

Environmental impacts of road traffic and route variants: An accurate way to support decision-making processes of mountain roads and tunnels in Austria

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Abstract

Almost 25% of the environmental impacts, based on the indicator of global greenhouse gas emissions, are caused by traffic. For designing new traffic routes and decision-making processes, it is thus essential, that integral life cycle assessments (LCA) are conducted to ensure sustainable solutions in long term and to achieve the UN Sustainable Development Goals (SDGs).

This basic study examines an ecological comparison between two fictitious traffic routes. Route A reflects a typical Austrian mountain pass road with an average gradient of approximately 3 %. Route B investigates a new route variant with a tunnel (length 1,000 m), which shortens the general route distance and minimises the inclines.

The LCA considers life cycle stages from raw material supply to the usage of the tunnel over an analysis period of 100 years. The results of route B are then compared with a traffic LCA, which considers the operational emissions of route A.

In assessing the tunnel, the LCA incorporates the New Austrian Tunnelling Method, Austrian materials as well as typical geological conditions. To study the traffic effects, the vehicles driven in Austria were included by the current vehicle stock and were analysed in accordance to EN 17472 and EN 15804.

The results (Global Warming Potential) show that the environmental impacts caused due construction, maintenance and operation of route B are lower than the operational traffic emissions of the mountain pass road. Consequently, the tunnel variant leads to general environmental savings. Hence, constructing and maintaining the tunnel gets environmentally amortised in a short period of about 10 years. Ultimately, the traffic usage counts as main emitter over the life cycle.

This research illustrates the importance of integral LCAs of transport infrastructures. Within this context, integral LCA studies support decision-making processes and will provide optimal support for a future proof sustainable built environment.

Keywords: Life cycle assessment, Transport infrastructure, Traffic, Tunnel vs. Pass Road.

1. INTRODUCTION

Designing new traffic routes is a really complex process and forces all involved parties with challenges. Traffic experts have to analyse the traffic situations, the number of journeys on the specific route and predict possible traffic growth in future. While the civil engineers deal with designing the path through the natural habitat by considering the construction of the road, the bridges and tunnels are needed. At least building a new traffic route is a big political and social issue. Policymakers, as also the population are highly involved. Many aspects like costs, regional behaviours, overall advantages and social issues are taken into account into the decision-making process by doing a new traffic route. However, are there also ecological aspects such as the environmental footprint etc. considered? This study is about to illustrate the need of including integral life cycle assessments (LCA) more in early stages of decisions. Therefore, a LCA study of a new typical fictitious Austrian road variant with a tunnel (route B) is carried

out and gets compared with the traffic emission of an existing fictitious mountain pass road (route A). Route B shortens the distance and flattens the gradients of the road. The goal of this study is to investigate the general environmental savings, using the fictitious example of route B and to analyse the duration of the amortisation of the environmental impacts caused by the tunnel construction.

2. METHODS

To assess and to compare the environmental impacts of constructing and using the tunnel with the traffic emissions on the pass route variant LCA studies are conducted. The investigated fictitious route variants are modelled in accordance to common Austrian conditions/ regulations and in collaboration with field-experts (e.g. tunnelling experts). The traffic loads used are estimated for this fictitious study, but the values represent a small Austrian pass road.

3. THE INVESTIGATED ROUTE VARIANTS

3.1. Route A – Mountain pass road

The route A represents a typical little Austrian mountain pass road with 5,000m total length and one lane in each direction. The examined road has two main sections. Section one has a length of 3,000m and a gradient of 3%, as section two's length is 2,000m with 2.5%. Depending on the direction of travel, the elevation differences is 50 or 90m.

To consider the traffic influences in this fictitious analysis, the traffic loads per day (see Table 1) were assumed depending on the direction of travel. The estimated traffic load in Table 1 represents an average load on a small mountain pass road. The number of vehicles were categorised into car-like vehicles (car equivalents) and truck-like vehicles (truck equivalents). The main direction of traffic is assumed to be from location A to B.

Table 1. Traffic load of route A (mountain pass road) per day

Direction of travel	Car eq.	Truck eq.	Total vehicles
Location A to B	1,250	45	1,295
Location B to A	1,000	20	1,020

3.2. Route B – Tunnel

The tunnel variant is about to shorten the general distance between the two fictitious locations, as well as to minimise the uphill and downhill driving. Therefore, route B has a total length of 3,000m including a 1,000m tunnel. The vertical meters get reduced to 20 or 52.5m. The sections before and after the tunnel show the same incline and declines from route A: Section 1 with 3% and 1,500m and section 2 with 2,5% and 500m. The gradients in the tunnel are assumed to be $\pm 7.5\%$ because of a symmetrical and longitudinal roof section. Concerning the traffic use of the new road variant an increase of +20% of vehicles is supposed per day and direction of travel (see Table 2).

Table 2. Traffic load of route B (tunnel) with a traffic increase of +20% per day

Direction of travel	Car eq.	Truck eq.	Total vehicles
Location A to B	1,500	54	1,554
Location B to A	1,200	24	1,224

4. LIFE CYCLE ASSESSMENT (LCA)

The quantifications and calculations are performed by using the software SimaPro and self-made LCA-

calculators in accordance to ISO 14040, EN 17472 and EN 15804.

The LCA can be further specified: The functional unit of the study is defined as the built tunnel, as well as the operational traffic use for a period of 100 years (ASI, 2021, 2022a; Klöpffer and Grahl, 2007). To specify the geographical system boundary, the Austrian territory is set as study basis (ASI, 2022b). The applied data is mainly sourced from Austrian material suppliers, field-experts or eco-databases such as ecoinvent database v3.10 or ökobaudat (ecoinvent; Ökobaudat, 2024). Due to the limited scope of the article, for this LCA-study only the popular impact indicator Global Warming Potential (GWP) with the unit kg CO₂ eq is utilised.

4.1. Tunnel LCA

The LCA of the tunnel includes all processes from raw material supply (A1-A3), transport to the construction site (A4), the construction (A5), the maintenance (B2) to the operation (B6 - operational energy usage) over an analysis period of 100 years (ASI, 2022b).

For the excavation and construction process the New Austrian Tunnelling Method (NATM) is applied (Flora et al., 2011). As background data and for modelling the 1,000m tunnel knowledge from Austrian (tunnelling-)experts is used. Typical energy consumptions, performance approaches, geological conditions, required construction and auxiliary materials, construction equipment, transport processes etc. were modelled by representing a typical Austrian situation.

By designing the new tunnel, a common excavation line is used. The excavation area measures 110m². The final clearance complies with all Austrian regulations in accordance to RVS 09.01.22 and allows bigger traffic loads on route B in future (FSV, 2010).

In collaboration with the tunnelling experts three tunnel classes were considered. These classes are representing typical geological ratios from moderately to difficult excavatable geology (hard rock). For the investigated tunnel it is assumed to have 75% hard rock and 25% moderate geological conditions, but the whole excavation process is done by blasting. The amount of the supporting materials (shotcrete, anchors, reinforcement steel etc.), the explosives, the required energy for the construction machinery and specific length of advance are therefore in correlation to the prevailing geological conditions.

To simplify and in conformity with the experts' recommendations several maintenance processes of the final tunnel were considered by applying a 5% surcharge to all construction processes.

4.2. Traffic LCA

Performing the traffic LCA, the initial step is to study the longitudinal gradients of the traffic route. The longitudinal inclines and declines are decisive for the additional energy consumption of the vehicles and ultimately responsible for the higher emission outputs (Gschösser, 2023; Hausberger et al., 2024; Hausberger and Gschösser, 2023; Liebl et al., 2014). Based on the longitudinal profiles of the two routes, the additional consumption from uphill and downhill driving is determined. To simplify matters, car equivalents and truck equivalents are used. The data basis is a traffic survey and LCA for cars in Austria (Hausberger et al., 2024). For this purpose, the weighted composition of the various cars is taken into account on the basis of different drive systems, emission classes, masses and vehicle ages (Hausberger et al., 2024).

Due to its widespread use in Austria, a EURO 6 diesel truck from the ecoinvent database v3.10 is used for the truck equivalents.

Based on the familiar emissions and fuel consumptions from driving in the plain, the additional consumptions by going uphill, are calculated for each route section by using the approach from (Liebl et al., 2014). The additional fuel consumptions get quantified by doing a LCA and added to the emissions from driving in flat terrain afterwards.

It is important to note that the calculated additional consumption is in correlation with the longitudinal gradient (Hausberger et al., 2024). Theoretically, the fuel consumption from driving uphill should be compensated through potential energy when going downhill. However, in practise it turned out that the uphill journey is only partially compensated due to braking manoeuvres (Gschösser, 2023; Hausberger et al., 2024). In the case of cars, the uphill drive is compensated by 50% and for trucks by 10%

(Gschösser, 2023).

The following equation from Liebl et al. (2014) was used to calculate the additional consumption:

$$\text{Fuel}_{\text{height}} \left[\frac{\text{l or kWh}}{100 \text{ km}} \right] = \text{vehicle mass [kg]} \cdot \text{height difference [m]} \cdot 9.81 \left[\frac{\text{m}}{\text{s}^2} \right] \cdot \frac{1}{1000 \cdot 3600} \cdot v_{\text{Pe}} \cdot \frac{100}{\text{distance [km]}} \cdot \frac{1}{0.98} \cdot v_{\text{Pe}} \left[\frac{1}{\text{kWh}} \text{ or kWh} \right] \dots \text{consumption efficiency; } v_{\text{Pe,petrol}}=0.264, v_{\text{Pe,diesel}}=0.220, v_{\text{Pe,gas}}=0.205, v_{\text{Pe,electr.}}=1 \quad (1)$$

With the driving emissions from the plain and gradients, the route profiles and the defined traffic flows per direction and day (see Table 1 and 2) the ecological footprints of the two traffic variants (with and without tunnel) were analysed.

5. RESULTS

5.1. Tunnel Construction

The environmental impacts of constructing the new tunnel (life cycle stages A1-A5) were analysed in a very detailed way. Due to the paper limitations only the general and overall results of the construction processes (excluding maintenance and operation) are visualised in Figure 1.

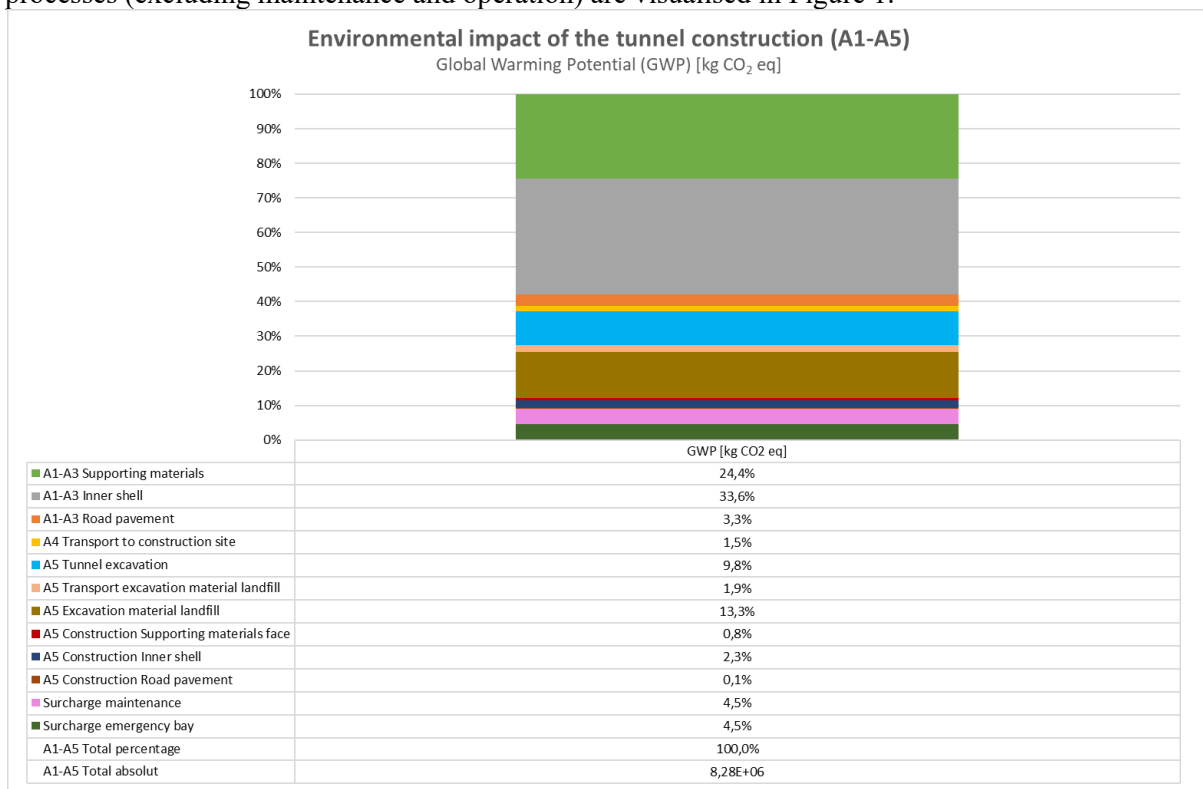


Figure 1. Environmental impact of the tunnel construction including the maintenance processes.

The LCA results in Figure 1 show the significant environmental impact of the construction materials. In particular, the supporting materials (shotcrete, anchors, reinforcing steel, etc.) and the inner shell have within 58% of the total GWP emissions a big influence of the construction phase (A1-A5). Compared to the materials used, the excavation process itself only accounts for approx. 10% of the environmental effects.

As mentioned above, the CO₂ emissions of the tunnel operation and maintenance processes were taken into account by means of surcharges. In this context, the tunnel operation includes the electricity for ventilation and lighting and accounts for approx. 12 tons of CO₂ eq per year.

The maintenance activities and the greater effort required by constructing the larger cross-section of the emergency bays were taken into account by a 5% surcharge on the total ecological footprint of tunnel construction. The maintenance activities and the emergency bays are each responsible for 376 tons of CO₂ eq over 100 years.

5.2. Tunnel vs. Traffic

The final part of the study focuses on comparing the existing traffic emissions of the pass road with the tunnel variant. The new tunnel construction (including maintenance and operation) and the increased traffic emissions of route B are compared with the traffic emissions of route A. Finally, the overall environmental savings from the route shortening and the tunnel are calculated. Figure 2 shows the environmental effects of the traffic route with tunnel.

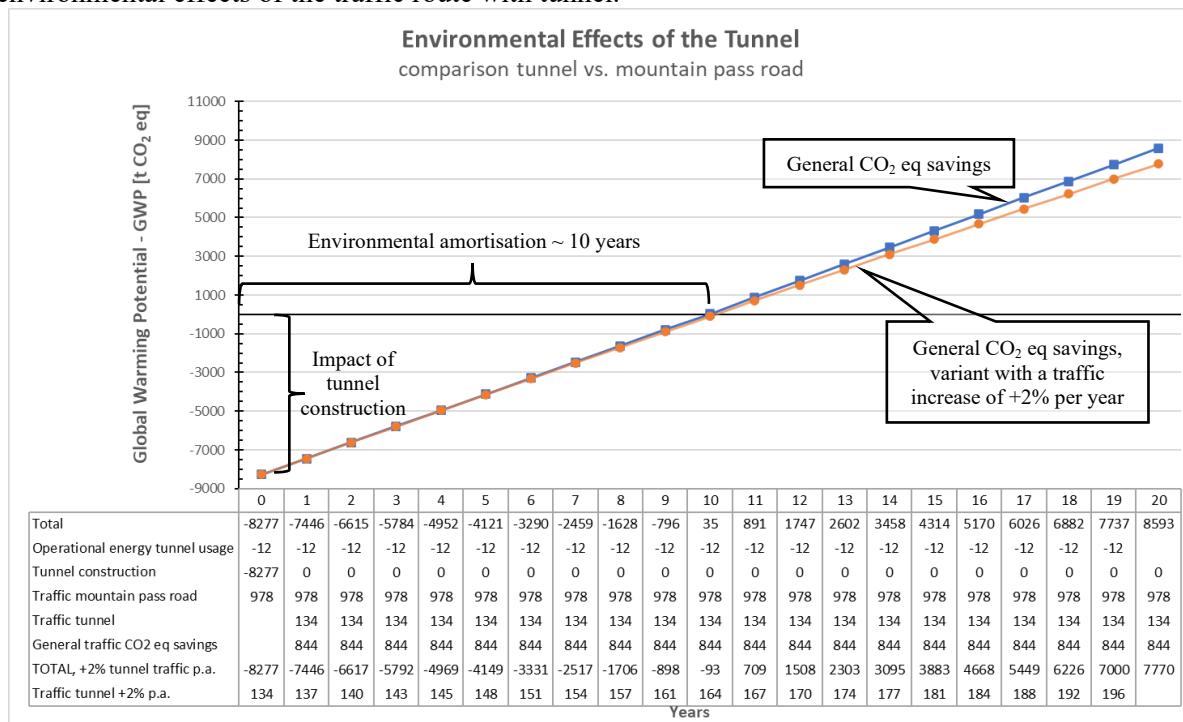


Figure 2. Environmental outcome due to the traffic use of the tunnel – presented for GWP.

Initially, 8.2 million kg CO₂ eq are emitted due to the construction of the tunnel, but the reduction of the vertical meters minimises traffic emissions significantly. The overall ecological savings are calculated starting from the ecological investment of constructing the new tunnel minus the difference in traffic emissions of the two route variants. Despite the 20% higher traffic flows and the only 40 meters lower apex, the environmental impact of the new tunnel construction is ecologically amortised within 10 years. This amortisation results only from the use of the tunnel.

By consistently increasing the vehicle journeys, e.g. about +2% per year (see Figure 2, orange graph), leads to slightly lower overall environmental savings and extends the duration of the ecological amortisation by several months.

However, it must be mentioned that this study is based on a linear approach. In other words, any effects resulting from technological developments, e.g. new driving systems or material improvements, were not taken into account and possible uncertainties will probably may arise over 100 years. Nevertheless, it can be assumed that the amortisation period will not change significantly. But the general impacts as well as the overall savings will be slightly lower. The graph from Figure 2 will not be linear anymore.

6. DISCUSSION AND CONCLUSION

Even if this study is only based on a fictitious example, it has shown that LCA studies can effectively support route comparisons. The results underline the potential of positive environmental effects of general route shortening and reducing uphill and downhill journeys through tunnels. Although additional aspects such as costs or social aspects were not considered in this analysis, the short ecological amortisation period of the tunnel variant is impressive regarding the small reduction of 40 elevation meters and only 2 km.

The goal of the study was to investigate ecological differences of the tunnel route and the mountain pass road and to implement a simple method to consider specific traffic operation in LCAs. Liebl's approach is sufficiently accurate for the traffic analysis of uphill and downhill journeys at this level of consideration. For a more detailed analysis of the journeys, however, the limitations of the approach (e.g. the gear changes are not considered etc.) must be highlighted and an extended analysis of traffic emissions is required.

The tunnelling methods included in this study were developed for and in compliance with Austrian conditions in collaboration with tunnelling experts. This means that Austrian materials, energy sources and construction processes were incorporated in the LCA.

For further studies, these approaches seem to be easily manageable, practicable and universally applicable. However, the background data (construction methods, materials, energy sources, vehicle technology, etc.) must always be harmonised with the local and country-specific conditions.

In the future, a broader application of LCA approaches/ tools seems to be helpful by assessing transport infrastructures and finding the best route option in early stages of designing. Hence, decision-making processes can be supported by these LCA results to choose the most sustainable solution for the traffic infrastructure.

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