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Life Cycle Analysis of Road Construction and Use

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Abstract: Both the construction and use of roads have a range of environmental impacts; therefore, it is important to assess the sources of their burdens to adopt correct mitigation policies. Life cycle analysis (LCA) is a useful method to obtain demonstrable, accurate and non-misleading information for decision-making experts. The study presents a "cradle to gate with options" LCA of a provincial road during 60 year-service life. Input data derive from the bill of quantity of the project and their impacts have been evaluated according to the European standard EN 15804. The study considers the impacts of the construction and maintenance stages, lighting, and use of the vehicles on the built road. The results obtained from a SimaPro model highlight that the almost half of impacts took place during the construction stage rather than the use stage. Therefore, the adoption of environmentally friendly road planning procedures, the use of low-impact procedures in the production of materials, and the use of secondary raw materials could have the largest potential for reducing environmental impacts.

Keywords: road construction; impact category; tunnel; bridge; embankment; trench; life cycle analysis

1. Introduction

In recent years, environmental aspects related to road infrastructure construction have increasingly come under examination [1,2] in order to apply environmental award criteria in calls for tender [3] and introduce the green public procurement (GPP). At the international level, several efforts have been made to apply GPP to the road sector: in Sweden, environmental aspects are integrated in road maintenance contracts [4–6]; in Finland, procurement methods are implemented to reduce the environmental impacts of roads [7]; in the Netherlands, GPP has been implemented to manage the main road network [8].

Currently, the Italian Ministry of the Environment is transposing the meaning of the document "Green Public Procurement Criteria for Road Design, Construction and Maintenance" published in 2016 by the European Union [9] to encourage the purchasing of products, services and works with reduced environmental impacts. Four criteria are proposed to assess the life cycle impacts of road construction: Life Cycle Impact Assessment (LCIA), Carbon footprint (CF), recycled and re-used content, and Low emissions from transport of heavy materials. The listed criteria have decreasing levels of ambition and technical complexity: in literature the most frequently adopted frameworks are LCIA and CF [10–13]. LCIA is a holistic assessment tool which considers different environmental impacts (e.g., acidification, eutrophication, abiotic depletion), while CF only evaluates the total amount of greenhouse gas emissions of road processes: CF is the result of a partial LCIA implementation. Recycled and re-used content and low emissions from transport of heavy materials focus respectively on the content of used recycled, re-used or by-products materials, and on CO_2 emissions from the transportation of aggregates. These last two approaches are alternatives to LCIA and CF, and it is recommended to combine both in order to achieve an overall environmental benefit. According to the EU environmental objectives and data available in the literature, authors adopted the

LCIA because it allows a quantitative and robust evaluation of each examined process [14]. Indeed, the unbiased and comparable results from LCIA depend on the specific production chain, it takes into account the specific boundary system and operational conditions, and could be adopted as an effective environmental decision support system [15]. Since the early 2000s, some research has used the life cycle assessment methodology to assess the environmental performances of a road and its different stages. With different analysis periods and functional units, they examined the environmental impacts of road materials [16–20] and compared construction techniques and maintenance activities [10,21–25] with different methods and software. Marzouk et al. [21] used the software Copert 4 [26] to assess the overall environmental impacts and primary energy associated with earthwork and pavement processes. Hammervold [22] applied the impact assessment method ReCiPe [27] to construction and maintenance activities of two highway projects in southern Norway in order to identify the main aspects affecting LCA results. Burdens of traffic are not considered. According to EN 15804 [28], Moretti et al. [23] assessed the environmental and human health impact of construction of two different road cross-sections (i.e., embankment and trench sections). Sayagh et al. [24] used the tool ERM (elementary road modulus) [29], to assess LCA of construction and maintenance activities three different road pavements. The EU project ECRPD [25] assessed impacts of wearing layers during their construction and maintenance, whereas initial phases of road and pavement construction (e.g., subgrade preparation and subbase construction) were excluded.

Conversely, this study aims to assess, according to the standard EN 15804 "Sustainability of construction works, environmental product declarations, core rules for the product category of construction products" [28] the environmental impacts of construction and use of a provincial road in Central Italy. The analysis starts considering the input data from the bill of quantity of the project: it considers all materials, works and processes needed to have the final product: "the road". Moreover, the analysis examines the use stage of the road during 60-year service life until its exceptional maintenance of structures occurs: all impacts from traffic and routine maintenance are assessed. The importance of this work is that it provides reliable LCIA results of the environmental impacts of construction and use of a real road. The interpretation of the results allows the identification of the majority of impacting processes currently used in this sector, in order to reduce its burdens and to develop an environmentally aware public procurement policy.

2. Materials and Methods

In this study, the LCIA methodology has been implemented to assess the environmental impacts of construction and use of an 8.5 km-long provincial road during 60 year-service life. The examined road offers a solution to the local and touristic traffic between two densely populated towns. Figure 1 represents the cross-section of the analyzed infrastructure: it is composed of two 1.25 m wide shoulders and two 3.50 m wide lanes.

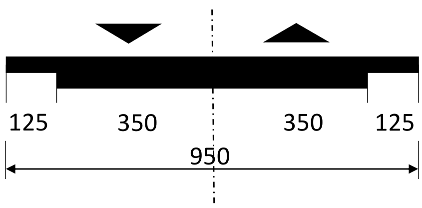

Figure 1. Design cross section (unit of measure: cm).

The road is in a mountainous region of central Italy, where the Appennine mountains are located. The territory morphology seriously affects the altimetric design of the infrastructure, whose 16.6% in length is raised on above- and under-grade structures. Indeed, the road is composed of:

- 7.1 km-long open road sections (not more than 5 m-high trench or embankment cross-sections);
- 0.3 km-long 4-span new bridge with reinforced-concrete slab on three U-shaped precast reinforced-concrete beams;

- 1.1 km of new single-tube tunnel built with mechanized excavation. According to the geological condition, one part of the rock is granite and the other one is shale. In the joint part the overlying bedrock thickness is approximately 200 m. Water inflows were expected when tunnel excavation approached the joint of two rocks. Therefore, foam consolidation and grouting method were designed to control the displacement of the rock and its supports.

Geometrical and functional issues were adopted for the road design to comply with the current Italian requirements for the construction of minor highways [30]; for the first 20 years of service life, the design traffic consists of the number of passes listed in Table 1.

Table 1. Passes of vehicles within the first 20 years of service life.

Vehicle Type	Maximum Mass (t)	Number of Passes
Commercial and heavy vehicles	56	1,500,000
Cars	3	15,000,000
Mopeds	0.5	189,000

Table 2 lists the traffic spectrum of commercial and heavy vehicles within the first 20 years of service life.

Table 2. Traffic spectrum within the first 20 years of service life.

Vehicle Code	Maximum Mass (t)	Number of Passes during the Service Life
V_1	12	882,000
V_2	16	441,000
V_3	26	88,500
V_4	36	42,000
V_5	56	3000
V_6	13	43,500

Given a subgrade resilient modulus equal to 90 MPa, and the traffic data in Tables 1 and 2, for a 20-year service life the flexible pavement is composed of [31]:

- 3 cm-thick asphalt wearing course;
- 5 cm-thick asphalt binder course;
- 12 cm-thick asphalt base course;
- 30 cm-thick cement-stabilized sub-base.

In order to assess the impacts of construction and use of the road for 60 years, the authors assumed that traffic volume and spectrum do not change during the overall reference service life.

The bill of quantity, which is not disclosed herein, due to privacy reasons, allowed the identification of works and materials needed for the road construction. These data constituted the Life Cycle Inventory (LCI) and they were modeled according to the characterization factors listed in EN 15804:2012+A1:2013 [28] in order to calculate the Life Cycle Impact Assessment (LCIA). The characterization factors allow for comparing the ability of different substances to cause the same environmental impact because they convert the results from LCI into a common unit of a category indicator, expressed as equivalent (eq.), (Equation (1)):

$$IC = \sum_{x} CF_{ic}(x) \cdot INV(x) \quad (1)$$

where IC is the Impact Category, obtained from the inventory of the substance x, $INV(x)$, and $CF_{ic}(x)$ is the characterization factor assigned to the substance x for the calculation of IC.

The database Ecoinvent 3.1 [32], integrated in the software package SimaPro 8.0.5.13 [33], was used to assess the impact categories listed in Table 3. These parameters describe the environmental impacts according to the EN 15804 [28].

Table 3. Impact categories considered in the LCA.

Impact Category	IC	Unit of Measure
Global Warming Potential	*GWP*	kg CO_2 eq.
Ozone layer Depletion Potential	*ODP*	kg CFC11-eq.
Acidification Potential of soil and water	*AP*	kg SO_2 eq.
Eutrophication Potential	*EP*	kg PO_4^{3-} eq.
Photochemical Ozone Creation Potential	*POCP*	kg C_2H_4 eq.
Depletion of abiotic resources-elements	*ADP-E*	kg Sb eq.
Depletion of abiotic resources-fossil fuels	*ADP-F*	MJ

The LCIA was carried out according to the standard EN 15804: for each impact category, the study evaluated the overall impact of road construction and/or use, and the partial contributions of four different stages:

1. stage A1: extraction and processing of raw materials, reuse of products or materials from a previous production system, processing of secondary materials used as input, and generation of electricity, steam and heat from primary energy resources, including their extraction, refining and transport;
2. stage A2: transportation of materials and machines to production and construction site;
3. stage A3: in-situ works for road construction (e.g., use of dumpers, graders, lighting installation, waste processing; on-site operations to the road, etc.);
4. stage A4: use of the road (i.e., environmental impacts due to the expected traffic, pavement maintenance, and tunnel lighting).

Figure 2 represents the flow diagram of the phases involved in the "from cradle to gate with options" LCIA.

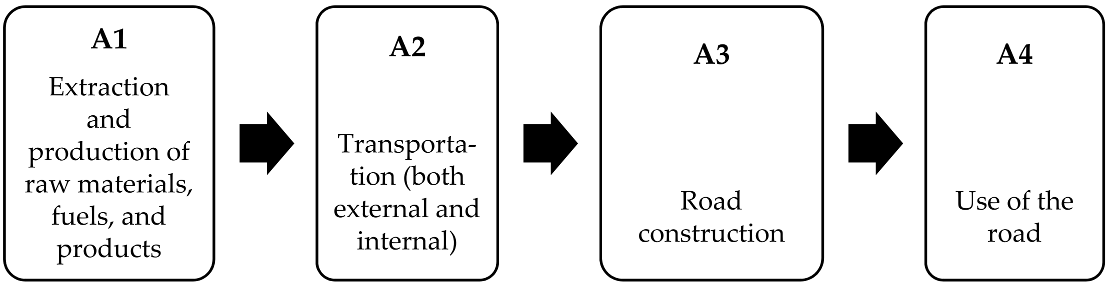

Figure 2. Flow diagram of the phases (or modules) involved in LCIA.

For pavement maintenance, the authors assumed preventive works according to Table 4 [34] for the first 20 years. At the end of 20th year, the pavement will be demolished, rebuilt and maintained according to Table 4.

Table 4. Pavement maintenance.

Type of Maintenance	Year	Extension
Wearing + binder course milling and patching	3	1% lanes' surface
Wearing course milling and re-construction	6	100% lanes + shoulders surface
Wearing + binder course milling and patching	9	2% lanes' surface
Wearing + binder course milling and re-construction	12	100% lanes + shoulders surface

For tunnel lighting, the authors derived data from previous studies [35,36]. Therefore, the lighting system complies with the requirements laid down by the Italian Organization for Standardization [37–40]. Particularly, the standard UNI 11095 [37] divides the longitudinal section of the tunnel in five reference zones (i.e., access, threshold, transition, interior and exit zones). Each zone differs for the minimum luminance value to be ensured as consequence of the design speed, the meteorological visibility distance, the horizontal lighting in the access zone, the natural luminance, and the optics type. As consequence of different daylight conditions, the tunnel lighting system is composed of one permanent and seven reinforcement installations. Lighting Emission Diode (LED) devices are installed, and they are arranged in a single line in permanent lighting, or in a quincunx geometric pattern in the reinforcement system. Table 5 lists details about the lighting system for each 20-year period of service life.

Table 5. Lighting design data.

Lighting Data	Value
Total installed power (W)	84,295
Annual consumption (kWh)	59,500

Table 6 lists the routine maintenance program for the lighting system.

Table 6. Routine maintenance program for the lighting system.

Type of Work	Frequency
Replacing of lamps	once every 10 years
Cleaning of lamps	once every 2.5 years

For maintenance of structures (e.g., the bridge and the tunnel), the authors assumed the routine maintenance program listed in Table 7.

Table 7. Routine maintenance program for structures.

Structure	Type of Work	Frequency
Bridge	Deck and crack sealing	once every 3 years
	Clean and flush drains	once every 2 years
	Clean and reseal deck joints	once every 10 years
	Exposed steel cleaning and repainting	once every 5 years
	Remove, replace, repair tiles and spalls	once every 2 years
Tunnel	Wash tunnel walls and ceiling	once every 1 year
	Repair or replace deteriorated or failed joints	once every 2 years
	Clean and seal exposed bars	once every 4 years

In order to analyze the effect of the examined stages and identify the most critical works, materials or processes, a sensitivity analysis was carried out. At this purpose, the authors assumed all processes would have a period of less than 20 years occur in cyclic form during the overall service life.

3. Results

The A1 to A3 LCIA results for the examined road are listed in Table 8. They refer only to the materials and processes needed for road construction, as required by the project. All construction materials are transported to the road site over distances no greater than 25 km.

Table 8. LCIA—A1 to A3 phases.

IC	Impact Category	Value	Unit of Measure
GWP	Global Warming Potential	3.58×10^8	kg CO_2 eq.
ODP	Ozone layer Depletion Potential	48.38	kg CFC11-eq.
AP	Acidification Potential of soil and water	1.37×10^6	kg SO_2 eq.
EP	Eutrophication Potential	3.94×10^5	kg $PO_4{}^{3-}$ eq.
POCP	Photochemical Ozone Creation Potential	3.03×10^5	kg C_2H_4 eq.
ADP-E	Depletion of abiotic resources-elements	37.34	kg Sb eq.
ADP-F	Depletion of abiotic resources-fossil fuels	3.44×10^9	MJ

The bar graph in Figure 3 shows the percentage contribution between phases of road construction.

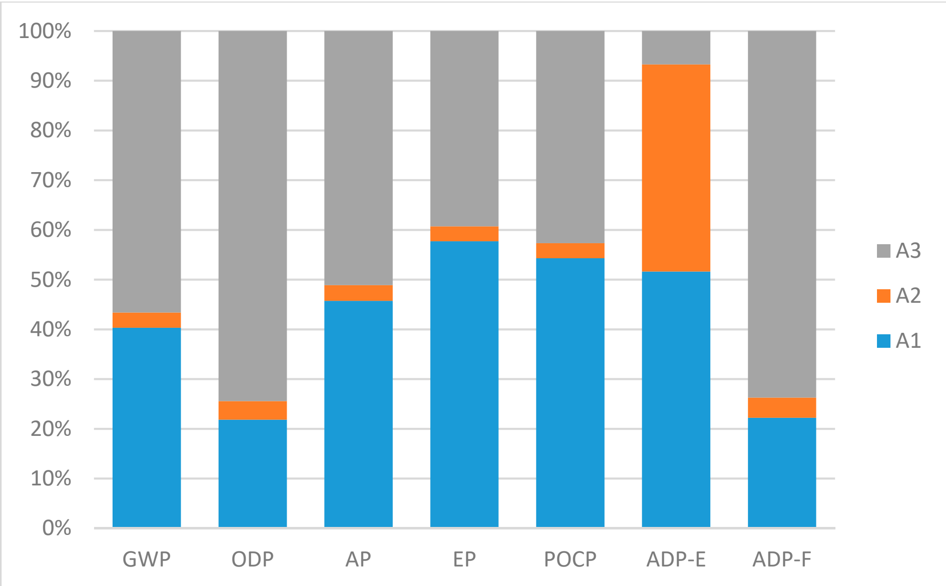

Figure 3. Environmental performances—A1 to A3 phases.

Four main observations can be extracted from Table 7 and Figure 3:

- in the "from cradle to use" analysis, the most impacting phases are A1 and A3: except for *ADP-E*, they account on average for more than 90% of total burdens;
- in the phase A1, *ODP* and *ADP-F* have the lowest contribution (i.e., 22%), while *EP* and *POCP* have the highest contributions (i.e., 58% and 54%, respectively);
- transportation (both external and internal) is the phase which implies the lowest contribution: A2 is on average 3.2%;
- in the phase A3, *ADP-F* and *ODP* give the highest contributions (on average 74.5%).

For each impact category, the authors examined the ten most impacting items, which contribute to more than 92% of the totals:

- for *GWP*, diesel machines for earth moving, tunnel excavation and cement grouting cause 1.99×10^8 kg CO_2 eq. (i.e., 53% of the overall impact). Aggregates, concrete, reinforcing steel, and lime mortar cause 38% of the overall impact; the most impacting freight transport (used for transport of cement concrete up to the roadwork site) causes emissions of 3.50×10^6 kg CO_2 eq. (i.e., 1% of total *GWP*);
- for *ODP* and *ADP-F*, diesel machines for earth moving, tunnel excavation, and cement grouting cause 70% and 69% of the overall impacts, respectively. Aggregates, concrete, reinforcing steel, and lime mortar cause 19% and 20% of the overall impact, respectively; the most impacting freight

transport (used for transport of cement concrete up to the roadwork site) causes respectively emissions of 6.03×10^{-1} kg CFC-11 eq. and 4.17×10^{7} MJ, (i.e., 1% of total ODP and 1% of total *ADP-F*);

- for *AP*, diesel machines for earth moving, tunnel excavation, and cement grouting cause 6.89 kg SO_2 eq. (i.e 48% of total *AP*). Aggregates, concrete, reinforcing steel, and lime mortar cause 43% of the overall impact. Freight transport contributions do not rank in the top ten items: the first one's contribution is related to transport of cement concrete up to the roadwork site and represents 1% of total *AP*;
- for *EP* and *POCP*, diesel machines for earth moving machines and cement grouting cause respectively 37% and 40% of the overall impacts, respectively. Aggregates, concrete, reinforcing steel, and lime mortar cause respectively 54% and 51% of the overall impact. For both *ICs*, transport of granular materials is 1% of total impact (i.e., 3.36×10^{6} kg PO_4^{3-} eq. and 2.93×10^{3} kg C_2H_4 eq., respectively);
- *ADP-E* is the impact category with the lowest contribution of earth moving machines (i.e., 32%), while construction materials account for 48% of total consumption of abiotic depletion for non-fossil resources. The most impacting transport items (transport of cement concrete and granular materials up to the roadwork site) imply 6% of the overall impact.

The analysis of the ten most impacting items for each *IC* highlights the need for adopting strategies to reduce the impacts of tunnel excavation, road materials production and excavation. In particular, it focuses on the serious impact of tunnel construction and calls for reflection on a wider scale, involving geometric and strategic choices in the design process. Moreover, the high impacts of "standard" building materials used for road construction point out the importance of using secondary raw materials to conserve resources and promote recycling in such sector. Indeed, for each impact category, the road pavement and its materials and works cause on average not more than 1% of total impacts; on the other hand, tunnel lighting equipment does not provide relevant contributions to *ICs*.

Table 9 lists the overall A4 impacts of traffic, pavement and structures maintenance, consumption and maintenance of tunnel lighting during the 60-year service life. For the effects of the design traffic, refer to Euro 4 and Euro IV vehicle stages in reference [41]. It is a conservative approach compliant with the current Italian total fleet.

Therefore, this analysis can be correctly defined a "cradle to gate with transportation to work site and use options" study.

Table 9. LCIA—A4 phase.

IC	Unit of Measure	Traffic	Pavement and Structures Maintenance	Tunnel Lighting Consumption	Tunnel Lighting Maintenance
GWP	kg CO_2 eq.	1.44×10^{8}	1.10×10^{7}	2.03×10^{8}	3.10×10^{8}
ODP	kg CFC11-eq.	1.06×10^{1}	1.81×10^{0}	3.60×10^{1}	4.92×10^{1}
AP	kg SO_2 eq.	6.26×10^{5}	4.34×10^{4}	7.02×10^{5}	1.05×10^{6}
EP	kg PO_4^{3-} eq.	2.27×10^{5}	1.18×10^{4}	1.55×10^{5}	2.92×10^{5}
POCP	kg C_2H_4 eq.	1.64×10^{5}	9.16×10^{3}	1.29×10^{5}	3.03×10^{5}
ADP-E	kg Sb eq.	1.95×10^{1}	1.56×10^{1}	2.51×10^{0}	3.42×10^{2}
ADP-F	MJ	7.74×10^{8}	1.40×10^{8}	2.54×10^{9}	3.46×10^{9}

The bar graph in Figure 4 represents the percentage contributions of A1 to A4 phases of the examined road during its 60-year reference service life.

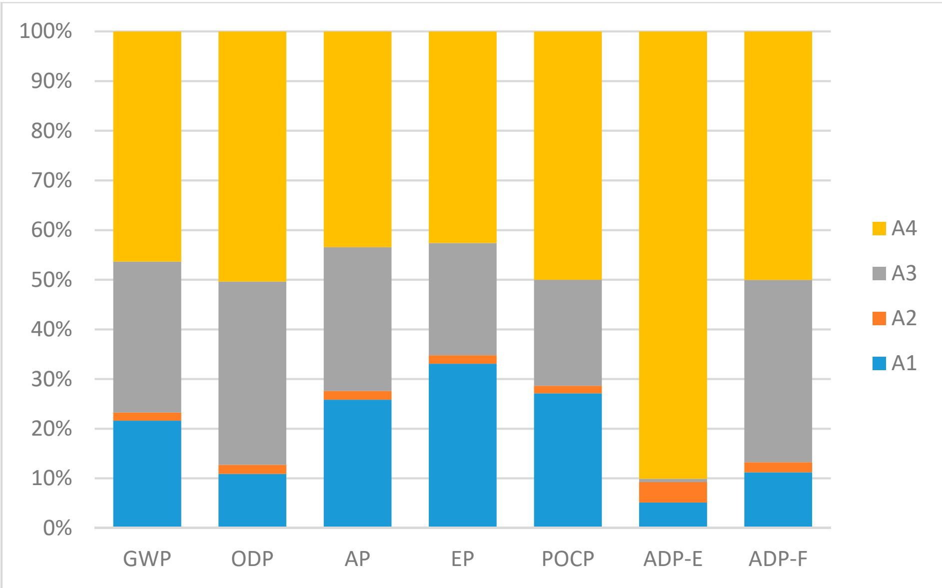

Figure 4. Environmental performances—A1 to A4 phases.

One main observation can be extracted from Figure 4: on average, A4 contributes to 53% of the overall impact of LCIA. Therefore, the reason why the road has been constructed has overall about half the total impact on the environment: raw materials, fuels, transportation and construction site set-up cause more than 47% of the overall impacts. The possible future renovation of total fleet (e.g., renovation of current fleet, use of environment-friendly engines and fuels as gas-propelled or electric vehicles) could accentuate the relative impact of the construction stage. Under the present conditions, the obtained results in terms of "transportation" incidence during the service life comply with reference [42]. According to Stripple [42], the emissions of NO_x, SO_2 and CO_2 are dominated by the road construction during a 40 year-service life.

As discussed above, the pavement contribution to the total impacts is not relevant; construction of the wearing, binder, base and subbase contribute on average to less than 1%. Even if motorization will change, loads to be transported on the road will not have substantial increases, and pavement contributions will maintain a low incidence. Accordingly, construction and impacts of big structures needed for the road (e.g., bridges and tunnels) will become even more significant.

Given the obtained results, an in-depth impact analysis with more severe traffic conditions has been carried out. According to reference [31], the authors modified the scenario and considered an increase of the road traffic volume. The number of passes of commercial and heavy vehicles varied from 1.5 million/20 years to 10 million/20 years, which is the maximum value expected in the Italian Catalogue of road pavements. The number of cars and mopeds varied accordingly to the traffic spectrum in Table 2. The increase in traffic volume required to adjust the road pavement composition [43] and its related construction and maintenance works in order to achieve the required level of service [44]. The new flexible pavement is composed of 5 cm-thick asphalt wearing course, 8 cm-thick asphalt binder course, 17 cm-thick asphalt base course, and 15 cm-thick granular sub-base.

Table 10 lists the A1 to A4 LCIA results for the amended scenario. The modification of pavement composition affects all the examined phases because it varies both the amount of materials and works (i.e., A1 to A3, upstream phases) before opening up to traffic volume and the maintenance works (i.e., A4). Conversely the increase in traffic volume only affects the use stage (i.e., A4).

Table 10. A1 to A4 LCIA of the amended scenario.

IC	Value	Unit of Measure
GWP	2.12×10^9	kg CO_2 eq.
ODP	3.39×10^2	kg CFC11-eq.
AP	7.19×10^6	kg SO_2 eq.
EP	2.01×10^6	kg $PO_4{}^{3-}$ eq.
POCP	2.02×10^6	kg C_2H_4 eq.
ADP-E	2.15×10^3	kg Sb eq.
ADP-F	2.33×10^{10}	MJ

With reference to Table 8, the assumed increase in traffic volume (+667%) more than triples the overall *IC* values: the differences range between +293% of *EP* and +567% of *ADP-E*.

Figure 5 represents the percentage contributions of A1 to A4 phases of the amended scenario during its 60-year reference service life.

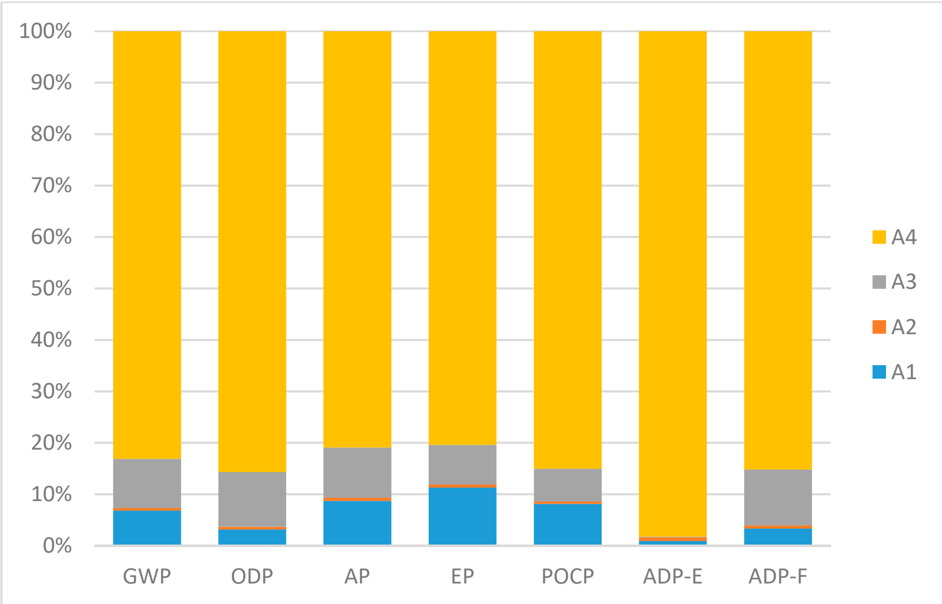

Figure 5. Environmental performances—A1 to A4 phases of the amended scenario.

All trends of the seven examined *ICs* significantly differ from the original scenario. All significant variations are due to the increase in traffic volume: the impacts of A1 to A3 phases in the amended scenario change by not more than 0.8% from the original results. An inversion of “until opening to traffic” vs “use” phase has been observed. Indeed, the contribution of A1 to A3 phases to the total impacts has almost halved (e.g., for *GWP* it decreases from 54% to 17%, for *ADP-F* from 50% to 15%). For *ADP-E*, due to its reliance on fuel consumption, the contribution of A4 phase varies from 10% to 2%.

Given the obtained results, it is possible to identify the breakeven point which represents the number of passes of commercial and heavy vehicles when the “until opening for traffic” impacts match the “use” ones. Figure 6 graphs the findings about the trend of the investigated ICs contributions: the millions of passes of commercial and heavy vehicles are represented on the abscissa, and the percentages of traffic impacts compared to the total value of each parameter are represented on the ordinate.

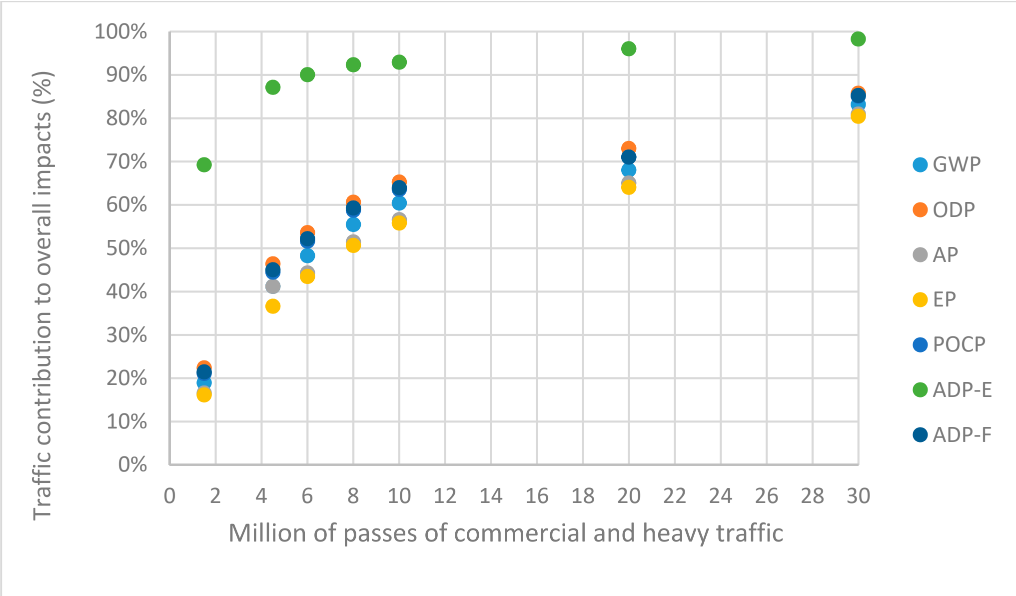

Figure 6. Incidence of traffic volume on traffic contributions to *ICs*.

According to Figure 6, the expected traffic volume during the overall service life (i.e., 4.5 million passes of commercial and heavy vehicles) causes 87% of total *ADP-E*, 46% of *ODP*, 45% of total *ADP-F*, 44% of ODP, 41% of *GWP* and *AP*, and 37% of *EP*. A traffic volume with more than 6 million passes of commercial and heavy vehicles is expected to set the condition for the traffic to contribute to half the overall environmental impacts for *ADP-F*, *POCP*, and *ODP* at least. More than 8 million passes of commercial and heavy vehicles are needed to obtain these results for *GWP*, *EP*, and *AP*.

4. Discussion

The obtained numerical results permitted to analyze the environmental impacts of the examined road and its theoretical amended scenario during their 60-year service life.

The quantitative measurements of environmental performances can be used to compare different equivalent proposals when decision-making must be carried out. Indeed, the adopted methodology can be applied to other studies in order to analyze different road projects and facilitate knowledge-based comparative assertions. Although the LCA results are quantitative, however in a (green) public procurement procedure, a decision process should identify the least environmentally damaging choice from a multidimensional perspective [45]. Comparison of all indicators against each other, which is possible only when all the adopted rules and procedures coincide, is not simple because the quantity of data, the multiple unit of measures, the various media to which substances outflow, therefore, a multicriteria decision analysis (MCDA) needs to interpret the results [46] and solve the trade-off between environmental impacts.

Moreover, the comparison of the environmental performances between the original and the amended scenario highlighted that LCA results are specific and each project should be examined under its own boundary system, geographical, social and operational conditions. In the examined case, the decision to construct a route resulted from deepen analysis and assessment of available strategic and theater lift assets, transportation infrastructure, and economic and financial forecasts. Therefore, as a result of the preliminary studies, the road alignment and geometric design cross mountain areas: this determines the structural and technical solutions, which are complex and environmentally-expensive compared to the design traffic, which is relatively low. Therefore, a comprehensive and critical analysis needs to establish the feasibility and sustainability of a road project [47]. To achieve this purpose, MCDA may be applied within the LCA context to aid interpretation of outcomes within the framework of sustainable and environmentally-friendly strategies. Indeed, the multicriteria approach would make it possible to reconcile environmental, economic, and social issues and to synthesize their various aspects.

5. Conclusions

Life Cycle Analysis has been recently adopted to study the environmental impacts of road transport infrastructure. This approach facilitates the unbiased assessment and critical interpretation of a product. This study compares—for the first time—reliable LCIA results of the environmental impacts of construction and use of an Italian provincial road. The importance of the obtained results is that they allow the identification of processes and technologies responsible for the majority of potential negative impacts on the environment. The examined road is in a mountainous region of the central Italy: therefore, 16.6% in length is raised on tunnels and viaducts. The design traffic consists of low volume: 4.5 million passes of commercial and heavy vehicles during 60-year reference service life. This condition seriously affects the LCA: the high incidence of "until opening for traffic" phases reflects the complexity of the work. According to the European standard EN 15804, seven impact categories have been assessed: the results showed that the largest part of burdens are from structural materials (e.g., aggregates, concrete, reinforcing steel and earth moving machines), while burdens from the "use" phase (i.e., maintenance, traffic, and lighting) are not more than 50% throughout the service life. Moreover, the results demonstrated that it is incorrect to consider only one environmental impact to identify the "greenest" process among several alternatives. Indeed, each indicator has a different incidence in terms of its environmental impact, and the contribution of each stage related to the LCA significantly differs from the examined parameters. In particular, the analysis highlighted the need for MCDA to interpret the results and solve the trade-off between environmental impacts.

Finally, it has been found that high traffic volumes may reduce the impacts of "until opening for traffic" to 28% of the total: when 30 million passes of commercial and heavy vehicles are expected, the "traffic" phase cause on average 82% of impacts. This demonstrates that there are important differences in the environmental performance of a road varying its design traffic: the same geometric design significantly varies its degree of environmental sustainability. Therefore, the proposed environmental approach should be integrated with social and economic criteria in order to obtain a comprehensive sustainability assessment.

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