22°C is considered and the corresponding fatigue parameters coefficient have the values $k_1 = 2{,}99E^{13}$ and $k_2 = 5{,}29$. S_{mix} denotes the temperature-dependent elastic modulus of the asphalt. It is calculated with the help of the equation:

$$S_{mix} = \frac{p_c}{145.04} \cdot \left[a \cdot \left(1 - \frac{VMA}{100}\right) + 145{,}04 \cdot 3 \cdot |G_{bit}^*| \cdot \frac{VFB \cdot VMA}{10000}\right] + \frac{(1-p_c)}{145{,}04} \cdot \left[\frac{1 - \frac{VMA}{100}}{a} + \frac{VMA}{145{,}04 \cdot VFB \cdot 3 \cdot |G_{bit}^*|}\right]^{-1} \tag{6}$$

with p_c coefficient equal to:

$$p_c = \frac{\left(b + \frac{VFB \cdot 145{,}04 \cdot 3 \cdot |G^*_{bit}|}{VMA}\right)^c}{d + \left(\frac{VFB \cdot 145{,}04 \cdot 3 \cdot |G^*_{bit}|}{VMA}\right)^c} \tag{7}$$

where: VMA presents the voids in the mineral aggregate considered equal to 18 %; VFB presents the voids filled with binder equal to 61 %; $|G^*_{bit}|$ is the binder stiffness, which after the calculation is equal to 11,86 MPa; a, b c, and d are the model parameters depending on the bitumen type that for the case of asphalt with paving grade bitumen (pen 50/70) are respectively equal to 3918366, 687,25, 1,05 and 135252,8 (3). The equivalent one-dimensional stress state σ_e is calculated with the equations:

$$\sigma_e = \frac{c-1}{2c} \pm \sqrt{\frac{(c-1)^2}{4c^2}(\sigma_1 - \sigma_3)^2 + \frac{1}{c}(\sigma_1 - \sigma_3)^2} \quad \text{for} \quad 1 \leq c < 3 \tag{8}$$

$$\sigma_e = -\frac{\sigma_1+\sigma_3}{2(q_c-2)} \pm \sqrt{\frac{(\sigma_1+\sigma_3)^2}{4(q_c-2)^2} - \frac{(\sigma_1-\sigma_3)^2}{4q_c(q_c-2)}} \quad \text{for} \quad c > 3 \tag{9}$$

where for a temperature equal to 13,22°C, the coefficients are equal: $c = 3{,}12$ and $q_c = 0{,}53$. σ_1 and σ_3 are the horizontal and vertical stresses at the bottom of the wearing course.

2.3. Life cycle assessment of bituminous pavement

The environmental impacts of roads are calculated following the recommendations of European standard EN-15804 [17]. Allocating the environmental impacts of processes and materials to the life cycle stages in which they occur, the systems boundary of the study is limited to: production (A1-A3), construction (A4-A5), and end of life (C1-C4). The functional unit is defined as a square meter of road over a year (m^2/yr). For the road design option defined by the RVS 03.08.63 norm, the reference service life is 20 years for bituminous pavement. While in the case of the road designed according to a performance-related approach, the service life is calculated. In this study, the assessment is focused on the global warming potential (GWP) indicator by relying on the characterization factors published in the IPCC 2013 report [18]. Ecoinvent database v 3.6. [19] is used as background data for calculating the impacts considering the system model "Allocation, recycled content", which is also referred to as the "cut-off approach".

3. **Case study**

In this study, we have analyzed the case of the A1 and A2 highways situated in Austria. Aiming to calculate the environmental impacts of traffic load´s effect on the embodied impact of road design options, these highways present the ideal cases since they have similar lengths and are classified in the same road group according to RVS 03.08.63 [15]. The A1 highway, with a length of 300 km, starts in Vienna and ends in the city of Salzburg on the border between Austria and Germany. The A2 highway has a length of 380 km and connects Austria with Italy. It starts in Vienna and ends in the city of Klagenfurt, on the border between these two countries. On average, the A1 and A2 highway have a traffic load equal to 1264113 trucks/yr and 887531 trucks/yr, respectively. Based on these traffic loads, according to the Austrian norm RVS 03.08.63, both highways are classified in the same group. The recommended road design option consists of a bituminous pavement with an asphalt wearing course thickness equal to 25 cm. The base and subbase are made of unbounded aggregates with thicknesses of 20 cm and 30 cm. For highways with such traffic loads and the corresponding design option, the RVS 03.08.63 norm recommends considering a lifetime of 20 years. However, the comparison of the traffic load over the length of the A1 highways with the range recommended by the RVS 03.08.63 norm shows that the section between the km of 25 and 170 has higher values.

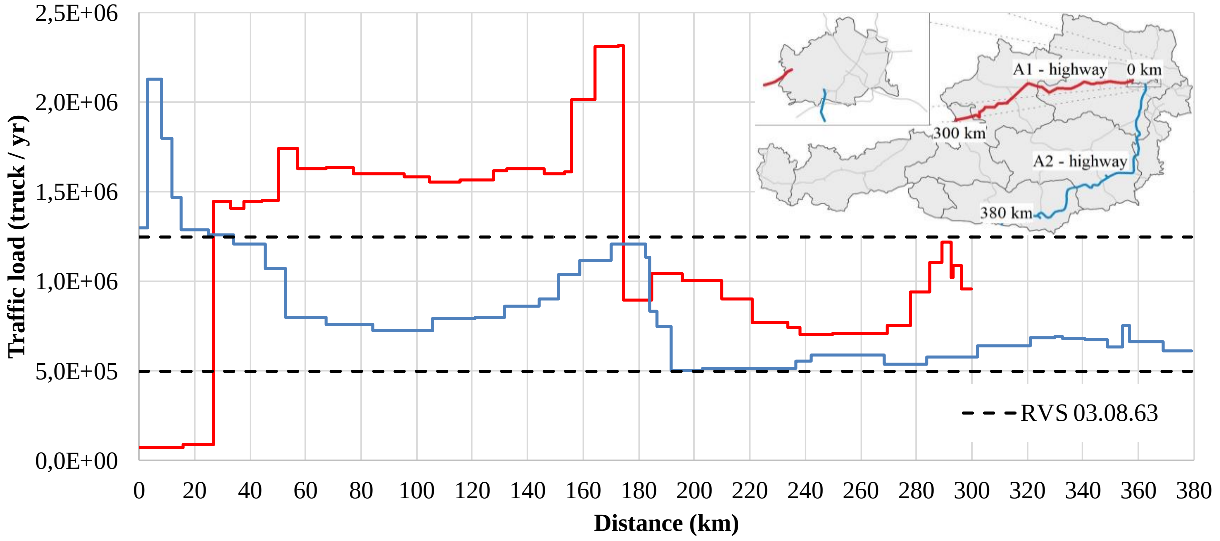

Figure 1: Traffic load for A1 and A2 highways and the range recommendation by RVS 03.08.63 for the respective road category.

For the A2 highway, the section between 190 to 380 km is closer to the lowest value of the range recommended by the norm. While the first section of this highway (0-25 km) has a higher traffic load (Figure 1). Due to these discrepancies and large variation between the real traffic load over the length and the recommended in the RVS 03.08.63 norm, an analysis of traffic on the service life of the recommended design option is required.

4. Results

Considering the real traffic load of A1 and A2 highways, the calculated lifetimes of the road design options recommended by the RVS 03.08.63 norm are presented in Figure 2. The average service life of the A1 and A2 highways is, respectively, 36 and 31 years. These values are higher than the 20-year service life recommended in the RVS 03.08.63 norm for bituminous pavement. However, it deserves to be highlighted that, on the one hand, the A1 highway has a higher traffic load but, on the other hand, also higher service life compared with the values obtained for the A2 highway. The unexpected service life values are due to sections 0-25 km of the A1 highway, which present a calculated lifetime equal to 380 years. By excluding this section, the average service life of the A1 highway is equal to 20 years. An in-depth analysis of the results presented in Figure 2 shows that section 25-170km of the A1 highway's service life is lower than 20 years.

Consequently, this section will often require replacing or repairing the wearing course. The other section, and almost all the A2 highway sections, has more than 20 years of service life. For these sections of roads, replacing the wearing course after 20 years is considered premature. Based on the obtained results, we can conclude that the service life of 20 years for the bituminous pavement recommended in the RVS 03.08.63 norm is not robust. Consequently a detailed and precise calculation is recommended to increase the results' reliability.

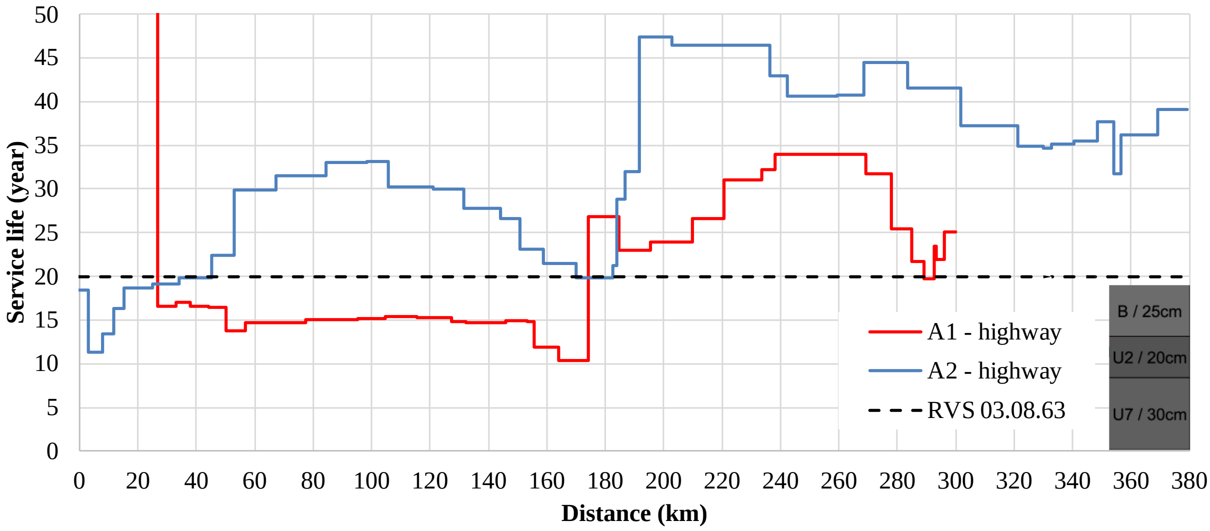

Figure 2: Variation of service life over the length of highways.

In order to analyze the influence of service life on the environmental impacts of roads, roads in Figure 3 are presented the results of the global warming potential (GWP) indicator over the length of the highways. The average values of GWP, respectively, for the A1 and A2 highways, are equal to 3,3 kg $CO_2e/m^2/yr$ and 2,4 kg $CO_2e/m^2/yr$. These values have a relative difference of 5,2 % and 26,1 % from the environmental impacts of the road design option recommended by the RVS norm, which has a GWP score equal to 3,2 kg $CO_2e/m^2/yr$.

Furthermore, the results indicate a large variation of the impacts for A1 highways (0,2-6,1 kg $CO_2e/m^2/yr$) and A2 highways (1,3-5,6 kg $CO_2e/m^2/yr$). Only the section between 25-170 km of the A1 highway and 0-25 km of the A2 highway have higher impacts than the scenario of RVS norm. It is the consequence of the section's service life, which was less than 20 years. For the other sections of the highways, the impacts are relatively lower. The variation of the impacts is strongly correlated with the road service life, which is a function of the traffic loads. In conclusion, the results show the necessity of a reliable calculation of the service life of roads to strengthen the robustness of the impact assessment of roads.

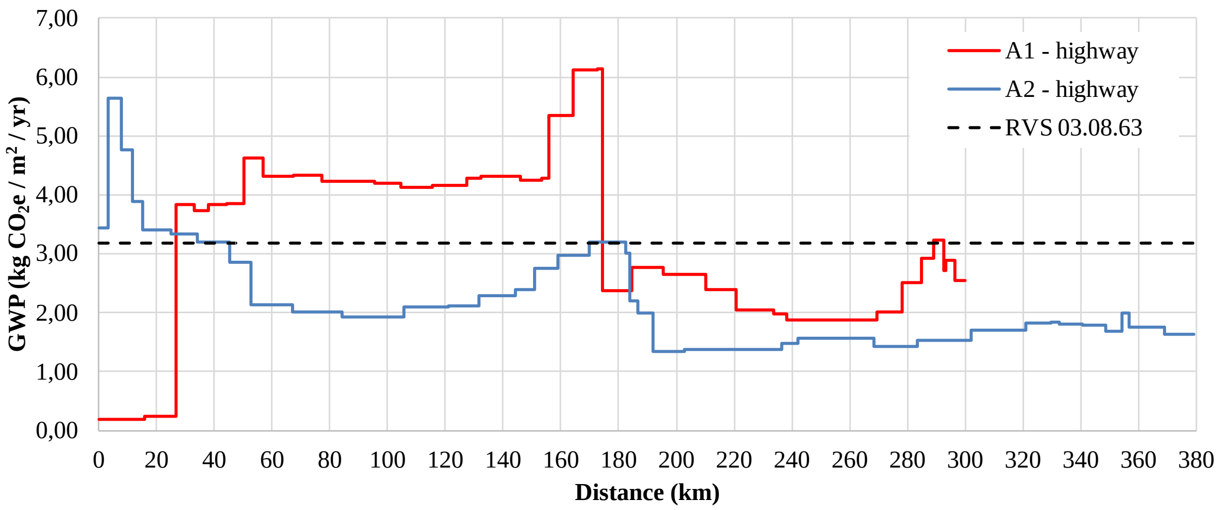

Figure 3: Results for global warming potential indicator.

To reduce the variability of the environmental impacts of A1 and A2 highways, Figure 4 presents the optimized wearing course thickness for a defined road service life of 20 years. Both highways have a service life of 20 years in all the sections of their length. The wearing course thickness is 24,7 cm and 23,8 cm, respectively, for A1 and A2 highways. Even though there isn't a big difference between the average thickness of the wearing course and the recommended design option of the RVS norm, there are a few places where the best values are different.

The thickness of the wearing layer for the first section (0-25 km) of the A1 highway can be reduced to 16 cm. In the following section, 25-170 km will require an increment to 26cm of the wearing course, which will avoid the replacement of the wearing course before reaching a lifetime of 20 years. While for the last section (170-300 km), the thickness of the wearing course can be reduced to 23 cm and 24 cm by allowing the reduction of the quantity of used asphalt.

For almost all the sections of the A2 highway, the thickness of the wearing layer can be lower than 25 cm. The results presented in Figure 4 show a section of this highway that can have a wearing course with a thickness equal to 22 cm to 24 cm.

These minimizations of the thickness of the wearing course influence the reduction of the environmental impacts of roads.

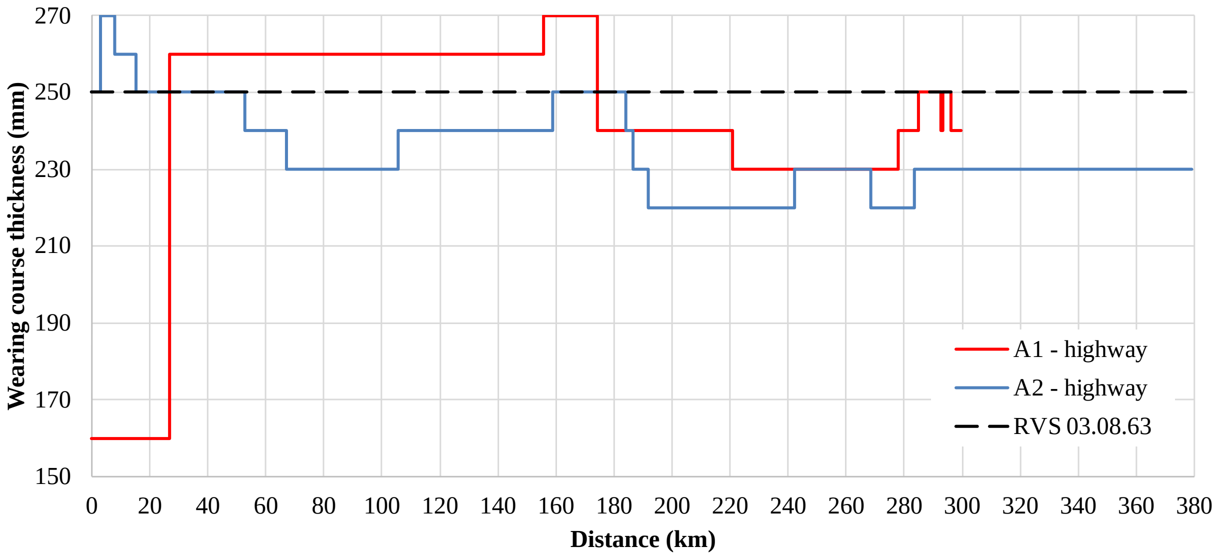

Figure 4: Variation of wearing course thickness over the length of highways

The environmental impacts of A1 and A2 highways with an optimized thickness of the wearing layer are presented in Figure 5. The average GWP score of the A1 highway is equal to 3,1 kg $CO_2e/m^2/yr$, while for the A2 highway, it is equal to 3 kg $CO_2e/m^2/yr$. These numbers are very close to the effect of the design option suggested by the RVS 03.08.63 standard.

In the case of the A1 highway, the GWP score varies between 2,2 kg $CO_2e/m^2/yr$ and 3,4 kg $CO_2e/m^2/yr$. For the A2 highway, the impact varies between 2,9 kg $CO_2e/m^2/yr$ to 3,4 kg $CO_2e/m^2/yr$, which is lower than the variation of the impacts of the A1 highway. The variation of impacts obtained with an optimized thickness of wearing course is lower than those by considering a single thickness (results presented in Figure 3). Based on these results, we can say that optimizing the thickness of the wearing course makes impacts less different.

The GWP score (3,3 kg $CO_2e/m^2/yr$) of the A1 highway with a wearing course thickness of 25 cm in all the lengths of the road is higher than the value (3,1 kg $CO_2e/m^2/yr$) obtained for optimized thickness. For the A2 highway, the GWP score (2,4 kg $CO_2e/m^2/yr$) for a wearing course thickness of 25 cm over the length of the road is lower than the value (3 kg $CO_2e/m^2/yr$) obtained for optimized thickness. Based on these comparisons, we can conclude that the increase in the thickness of the wearing course can significantly increase the lifetime of roads, consequently reducing the impact on the unit reference kg $CO_2e/m^2/yr$. In order to reduce the impacts of roads and the variability of GWP results over the length of the highway, it is recommended to add 1-2 cm to the values of the optimization thickness of the wearing course.

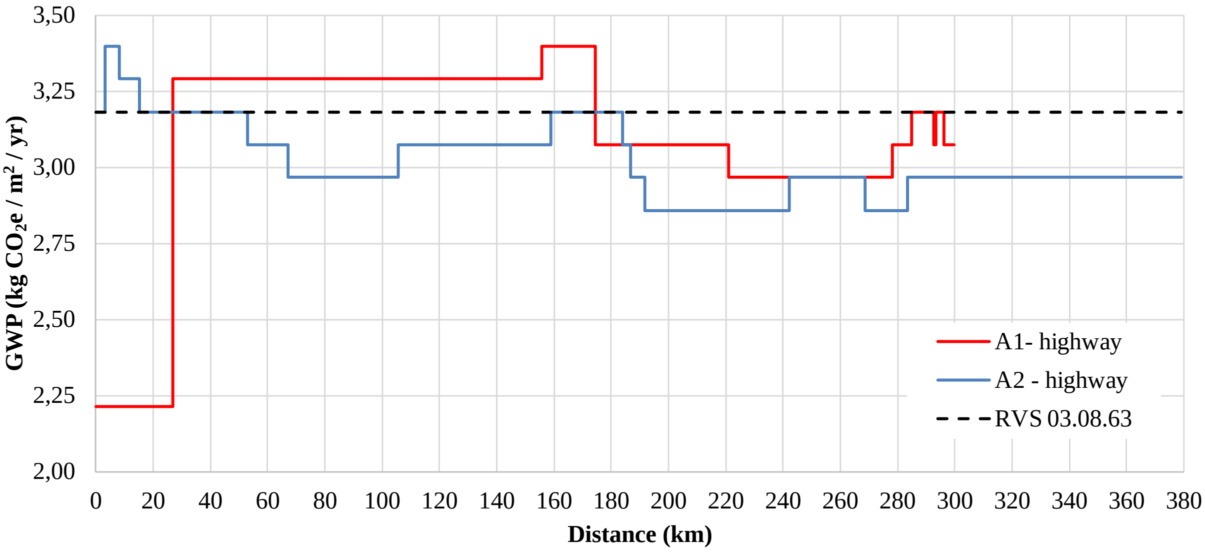

Figure 5: Results for global warming potential indicator for optimized thickness of wearing course.

5. Conclusion

In this article, based on previous studies, the environmental impacts of road structures were calculated and studied in more detail, focusing on the influence of traffic load. We assumed that a variable traffic load, in contrast to the static traffic load specified in the RVS norm, will optimize the design options of road construction and thus reduce the environmental impacts.

Based on the traffic data, it was shown that there are different traffic loads on the two highways, A1 and A2. Depending on the section, the level of traffic load changes due to larger cities near sections and the different numbers of highway entrances and exits. However, in reality, this dynamic traffic load is contrasted with a fixed the traffic load in the RVS norm. It leads to the fact that the highways, depending on their category, have the same design options over the entire road length. In addition, the same service lives, and thus the same repair and replacement cycles are therefore predefined.

A life cycle assessment (LCA) was carried out to assess the environmental impacts of the highways based on the specified traffic load and assuming a dynamic traffic load derived from the real traffic load. The results show that the service life of 20 years for the bituminous pavement recommended in the RVS 03.08.63 norm is not robust. A detailed and precise calculation is recommended to increase the results' reliability and better organize asphalt repair and pavement replacement. The results also show that a good way to figure out how long a road will last is needed to make the road impact assessment more accurate.

Assuming a dynamic traffic load, the thickness of the wearing course can be reduced. This minimization of wearing course thickness influences reducing the environmental impact of roads. From these results, it can be concluded that optimizing the wearing course thickness reduces the variability of the impacts. However, based on the comparisons, we can conclude that increasing the thickness of the wearing course can significantly extend the life of roads, which subsequently reduces the impact on the reference unit of kg $CO_2e/m^2/year$. To reduce the impact of roads and the variability of GWP results along the length of the highway, it is recommended to add 1-2 cm to the values of the optimization thickness of the wearing course. The presented results present procedural work, including a life-cycle perspective for the further (environmental) development of the RVS norm. The findings demonstrate value for road designers, planners, and engineers in the early design phase of road construction to reduce the environmental impacts.

Acknowledgement
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